The upgrade and characterisation of a heated two-tank system emulating typical fault conditions

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Engineering in Electrical and Electronic Engineering* at the North-West University

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Graduation: April 2024

Abstract

This dissertation covers the process of determining the shortcomings of the original heated two-tank system, as designed and constructed by P. Oberholzer [1], the improvements that were made, and the set of expanded features that were added. The dissertation also includes the characterisation of the fault emulation capabilities of the upgraded system.

The original system's effective operational range was analysed and quantified, specifically focusing on the limitations caused by component sizing. This also included an in-depth analysis regarding the effect control valves with different orifice sizes and flow characteristics had on the dynamic behaviour of the system. The system is then redesigned and upgraded based on the results of the analysis, mainly focusing on improving the control valve range and behaviour as well as the controllable temperature range. The control valve range is based on the utilised valve lift range for controlling the level and temperature of the system. The controllable temperature range is defined as the maximum temperature difference that the system can maintain between the two tanks as well as the maximum and minimum recommended temperature that can be maintained by the system. The effect of the component sizing redesign is then shown based on the upgraded system's dynamic range.

Lastly, the fault emulation capabilities of the upgraded system are explored. This is done by defining the faults that the upgraded system can emulate and then analysing and characterising these faults.

Keywords: FDI, Valve sizing, Benchmarking systems, Heated two-tank system, Fault emulation, System characterisation, PLC, Control systems.

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Abbreviations

FDI Fault Detection and Isolation. 1, 3, 7, 9, 10, 11, 16, 37, 67, 113, 114, 122

HMI Human Machine Interface. 6, 7, 21, 34, 36, 119, 122, 133, 140, 141, 142

IEC International Electrotechnical Commission. 38

IFAC International Federation of Automatic Control. 10

PCA Principal Component Analysis. 122

PLC Programmable Logic Controller. 2, 4, 6, 7, 21, 34, 36, 122, 128, 140

VSD Variable Speed Drive. 3

1 Introduction

1.1 Background

A major challenge in modern large-scale industrial processes is the effective and efficient operational control of the plant. The operation of a plant as defined by O. M. Rouhani in [2] is the proactive, organised, and systematic coordination of the conversion, distribution, and utilisation of energy. One of the key factor to efficient plant operation lies in energy efficiency. The upkeep cost of a large-scale industrial plant is greatly increased when an entire section has to be taken offline during maintenance. According to C. Karlsson in [3] the probability of a major plant breakdown resulting in the plant having to be taken offline can be greatly reduced by utilising appropriate Fault Detection and Isolation (FDI) schemes. It is however difficult to test these FDI schemes on actual process control plants since they can rarely be taken offline or reconfigured to emulate an actual fault that could occur. Such faults could potentially harm the plant. Therefore a simulation model of the process plant can be utilised to test various FDI schemes and fault conditions. These simulation models will always be limited in functionality to a certain degree since it takes time to develop an accurate model of any system. This is where a benchmarking system shines most since it emulates a process control plant and provides practical data that can be used.

The existing heated two-tank system situated in the chemical labs at the NWU, as shown in figures 1.1, 1.2, and 1.3, that will be used throughout this dissertation was originally designed and constructed by P. Oberholzer [1]. The piping and instrumentation diagram of the original system can be found in appendix B. The purpose of the heated two-tank system is to serve as a multi-domain physical benchmarking system that can emulate typical process faults for the purpose of condition monitoring. The system therefore allows researchers to obtain practical data on a physical benchmarking system instead of having to rely on simulations. The heated two-tank system has thermal-fluid, mechanical, electrical, and non-linear characteristics which makes it an ideal multi-domain benchmarking system.

The original heated two-tank system does however have some shortcomings that can be improved upon. The inner diameter of the proportional valves used to regulate the cold water input flow rate of both tanks and the hot water flow rate of the heating coils within both tanks is currently too big. This significantly limits the operating range of the proportional valves. Therefore, the control valves are only used within a small region of their full valve lift range thereby effectively decreasing the controllable valve lift resolution. The temperature sensors used to measure the temperature of both the cold and hot water input only have

Figure 1.1: Original heated two-tank system [1]

a resolution of 1 °C. Due to thermal inertia the actual temperature measurement accuracy might not be higher than 1 °C, however, having a higher resolution will increase the sensitivity of the temperature sensors and give a better indication of the temperature fluctuations. The gas heater (Bosch Optiflow 26L) used to regulate the temperature in the hot water cycle fluctuates around its own setpoint. This causes the temperature of the hot water reservoir to also fluctuate. The temperature of the hot water flowing through the heating coils within the two tanks therefore also fluctuates which negatively impacts the repeatability of any test run on the system.

The functionality of the heated two-tank systems can potentially be extended with the following suggestions. The heat transfer between the heating coils and the tanks can be determined by adding temperature sensors to both the input and output of the heating coils. This can also potentially be used to determine the fouling of the heating coils. Currently, there is no dedicated temperature sensor within the hot water reservoir. The hot water temperature is currently only being measured at the input to the heating coils. As previously mentioned this temperature sensor has a resolution of only 1°C and therefore causes the gas heater to overcompensate leading to the hot water reservoir temperature to fluctuate. This is due to the fact that the gas heater's proprietary controller has a time delay of several tens of seconds resulting in significant overshoot. This is especially the case when a bang-bang controller on the PLC is used to activate and deactivate the hot water circulation pump connected to the gas heater. This behaviour can be improved upon in various ways. The simplest method would be to add a dedicated temperature sensor within the reservoir which will allow the hot water cycle to better regulate the temperature. Furthermore, the pump connected between

Figure 1.2: Original heated two-tank system - Heating coils [1]

the gas heater and the reservoir can be replaced with a VSD controlled pump. This allows the hot water cycle to control the flow rate of hot water to the reservoir thereby further improving the temperature regulation of the reservoir.

The temperature of tanks 1 and 2 is currently regulated by adjusting the flow rate of hot water within the respective heating coils. The system settling time to a change in the temperature setpoint can be decreased by additionally controlling the temperature of the hot water cycle. This does however pose a control problem/complexity since both tanks would then be able to control the hot water temperature resulting in conflicting setpoints.

1.2 Research objectives

It was discovered that the original heated two-tank system is limited in terms of its overall functionality during the previous study done by W. Wolmarans [5]. This led to the results obtained during the study not accurately portraying the capability of the energy-based FDI technique. The actual functionality of the current heated two-tank system should therefore be investigated. The objective of this research is to analyse the functionality of the current system and based on the outcome, upgrade and characterise the system for future research.

1.2.1 Analyse the current functionality of the system

Analyse the current functionality of the heated two-tank system to determine the level and temperature control functional ranges. This is done in order to determine the extent to which the current system can control the level and temperature of both tanks.

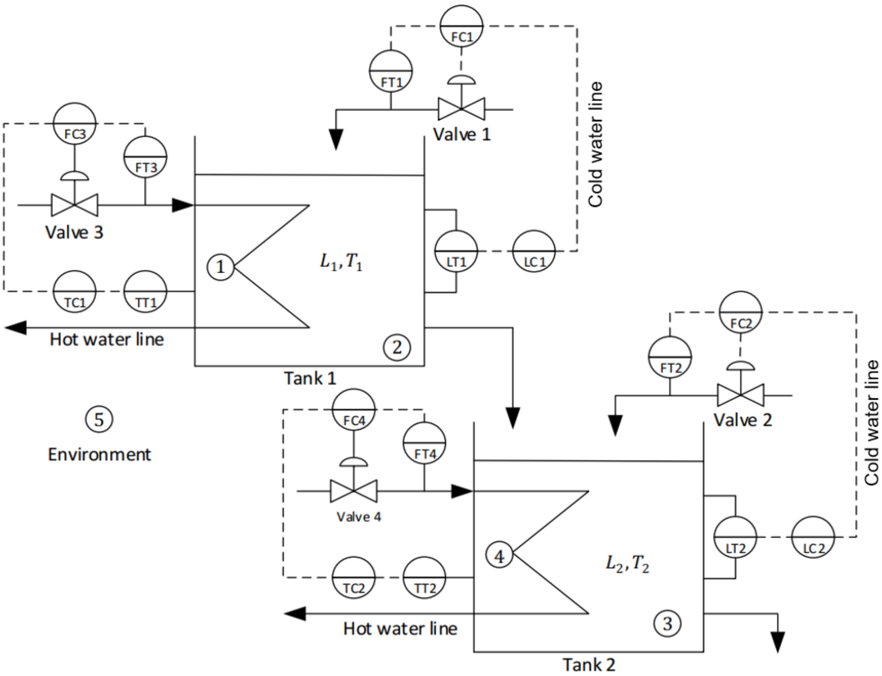


Figure 1.3: Simplified heated two-tank system [4]

The functional level control range determines the extent to which the system can control the actual level of both tanks. This includes the full set of level setpoint combinations that the system can maintain within both tanks.

The functional temperature control range determines the extent to which the system can control the actual temperature within both tanks. This includes the temperature that the system can maintain within both tanks as well as the difference in temperature that the system can maintain between the two tanks.

1.2.2 Detail design of system upgrades

Produce a detailed design of the system upgrades. This includes specific component upgrades along with the reason for these specific upgrades.

1.2.3 Implementation of system upgrades

Upgrade the actual system with the determined upgrades. This includes the construction of new piping networks and the installation of sensors, control valves, and pumps. The PLC is also upgraded.

The upgraded system, depending on the chosen upgrades to be made, allows the system to more accurately measure process variables and emulate additional faults. The upgraded control system and UI allow for more complex experimental procedures to be carried out thereby also allowing additional complex and time-varying faults to be emulated.

1.2.4 Upgraded system characterisation

Analyse the functionality of the upgraded heated two-tank system and determine the level and temperature control functional ranges.

The upgraded heated two-tank system should be analysed to determine the level and temperature control functional ranges. This is done to determine the extent to which the upgraded system can control the level and temperature of both tanks.

The functional level control range determines the extent to which the system can control the actual level of both tanks. This includes the full set of level setpoint combinations that the system can maintain within both tanks.

The functional temperature control range determines the extent to which the system can control the actual temperature within both tanks. This includes the temperature that the system can maintain within both tanks as well as the difference in temperature that the system can maintain between the two tanks.

Characterising the upgraded heated two-tank system's functionality and behaviour provides additional information regarding the system's capabilities thereby clearly defining the operating limits of the actual system. The normal operational conditions are also properly defined.

1.2.5 Analyse the upgraded system fault emulation capabilities

Analyse the fault emulation capabilities of the upgraded system.

Characterising the upgraded heated two-tank system's fault emulation capabilities allows the system to more accurately emulate typical process faults. The emulated fault magnitudes are also defined in terms of applicable units such as l/min instead of valve lift.

1.3 Research methodology

1.3.1 Analyse the current functionality of the system

Analyse the current functionality of the heated two-tank system using the operational data obtained experimentally. This is achieved by operating the system at various level and temperature setpoints.

The functional level control range is determined by analysing the system at various level setpoint combinations for both Tank 1 and Tank 2. This is done to determine the flow rate range required to control both tank levels as well as the level control valve flow characteristics.

The functional temperature control range is determined by analysing the system at various temperature setpoint combinations for both Tank 1 and Tank 2. This is done to determine the flow rate range required to control both tank temperatures as well as the temperature control valve flow characteristics.

This is achieved by designing an experimental flow diagram that defines the entire testing procedure. The experimental flow diagrams indicate the various level and temperature setpoints required for each test as well as the order in which, and the condition at which each setpoint is changed. The original system's level and temperature control experimental designs are covered in detail in Chapter 3.

1.3.2 Detail design of system upgrades

Recommend various upgrades based on the results obtained while analysing the functionality of the current heated two-tank system. Including possible new control valves, pumps, sensors, and control system functionality.

A detailed valve sizing design is done based on the current system's level and temperature control valve characteristics. This includes various valve sizing techniques.

The features that the system's PLC are currently lacking are discussed. The improvements that can be made to the PLC and the HMI are covered and designed.

1.3.3 Implementation of system upgrades

The implementation of the system upgrades entails the modification of the system as well as the installation of all of the upgrades indicated during the original system analysis. This also includes a functional check of the system during operation to ensure that all of the upgrades are successful. The process variable sensors are calibrated and the values reported to the PLC are verified to ensure that they are interpreted correctly.

The PLC controlling the system is also upgraded. These upgrades include various control improvements as well as additional functionality added to improve data gathering and experimental setup for the rest of this study as well as future research done on the heated two-tank system

1.3.4 Upgraded system characterisation

Analyse the upgraded system functionality using experimental data obtained on the upgraded system. This is achieved by operating the system at various level and temperature setpoints.

The functional level control range is determined by analysing the system at various level setpoint combinations for both Tank 1 and Tank 2. This is done to determine the flow rate range required to control both tank levels as well as the level control valve flow characteristics.

The functional temperature control range is determined by analysing the system at various temperature setpoint combinations for both Tank 1 and Tank 2. This is done to determine the flow rate range required to control both tank temperatures as well as the temperature control valve flow characteristics.

This is achieved by designing an experimental flow diagram that defines the entire testing procedure. The experimental flow diagrams indicate the various level and temperature setpoints required for each test as well as the order in which, and the condition at which each setpoint is changed. The upgraded system's level and temperature control experimental designs are covered in detail in Chapter 5.

1.3.5 Analyse upgraded system fault emulation capabilities

Analyse the extent to which the upgraded system can emulate various faults using the same methodology used to determine the functional level and temperature control ranges. Each fault is induced separately into the system and the effect of the fault is determined by comparing the system behavior with and without the fault.

1.4 Dissertation outline

Chapter 2 (Literature study) presents the key literature to the study including research covering fault emulation, fault detection and isolation, chemical process control, control valves, and the modelling of mechanical systems. Chapter 3 (Original system analysis) presents the analysis of the original heated two-tank system including its functional level and temperature control ranges as well as various shortcomings. Chapter 4 (System upgrade) presents the detailed design of the upgraded system, which includes the detailed design done on the control valves, the additional features added to the system itself, and the upgrade and improvement of the system PLC and HMI. Chapter 5 (Upgraded system characterisation) presents the analysis of the upgraded heated two-tank system including its functional level and temperature control ranges. The valve sizing method and valve upgrades are also validated by comparing the actual and theoretical valve characteristics of the upgraded system. The faults that the upgraded system can emulate are analysed and characterised. This includes single-fault system characterisation in which a single fault is induced into the system and the system's behaviour is analysed to determine the effect that the fault has on the system. Chapter 6 (Data in brief) presents a benchmarking system-oriented data set to the FDI research community. Chapter 7 (Conclusion) concludes the dissertation based on the outcome of the system upgrade and characterisation. Recommendations are made regarding future research and possible system improvements. The study as a whole is also reflected upon.

2 Literature study

2.1 Introduction

In Chapter 1, the motivation for analysing the performance of the current heated two-tank system was made clear. This chapter aims to discuss the relevant literature within the field of benchmarking systems, fault detection, and fault emulation. The key aspects of benchmarking systems are briefly covered along with relevant studies done on several practical and theoretical benchmarking systems. After this, the principles of fault detection are covered along with the need for benchmarking systems to test FDI schemes on. System faults are then characterised along with possible fault emulation strategies.

A brief introduction to the modelling of control valves, flow types, and pressure drops is also given. Finally, the chapter concludes with a brief critical literature review to highlight the applicability of the surveyed literature.

2.2 Benchmarking systems

Within the process control industry, well-tested and established methods are preferred above new techniques. Therefore new technologies have to be thoroughly tested and validated before they can be implemented in large-scale industrial processes. It was proposed by R. S. Smith in [6] to use laboratory systems for testing purposes since experimenting with large-scale industrial systems can be quite expensive and may lead to significant downtime resulting in a loss in production. This is where the use of benchmarking systems, scale models, and digital twins comes into play. Benchmarking systems and scale models give the researcher access to a physical system on which the new technology can be tested and developed without the risk of revenue loss. Digital twins on the other hand have no physical risk associated with them since they operate entirely within the digital domain [7].

Benchmarking is defined as the process of comparing or measuring a device, process, plant, control strategy etc. against a known and verified standard. A benchmarking problem is a reference problem that can be used to perform a benchmarking analysis. Therefore a benchmarking system can be defined as a system that can be used to emulate typical benchmarking problems and perform benchmarking analysis. These systems also have the added benefit of being a physical system that has to adhere to cycle times, discrete sampling intervals, communication overhead with the processor, and model mismatch [8]. In the control and FDI communities a benchmarking system is used to analyse the performance of new and untested control and FDI strategies, thereby narrowing the gap between theory and practice [9, 10].

A collection of control system benchmarking problems was published by IFAC in [11]. The idea behind this report was to provide the control community with a collection of standard problems which could be used to compare existing or new control strategies and control system design tools. This allowed the control community to standardise the testing methodology of new control strategies. The report contains a list of 13 benchmarking problems that are based on real-world problems.

Juliani and Garcia [12] presented a list of typical chemical plant benchmarking processes. These benchmarking processes were used to investigate several plantwide control methods. The pulp mill benchmarking problem is described by J.J. Castro and F.J. Doyle in [13]. It highlights the usefulness of benchmarking systems that cover plantwide control and consist of several interlinked components. It is also mentioned that the process variables along with their associated operational costs can be used to perform a plantwide cost optimisation study.

The classic two-tank system benchmarking control problem was proposed by Smith and Doyle [6]. The system was designed not to mimic the physical details of a practical engineering system but rather to provide a similar control design problem. The system consisted of two tanks of which the first was supplied with both a cold and hot water supply and the second being supplied with the output of the first as well as a constant cold water supply. This configuration allows the system to control the level of the first tank and the temperature of both tanks. The paper also highlights the characterisation of the system that was done in an attempt to create an accurate system model.

A three-tank benchmarking problem is proposed by B. Heiming in [14]. The benchmarking problem is defined to be the ability to find a new control strategy if a fault occurs in the technical plant. The fault emulation capabilities of their system include sensor faults, actor faults, blocked valves, and a leaking tank.

2.3 Fault detection and emulation

K. Severson [15] defined a disturbance to be an unknown and uncontrolled input that is acting on a system, a fault to be an unpermitted deviation of at least one characteristic property or parameter of the system from the normal operating conditions, and a failure to be a permanent interruption of a system's ability to perform a required function under specified conditions. A fault is defined by V. Venkatasubramanian [16] as a deviation from an acceptable range of an observed variable or a calculated parameter linked to a process. This defines a fault as a process abnormality where the underlying cause is referred to as the root cause. Generally process faults can be categorised by the following: Gross parameter changes in a model caused by an external disturbance entering the process through one or more independent variables; Structural changes in the process itself leading to changes in the information flow between various variables; and Malfunctioning sensors and actuators.

V. Venkatasubramanian [17] states that in real process operations, the system will be subjected to random disturbances and noise. For a stochastic system, its future state is not entirely determined by past or present states nor future control actions. The process variable measurements are considered to be statistical time series. If the system is under control then the system observations will have probability distributions associated with them that correspond with the normal operation of the system. These distributions are normally characterised by statistical parameters such as the observations mean and standard deviation values. These distributions can however change when a fault occurs within the system. Fault detection is therefore the process of detecting changes in the parameters of a static or dynamic stochastic system [17].

In his dissertation, J. J. Miskin [18] did a comprehensive study on the type of faults that can occur in a chemical plant. He defined a fault characteristic as a quality of features that belong to and describe a fault. The fault characteristics are divided into the following 6 categories: Classification, fault transition rate, frequency of fault occurrence, priority of fault mitigation, type of fault, and fault symptoms. Fault classification has to do with the location where a fault originates such as controller malfunctions, actuator faults, structural failures, and sensor failures. The fault transition rates are categorised into abrupt faults, incipient faults, and intermittent faults. The frequency of fault occurrence is used to determine the severity of a fault based on its occurrence rate. Priority of fault mitigation can be used to analyse the fault risk. The fault types are divided into additive faults, which result in the output of a process having an offset equal to that of the fault magnitude, and multiplicative faults, which result in the output of a process changing based on both the input of the process and the fault magnitude. Lastly, fault symptoms are defined as the indications that a system presents when a fault occurs, such as a deviation in pressure, temperature, flow rate, and level measurements. J. J. Miskin [18] also provided a comprehensive list of typical faults that can occur in a chemical plant. These faults included sensor drift and bias, unwanted setpoint changes or incorrect setpoints, stuck valves, pipe blockages, system leakages, improper mixing, sedimentation, and instrument failure.

A benchmarking system should therefore be able to emulate typical process faults in order for it to be used in FDI research. M. Hsueh [19] discussed several fault injection techniques and tools that can be used to evaluate the dependability of computer systems. One of the key concepts mentioned is the fact that fault injection can be achieved by using either additional fault hardware or emulating a fault using software.

2.4 Modelling

The modelling sections gives the relevant literature required for the analysis and designs chapters. This section creates the foundation upon which the concepts in Chapters 3, 4, and 5 are based on.

2.4.1 Control valves

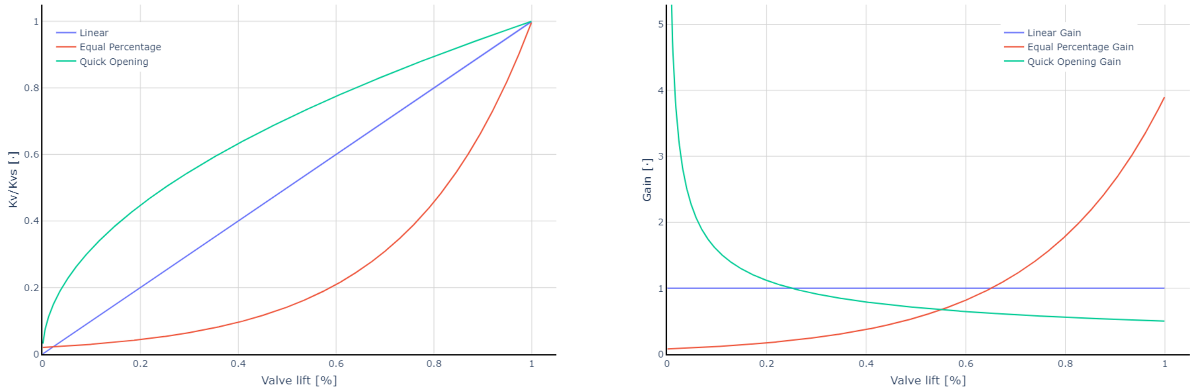
Control valves are most commonly used in process control plants to regulate process variables around a desired setpoint [20]. The control valve regulates the flow rate of a liquid or a gas by adjusting the position of the valve plug or disk via the valve actuator. Typical process variables include mass flow rate, pressure, and temperature. Control valves come in a range of types and characteristics and choosing one requires careful consideration in relation to the application and required system performance.

Valves are usually rated by their nominal orifice diameter and K_{vs} values. The K_{vs} value describes the flow rate of water, at 20°C, through a valve with a 1 bar pressure loss at maximum valve lift. The K_v value of a valve describes the flow rate at a specific valve lift and pressure. Therefore a valve can be sized by determining a range of required K_v values (K_{vr}) at the desired flow rates - typically at the mean and maximum desired flow rates. A general rule of thumb is to ensure that the K_{vr} at the maximum desired flow rate is 10% smaller than the chosen valve K_{vs} value. The K_v value can typically be calculated as follows:

$$K_v = Q\sqrt{\frac{\rho}{1000\Delta p}}, \tag{2.4.1}$$

with Q the flow rate in m^3/h, Δp the pressure drop across the valve in bar, ρ the fluid density in $\mathrm{kg/m}^3$.

Most control valves will have one of the following three typical flow characteristics: Quick opening, linear, and equal percentage. Quick opening valves are used for on/off control. They produce a high flow gain for a small change in valve lift. Linear valves have a linear relationship between their lift and flow rate. Lastly, equal percentage valves will produce an equal percentage gain in flow rate for a corresponding change in valve lift. The three control valve flow characteristics are depicted in figure 2.1a with their corresponding gain characteristics in figure 2.1b. The standard process control model is given in [21] and is depicted in figure 2.2. It includes the process controller (G_c), control valve transfer function (G_v), process transfer function (G_p), disturbances (G_d), and sensor/measurement transfer



(a) Flow Characteristics (b) Valve Gain

Figure 2.1: Basic valve configurations

function (G_m). In order for the closed-loop control to be stable the open-loop gain (2.4.2) should either remain constant or stick within the system stability margins.

$$K_{OL} = |K_p| K_v K_m K_{IP} K_c, \tag{2.4.2}$$

with K_p the plant gain, K_v the control valve gain, K_m the sensor gain, K_{IP} the current to pressure transducer gain, and K_c the controller gain.

This can be achieved by specifically choosing an appropriate valve flow characteristic to counteract the change in the process gain thereby effectively cancelling out or minimising the overall change. For level control, it is recommended to use linear control valves since level control applications usually have short pipe lengths resulting in most of the pressure to be dropped across the valve. Equal percentage valves are usually specified for temperature control systems as these applications usually require longer pipe runs and they then have nearly linear installed characteristics because the pipe pressure drop increases with increasing flow, leaving less pressure drop across the valve..

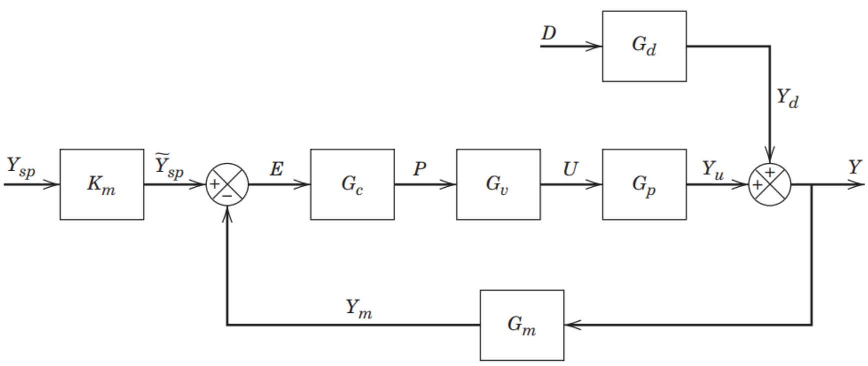


Figure 2.2: Basic process control block diagram [21]

2.4.2 Flow in pipes

The Reynolds number is a dimensionless quantity that can be used to predict fluid flow patterns or in other words whether or not the flow is more likely to be laminar or turbulent [22]. It can be determined using the following:

$$Re = \frac{\rho D v}{\mu} = \frac{4\rho Q}{\pi D \mu}, \tag{2.4.3}$$

with ρ the density of the fluid (kg/m^3), D the internal diameter of the pipe (m), v the liquid velocity (m/s), μ the dynamic liquid viscosity (Pa $\cdot$ s), Q the mass flow rate (m^3/s).

2.4.3 Pressure drop

The pressure drop across the control valve is an important design characteristic since it affects the type of flow through the valve [20]. If the valve outlet pressure is situated around the vapour pressure of the liquid flowing through it, it could result in either cavitation or flashing flow. The pressure drop across the valve should therefore be determined or designed for in such a way as to ensure the desired behaviour.

The system head loss is defined as the pressure difference between the inlet and outlet of the system. For an open system the inlet pressure would be the head provided by the pump and the outlet pressure would be at atmospheric pressure. The total system head loss can be described by the following:

$$\Delta P_{system} = P_{Inlet} - P_{Outlet}. \tag{2.4.4}$$

The head loss of the system is the net sum of the head loss across the different components situated within the system itself. These components most commonly consist of the head loss due to a change in elevation, the head loss due to pipe friction, the head loss due to an inline sensor, and the head loss due to a valve. The total system head loss can therefore be described as follows:

$$\Delta P_{system} = \Delta P_{Elevation} + \Delta P_{Friction} + \Delta P_{Sensors} + \Delta P_{Valves}, \tag{2.4.5}$$

with $\Delta P_{Elevation}$ the head loss due to gravity, $\Delta P_{Friction}$ the head loss due to the friction within the pipes, $\Delta P_{Sensors}$ the head loss due to any inline sensors installed in the system, and ΔP_{Valves} the head loss due to any valves installed in the system.

The Head loss due to elevation is given by,

$$\Delta P = \rho g h, \tag{2.4.6}$$

with ρ the density of the fluid (kg/m^3), g the acceleration due to gravity (m/s^2), and h the difference in elevation (m).

The Head loss due to friction is given by,

$$\Delta P = f \left[\frac{\rho L}{2D}\right] \left[\frac{Q}{A}\right]^2, \tag{2.4.7}$$

with f the Darcy friction factor, ρ the density of the fluid (kg/m^3), L the equivalent pipe length (m), D the internal pipe diameter (m), Q the mass flow rate (m^3/s), and A the inner pipe area (m^2).

The equivalent length of the pipe is equal to the sum of all of the pipe lengths and the equivalent lengths of each elbow and bend. The equivalent length of an elbow connector is affected by the ratio of the elbow radius to its diameter. The equivalent length of most standard elbow connectors and fittings has already been calculated and readily provided such as in [23].

The Darcy friction factor can be determined by using the Colebrook-White equation as follows:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log_{10}\left[\frac{\varepsilon}{3.7 \cdot D} + \frac{2.51}{Re\sqrt{f}}\right], \tag{2.4.8}$$

with f the Darcy friction factor, ε the pipe's effective roughness (m), D the internal pipe diameter (m), and Re the Reynolds number. This is however an implicit equation. It can therefore only be solved iteratively. There are however other methods that can be used to approximate the Darcy friction factor without having to rely on an implicit equation. These methods include the Churchill (2.4.9), and Zigrang-Sylvester (2.4.10) approximations.

Churchill approximation:

$$\frac{1}{\sqrt{f}} = -2 \cdot \log_{10}\left[\frac{0.27\varepsilon}{D} + \left(\frac{7}{Re}\right)^{0.9}\right], \tag{2.4.9}$$

with $1E - 6 \leq \varepsilon \leq 1E - 5$.

Zigrang-Sylvester approximation:

$$\frac{1}{\sqrt{f}} = -4 \log_{10}\left[\frac{\varepsilon}{3.7D} - \frac{5.02}{Re} \cdot \log_{10}\left(\frac{\varepsilon}{3.7D} + \frac{13}{Re}\right)\right]. \tag{2.4.10}$$

Most manufacturers of invasive type sensors, such as flow sensors, will provide a pressure loss vs. flow rate curve in the sensor's datasheet. The pressure loss due to the sensor at a given flow rate can therefore be read directly from the datasheet.

The pressure drop across the valve can then be calculated by determining the valve inlet and outlet pressures based on the requirements/specifications of the system upstream and downstream from the valve. The valve pressure drop can also be determined by simply calculating the pressure drop across the rest of the system. This can be shown mathematically by rewriting (2.4.5) in terms of the pressure drop across the valve as follows:

$$\Delta P_{Valves} = \Delta P_{system} - \Delta P_{Elevation} - \Delta P_{Friction} - \Delta P_{Sensors}, \tag{2.4.11}$$

2.5 Critical literature review

The relevant literature sources for this study have been covered throughout the literature study thus far. The key concepts relevant to this study are as follows: The use of benchmarking systems in control and FDI research as well as the basic configuration of a benchmarking system; typical chemical plant faults that can occur; the basics of fault detection; the modelling theory of control valves, fluid system pressure drops and flow types.

The articles by V. Venkatasubramanian [16,17,24] are fundamental to understanding the key concepts behind fault detection. Especially the fact that the statistical distributions of the system observation change when a fault occurs. V. Venkatasubramanian also presented a set of desirable characteristics that an ideal diagnostic system should have. These characteristics include the following: quick detection and diagnosis, isolability, robustness, novelty identifiability, classification error estimate, adaptability, explanation facility, modelling requirements, storage and computational requirements, and multiple fault identifiability. While this study does not focus on FDI schemes, these characteristics can still be useful while upgrading the current system since they can be used to identify the system's shortcomings and potential upgrades and improvements that can be made to address these shortcomings.

The master's dissertation done by J. J. Miskin [18] provides useful information regarding typical faults that can occur in a chemical plant. This information can be used when upgrading the fault emulation capabilities of the heated two-tank system.

The 'Fundamentals of Fluid Mechanics' textbook [22] provides useful information regarding fluid flow types and pressure drop calculations. This information provides the fundamental principles required for analysing the behaviour of the heated two-tank system. Such as the basics behind the dynamics of a liquid flowing through a pipe and the basic principles behind heat transfer which can be used to analyse the dynamic model of the heated two-tank system as designed by B. Lidner in [25]. This textbook can also be used along with the Control Valve Handbook [20] to properly analyse the control valves and perform a valve sizing exercise.

3 Original system analysis

3.1 Introduction

It was previously discussed that during the study done by Wolmarans [5] it was discovered that the current heated two-tank system had some possible shortcomings. Based on these results and a preliminary analysis of the current operation of the heated two-tank system the following hypotheses are presented:

1. The control valves are oversized resulting in a smaller valve operating range
2. The control valves exhibit inappropriate flow characteristics resulting in higher controller effort
3. The cold water cycle heat exchanger is undersized limiting the temperature range of the system

The purpose of this chapter is, therefore, to prove or disprove these hypotheses as well as to discover any other possible system shortcomings. This is done by analysing the current functionality of the heated two-tank system, as designed and built by Pieter Oberholzer in [1]. Based on the outcome of the system analysis a list of possible system upgrades and improvements will be given.

3.2 System analysis

The basic operation of the heated two-tank system can be divided into two categories: Level control and temperature control. Both level and temperature control are implemented using a closed-loop feedback control scheme. Level control is achieved by controlling the cold input flow rate of each tank by adjusting the cold input valve lift of each tank. Temperature control is achieved by controlling the flow rate through each of the tank's heating coils by adjusting the hot input valve lift of each heating coil. The detailed piping and instrumentation diagram of the heated two-tank system can be found in appendix B.

The first hypothesis postulates that the system control valves are oversized resulting in a smaller valve operating range. This extends to both the level control and temperature control valves. Oversized control valves tend to add a large amount of flow gain for a small increment in valve lift leaving less flexibility in adjusting the controller output. The control valves are also more likely to operate more frequently due to the disproportionate amount of flow change per valve lift increment. The oversized valves, therefore, tend to act more like quick-opening valves which are usually not recommended for use in proportional control systems. This is due to the fact that quick-opening valves act like on-off valves [20]. The system's operational range and the corresponding control valve control range have to be determined in order to be able to prove or disprove this hypothesis.

The second hypothesis postulates that the system control valves exhibit inappropriate flow characteristics leading to higher controller effort. Different processes call for different types of control valves based on the available pressure across the control valve and the desired valve gain. In general level control calls for a linear control valve whereas temperature control benefits more from an equal-percentage control valve [20]. In order to prove or disprove this hypothesis the control valve flow characteristics will have to be determined. In the case where they do exhibit inappropriate flow characteristics the control valves will have to be resized and the upgraded control valves controller effort will have to be compared with that of the original systems.

The third hypothesis postulates that the cold water cycle heat exchanger is undersized limiting the temperature range of the system. This can cause the temperature of the cold water reservoir to change based on the current temperature setpoints of the two tanks. This means that the cold water input temperature will not be constant across the entire temperature range of the system. The system's operational temperature range and the corresponding cold water reservoir temperature have to be determined in order to be able to prove or disprove this hypothesis.

Analysing the functionality of the original system, therefore, requires the following system aspects to be determined: The level and temperature control operational range, the level and temperature controller efforts, and the level and temperature control valve flow characteristics. It should however be noted that this chapter aims to simply analyse the original system and not characterise it. The level and temperature control operational ranges will therefore only be given to the extent that is needed to determine whether or not there are aspects that can be improved upon.

3.2.1 Operational range and valve characteristics

3.2.1.1 Level control

The level control operational range is defined as the level at which each of the two tanks can be maintained. This includes the input flow rate required for each tank at a given level. The level control valves are analysed by determining the range of valve lifts that are required to control the levels of each tank. The level control valve flow characteristics are defined as the connection between the level control valve lift and the corresponding mass flow rate through the valve.

The level control operational range will be documented after analysing the system by presenting the operational range in both tabular and graphical formats. The range of levels at which each tank can be maintained will be given along with the corresponding mass flow rates and control valve lifts.

3.2.1.2 Temperature control

The operational temperature control range is defined as the temperature at which each of the tanks can be maintained and the corresponding input flow rate required at each of these tank temperatures. This also includes the temperature difference that can be maintained between the two tanks.

The temperature control valves are analysed by determining the range of valve lifts that are required to control the temperature of each tank.

The temperature control valve flow characteristics are defined as the connection between the temperature control valve lift and the corresponding mass flow rate through the valve.

The temperature control operational range will be documented after analysing the system by presenting the operational range in both tabular and graphical formats.

3.2.2 Controller effort

Controller effort does not have an explicit definition and may refer to anything from the instantaneous controller output to the power related to the control signal. For the purposes of this dissertation the term controller effort refers to the amount of effort that the controller has to exert to maintain the steady-state condition of a controlled process variable. The amount of effort will be defined by both the standard deviation of the controller output signal during steady-state as well as the normalised variability of the controller output over time [26]. The standard deviation of the controller output can be determined using the following:

$$\sigma = \sqrt{\frac{\Sigma(x_i - \mu)^2}{N}}, \tag{3.2.1}$$

with x_i the i^{th} element of the controller output, μ the mean value of the controller output, and N the number of elements in the controller output vector.

The normalised variability of the controller over time can be determined using the following:

$$Q_K = \frac{1}{T}\frac{1}{\Delta x}\sum_{k=1}^{K-1}\left|x_k - x_{k-1}\right|, \tag{3.2.2}$$

with Q_k the controller effort, T the time horizon, Δx the nominal range of the controller output, and x_k the controller output at element k.

3.2.3 System shortcomings

3.2.3.1 Sensors

It is currently assumed that the heat transferred from the heating coils to the water situated within each tank is constant. This is however not the case since the heat transfer capability of the heating coils is dependent on the exposed contact area of the heating coil with the water within the tank. The heat transferred from the heating coils to the water situated within each tank can be determined by measuring both the input and output temperature of each heating coil at different tank level and temperature setpoints.

There is no dedicated temperature sensor measuring the temperature of the hot water reservoir. It is currently only being measured using the built-in temperature sensor of the flow sensors (ifm SBG246). These sensors have a limited temperature resolution of 1°C and will only measure the temperature of the hot water reservoir if there is water flowing through the heating coils. This affects the response time of the bang-bang controller used to control the hot circulation pump connected to the gas heater leading to a severe dip in the hot water reservoir temperature.

There is no dedicated temperature sensor measuring the temperature of the cold water reservoir. It is currently only being measured using the built-in temperature sensor of the flow sensors (ifm SBG246). These sensors have a limited temperature resolution of 1°C. Using these sensors should however not pose as big a problem as with the hot water reservoir since the input flow rate of either one of the tanks will almost always be non-zero except for the case where the tanks are being drained or the level decreased significantly.

3.2.4 Fault emulation

There is currently no blockage valve on the output of Tank 2. This is due to the fact that the previous blockage valve was too small causing the input flow rate of Tank 2 to be extremely low and could lead to Tank 2 overflowing due to the output flow rate of Tank 1.

The current system only emulates pipe leakages in the cold water cycle. This leakage emulation functionality can easily be extended to the hot water cycle by installing two additional leakage valves. Emulating a leakage in the hot water cycle is however somewhat more involved since a loss of water in the hot water cycle also constitutes a loss of energy.

The current system's fault emulation functionality with respect to stuck valve faults and sensor drift faults is somewhat limited. The stuck valve faults are limited to the level control valves whereas the sensor drift faults are limited to the tank temperature sensors. The fault emulation capability can be extended to the rest of the control valves and sensors without any additional costs since a stuck valve and sensor drift fault is implemented in software.

3.2.4.1 PLC, HMI, and data acquisition

The data stored during an experiment lack several process variables and setpoints. This means that a data set can not be interpreted without an accompanying experimental setup document and even then it is difficult to determine the magnitude and exact index at which a fault is induced or a process variable setpoint changed.

The current control system requires the operator to manually adjust the system parameters for each step in an experiment. This means that a multi-step experiment requires the operator to be present for each step and that the duration of a step has to be timed externally from the PLC. This results in inconsistent experiments and is significantly more susceptible to human error.

The HMI used to relay information regarding the system to the operator is lacking. There is currently no way of inspecting the valve lift of any of the control or fault valves, the rest of the process variables are given on a graphical screen containing a lot of visual clutter. This is a good method to relay an overview of the system functionality and operational state to an operator but not a great way of relaying critical system information. There is also no way of currently viewing the time-based data of the system without having to first export the system data saved to the SD card.

3.2.4.2 System characterisation

There is currently no information regarding the actual functionality of the heated two-tank system. The level control and temperature control ranges are not properly defined. The fault emulation capability of the system is mentioned, however, no indication is given as to the extent to which any of these faults can be induced within the system nor how these faults affect the rest of the system. The faults are defined according to the fault emulation control valve lifts which gives no insight as to the actual severity of a fault.

3.3 Experimental design

The experimental design section covers the experimental procedures that have to be followed in order to obtain the required data to determine the level and temperature operational control range as well as the control valve flow characteristics. Table 3.1 is used to simplify the discussion of various process variables by assigning a reference designator to each of the process variables. Every experimental procedure is described briefly and depicted using a flow

Table 3.1: Heated two-tank system - Process variables

Component	Reference designator		Unit
	Tank 1	Tank 2	
Cold input flow rate	F_{T1Cin}	F_{T2Cin}	l/min
Cold input temperature	T_{T1Cin}	T_{T2Cin}	°C
Cold input control valve lift	V_{T1C}	V_{T2C}	%
Cold output flow rate	F_{T1Cout}	F_{T2Cout}	l/min
Tank temperature	$T_{1_{Tmp}}$	$T_{2_{Tmp}}$	°C
Tank level	$T_{1_{Lvl}}$	$T_{2_{Lvl}}$	%
Heating coil input flow rate	F_{T1H}	F_{T2H}	l/min
Heating coil input temperature	T_{T1Hin}	T_{T2Hin}	°C
Heating coil output temperature	T_{T1Hout}	T_{T2Hout}	°C
Heating coil control valve lift	V_{T1H}	V_{T2H}	%

diagram. The flow diagrams used to describe the experimental procedure utilise standard flow chart notation and blocks as described in table 3.2.

3.3.1 Operational range

3.3.1.1 Level control

The system has to be operated in steady-state at various level setpoint combinations for both tanks in order to determine the level control operational range of the system. This can be achieved by systematically adjusting the tank level setpoint. The level should remain in steady state for a predetermined amount of time before the level setpoint is adjusted again. The process of analysing Tank 1's level control range is fairly straightforward since the input flow rate (F_{T1Cin}) is not dependent on any other process variables. Tank 1 can therefore be analysed by simply adjusting its own level setpoint. The process is described in detail in figure 3.1 along with the process variable initial, final, and step values in table 3.3.

The process of analysing Tank 2's level control range is slightly more involved than that of Tank 1's since the cold input flow rate of Tank 2 (F_{T2Cin}) is dependent on the output flow rate of Tank 1 (F_{T1Cout}). The experimental procedure used to analyse Tank 1 can simply be modified to also account for F_{T1Cout} or in other words the level in Tank 1. Tank 2 can therefore be analysed by iterating through its own level setpoint set for various Tank 1 level setpoints. This process is described by the flow diagram in figure 3.2 along with the process variable initial, final, and step values in table 3.4.

Table 3.2: Flow diagram block descriptions

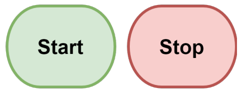
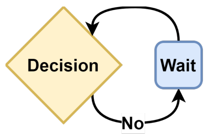
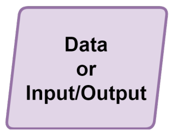
Name	Description	Block
Terminator	The Terminator block is used to indicate the starting or stopping point of a flow diagram	
Process	The Process block is used to define a specific task or operation to be performed	
Decision	The Decision block is used to indicate that a decision has to be made and based on the outcome a specific path should be followed. It is also used to check whether or not a variable is within a specific value range	
Wait	The Wait block is used to indicate that the system should wait until a specific condition has been met	
Data, Input/Output	The Data, or Input/Output block is used to initialise process variables or store the current value of a variable	

Table 3.3: Tank 1 - Operational level control range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
$T_{1_{LVL}}$	Initial	10%	10%	10%
	Final	90%	90%	100%
	Step	10%	10%	10%

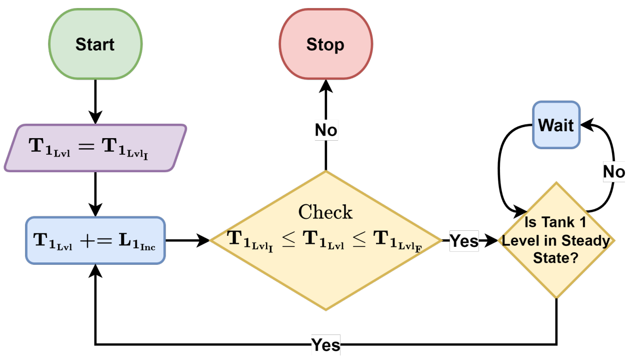


Figure 3.1: Tank 1 - Operational level control range analysis - Flow diagram

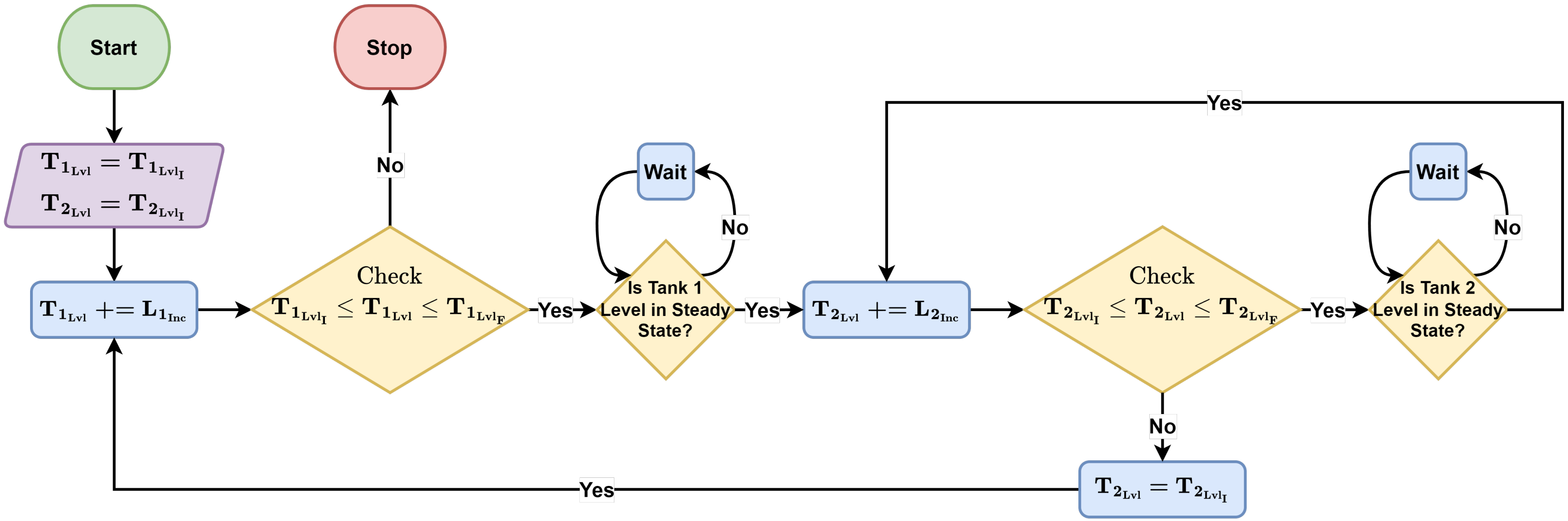


Figure 3.2: Tank 2 - Operational level control range analysis - Flow diagram

Table 3.4: Tank 2 - Operational level control range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
$T_{1_{LVL}}$	Initial	10%	0%	10%
	Final	90%	90%	100%
	Step	40%	10% → 40%	10%
$T_{2_{LVL}}$	Initial	10%	10%	10%
	Final	90%	90%	100%
	Step	10%	10%	10%

3.3.1.2 Temperature control

The operational temperature control range of the heated two-tank system is dependent on several process variables which complicate the procedure of practically/experimentally determining it. By analysing the energy balance equations, (3.3.2) and (3.3.3), for the two tanks it can be observed that the change in internal energy, given by $\rho C_p \frac{dVT}{dt}$, is dependent on the input and output flow rate of the tank, the temperature and flow rate through the heating coils, and the heat transfer capability of the heating coil dictated by its heat transfer coefficient. The heat transfer coefficient of the heating coils can be described by

$$h = \frac{q}{\Delta T}, \tag{3.3.1}$$

with h the heat transfer coefficient (W/m^2/K), q the heat flux (W/m^2), and ΔT the temperature difference between the water in the tank and the temperature of the heating coil. From this equation, it is clear that the heat transfer coefficient is dependent on the surface area of the heating coil directly in contact with the water situated within the tank.

The energy balance equations, as described by Brian Lidner in [25], for both tanks are given in (3.3.2) and (3.3.3).

Energy balance of Tank 1:

$$\begin{aligned} \rho C_p \frac{dV_1 T_{T1}}{dt} &= \rho C_p \left(F_{T1Cin} \cdot T_{T1Cin} - F_{T1Cout} \cdot T_{T1} \right) - \\ &\quad \frac{aHeat F_{T1H}^{b+1}}{F_{T1H} + \frac{aHeat F_{T1H}^{b}}{2\rho C_p}} \cdot \left(T_{T1} - T_{T1Hin} \right), \end{aligned} \tag{3.3.2}$$

with V_1 the water volume of Tank 1, ρ the density of water (kg/m^3), C_p the heat capacity of water (J/Kg $\cdot$ K), and $aHeat$ the heat transfer coefficient constant of the heating coils.

Energy balance of Tank 2:

$$\rho C_p \frac{dV_2 T_{T2}}{dt} = \rho C_p \left(F_{T1Cout} \cdot T_{T1} + F_{T2Cin} \cdot T_{T2Cin} - F_{T2Cout} \cdot T_{T2} \right) - \frac{aHeatF_{T2H}^{b+1}}{F_{T2H} + \frac{aHeatF_{T2H}^{b}}{2\rho C_p}} \cdot \left(T_{T2} - T_{T2Hin} \right), \tag{3.3.3}$$

with V_2 the water volume of Tank 2.

Therefore the temperature control range can be determined experimentally by varying the tank levels and temperatures. This can be achieved by systematically adjusting the temperature setpoint within a tank across a range of tank levels. The two tanks will have to be analysed simultaneously in a certain sense since the energy stored within the hot water reservoir is used to heat up both tanks. Therefore the level and temperature setpoints of both tanks must be controlled and altered throughout the experiment in order to obtain a representative dataset. This process is depicted in detail in figure 3.3 along with the process variable initial, final, and step values in table

Table 3.5: Tank 1 - Operational temperature range analysis - Parameters

Variable	**Condition**	**Minimum**	**Proposed**	**Full**
	Initial	90%	10%	0%
$T1_{LVL}$	Final	90%	90%	100%
	Step	0%	40%	10%
	Initial	90%	90%	0%
$T2_{LVL}$	Final	90%	90%	100%
	Step	0%	0%	10%
	Initial	28°C	26°C	20°C
$T1_{Temp}$	Final	28°C	30°C	30°C
	Step	0°C	1°C	1°C
	Initial	28°C	30°C	20°C
$T2_{Temp}$	Final	28°C	30°C	30°C
	Step	0°C	0°C	1°C

Table 3.6: Tank 2 - Operational temperature range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
$T_{1_{LVL}}$	Initial	90%	90%	0%
	Final	90%	90%	100%
	Step	0%	0%	10%
$T_{2_{LVL}}$	Initial	90%	10%	0%
	Final	90%	90%	100%
	Step	0%	40%	10%
$T_{1_{Temp}}$	Initial	28°C	30°C	20°C
	Final	28°C	30°C	30°C
	Step	0°C	0°C	1°C
$T_{2_{Temp}}$	Initial	28°C	26°C	20°C
	Final	28°C	30°C	30°C
	Step	0°C	1°C	1°C

3.3.2 Cold water cycle heat exchanger

The maximum heat that can be removed by the heat pump can be determined experimentally by disabling the heating subsystem of the heated two-tank system thereby limiting the temperature control functionality of the system to that of the cold water cycle heat exchanger. This can be achieved by setting the temperature of Tank 1 to 0°C and varying Tank 2's temperature. The cold reservoir temperature is highly dependent on the level of Tank 2 and the temperature of Tank 2, especially during steady state operation. During transient operation the temperature of Tank 2 is dependent on the rest of the system. This can be deduced from the fact that the only heat transferred to the cold reservoir comes directly from the output of Tank 2. By ensuring that no heat is transferred to Tank 1 the maximum temperature difference between Tank 1 and Tank 2 (with Tank 1 being at a lower temperature than Tank 2) can be determined as such. The maximum temperature difference between the two tanks (with Tank 1 being at a higher temperature than Tank 2) can be determined by setting Tank 2's temperature to 0°C and then varying Tank 1's temperature. For both instances, the levels of both tanks will also have to be varied.

This process can be described using the same process flow diagram used to determine the operational temperature range with only the process variable initial, final, and step values being changed as described in tables 3.7 and 3.8.

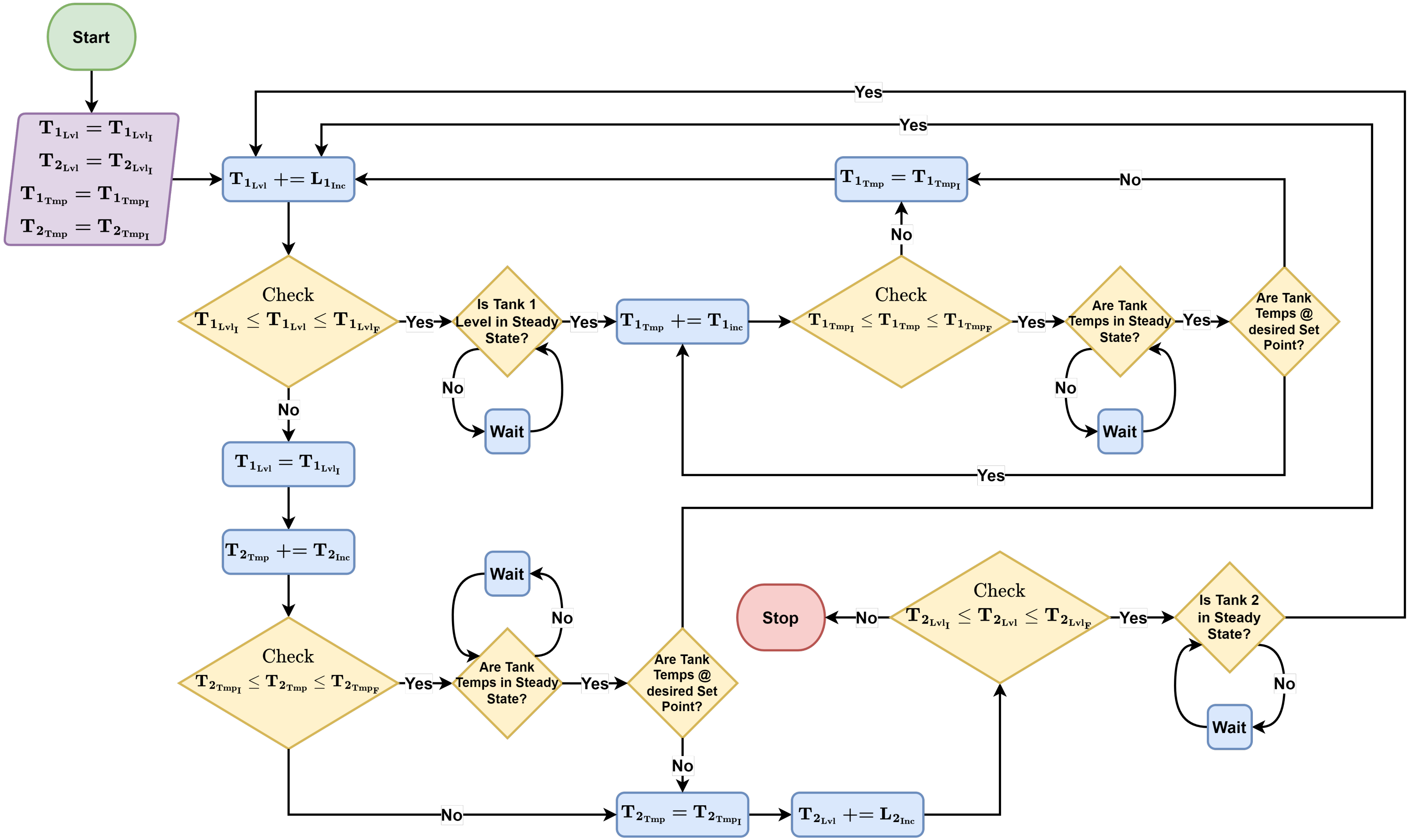


Figure 3.3: Tank 1 & 2 - Operational temperature control range analysis - Flow diagram

Table 3.7: Max tank temperature difference - Tank 1 low & Tank 2 high - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	0°C	0°C	0°C
$T1_{Temp}$	Final	0°C	0°C	0°C
	Step	0°C	0°C	0°C
	Initial	28°C	27°C	20°C
$T2_{Temp}$	Final	28°C	29°C	30°C
	Step	0°C	1°C	1°C

Table 3.8: Max tank temperature difference - Tank 1 high & Tank 2 low - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	27°C	20°C
$T1_{Temp}$	Final	28°C	29°C	30°C
	Step	0°C	1°C	1°C
	Initial	0°C	0°C	0°C
$T2_{Temp}$	Final	0°C	0°C	0°C
	Step	0°C	0°C	0°C

3.3.3 Control valve flow characteristics

The control valve Flow characteristics can be determined by measuring the flow rate through the valve at varying valve lift values. Care has to be taken to ensure that either one of the tanks does not overflow while conducting this experiment since all of the safety interlocks will be deactivated. This process is depicted in figure 3.4 with the process variable initial, final, and step parameters given in table 3.9.

Table 3.9: Control valve flow characteristic analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	0%	0%	0%
Valve Lift	Final	100%	100%	100%
	Step	25%	10%	10%

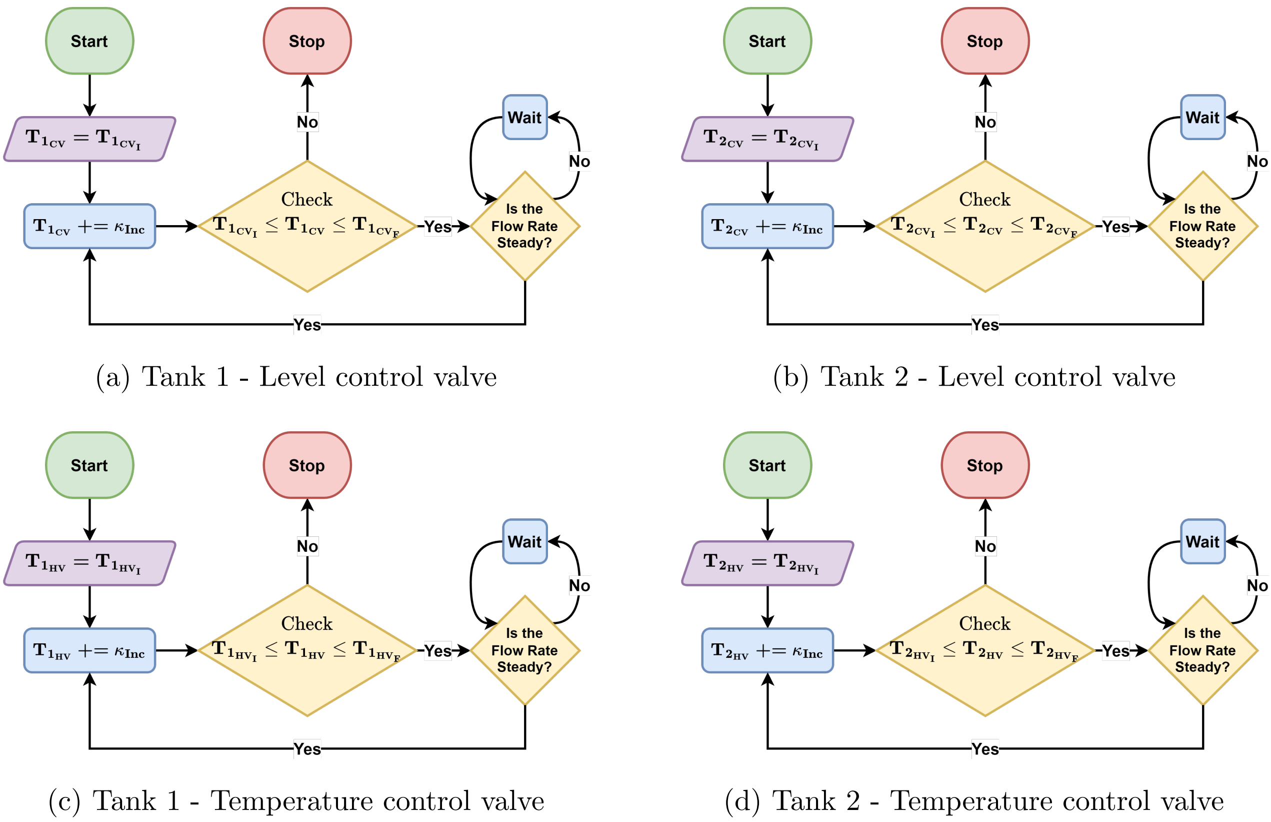


Figure 3.4: Control valve flow characteristic analysis flow diagrams

3.4 Experimental results

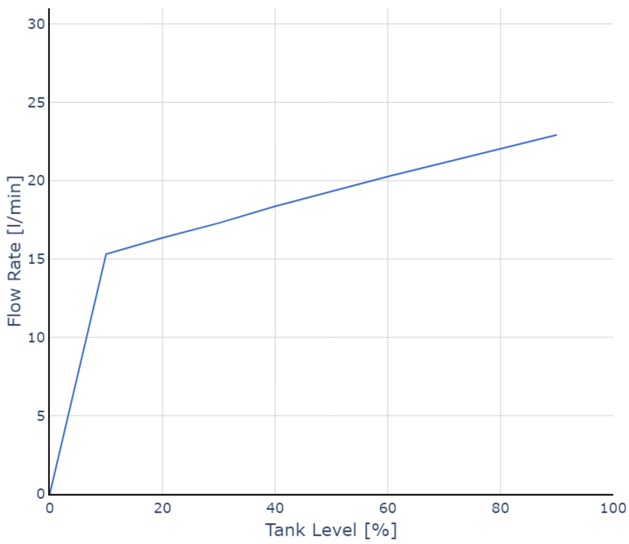
3.4.1 Level control

The operational level control range analysis experimental results are depicted in figures 3.5 and 3.6. The experimental data used to obtain these results are discussed and given in Appendix A (Original system data). The minimum and maximum required flow rate and corresponding control valve lift are given in table 3.10. From these results, it is clear that the Tank 1 level control valve is oversized only using roughly 5% valve lift variation to control the level between 10% and 90%. The level control valve for Tank 2 is reasonably sized since it utilises roughly 40% valve lift variation to control the level of Tank 2 between 10% and 90% while the level in Tank 1 is also between 10% and 90%.

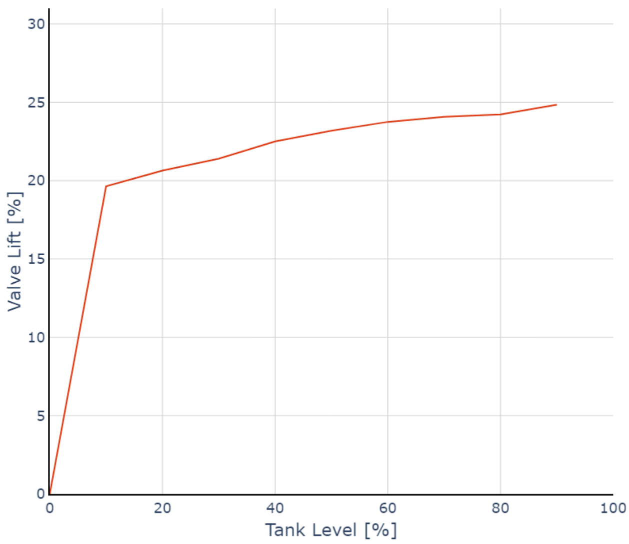
It can therefore be concluded that the first hypothesis is valid. The Tank 1 level control valve is clearly oversized while Tank 2's level control valve is reasonably sized.

Tank	**Flow Rate [l/min]**		**Valve Lift [%]**	
	Min	Max	Min	Max
Tank 1	15	23	20	25
Tank 2	10	40	15	55

Table 3.10: Operational level control range - Results

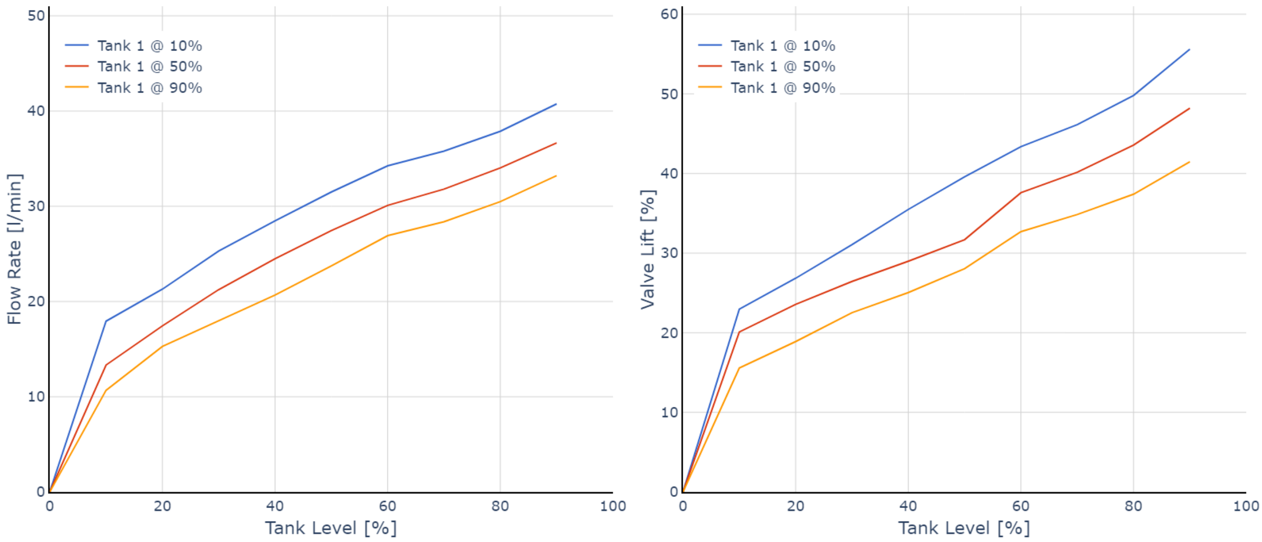


(a) Flow rate vs. tank level



(b) Valve Lift VS. Tank Level

Figure 3.5: Tank 1 - Operational level control analysis - Results



(a) Flow rate vs. tank level (b) Valve lift vs. tank level

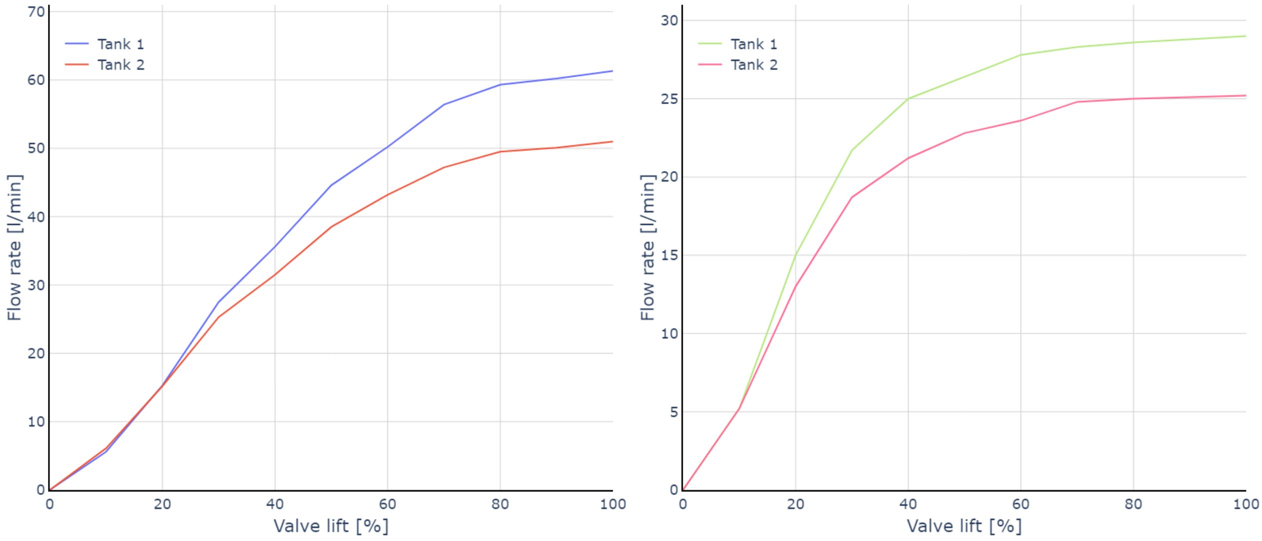
Figure 3.6: Tank 2 - Operational level control analysis - Results

3.4.2 Temperature control

During the level control experimental runs, it was observed that the heated two-tank system's temperature control was no longer fully functional. This was due to a faulty pump leading to insufficient mass flow to the gas heater which in turn caused the gas heater to no longer be able to maintain the temperature of the hot water reservoir. Based on the results of the temperature control valve flow characteristic analysis it was decided that, since the temperature control system has to be improved upon, it is not logical nor viable to fix the current system just to obtain a single dataset. This also means that the third hypothesis can not be proven on the original system since the cold water cycle heat exchanger can not be characterised without a functioning temperature control system. It will therefore be done after the system has been upgraded and full functionality has been restored.

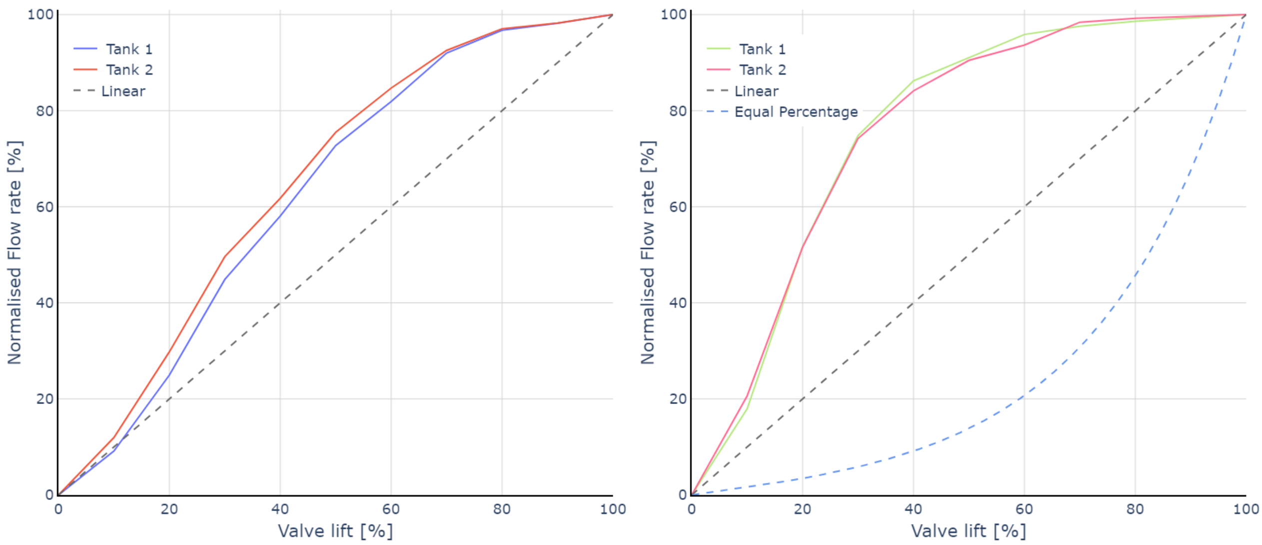
3.4.3 Control valve flow characteristics

The control valve flow characteristic analysis experimental results are depicted in figures 3.7 and 3.8. The level control valve flow characteristic for both tanks tends more towards a quick opening flow characteristic as seen in figure 3.7a. This is confirmed by normalising the flow characteristic and plotting it against an ideal linear valve (see figure 3.8a). The temperature control valve flow characteristics are also clearly quick opening as can be seen from figures 3.7b and 3.8b. Both the level and temperature control valves exhibit quick-opening flow characteristics thereby proving the first half of the second hypothesis. The effect that the quick-opening flow characteristics will have on the controller effort of each control valve can however only be determined after the control valves have been upgraded. Therefore the second hypothesis can be completely proven by comparing the control valve controller effort of the original and upgraded system.



(a) Level control (b) Temperature control

Figure 3.7: Original system - Installed valve flow characteristics



(a) Level control (b) Temperature control

Figure 3.8: Original system - Installed valve flow characteristics - Normalised

3.5 System upgrade requirements

Based on the system shortcomings discussed at the start of the chapter and the experimental results obtained it is clear that the system can indeed be upgraded and improved upon. The first half of the second hypothesis was also proven to be correct. Therefore the control valves will have to be resized to ensure that the upgraded control valves exhibit the correct valve flow characteristics. The recommended upgrades to be investigated are divided into hardware, software, and fault emulation improvements and are given in tables 3.12 and 3.11.

Table 3.11: Recommended software changes

Software changes		
Fault emulation	***PLC***	***HMI***
Stuck valves	Process variable storage	User interface/experience
- Level control	Automatic control mode	Full system control
- Temperature control		OPC server
Sensor drift		
- Tank level		
- Tank temperature		

Table 3.12: Recommended hardware changes

Hardware changes		
Control valves	***Temperature sensors***	***PLC***
Level control	Heating coils	HMI 12" upgrade
- Tank 1	- Tank 1	
- Tank 2	- Tank 2	
Temperature control	Hot water reservoir	
- Tank 1	- Circulation	
- Tank 2		
Blockage valves		
- Tank 2		
Draining valves		
- Tank 1		
- Tank 2		

3.6 Conclusion

The original system analysis chapter covered the entire process of analysing the original system's functionality and its shortcomings. Several hypotheses were given that provided additional insight regarding the scope of the first research objective. Along with each hypothesis a secondary set of objectives was given that would allow the experimental verification of said hypothesis. The system shortcomings were discussed, covering the sensors, PLC and HMI, data acquisition, and fault emulation. The experimental design section covered the experimental setup and procedures required to analyse the functionality of the current system.

During the experimental results section, the first hypothesis was proven correct by comparing the operational level control range of the control valves with the corresponding valve lift range. From this, it was shown that the Tank 1 level control valve only used roughly 5% valve lift variation while the Tank 2 level control valve utilised roughly 40% valve lift variation. The first half of the second hypothesis was also proven correct by analysing the installed level and temperature control valve flow characteristics with the desired control valve flow characteristics. Lastly, a list of possible upgrades and improvements, based on the system shortcomings analysis and experimental results, was given.

The following chapter will therefore cover the design and implementation of the chosen system upgrades and improvements.

4 System upgrade

4.1 Introduction

The recommended system upgrade requirements were given at the end of Chapter 3. It was shown that the system has several hardware and software-oriented aspects that can be improved upon. The purpose of this chapter is therefore to cover the upgrades and improvements that should be implemented in order to improve the functionality of the heated two-tank system. The chapter consists of the upgrades and additional features that are made to the system, an in-depth control valve sizing exercise consisting of several valve sizing techniques as well as a comparison between them, and the final valve selection.

4.2 System upgrades and additional features

The upgrades made to the system are listed in tables 4.2 and 4.1. The upgrade list was limited to the primary control valves and hot water cycle temperature sensors due to budgetary concerns. The control valve design will be covered in detail in this chapter. The work done on the PLC, HMI, and the upgrade implementation can be found in Appendix B (System design).

The upgraded control system and data acquisition capabilities of the PLC and the improved user experience on the HMI are included among the chosen upgrades and improvements since they will allow the upgraded system to be more aligned with an ideal research system. The ability to automate any experiment, control any aspect of the system, and obtain substantially more behavioural data during experiments is invaluable and will provide significant insight into the workings of the upgraded heated two-tank system. The improved data acquisition

Table 4.1: Software changes to be implemented

Software changes		
Fault emulation	***PLC***	***HMI***
Stuck valves	Process variable storage	User interface/experience
- Level control	Automatic control mode	Full system control
- Temperature control		
Sensor drift		
- Tank level		
- Tank temperature		

capabilities along with the additional sensors will also be key to upgrading the simulation models of the heated two-tank system during one of the follow-up studies.

These upgrades will also allow the FDI oriented research that will be done in the future to be tested against the ideal FDI characteristics mentioned by [16]. This is due to the fact that the improved control system and UI will allow researchers to configure the heated two-tank system to emulate more complex and time-varying faults that can be used to better test the functionality of the used FDI scheme. The additional sensors could also provide researchers with additional data regarding the operation of the system as well as allow them to potentially determine which process variables provide the most information regarding specific faults and which process variables can be ignored during fault detection.

Table 4.2: Hardware changes to be implemented

Hardware changes	
Control valves	***Temperature sensors***
Level control	Heating coils
- Tank 1	- Tank 1
- Tank 2	- Tank 2
Temperature control	Hot water reservoir
- Tank 1	- Circulation
- Tank 2	

4.3 Control valves

Various control valve flow characteristics can be advantageous for distinct types of chemical processes. Analysing the open-loop gain of the system can determine the optimal valve flow characteristic for a chemical process. The control valve gain should counteract variations in the open-loop gain of the system in an attempt to limit the overall open-loop gain within the system's stability margins. This can be accomplished to varying degrees of complexity, with some levels exceeding the scope of this dissertation. Hence, the analysis of the control valve flow characteristics will be limited to ensuring that the appropriate flow characteristics are selected for each control system and the corresponding optimal control strategy will be left for a follow-up study.

The control valve sizing is covered in detail to emphasise the importance of proper valve sizing and to show how several factors can influence the behaviour of the valves leading to different control behaviours. This is also done to adhere to the requirements set by the second hypothesis (resize the control valves to ensure proper valve flow characteristics). The verification method used for the valve sizing exercise is also constructed using the methods described in the different valve sizing techniques.

4.3.1 Shorthand valve sizing

There is no easy single-step method to size a control valve properly. It is nevertheless possible to determine a rough estimated valve size based on the pump characteristics and the controlled process type. A liquid-level control system will have most of the pressure drop absorbed by the control valve itself. Therefore, it benefits from the use of a control valve with constant gain typically achieved by a linear valve. In the case of temperature control, the opposite holds true, as the system absorbs the majority of the pressure drop, with only a small percentage occurring across the control valve [20]. Therefore, it benefits from the use of an equal percentage gain valve. The following rules of thumb can therefore be used in order to obtain a rough valve sizing estimate:

- For a level control system:
  - Roughly 75% of the pump head at maximum desired flow should be absorbed by the control valve.
- For a temperature control system:
  - Roughly 25% of the pump head at maximum desired flow should be absorbed by the control valve.

4.3.2 Standardised valve sizing

Throughout the years, different valve manufacturers have used their own equations and methodologies to appropriately size control valves. However, in the modern age, there has been an ever-increasing trend to standardise design methodologies to ensure universal cross-compatibility. The standardised control valve sizing method was proposed by the IEC. The standardised control valve sizing method is described in [20, 27]. The method consists of the following 5 steps:

1. Specify the required valve sizing parameters
2. Determine the equation constants
3. Determine the piping geometry factor (F_p)
4. Determine the maximum flow rate (Q_{max}) or valve pressure drop (ΔP_{max})
5. Determine the required valve coefficient (K_v)

The aforementioned steps are discussed in further detail below.

4.3.2.1 Specify the required valve sizing parameters

As with any other design the system specifications should first be determined. The following parameters are required in order to size the control valve:

- The valve type and design (Quick opening, linear, equal percentage)
- Initial Valve coefficient (K_{vi})
- Desired flow rate (Q)
- The inlet (P_1) and outlet (P_2) valve pressure OR the valve pressure drop (ΔP_v)
- Liquid or gas properties
  - Temperature (T)
  - Specific gravity (G_f)
  - Vapour pressure (P_v)
  - Critical pressure (P_c).

4.3.2.2 Determine the equation constants (N)

There exist several different systems of units that can be used for valve sizing. The equations used by the standardised method are compatible with several different systems of units and the equation constants (N) are therefore used to select a specific system of units. The equation constants used by the standardised method are given in table 4.3 with the full table available in [20].

Table 4.3: Standardised method - Equation constants

Constant	N	Q	P	d, D
N_1	0.0865	Nm^3/h	kPa	—
	0.865	Nm^3/h	bar	—
	1.00	GPM	psia	—
N_2	0.00214	—	—	mm
	890	—	—	inch

4.3.2.3 Determine the piping geometry factor (F_p)

The piping geometry factor is used to account for the pressure losses due to any fittings attached directly to the valve inlet or outlet. The piping geometry factor can initially be determined using (4.3.1). However [27] recommends that F_p be determined experimentally.

$$F_p = \left[1 + \frac{\Sigma K}{N_2}\left(\frac{1.156K_{vs}}{d^2}\right)^2\right]^{-1/2}, \tag{4.3.1}$$

$$\Sigma K = K_1 + K_2 + K_{B1} + K_{B2}, \tag{4.3.2}$$

with d the assumed nominal valve diameter in mm, ΣK the algebraic sum of the velocity head loss coefficients consisting of the fitting resistance K_n and the Bernoulli K_{Bn} coefficient. The subscript n indicates that the coefficient refers to either the inlet/upstream 1 or outlet/-downstream 2 geometry. If the inlet and outlet geometries differ then the velocity vector sum can be calculated using (4.3.3), (4.3.4), and (4.3.5). In the case where the inlet and outlet geometries are identical then (4.3.6) can be used.

$$K_B = 1 - \left(\frac{d}{D}\right)^4, \tag{4.3.3}$$

$$K_1 = 0.5\left(1 - \frac{d^2}{D^2}\right)^2, \tag{4.3.4}$$

$$K_2 = \left(1 - \frac{d^2}{D^2}\right)^2. \tag{4.3.5}$$

$$K_1 + K_2 = 1.5\left(1 - \frac{d^2}{D^2}\right)^2, \tag{4.3.6}$$

with d the nominal valve diameter (mm) and D the internal diameter of the pipe connected to the valve (mm).

4.3.2.4 Determine the maximum flow rate (Q_{max}) or valve pressure drop (ΔP_{max})

It is recommended that either Q_{max} or ΔP_{max} be determined if there is a concern that choked flow may occur within the system due to the control valve. Equations (4.3.7) and (4.3.8) can be used to determine Q_{max} and ΔP_{max} respectively.

$$Q_{max} = 1.156K_{vs}N_1\left(\frac{F_{LP}}{F_p}\right)\sqrt{\frac{P_1 - F_F P_v}{G_f}} \tag{4.3.7}$$

$$\Delta P_{max} = \left(\frac{F_{LP}}{F_p}\right)^2 (P_1 - F_F P_v), \tag{4.3.8}$$

with F_F the critical pressure ratio factor (4.3.9), F_{LP} the valve recovery factor (4.3.10) in the case where the upstream and downstream piping geometries differ, and F_L the valve recovery factor in the identical case.

$$F_F = 0.96 - 0.28\sqrt{\frac{P_v}{P_c}} \tag{4.3.9}$$

$$F_{LP} = \left[\frac{K_1 + K_{B1}}{N_2}\left(\frac{1.156K_{vs}}{d^2}\right)^2 + \frac{1}{F_L^2}\right]^{-1/2} \tag{4.3.10}$$

4.3.2.5 Determine the required valve coefficient (K_{vr})

The required valve coefficient K_{vr} can be determined by using

$$K_{vr} = \frac{Q}{1.156 F_p N_1} \sqrt{\frac{\rho}{1000\,|\Delta P|}}. \tag{4.3.11}$$

The process that has thus far been described should be repeated until K_{vr} and K_{vi} are approximately the same. This is due to the fact that the calculated K_{vr} value is dependent on K_{vi} resulting in a different answer for each iteration.

4.3.3 Data driven valve sizing

The data-driven method aims to make use of the existing system's operational data to aid with the control valve resizing. The idea is that the operational data can be used to determine the expected or approximate K_v values of the installed valve across the entire system flow rate range. The operational K_v value range can then be determined from which a new K_{vs} value can be chosen. The operational K_v value range describes the set of K_v values that are actually used during operation. This method was devised during the original system's analysis chapter as a means of analysing the system characteristics without having to run dedicated experimental data runs on the system.

The data-driven method consists of the following high-level steps

1. Determine the installed valve's flow rate vs valve lift characteristics
2. Determine the approximate K_v value vs flow rate characteristic
3. Choose a new K_{vs} value based on the desired maximum flow rate

4.3.3.1 Determine the installed valve's flow rate vs valve lift characteristics

The installed valve's flow rate vs lift characteristics can experimentally be determined by ideally operating the control valve at different valve lifts and then recording the corresponding flow rate through the valve. This will, however, in certain cases, not be possible since the system can not be taken offline due to the plant operation or the system might not have been designed to be operated at each valve lift value. This will especially be the case if the installed valve is oversized since large valve lift values will produce large flow rates for which the system was not designed for. Another approach should therefore be followed. It is proposed that the system be operated at different operating points for which it was designed and then switch between these operating points in different combinations. The idea is that the steady-state operation will provide the most reliable data that can be used to determine the system's nominal flow rates. The transient data obtained when switching from one operating point to another can then be used to obtain the upper limits of the system's flow rate. The operational data can then be filtered and sorted in order to obtain the flow rate vs valve lift characteristic.

4.3.3.2 Determine the approximate K_v value vs flow rate characteristic

The approximate K_v value gives an indication of the K_v value required in order to produce a corresponding flow rate in the actual system. To simplify some of the equations the valve can be described as a variable area orifice. According to Irving Shames [28] the missing process variables such as the differential pressure across the control valve can be determined by using a simplified version of Bernoulli's equation as follows:

$$Q = A_v \sqrt{\frac{2|\Delta P|\frac{1}{\rho}}{1 - \left(\frac{A_v}{A_p}\right)^2}}, \tag{4.3.12}$$

with Q the flow rate through the valve (m^3/s), A_v the nominal area of the valve (m^2), A_p the nominal area of the pipe (m^2), ΔP the differential pressure across the valve (N/m^2), and ρ the fluid density (kg/m^3). However, Bernoulli's equation assumes ideal conditions which means that the flow rate calculated with (4.3.12) will differ from the actual flow rate. This can be accounted for by adding a discharge coefficient (C_d) as follows:

$$Q = C_d A_v \sqrt{\frac{2|\Delta P|\frac{1}{\rho}}{1 - \left(\frac{A_v}{A_p}\right)^2}}, \tag{4.3.13}$$

with

$$C_d = \frac{Q_{actual}}{Q_{theoretical}}.$$

This equation should further be modified in order to take into account the valve lift, since currently, it assumes that A_v and C_d remain constant. Therefore both A_v and C_d should be rewritten as functions of valve lift (κ). The valve area can be related to the valve flow characteristics and the discharge coefficient should either be given by the manufacturer or determined experimentally. According to the ANSI/ISA-75.01.01 and API STD 520 standards [29, 30], the discharge coefficient is related to the valve coefficient and can be determined as follows:

$$C_d = \frac{C_v}{38 \cdot A}, \tag{4.3.14}$$

with A the effective valve area in in^2 and C_v the valve coefficient in imperial units. The valve coefficient can be converted to metric units as follows:

$$K_v = \frac{C_v}{1.156}. \tag{4.3.15}$$

Equation (4.3.14) and (4.3.15) can be combined to obtain the discharge coefficient using metric units as follows:

$$C_d = \frac{1.156}{58900 \cdot A} \cdot K_v, \tag{4.3.16}$$

with A the effective valve area (m^2).

According to the BPVC standard [31], the discharge coefficient of a liquid control valve will usually be between 0.6 and 0.8 as shown in figure 4.1. These limits could therefore also be used instead of using (4.3.16) when estimating the discharge coefficient.

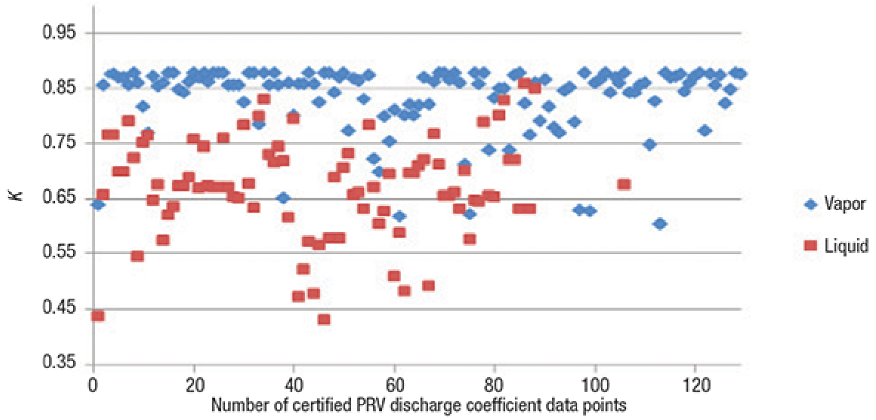


Figure 4.1: Typical valve discharge coefficient distribution [31]

Another factor that can be taken into account is the fact that the valve area (A_v) in (4.3.12) actually refers to the minimum area of the fluid stream after the orifice. This minimum area is referred to as the Vena Contracta and it is due to the viscous effect of the fluid flowing through the orifice [28]. The Vena Contracta can however only be determined by using specialised equipment and will therefore not be accounted for.

The approximated K_v value can then be determined using either (2.4.1) or (4.3.11) once all of the required process variables have been obtained or calculated.

4.3.3.3 Choose a new K_{vs} value based on the desired maximum flow rate

The installed control valve's effectiveness can be determined by comparing its operational K_v value and full K_v value ranges. If the operational K_v range is significantly smaller than the full range then the valve might be oversized.

4.3.4 Analytical

The method for determining the pressure drop across the control valve as described in section 2.4.3 can be taken a step further by taking into account the type of valve flow characteristic of the control valve. The valve coefficient (K_v) of a control valve is usually determined at a maximum valve lift (K_{vs}), however, it is not limited to the maximum valve lift. It is, therefore, possible to determine the pressure drop across the valve at a given valve lift and mass flow rate by rewriting (2.4.1) or (4.3.11) in terms of the pressure drop as follows:

Normal K_v equation:

$$\Delta P = \left[\frac{\rho}{1000}\right]\left[\frac{Q}{K_v}\right]^2. \tag{4.3.17}$$

Standardised K_v equation:

$$\Delta P = \left[\frac{\rho}{1000}\right]\left[\frac{Q}{1.156 F_p N_1 K_v}\right]^2. \tag{4.3.18}$$

The valve coefficient now becomes a function of the valve lift (κ) and can be described by the type of inherent flow characteristic of the valve as follows (some manufacturers might also provide a table with K_v values at different lift values):

Quick opening valve:

$$K_v = K_{vs} \cdot \sqrt{\kappa}. \tag{4.3.19}$$

Linear valve:

$$K_v = \kappa \cdot K_{vs}. \tag{4.3.20}$$

Equal percentage valve:

$$K_v = K_{vs} \cdot \left[\frac{e^{\ln(\tau)\cdot\kappa}}{\tau}\right]. \tag{4.3.21}$$

The equation used for equal percentage valves (4.3.21) does however predict that the flow rate through the valve will be non-zero at zero valve lift. This can be corrected by modifying (4.3.21) as follows:

$$K_v = K_{vs} \cdot \left[\frac{e^{\ln(\tau)\cdot\kappa} - e^{-\ln(\tau)\cdot\kappa}}{\tau}\right]. \tag{4.3.22}$$

This does however change the inherent valve flow characteristic for the first 20% - 30% by some margin as shown in figure 4.2. Therefore this modification will not be used by default and should only be used when the valve manufacturer provides a K_v vs. valve lift table that can be approximated by (4.3.22).

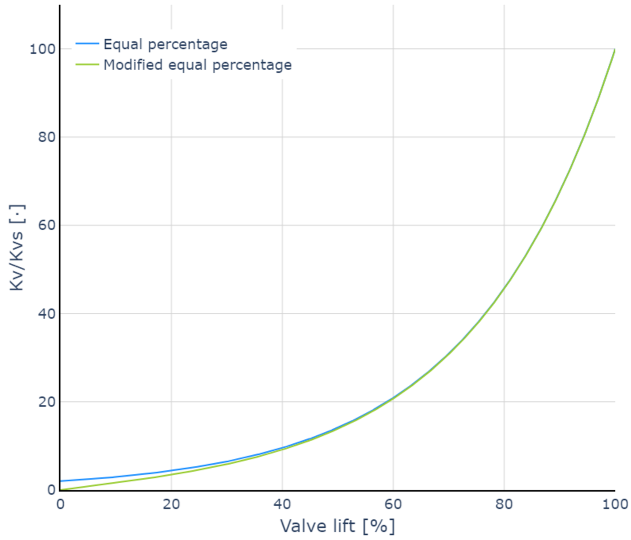


Figure 4.2: Equal percentage vs. modified equal percentage

If the same methodology described in the previous sizing methods were to be followed then the next step would be to simply determine the total system head loss at the desired mass flow rate and then match that with the head provided by the pump at the same mass flow rate. If the pump can provide an adequate amount of head then the required valve size has been determined... It is however not entirely that straightforward. The main problem lies in the fact that the equation obtained by combining (4.3.17) or (4.3.18) with either one of (4.3.19), (4.3.20), or (4.3.21) has two variables as shown below:

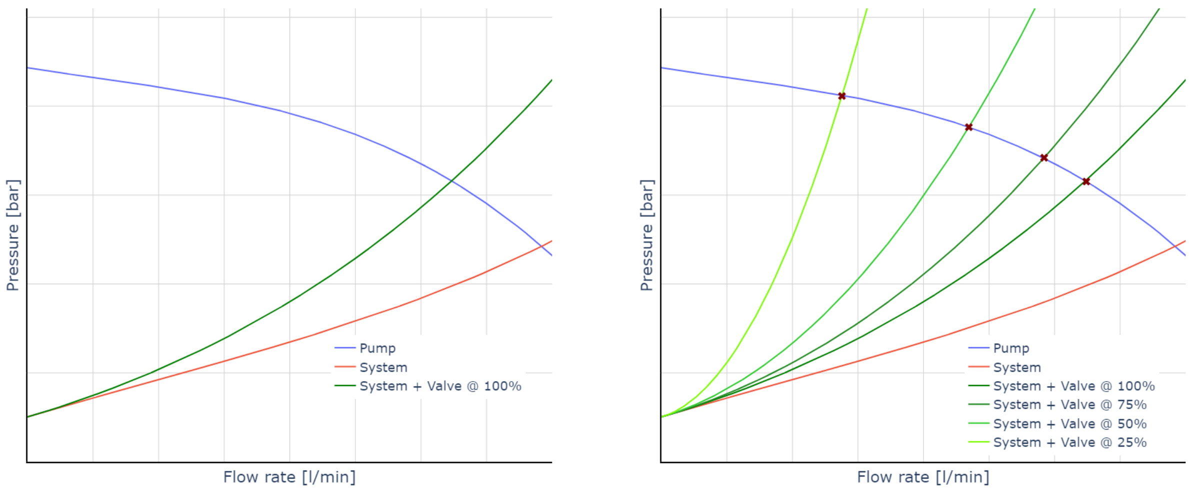
$$\Delta P_{Valves}(Q,\kappa) = \Delta P_{system}(Q) - \Delta P_{Elevation} - \Delta P_{Friction}(Q) - \Delta P_{Sensors}(Q).$$

The desired flow rate Q and the valve lift κ at which the desired flow rate occurs, which, at this point, is still unknown. The valve lift required to achieve the desired mass flow rate can be determined by calculating the pressure drop across the valve, given a pre-determined valve size and known inherent valve flow characteristic, and using it along with (4.3.17) or (4.3.18) with either one of (4.3.19), (4.3.20), or (4.3.21) to solve for κ. If the calculated κ value is achievable (i.e. $0 < \kappa \leq 1$) then the chosen valve should be able to maintain the desired mass flow rate. The required K_v value (K_{vr}) can also be determined by using either one of (4.3.19), (4.3.20), or (4.3.21) depending on the inherent valve flow characteristics of the chosen valve. If K_{vr} is significantly smaller than the valve's K_{vs} value or in other words the required valve lift is well below maximum lift then the chosen valve might be oversized.

This sizing method is, therefore, a slightly more involved version of the standardised method with the added benefit of calculating the approximate valve lift required at a desired mass flow rate. It also gives an estimated maximum mass flow rate when the valve pressure is analysed at maximum lift.

The method can, however, be further extended. Rather than focusing on a single or even a couple of flow rates at which the valve lift and pressure drop should be analysed (as shown in figure 4.3a), it is proposed that the entire mass flow rate range or valve lift range be analysed. The initial mass flow rate range can be estimated from the pump head curve.

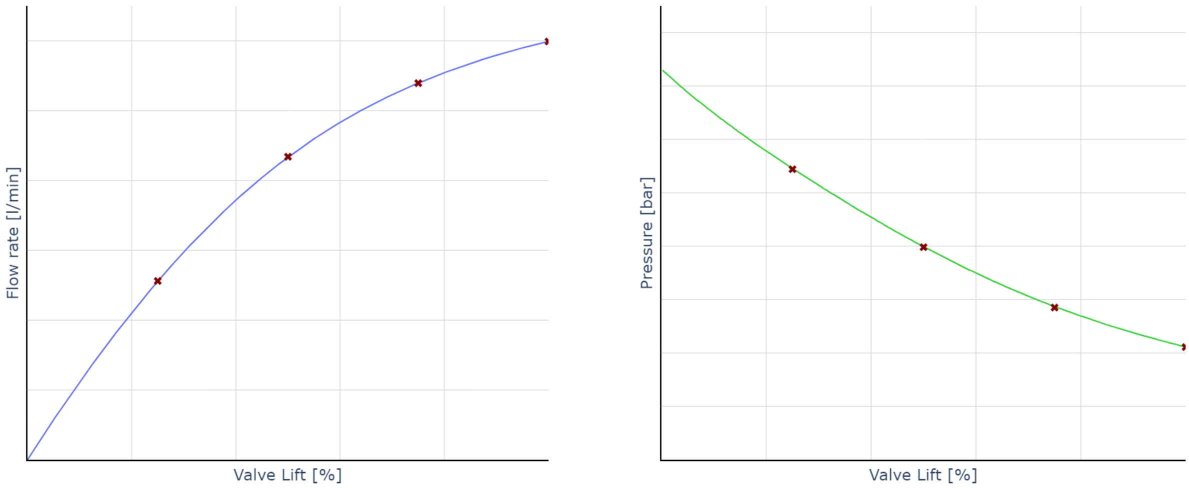
This can be achieved by constructing the total system head loss curve for various valve lift values and comparing it to the pump head curve as shown in figure 4.3b. The pump head curve can be adjusted depending on the outlet pressure of the system in order to represent the total system head loss. The point where the system curve, representing system head loss, intersects with the pump head curve signifies the attained mass flow rate for a specific valve lift.



(a) Valve at maximum lift (b) Valve at varying lift values

Figure 4.3: System curves (Pressure vs. mass flow rate)

The resulting mass flow rate vs. valve lift curve represents the installed valve flow characteristics as shown in figure 4.4a. The installed valve flow characteristics will differ from the inherent valve flow characteristics since it assumes that the pressure drop across the valve will remain constant. The valve pressure drop is given by the difference between the pump head curve and the valveless system curve as shown in figure 4.4b.



(a) Flow rate vs. valve lift

(b) Pressure vs. valve lift

Figure 4.4: Predicted installed valve characteristics

These two figures can be combined along with the total system curve in order to obtain a more comprehensive representation of the control valve's installed characteristic curves. The resulting 3-dimensional surface represents the valve's installed flow and pressure characteristics independent of the pump head curve and outlet pressure as depicted in figure 4.5. The upper-pressure boundary is set to the chosen pump head curve to simplify the visualisation of the 3D surface.

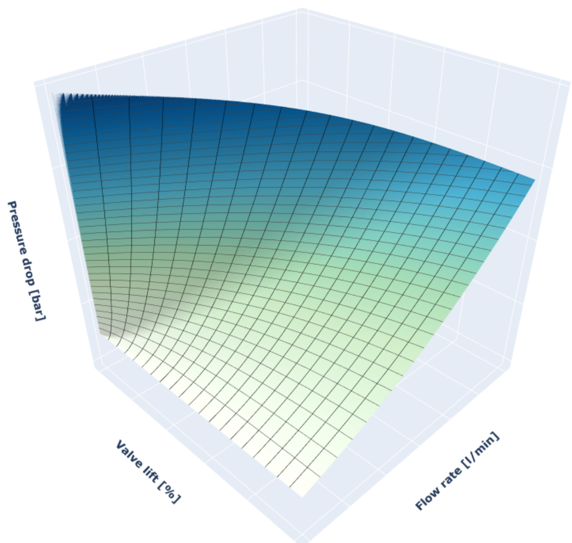


Figure 4.5: Installed control valve characteristic curve/surface

The final valve K_{vs} value can therefore be chosen based on the desired maximum flow and the installed valve flow characteristics. Similar results can be obtained by using simulation software such as Flownex, Nelprof, or Simcenter Amesim. However, automating the process in a Python script allows significantly more customisability. The analytical valve sizing method does however still require an initial K_v value before it can be utilised. Therefore, the previously covered valve sizing methods can be used to provide an initial K_v value which can then be iterated upon until the desired installed valve flow characteristics and maximum mass flow rate are achieved. This method will therefore also be used to verify the valve sizing exercise and compare all of the valve sizing methods. The valve sizing exercise will be validated during the upgraded system characterisation chapter.

4.4 Valve sizing

The following parameters are required in order to properly size the control valves for the system using the aforementioned sizing methods:

- Pump head curve
- Head loss curve of any sensors installed in the piping network
- Piping network parameters
  - Pipe diameter (∅)
  - Net pipe length
  - Net pipe elevation
  - Pipe roughness
- Fluid properties at nominal temperature (25°C for level control and roughly 40°C for temperature control)
  - Fluid density
  - Fluid viscosity

The pump head curves for the centrifugal pumps currently installed in the system and possible upgraded pumps are depicted in figure 4.6 as obtained from their respective datasheets. The level control subsystems are currently being driven by Leo ACm 25 centrifugal pumps and the temperature control subsystems are being driven by Pedrollo CPm 130 centrifugal pumps. The head loss curve of the IFM SBG246 flow sensor is depicted in figure 4.8. The rest of the system parameters are given in table 4.4. The net equivalent length for the level control systems is calculated using the actual length parameters of both level control sub-systems. The equivalent length for the temperature control sub-systems is estimated based on the maximum flow rate measured during the previous chapter as indicated in figure 4.7. This was done due to the fact that the heat exchanger coils used inside both of the tanks were custom-made and therefore did not come with a head loss curve. All of the calculations are done using either Excel (as seen in Appendix B.5.1) or Python.

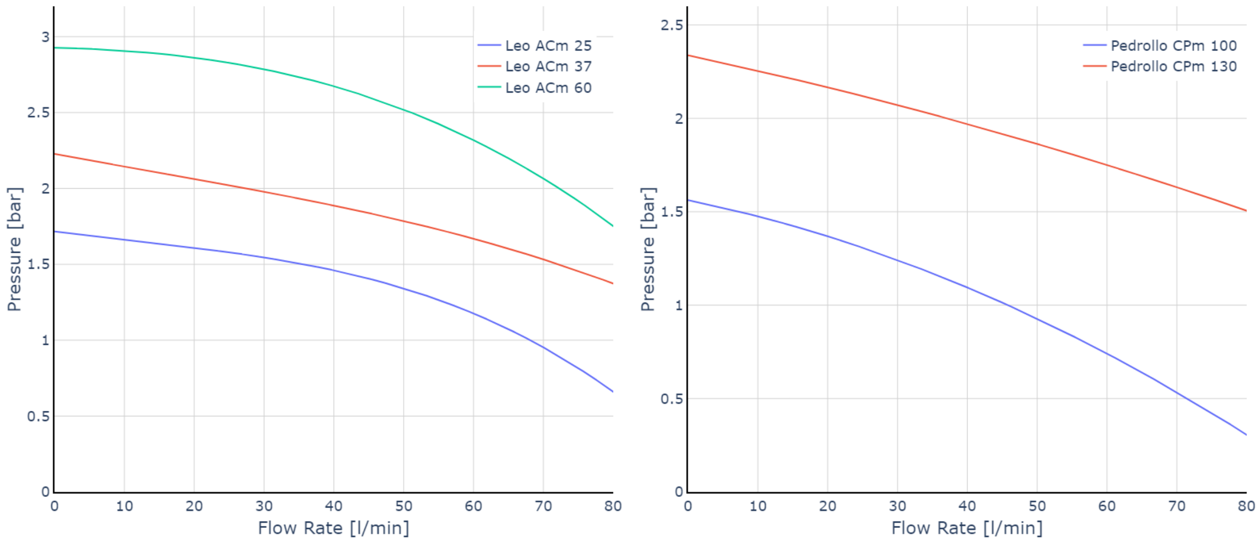
Table 4.4: System parameters

System parameters		Tank 1		Tank 2	
Parameter	Unit	Level	Temperature	Level	Temperature
Pipe ∅	[mm]	21.6	20.2	21.6	20.2
Net pipe length	[m]	9.5	145	12.4	185
Net pipe elevation	[m]	2.4	0.04	1.0	0.04
Pipe roughness	[mm]	7e-3	1.5e-3	7e-3	1.5e-3
Fluid density	[kg/m^3]	997	997	997	997
Fluid viscosity	[N · s/m^2]	1.0e-3	0.6531e-3	1.0e-3	0.6531e-3

The nominal and maximum mass flow rates for the system are based on the results obtained in the previous chapter. The nominal mass flow rate for the level control system corresponds with a level of roughly 90% within both tanks. The nominal mass flow rate for the temperature control system is based on the average flow rate within the heating coils required to achieve a temperature of roughly 28°C within both tanks at a 90% level. The maximum mass flow rates were chosen to ensure that the maximum required flow rate of either tank can be met as well as to leave some headway to allow for some overshoot during level control.

Table 4.5: System nominal and maximum flow rates

Subsystem		Flow rate [l/min]	
		Nominal	Maximum
Level	Tank 1	23	45
	Tank 2	30	45
Temperature	Tank 1	15	25
	Tank 2	15	25



(a) Leo pumps

(b) Pedrollo pumps

Figure 4.6: Pump head curves

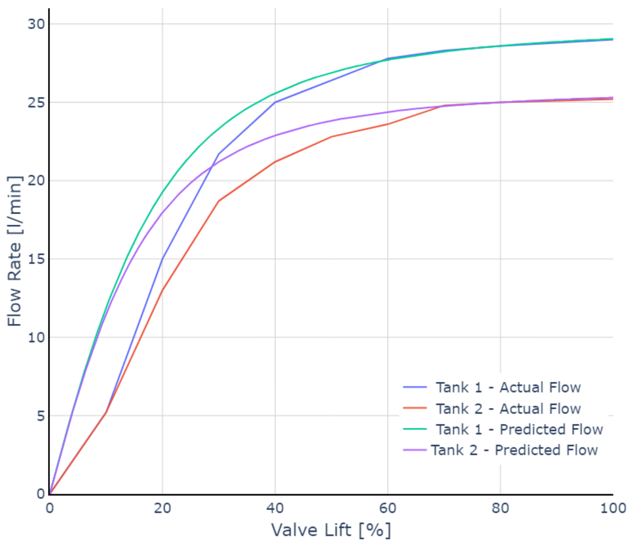


Figure 4.7: Temperature control valve - Estimation of equivalent piping length

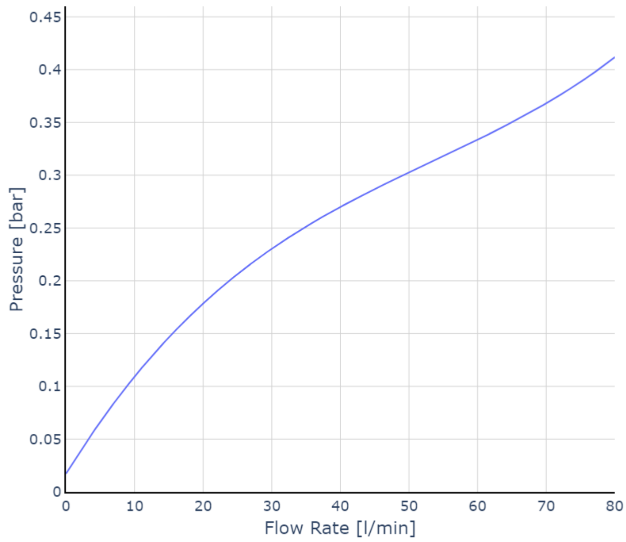


Figure 4.8: IFM SBG246 flow sensor head loss

4.4.1 Theoretical calculations

4.4.1.1 Shorthand

The shorthand valve sizing method is computationally simple since it only requires the desired flow rate and an approximated valve pressure drop. The shorthand valve sizing results are given in table 4.6.

Table 4.6: Valve sizing results - Shorthand

Subsystem		**Nominal flow rate**			**Maximum flow rate**		
		Flow rate [l/min]	ΔP_{Valve} [bar]	K_{vr} [m^3/h]	Flow rate [l/min]	ΔP_{Valve} [bar]	K_{vr} [m^3/h]
Level	Tank 1	23	1.160	1.48	45	1.018	3.09
	Tank 2	30	1.120	1.96	45	1.018	3.09
Temperature	Tank 1	15	0.528	2.48	25	0.505	4.22
	Tank 2	15	0.528	2.48	25	0.505	4.22

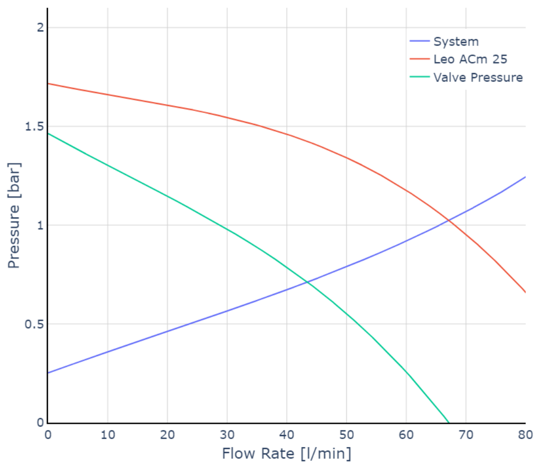
4.4.1.2 Standardised

The system pressure curves used during the standardised valve sizing method are depicted in figure 4.9. These system curves consist of the pump head curve; the pressure drop across the system due to the piping network, installed flow sensors, and the elevation difference between the inlet and the outlet of each subsystem; and the pressure drop across the proposed control valve. The maximum flow rate that the calculated required valves can achieve could not be determined using (4.3.7) since Burkert does not provide the valve recovery factor on their valve datasheets. Burkert was chosen as the primary supplier of control valves due to the standing relationship between them and North-West University.

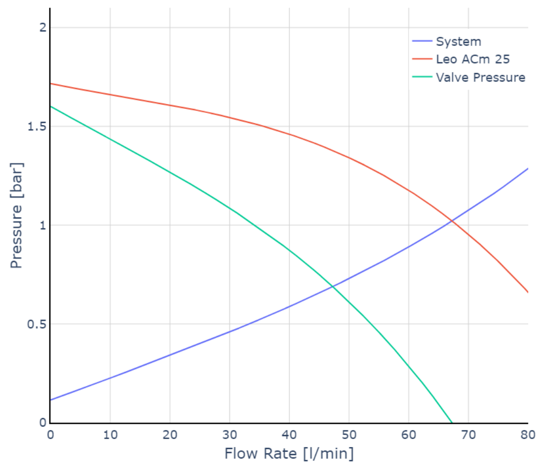
The standardised valve sizing results are given in table 4.7.

Table 4.7: Valve sizing results - Standardised

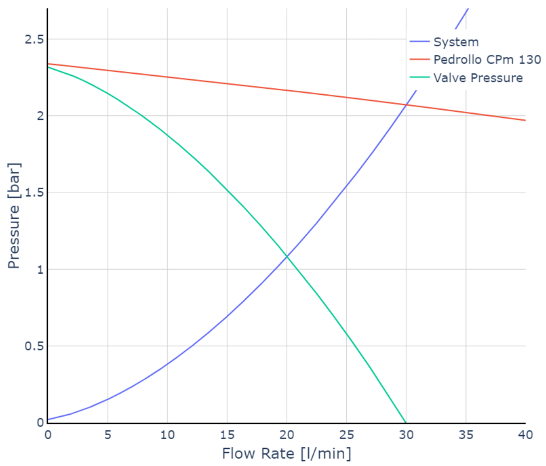
Subsystem		**Nominal flow rate**			**Maximum flow rate**		
		Flow rate [l/min]	ΔP_{Valve} [bar]	K_{vr} [m³/h]	Flow rate [l/min]	ΔP_{Valve} [bar]	K_{vr} [m³/h]
Level	Tank 1	23	1.098	1.57	45	0.674	3.75
	Tank 2	30	0.979	2.02	45	0.674	3.75
Temperature	Tank 1	15	1.560	0.72	25	0.681	1.83
	Tank 2	15	1.560	0.72	25	0.681	1.83



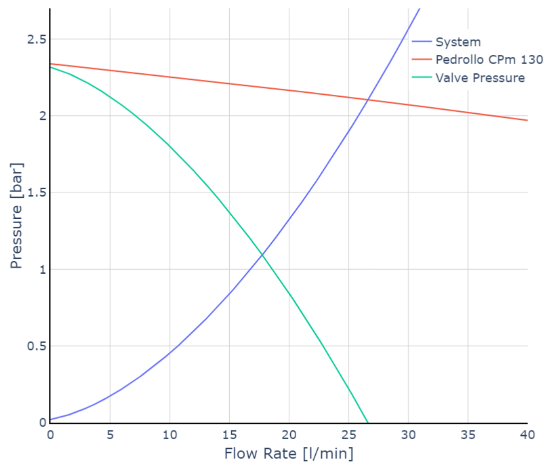
(a) Tank 1 - Level control valve



(b) Tank 2 - Level control valve



(c) Tank 1 - Temperature control valve



(d) Tank 2 - Temperature control valve

Figure 4.9: Valve sizing system curves - Standardised method

4.4.1.3 Data driven

The data-driven valve sizing method process is shown in detail for the sizing of the Tank 1 level control valve. The same methodology is applied to the rest of the subsystems in order to obtain the final results as documented in table 4.8.

The first step of the data-driven valve sizing method requires the control valve's flow characteristics. The installed control valve flow characteristics determined in the previous chapter as depicted in figure 3.7 can be used. Another approach can also be followed where a normal operational data set (depicted in figure 4.10) that contains some transient behaviour is used to determine the installed valve flow characteristics without having to run a characterisation experiment as described in figure 3.4.

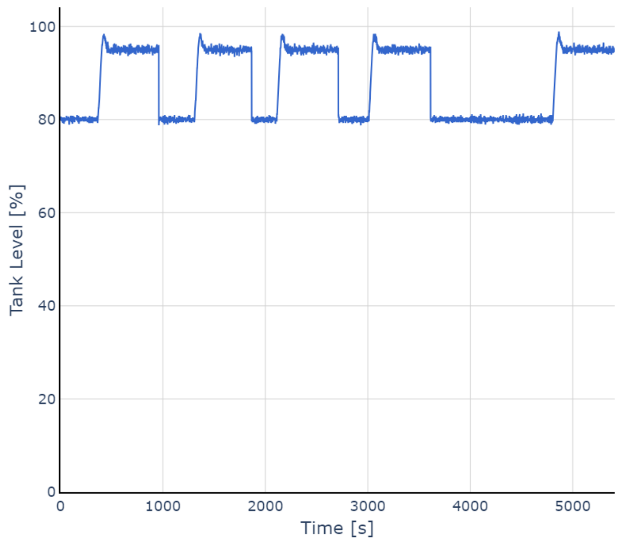
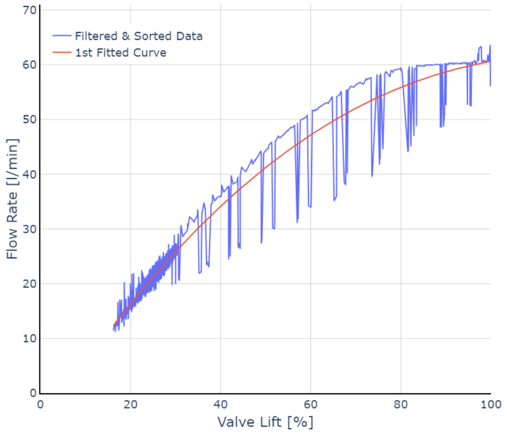


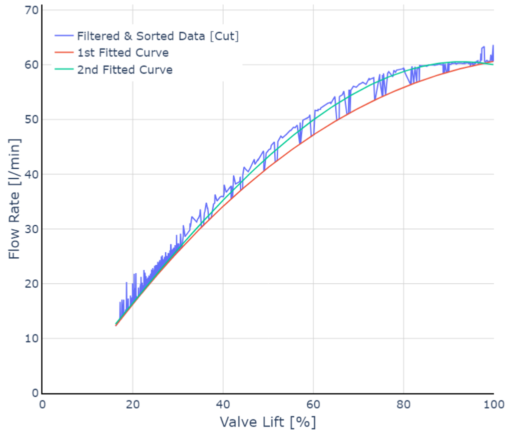
Figure 4.10: Normal operational data - Tank 1 level control

The operational data can be filtered using a simple first-order Butterworth filter to remove any high-frequency noise before it is sorted using Python to obtain a rough estimation of the installed valve flow characteristics (figure 4.11a). Data filtering will only get you so far. If the filtered data still has some outlying data points that cause the fitted curve to deviate from the ideal fitted curve then additional filtering will only yield similar results. This problem can be circumvented by removing any outlying data points from the sorted data set around the first fitted curve (in the case of figure 4.11b the outliers below the fitted curve were removed) and to then fit a second curve to the modified data set. The second fitted curve should then better fit the original sorted data set. This method of filtering does give mixed results based on the original data set and should therefore only be used when the data set contains a significant amount of obvious outlying data points.

The second step of the data-driven valve sizing method requires the pressure drop across the



(a) First iteration



(b) Second iteration

Figure 4.11: Estimating the installed control valve flow characteristics - Data-driven

installed control valve. If the pressure across the control valve is not being measured then it can be estimated by rewriting (4.3.13) in terms of the pressure across the valve. Equation (4.3.13) requires the equivalent valve area and discharge coefficient as a function of valve lift. The equivalent area of a linear control valve should have a linear relationship with the valve lift [20]. Therefore, the assumption is made that the valve area is simply scaled by the valve lift as depicted in figure 4.12.

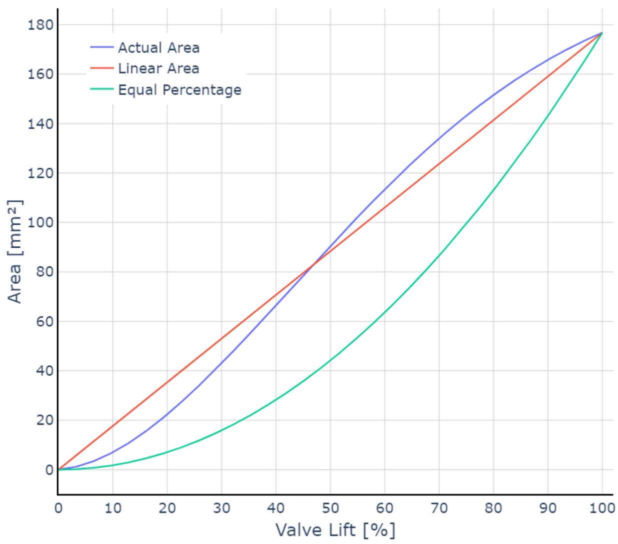
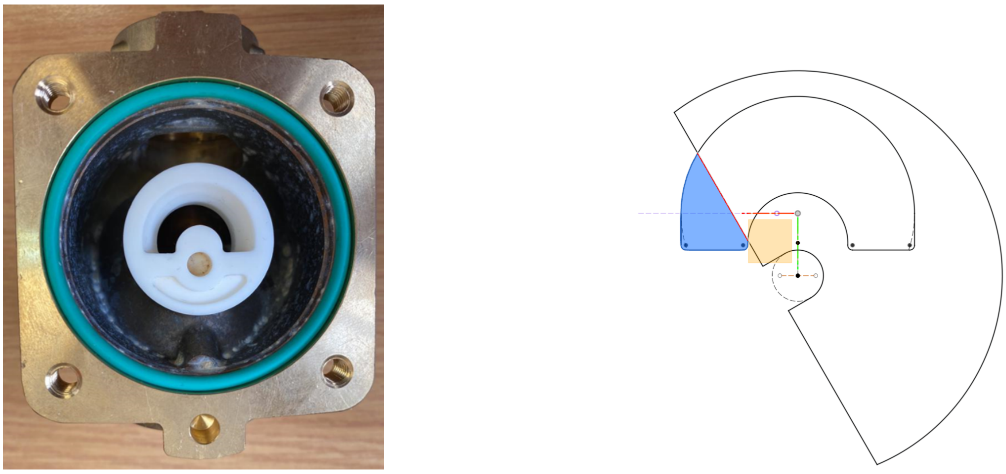


Figure 4.12: Data-driven - Valve area

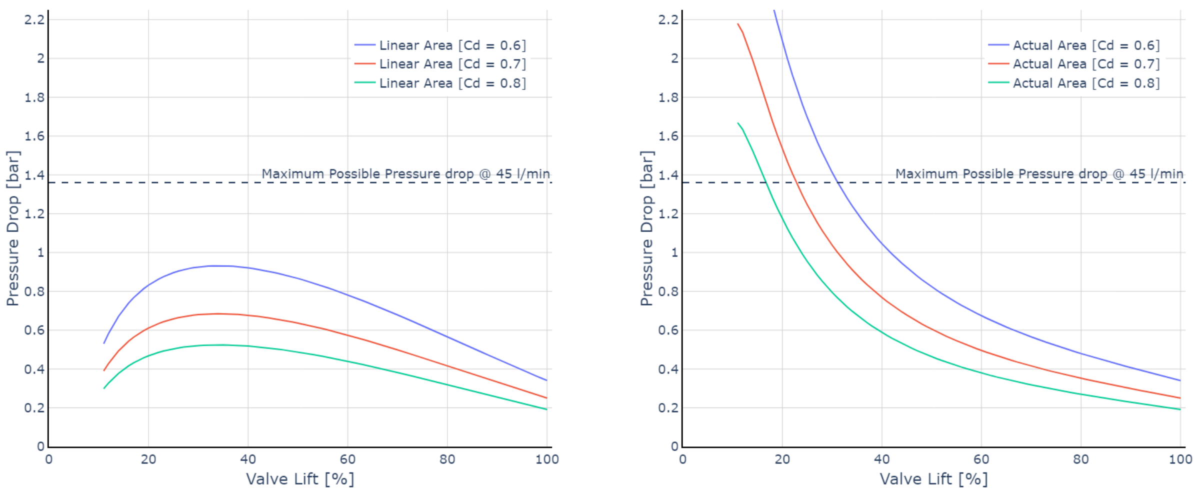
Another approach can also be followed where the actual area of the valve seat is used. Most manufacturers will however not provide a valve area vs. valve lift curve. Therefore if this approach is to be used the actual valve seat area has to be determined. This was achieved by recreating the valve plug and seat within Autodesk Fusion 360. The total valve plug travel was determined to be 155° and rotated in linear increments. The valve seat area can then be determined by measuring the open valve area as depicted in figure 4.13b.



(a) Valve body and seat (b) Valve area calculation

Figure 4.13: Installed control valve

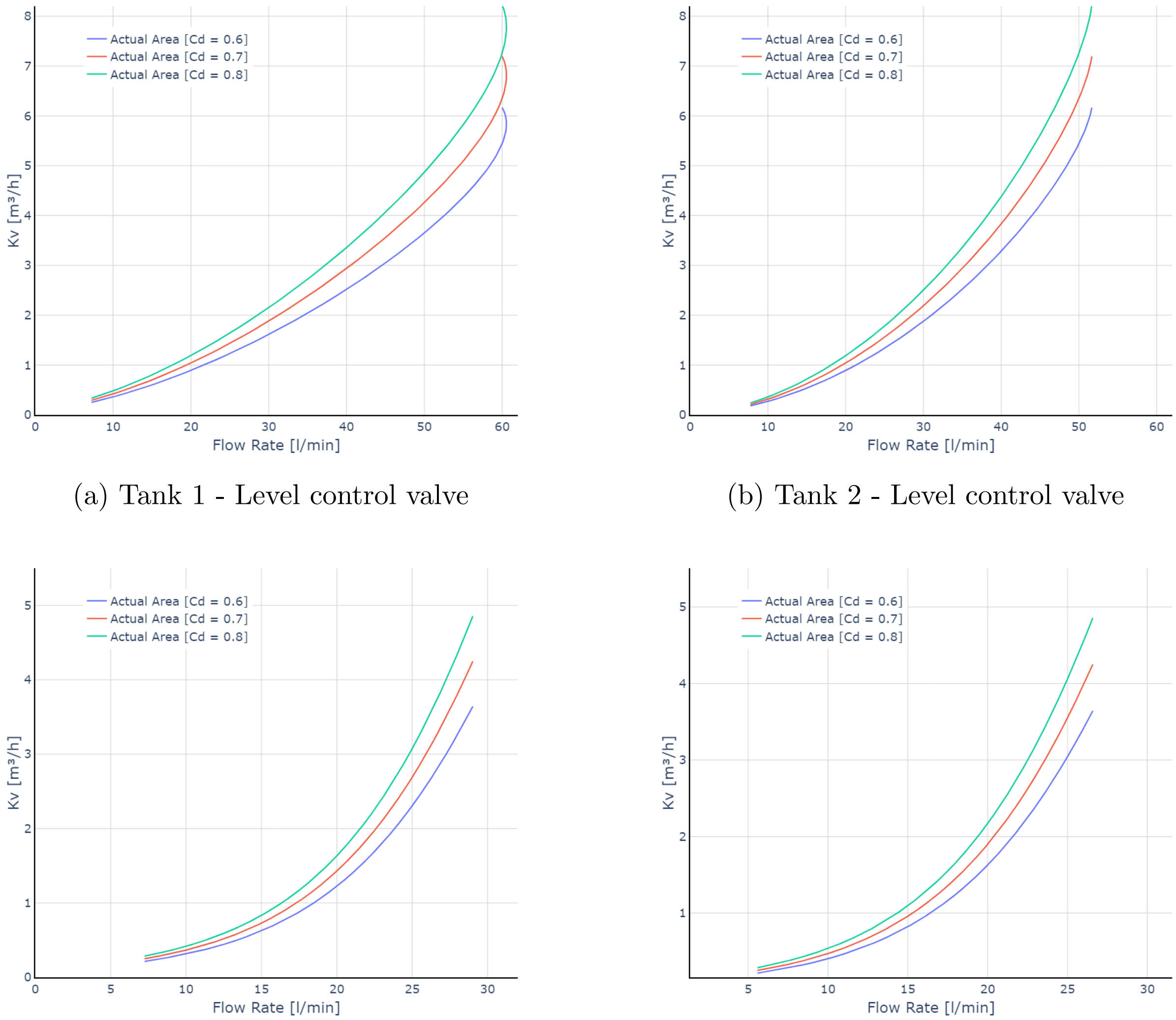
Using the approximated linear valve area or the actual valve area the pressure drop across the valve can be determined for the predetermined range of C_d values as described by [31] ($0.6 \leq C_d \leq 0.8$) and depicted in figure 4.14. The absolute maximum pressure drop across the control valve at the desired maximum flow rate is also depicted to indicate the range of reasonable pressure drop values. This has to be done since the C_d value has a significant effect on the pressure drop and if the actual C_d values are unknown then the estimated valve pressure drop becomes a guessing game. It can also be seen that the estimated valve pressure drop, when using a linear valve seat area, is unrealistic since the pressure seems to be decreasing for small valve lift values instead of increasing. Therefore the rest of the calculations are based on the actual valve area instead of the linear valve area.



(a) Linear area (b) Actual area

Figure 4.14: Valve pressure drop (Pressure vs. valve lift)

Lastly, the calculated valve pressure drops can be used to determine the required K_v value at each mass flow rate value in the system (depicted for all sub-systems in figure 4.15). These curves can then be used to determine the K_{vr} value at the desired nominal and maximum mass flow rates.



(a) Tank 1 - Level control valve

(b) Tank 2 - Level control valve

(c) Tank 1 - Temperature control valve

(d) Tank 2 - Temperature control valve

Figure 4.15: K_v vs. flow rate curves - Data-driven method

Table 4.8: Valve sizing results - Data-driven

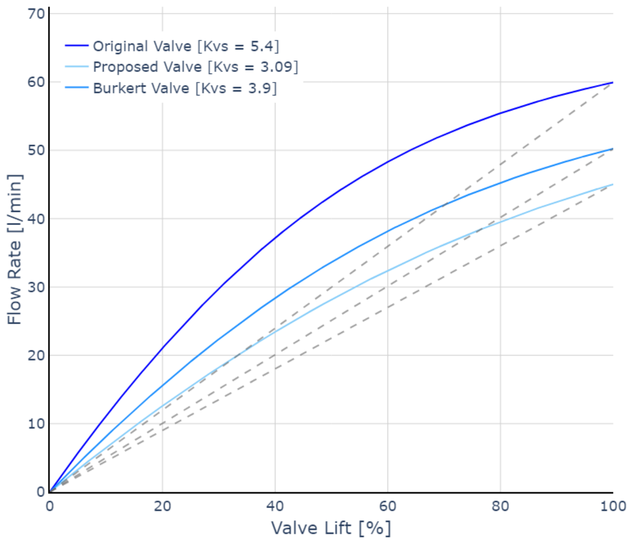
Subsystem		**Nominal flow rate**		**Maximum flow rate**	
		Flow rate [l/min]	K_{vr} [m^3/h]	Flow rate [l/min]	K_{vr} [m^3/h]
Level	Tank 1	23	1.12 - 1.49	45	3.10 - 4.12
	Tank 2	30	1.84 - 2.45	45	4.18 - 5.57
Temperature	Tank 1	15	0.63 - 0.83	25	2.32 - 3.07
	Tank 2	15	0.82 - 1.10	25	3.05 - 4.10

4.4.2 Valve sizing verification and comparison

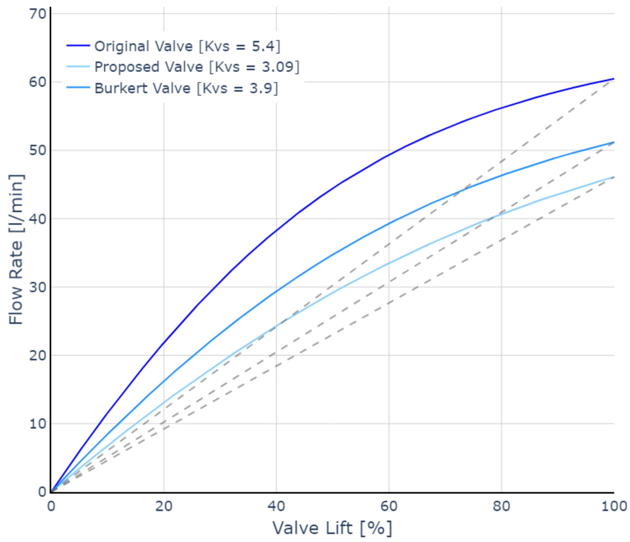
The analytical valve sizing method can be used to verify the results obtained during the shorthand, standardised, and data-driven valve sizing exercises. Each of the calculated desired maximum flow rate results is compared to the original valve used for each sub-system, the closest matching control valve supplied by Burkert, and an ideal linear valve flow characteristics to which the installed valve flow characteristics can be compared.

4.4.2.1 Shorthand

The verified shorthand valve sizing results are depicted in figures 4.16 and 4.17. From figure 4.16 it can be seen that the proposed level control valves [K_{vs} = 3.09] do in fact provide sufficient mass flow to supply the maximum desired mass flow rate. The proposed valves do however still exhibit some quick opening flow characteristics which are only worsened when using the closest available Burkert valve [K_{vs} = 3.9].



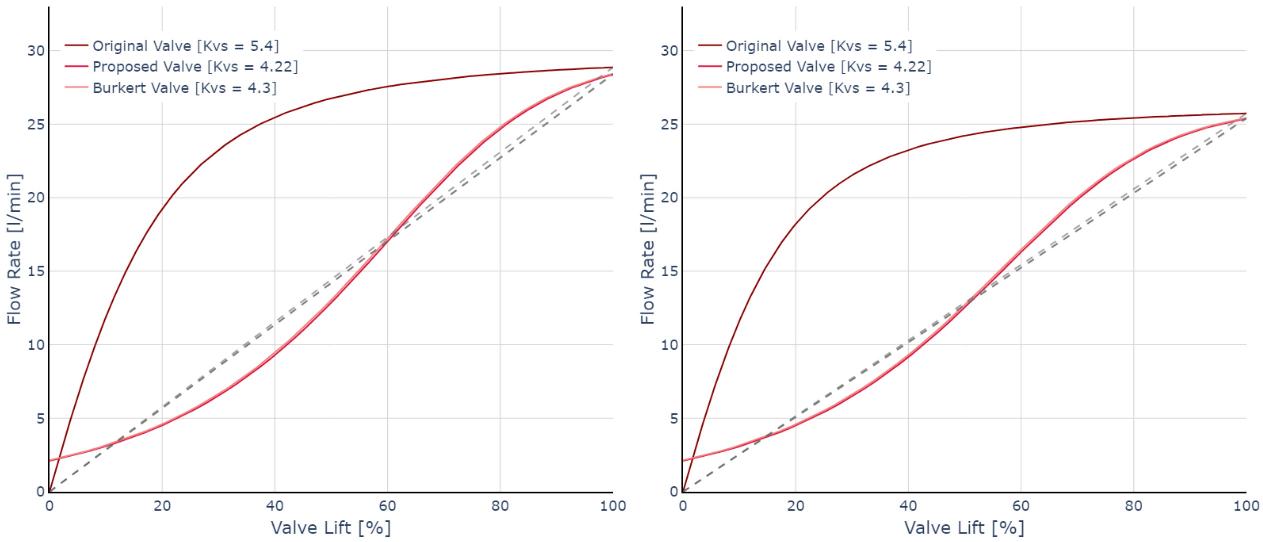
(a) Tank 1



(b) Tank 2

Figure 4.16: Verification of shorthand valve sizing - Level control

From figure 4.17 it can be seen that the proposed temperature control valves [K_{vs} = 4.22] also provide sufficient mass flow to supply the maximum desired mass flow rate. The predicted installed valve flow characteristics for both the Tank 1 and Tank 2 control valves are significantly better than the original control valves. However, the predicted flow characteristics are for the most part linear instead of equal percentage thereby leaving room for improvement.

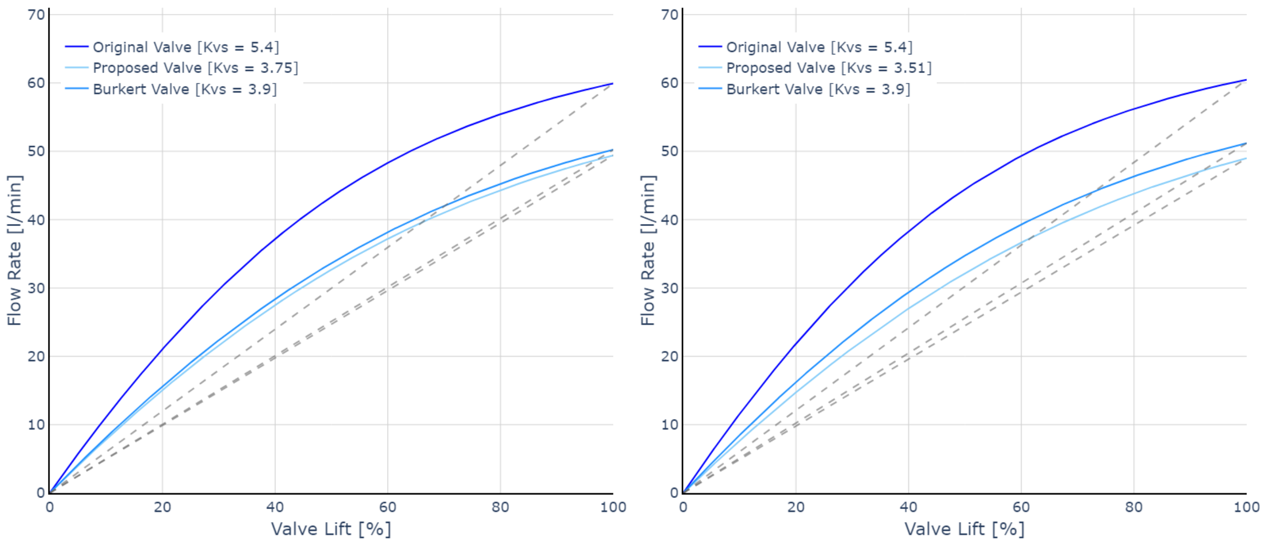


(a) Tank 1 (b) Tank 2

Figure 4.17: Verification of shorthand valve sizing - Temperature control

4.4.2.2 Standardised

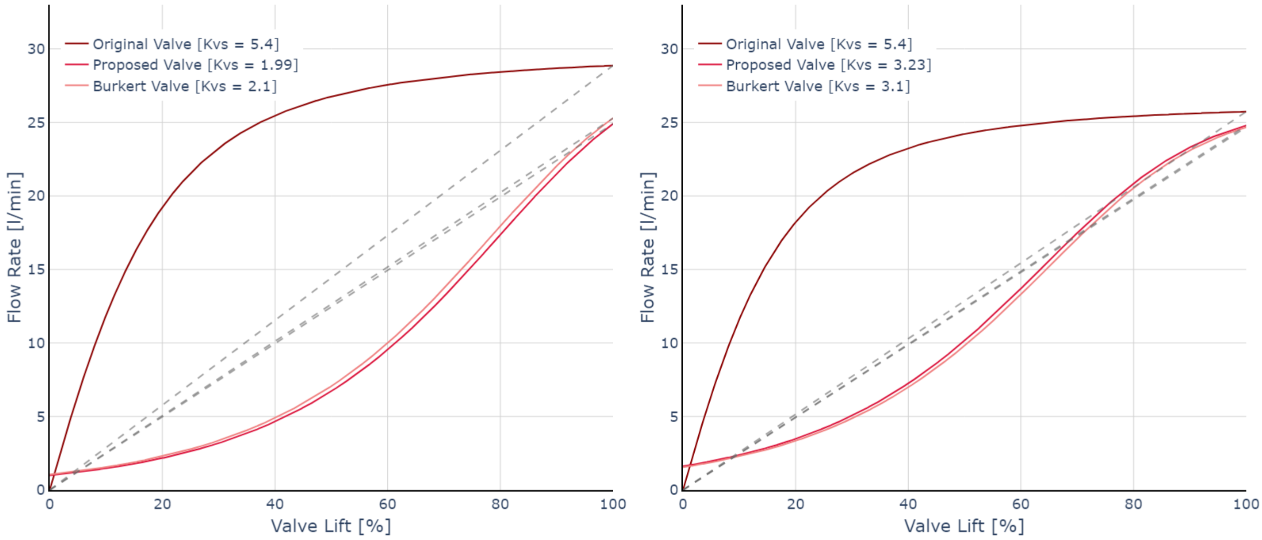
The verified standardised valve sizing results are depicted in figures 4.18 and 4.19. From figure 4.18 it can be seen that the proposed level control valves [Tank 1 - K_{vs} = 3.75 & Tank 2 - K_{vs} = 3.51] do in fact provide sufficient mass flow to supply the maximum desired mass flow rate. However, the same problem arises, as with the shorthand method, that the predicted installed valve flow characteristics are still more quick opening than desired.



(a) Tank 1 (b) Tank 2

Figure 4.18: Verification of standardised valve sizing - Level control

From figure 4.19 it can be seen that the proposed temperature control valves [Tank 1 - K_{vs} = 1.99 & Tank 2 - K_{vs} = 3.23] also provide sufficient mass flow to supply the maximum desired mass flow rate. The predicted installed valve flow characteristics for both the Tank 1 and Tank 2 control valves are also significantly better than the original control valves. The proposed Tank 1 temperature control valve also exhibits a desirable equal percentage installed flow characteristic. However, the predicted flow characteristic for the Tank 2 temperature control valve is slightly more linear than equal percentage.

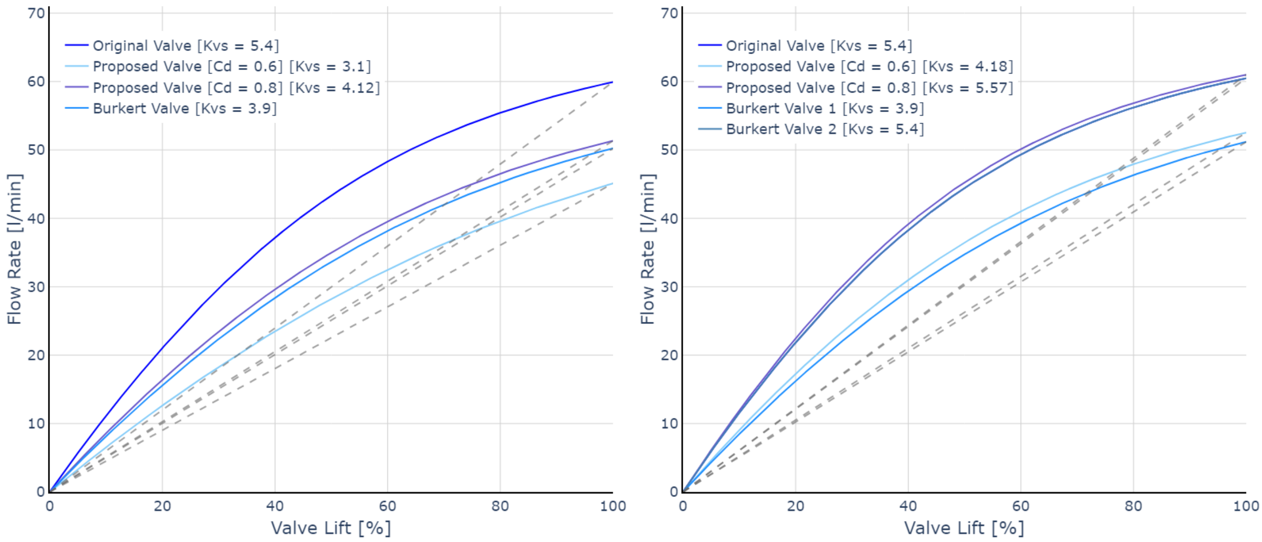


(a) Tank 1 (b) Tank 2

Figure 4.19: Verification of standardised valve sizing - Temperature control

4.4.2.3 Data-driven

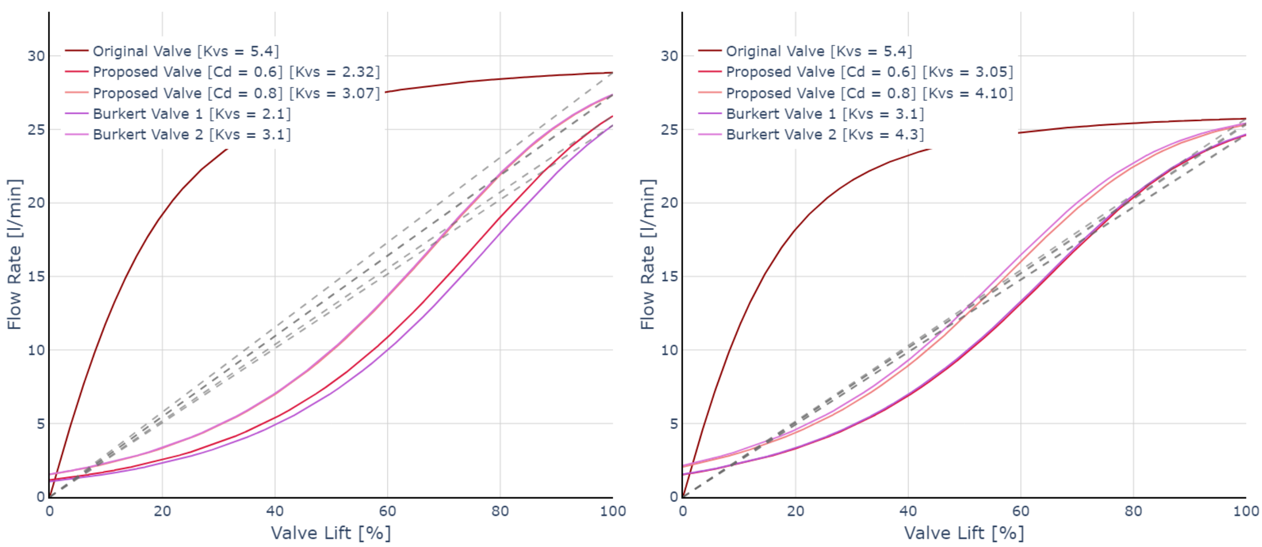
The verified data-driven valve sizing results are depicted in figures 4.20 and 4.21. From figure 4.20 it can be seen that the proposed level control valves [Tank 1 - $K_{vs} = 3.1 - 4.12$ & Tank 2 - $K_{vs} = 4.18 - 5.57$] do provide sufficient mass flow to supply the maximum desired mass flow rate. However, the same problem arises, as with the previous methods, that the predicted installed valve flow characteristics are still more quick opening than desired, especially the Tank 2 level control valve. One of the biggest drawbacks of this technique is the fact that the amount of assumptions that have to be made in order to obtain a K_v value drastically affects the accuracy of the calculated K_v values. If the C_d vs. valve lift curves are not provided then the final answer will always lie within a predicted range of C_d values which only further affects the trustworthiness of the answers. From figure 4.20b it can clearly be seen that due to the uncertainty of C_d the proposed K_v values provide a maximum mass flow rate between 10% and 30% higher than the desired maximum mass flow rate.



(a) Tank 1 (b) Tank 2

Figure 4.20: Verification of data-driven valve sizing - Level control

From figure 4.21 it can be seen that the proposed temperature control valves [Tank 1 - $K_{vs} = 2.32 - 3.07$ & Tank 2 - $K_{vs} = 3.05 - 4.10$] also provide sufficient mass flow to supply the maximum desired mass flow rate. The predicted installed valve flow characteristics for both the Tank 1 and Tank 2 control valves are yet again significantly better than the original control valves. However, due to the range of required K_v values, the predicted installed valve flow characteristics for Tank 1 range from linear to equal percentage whereas Tank 2's are all mostly linear.



(a) Tank 1 (b) Tank 2

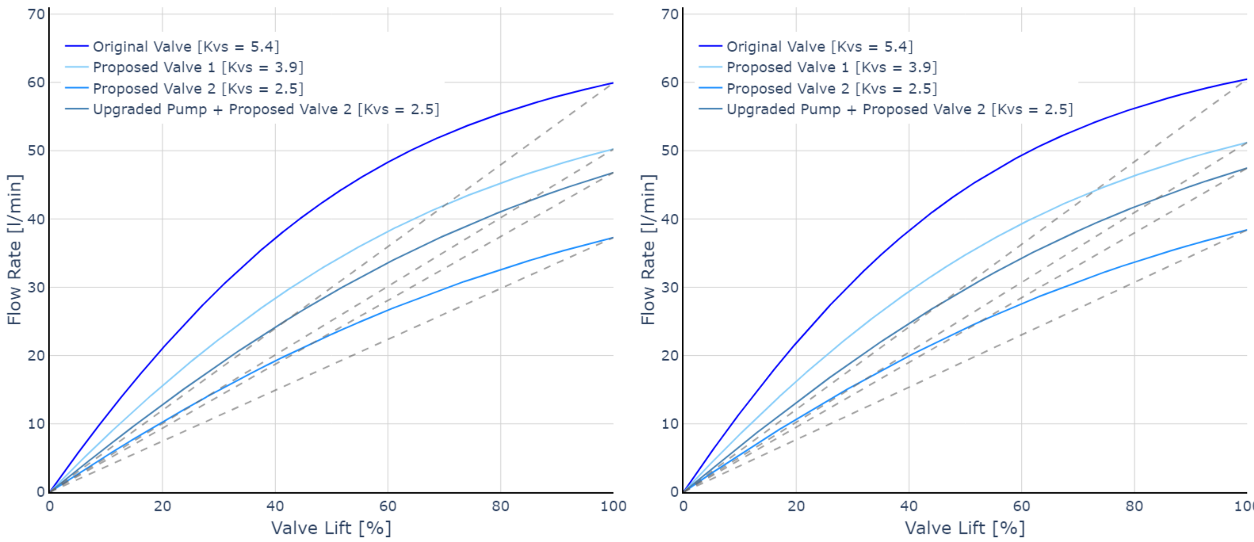
Figure 4.21: Verification of data-driven valve sizing - Temperature control

4.4.2.4 Hybrid - Standardised and analytical

Based on the results obtained thus far it is clear to see that not a single one of the valve sizing techniques accounts for everything and can be used without some form of verification or simulation. The shorthand method overshot the sizing of the temperature control valves and only provided a somewhat usable answer due to the fact that the maximum desired mass flow rate was chosen to be near the maximum achievable flow rate in the system. If this had not been done then the desired maximum mass flow rate could easily have been unachievable due to the fact that the technique does not take the system itself into account leading to the false assumption that the pump used for temperature control can achieve any mass flow rate indicated by it's head curve. The data-driven technique has to potential to solve this problem since it utilises practical data obtained from the system itself. This will however only be valid if the data set used for the data-driven method contains a wide enough range of valve lift and flow rate values to accurately predict the installed valve flow characteristics. The data-driven method does however have other disadvantages, such as the fact the discharge coefficient should be known otherwise the accuracy of the method will plummet, that also put into question the result obtained by using it. The standardised sizing method gave the most consistent results due to the fact that both the level control and temperature control valve sizing exercises yielded results that closely matched the desired maximum mass flow rates. The technique, as used in the context of this dissertation, also takes into account the system itself thereby yielding better results. It is therefore proposed that the standardised method be used in conjunction with the analytical sizing method to determine the final control valves for the heated two-tank system.

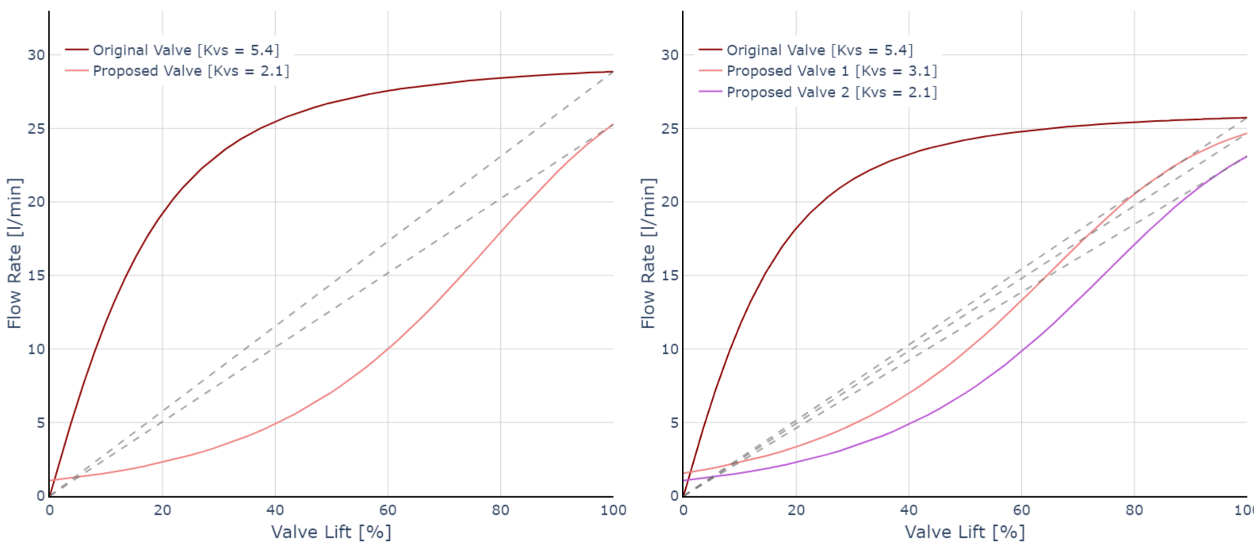
The initial standardised valve sizing exercise already yielded promising results however with some iteration the results can be improved upon. The level control valves can achieve more linear installed flow characteristics if the K_v value is chosen even smaller [$K_{vs} = 2.5$]. This does however limit the maximum mass flow rate to below 39 l/min which is not ideal. Therefore the flow rate can be increased by installing a large centrifugal pump [Leo ACm 25 → Leo ACm 60] thereby increasing the maximum flow rate to roughly 46 l/min while maintaining a similar linear installed valve flow characteristic (depicted in figure 4.22).

The temperature control valve for Tank 1 already exhibits a desirable equal percentage installed valve flow characteristic and does not have to be iterated upon. The temperature control valve for Tank 2 can however be improved upon in order to exhibit more equal percentage installed flow characteristics by decreasing the K_v value [$K_v = 2.1$]. This yet again lowers the maximum achievable flow rate to 23 l/min which is not ideal. The flow rate can be increased by upgrading the size of the centrifugal pump. This is however not recommended in this scenario since the cost associated with a larger pump in order to achieve 2 l/min higher flow rate can not be justified. This will slightly limit the maximum maintainable temperature within Tank 2 however the extent should be of little concern to the overall functionality of the heated two-tank system. In the event that the decrease in flow rate does have a noticeable effect then the valve seat can simply be swapped with the original larger seat.



(a) Tank 1 (b) Tank 2

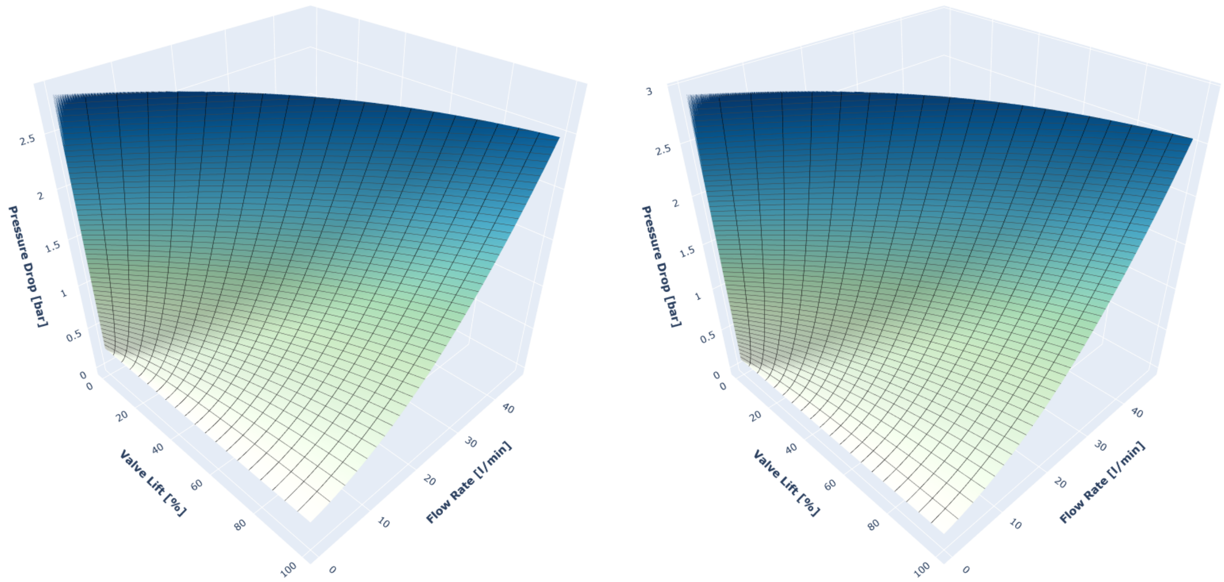
Figure 4.22: Hybrid valve sizing - Level control



(a) Tank 1 (b) Tank 2

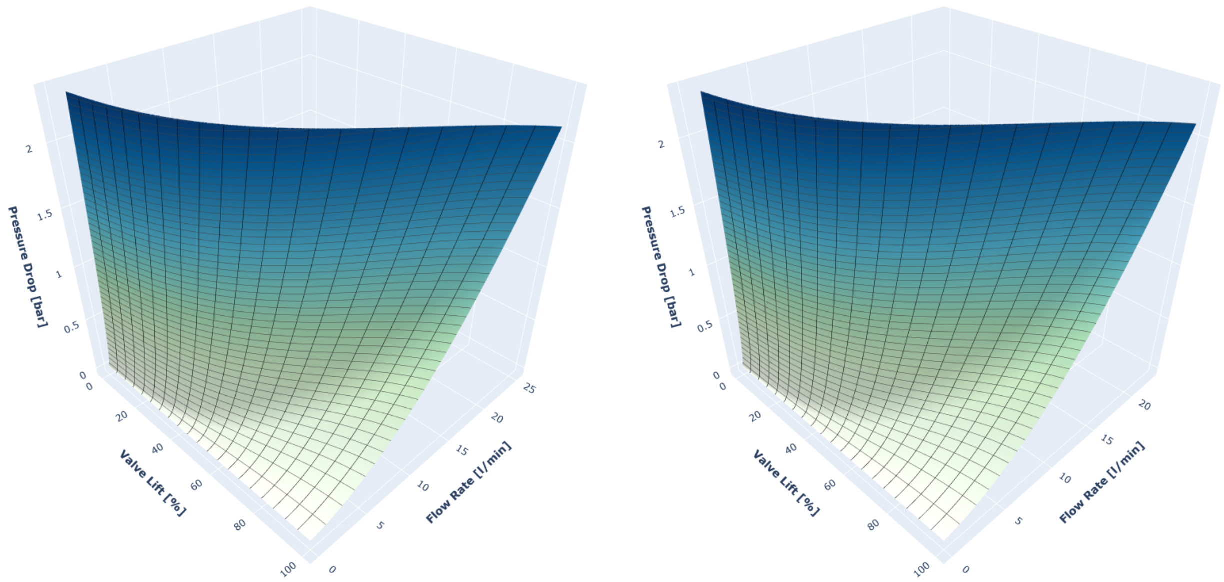
Figure 4.23: Hybrid valve sizing - Temperature control

The installed control valve characteristic surfaces are depicted in figures 4.24 and 4.25. These surfaces give an indication of how the control valves interact with each of the heated two-tank system's sub-systems regardless of the pump head curve. The upper limit on each surface is set to the respective pump head curve of each sub-system. These characteristic surfaces can be used to determine the required pump head curve for a desired installed valve flow characteristic. This can be achieved by projecting the desired installed valve flow characteristic onto the characteristic surface. The intersection between the surface and the desired installed valve flow characteristic will represent the required pump head curve.



(a) Tank 1 (b) Tank 2

Figure 4.24: Upgraded level control valve characteristic curve/surface



(a) Tank 1 (b) Tank 2

Figure 4.25: Upgraded temperature control valve characteristic curve/surface

4.4.2.5 Control valve and sensor selection

The control valves chosen in the previous section are summarised in table 4.9 along with the corresponding pneumatic valve positioners in table 4.10.

Table 4.9: Upgraded control valves

Subsystem		Description	Type	Control	Flow	Diameter	K_{vs}
Level	Tank 1	Burkert 3285	Disk	Electric	Linear	10 mm	2.5
	Tank 2	Burkert 2301	Globe	Pneumatic	= %	15 mm	2.1
Temperature	Tank 1	Burkert 3285	Disk	Electric	Linear	10 mm	2.5
	Tank 2	Burkert 2301	Globe	Pneumatic	= %	15 mm	2.1

Table 4.10: Pneumatic valve positioners

Subsystem		Description	Supply pressure	Communication
Temperature	Tank 1	Burkert 8694	3-7 bar	IO-Link
	Tank 2	Burkert 8694	3-7 bar	IO-Link

The temperature sensors used to upgrade the system are given in table 4.11 and the pressure sensors are given in table 4.12.

Table 4.11: Temperature sensors

Subsystem	Description	Range	Resolution	Length	Communication
Heating Coils	ifm TV7405	$-50 - 150°C$	$0.04°C$	25mm	IO-Link
Geyser	ifm TA2115	$-50 - 150°C$	$0.04°C$	50mm	IO-Link

Table 4.12: Pressure sensors

Subsystem	Description	Range	Resolution	Communication
Level	ifm PP7554	-1-10 bar	50 mbar	IO-Link
Temperature	ifm PP7554	-1-10 bar	50 mbar	IO-Link

4.5 Conclusion

The system upgrade chapter covered the design and implementation of the chosen upgrades as proposed in Chapter 3. The chosen upgrades were covered briefly. The control valve design and sizing were covered in detail. This was done to emphasise the importance of proper control valve sizing since the control valves are the only way to directly influence the system and therefore their behaviour and flow characteristics will also have a direct impact on the overall behaviour of the system. Several control valve sizing methods were compared to one another. It was shown that the standard method of valve sizing does not take into account the inherent or installed valve flow characteristics which may lead to choosing a control valve that does not behave as intended. The valve sizing exercise along with the hybrid valve sizing method was verified using an analytical approach and based on the outcome the final control valve selection was made.

Several improvements were also made to the system based on the chosen system upgrades and improvements. These improvements are covered in Appendix B (System design).

The following chapter will cover the characterisation of the upgraded heated two-tank system. The valve sizing exercise will also be validated.

5 Upgraded system characterisation

5.1 Introduction

The previous chapter covered the upgraded system design and implementation. This included a detailed control valve sizing exercise, highlighting the importance of proper valve sizing when the valve flow characteristics are of interest, as well as several improvements to the fault emulation and data acquisition capabilities of the system. The purpose of this chapter is therefore to characterise the upgraded system and verify the validity of the implemented upgrades. This chapter focuses on the normal functionality of the system as well as the fault emulation capabilities and fault emulation characteristics of the heated two-tank system. The normal operation characterisation is briefly covered since it is mostly a repeat of the characterisation done on the original system during Chapter 3. The faults that the system can emulate are also covered after which the fault characterisation aim, characterisation methodologies, and characterisation process are explained in detail. The chapter is then concluded by analysing the system's operational and fault emulation characteristics.

5.2 System characterisation

The upgraded system characterisation repeats the characterisation done on the original system in order to determine how the system upgrades affected the system characteristics. The upgraded system characterisation therefore consists of the following:

- Control valve flow characteristics
  - Ensure that the upgraded control valves exhibit the desired flow characteristic
  - Validate the control valve sizing exercise
- Operational control range
  - Level control
  - Temperature control
- Cold water cycle heat exchanger
  - Prove or disprove the third hypothesis.
  - This is added due to the fact that the original system was incapable of controlling temperature during the period it was characterised.
- Controller effort
  - Prove or disprove the second hypothesis
  - Determine how the upgraded control valves affected the system's controller effort.

A direct comparison can be made for the level control valves, however, due to the original system's inability to control temperature during the characterisation period, the temperature control's controller effort has nothing to be directly compared to. The effect of the upgraded temperature control valves on the temperature control's controller effort is therefore only an estimate.

5.3 Fault characterisation

The heated two-tank system's main function is to be used to obtain practical data from a multi-physics system that can be used in FDI-based research. The system faults are therefore characterised to allow the researchers to configure the heated two-tank system fault emulation test with not only a specific fault but also a specific fault magnitude. The fault characterisation also gives the researcher an insight into the effect that a specific fault has on the system's behaviour and other process variables. This also includes the extent to which a specific fault can be induced without completely altering the steady-state operation of the system.

It should however be noted that each fault will not be characterised with respect to every other process variable since this is out of the scope of this study. Each fault characterisation process will however be covered in such a way that each fault can be characterised with respect to any other process variable, excluding other faults, if the entire characterisation process is completed. For the purposes of this study, each of the faults will only be characterised with respect to a specific process variable or set of process variables. The chosen process variables for each fault will be discussed during the experimental design sections for each fault.

5.3.1 System faults

The way the heated two-tank system emulates faults can be divided into the following two categories: Hardware-based, and software-based fault emulation. Hardware-based fault emulation is achieved by installing additional hardware in the system that can alter the behaviour of the system in such a way that a hardware-based fault can be induced without damaging the system itself. Software-based fault emulation is achieved by altering either the behaviour of specific components in the system or by altering the way that the received process data is interpreted or acted upon. The hardware and software-based faults that the upgraded two-tank system can emulate are as follows:

Table 5.1: Heated two-tank system: Hardware and software-based faults

	Hardware-based fault emulation			**Software-based fault emulation**		
Fault	Leakages	Blockages	Fouling	Stuck valves	Sensor Drift	Fouling
Type	Cold flow	Cold flow		Cold flow	Flow-rate	
		Hot flow		Hot flow	Level	
					Temperature	

5.3.2 Fault characterisation method

Several different fault characterisation methods have been defined for this study. The reasoning behind this is that not all faults are the same and consequently not all faults can be characterised in the same way. The fault characterisation methods are as follows:

- Characteristic curves,
- Mathematical equation,
- Boundary condition.

The characteristic curve method utilises process data to correlate the fault magnitude and the effect that the fault has on the system. The process data is obtained during a predefined experimental testing procedure specifically designed to characterise a fault. The process data can then be used to construct a characteristic curve that graphically represents said correlation. The advantage of this method lies in the system's ability to log multiple process variables at once. This allows the fault to be characterised by multiple process variables instead of just one (e.g. Cold flow leakage valve lift vs. Cold flow flow rate vs. Tank Level). The mathematical equation method characterises a fault based on a mathematical equation. The fault characteristics are therefore related to various process variables via a mathematical equation. This is mostly used for software-based fault emulation since the fault itself is defined within the software and in certain cases, the effect of the fault can be predicted purely based on the software-defined fault magnitude. Lastly, the boundary condition method is used to determine the maximum allowable fault magnitude that can be induced in the system without altering the steady-state value of the system setpoints. The reasoning behind this is that a fault induced in the system that alters the steady state value of the system setpoints would not require an FDI scheme to be identified. This method is mostly used to characterise faults that would otherwise be impractical to characterise due to the sheer amount of process data required to accurately do so.

Ideally, each of the faults will either be characterised using the characteristic curve method or the mathematical equation method. Therefore an experimental design is done for each of the faults in such a way that the data obtained during the experiments can be used to successfully construct a characteristic curve or a subset thereof unless stated otherwise. The characterisation process is then analysed to determine which characterisation method is best suited for each fault. The aim of the characterisation process and the limitations and restrictions placed upon it are also explained. Most of the faults are limited to a subset of the entire characterisation process due to the amount of data required and the practicality of the tests. These tests also consume quite a lot of natural gas when the temperature control of both tanks is active. The primary time-saving method is to limit the characterisation process to the normal operating conditions of the heated two-tank system as described in table 5.2. The normal operating conditions are the conditions at which the system is primarily operated during most of the previous studies.

Table 5.2: Heated two-tank system - Normal operating conditions

Variable	Min	Nominal	Max
$T_{1_{Lvl}}$	80%	90%	100%
$T_{2_{Lvl}}$	80%	90%	100%
$T_{1_{Tmp}}$	26°C	28°C	29°C
$T_{2_{Tmp}}$	26°C	28°C	29°C

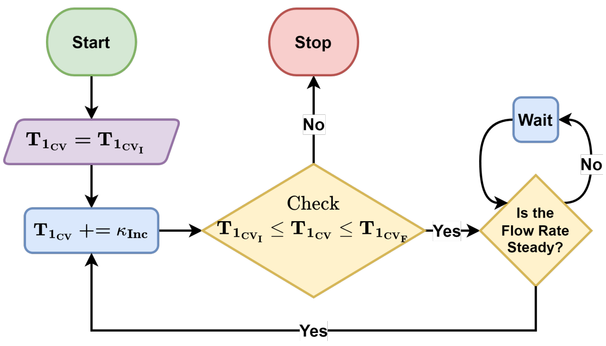
5.4 Experimental design

5.4.1 Control valve flow characteristics

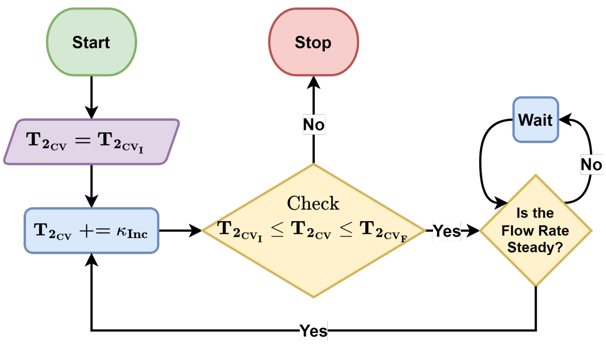
The control valve Flow characteristics can be determined by measuring the flow rate through the valves at varying valve lift values. Care has to be taken to ensure that either one of the tanks does not overflow while conducting this experiment since all of the safety interlocks will be deactivated. This process is depicted in figure 5.1 with the process variable initial, final, and step parameters given in table 5.3.

Table 5.3: Control valve flow characteristic analysis - Parameters

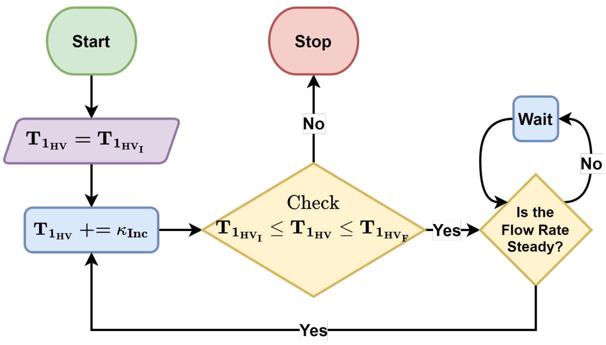
Variable	Condition	Minimum	Proposed	Full
	Initial	0%	0%	0%
Valve Lift	Final	100%	100%	100%
	Step	25%	10%	10%



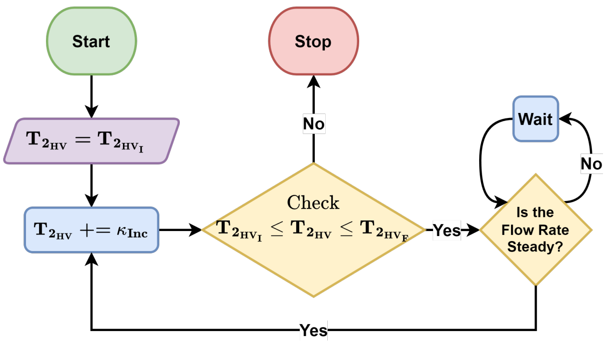
(a) Tank 1 - Level control valve



(b) Tank 2 - Level control valve



(c) Tank 1 - Temperature control valve



(d) Tank 2 - Temperature control valve

Figure 5.1: Control valve flow characteristic analysis - Flow diagrams

5.4.2 Operational range

5.4.2.1 Level control

The level control of the heated two-tank system is simply used to control the level within either one of the tanks. This is achieved by controlling the input mass flow rate of each tank individually. The level control of each tank is characterised in order to quantify the input mass flow rate and corresponding level control valve lift required to maintain any level setpoint within either one of the tanks. The characterisation process for both tanks is identical to the ones used in Chapter 3 and is described in detail in figures 5.2 and 5.3 along with the process variable initial, final, and step values in table 5.4 and 5.5 for Tank 1 and Tank 2 respectively.

Table 5.4: Tank 1 - Operational level control range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	10%	10%	10%
$T_{1_{LVL}}$	Final	90%	100%	100%
	Step	10%	10%	10%

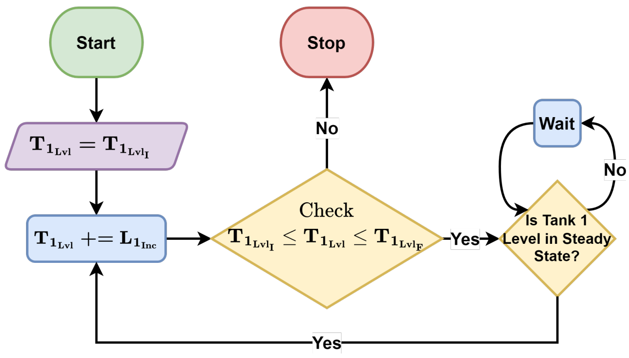


Figure 5.2: Tank 1 - Operational level control range analysis - Flow diagram

Table 5.5: Tank 2 - Operational level control range analysis - Parameters

Variable	**Condition**	**Minimum**	**Proposed**	**Full**
	Initial	10%	0%	10%
$T_{1_{LVL}}$	Final	90%	90%	100%
	Step	40%	10% → 40%	10%
	Initial	10%	10%	10%
$T_{2_{LVL}}$	Final	90%	100%	100%
	Step	10%	10%	10%

5.4.2.2 Temperature control

The temperature control of the heated two-tank system is used to control the temperature of the water within each tank. This is achieved by controlling the mass flow rate through the heating coils situated within each tank separately. The temperature control of each tank is characterised in order to quantify the mass flow rate through the heating coils and the corresponding valve lift required to control the temperature of both tanks at various tank levels. The characterisation process was covered in detail in Chapter 3 and is depicted in figure 5.4 along with the process variable initial, final, and step values in table 5.6 and 5.7 for Tank 1 and Tank 2 respectively. The temperature ranges in table 5.6 and 5.7 are based on the results obtained while characterising the maximum heat that can be removed by the cold water cycle heat exchanger described in the following section. The ranges are chosen to ensure that the flow rates and valve lifts of the temperature control system are situated within the nominal temperature control range of the system.

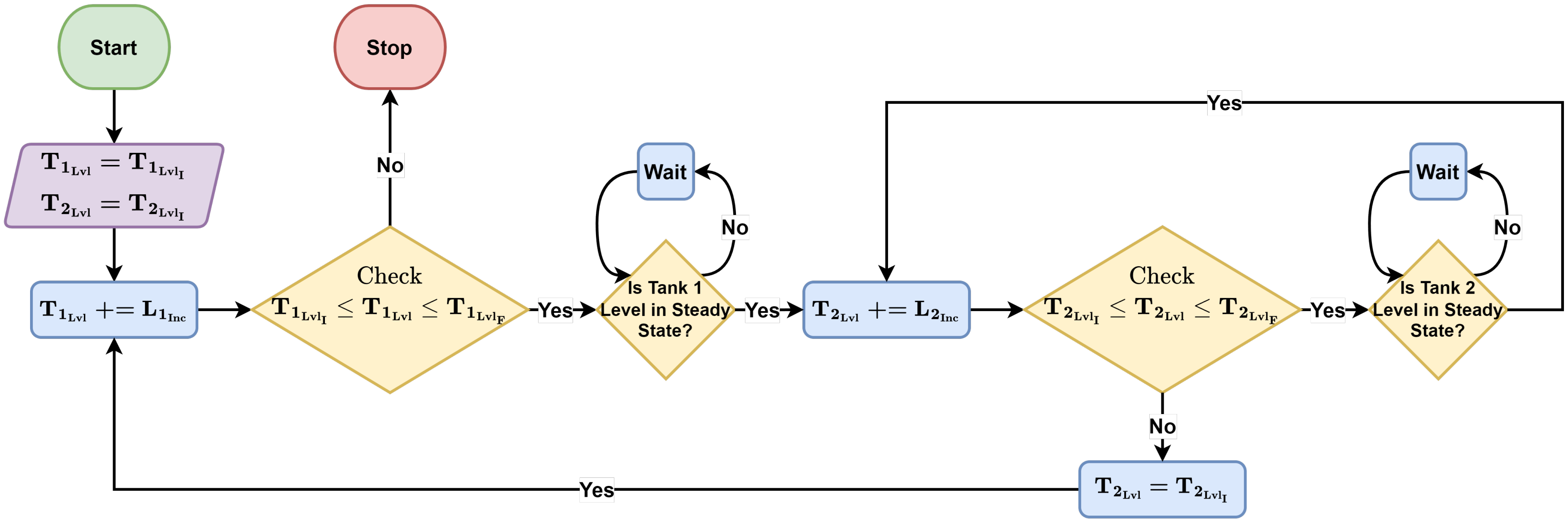


Figure 5.3: Tank 2 - Operational level control range analysis - Flow diagram

Table 5.6: Tank 1 - Operational temperature range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	27°C	20°C
$T1_{Temp}$	Final	28°C	29°C	30°C
	Step	0.0°C	0.5°C	1.0°C
	Initial	28°C	28°C	20°C
$T2_{Temp}$	Final	28°C	28°C	30°C
	Step	0.0°C	0.0°C	1.0°C

Table 5.7: Tank 2 - Operational temperature range analysis - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	28°C	20°C
$T1_{Temp}$	Final	28°C	28°C	30°C
	Step	0.0°C	0.0°C	1.0°C
	Initial	28°C	27°C	20°C
$T2_{Temp}$	Final	28°C	29°C	30°C
	Step	0.0°C	0.5°C	1.0°C

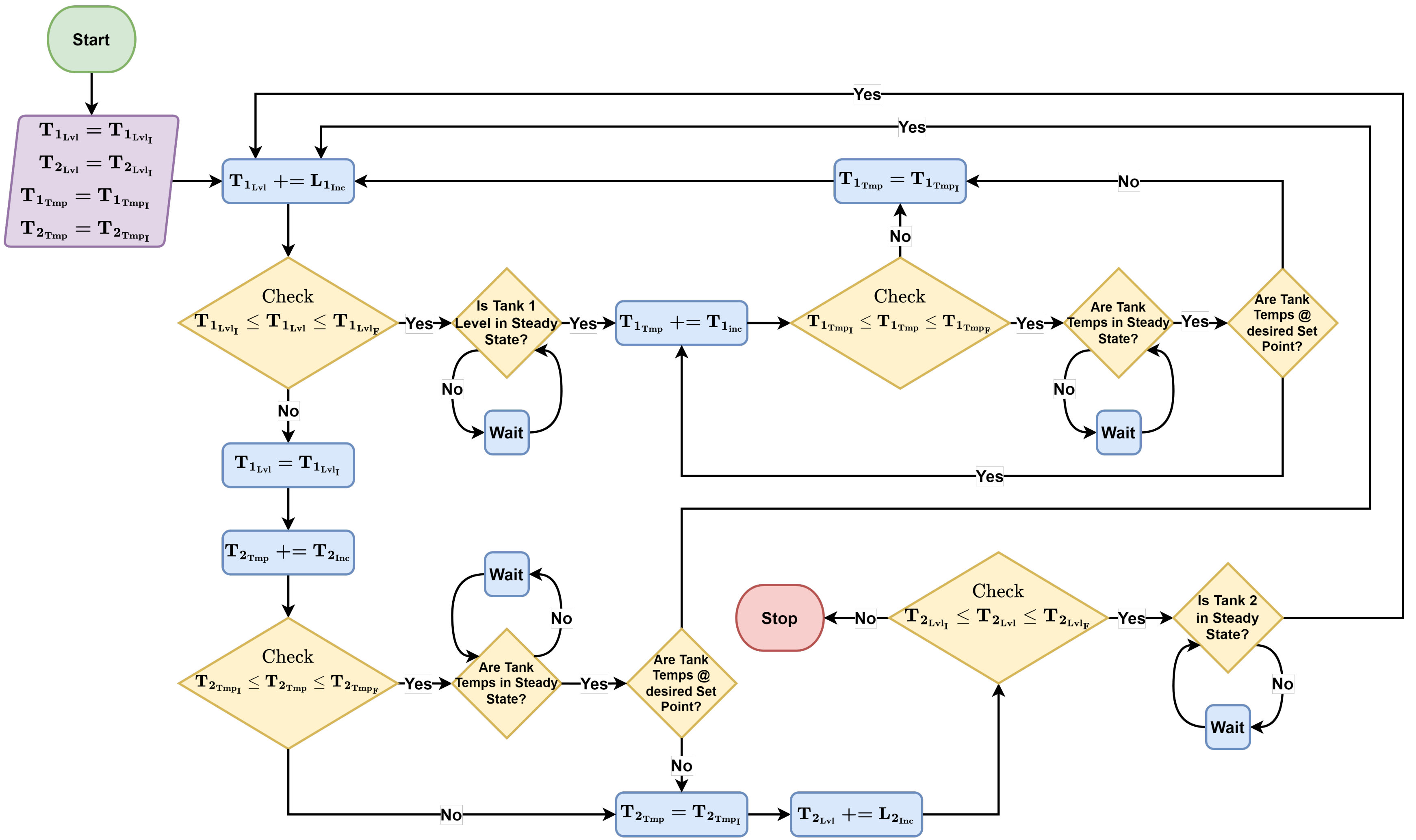


Figure 5.4: Tank 1 & 2 - Operational temperature control range analysis - Flow diagram

5.4.3 Cold water cycle heat exchanger

The cold water cycle heat exchanger (see the P&ID in appendix B.3 for C-N301) is used to regulate the temperature of the cold water reservoir and ideally ensure that its temperature remains constant. However, the third hypothesis postulated that this is not the case. The hypothesis could however not be proven on the original system due to its inability to control temperature during the final characterisation period.

The third hypothesis can be proven by monitoring the cold water reservoir temperature while operating the heated two-tank system at different temperatures and level setpoints. This process is identical to the one used to characterise the operation control range as depicted in figure 5.4.

The maximum heat that can be removed by the heat pump can be determined experimentally by disabling the heating subsystem of the heated two-tank system thereby limiting the temperature control functionality of the system to that of the cold water cycle heat exchanger. This can be achieved by setting the temperature of Tank 1 to 0°C and varying Tank 2's temperature. The cold reservoir temperature is highly dependent on the level of Tank 2 and the temperature of Tank 2. This can be deduced from the fact that the only heat transferred to the cold reservoir comes directly from the output of Tank 2. By ensuring that no heat is transferred to Tank 1 the maximum temperature difference between Tank 1 and Tank 2 (with Tank 1 being at a lower temperature than Tank 2) can be determined as such. The maximum temperature difference between the two tanks (with Tank 1 being at a higher temperature than Tank 2) can be determined by setting Tank 2's temperature to 0°C and then varying Tank 1's temperature. For both instances, the levels of both tanks will also have to be varied.

This process can be described using the same process flow diagram used to determine the operational temperature range (figure 5.4) with only the process variable initial, final, and step values being changed as described in table 5.8 and 5.9

Table 5.8: Max tank temperature difference - Tank 1 low & Tank 2 high - Parameters

Variable	**Condition**	**Minimum**	**Proposed**	**Full**
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%

Table 5.8 continued from previous page

Variable	Condition	Minimum	Proposed	Full
	Initial	0°C	0°C	0°C
$T_{1_{Temp}}$	Final	0°C	0°C	0°C
	Step	0°C	0°C	0°C
	Initial	28°C	27°C	20°C
$T_{2_{Temp}}$	Final	28°C	29°C	30°C
	Step	0°C	1°C	1°C

Table 5.9: Max tank temperature difference - Tank 1 high & Tank 2 low - Parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T_{1_{LVL}}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T_{2_{LVL}}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	27°C	20°C
$T_{1_{Temp}}$	Final	28°C	29°C	30°C
	Step	0°C	1°C	1°C
	Initial	0°C	0°C	0°C
$T_{2_{Temp}}$	Final	0°C	0°C	0°C
	Step	0°C	0°C	0°C

5.4.4 Flow leakages fault emulation

The flow leakage fault emulates a leakage within the system. The system can currently only emulate leakages within the level control system i.e. cold flow leakages. The cold flow leakage faults emulate a leak between the cold flow pump and the tank. The leakage faults are emulated by installing additional valves that redirect some of the flow back to the cold water reservoirs. The system does have leakage valves installed on the temperature control system i.e. hot flow leakages, however, the problem with these leakage valves is the fact that a leakage within the temperature control system should result in a loss of flow rate as well as a loss in overall energy. This is however not the case since the installed hot leakage valves simply redirect the hot water back to the hot water reservoir resulting in no energy loss. Therefore, the hot leakage valves are omitted during this study and should be revisited in the future.

5.4.4.1 Cold flow leakage (level control)

The cold leakage fault is characterised in order to quantify the cold leakage flow rate under various conditions. This is achieved by experimentally determining how the cold leakage valves will affect the input cold water flow rate to each of the tanks at various tank levels.

Tank 1 - Cold leakage: The input cold water flow rate of Tank 1 is only affected by the level setpoint of Tank 1. The characterisation of Tank 1's cold leakage fault therefore only has to account for the level in Tank 1. This is achieved by steadily opening the Tank 1 cold leakage valve until the current level setpoint of Tank 1 can no longer be maintained. This process is then repeated for various tank-level setpoints. This process is depicted in detail in the flow diagram in figure 5.5.

The proposed characterisation method only contains a single iteration loop, Tank 1 Level, and will therefore not require a significant amount of process data, as compared to some of the other fault characterisations. Table 5.10 describes the initial and final values for the process variable setpoints required to characterise Tank 1's cold leakage fault. These values are divided into the minimum amount of iterations required for characterisation, the proposed setpoints for characterisation, and the setpoints required to fully characterise the fault.

Table 5.10: Tank 1 - Cold leakage fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Complete
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	0%	0%	0%
$T1_{CLeak}$	Final	100%	100%	100%
	Step	25%	10%	10%

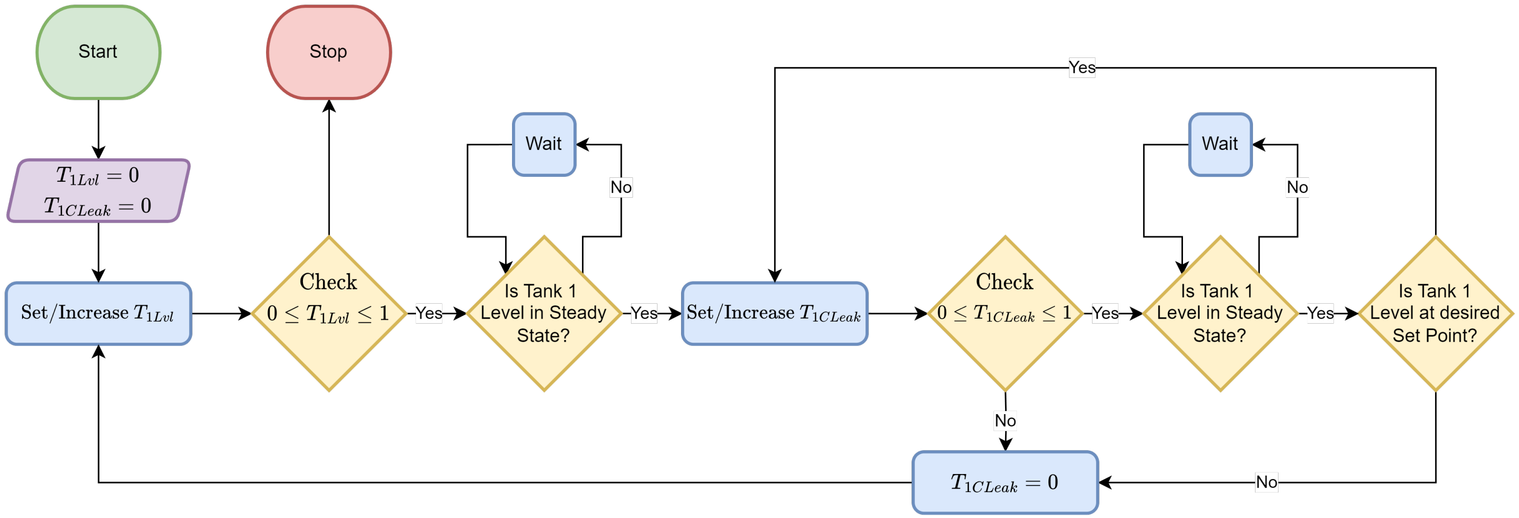


Figure 5.5: Tank 1 - Cold leakage fault characterisation process - Flow diagram

Tank 2 - Cold leakage: The input cold water flow rate of Tank 2 is affected by the output flow rate of Tank 1 and therefore the level of Tank 1. The characterisation of Tank 2's cold leakage fault should therefore account for both the level in Tank 1 and Tank 2. This is achieved by steadily opening the Tank 2 cold leakage valve until the current level setpoint of Tank 2 can no longer be maintained. This process is then repeated for various Tank 2 level setpoints as well as various Tank 1 level set points. This process is depicted in detail in the flow diagram in figure 5.6.

The proposed characterisation method requires two iteration loops, Tank 1 level and Tank 2 level. Table 5.11 describes the initial and final values for the process variable setpoints required to characterise Tank 2's cold leakage fault.

Table 5.11: Tank 2 - Cold leakage fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T_{1_{LVL}}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T_{2_{LVL}}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	0%	0%	0%
$T_{2_{CLeak}}$	Final	100%	100%	100%
	Step	25%	10%	10%

5.4.5 Stuck valve fault emulation

The stuck valve fault emulates a stuck valve in the system. It falls under software-based fault emulation since the behaviour of an existing valve is altered in software in order to act as a stuck valve by setting the valve lift to a specific value and disabling the active control of the valve. There are a total of four valves in the system whose behaviour can be altered to act as stuck valves. These are the two cold flow level control valves and the two hot flow temperature control valves.

5.4.5.1 Cold flow stuck valve (level control)

The cold flow stuck valve faults are characterised to determine the effect that a stuck level control valve has on the heated two-tank system.

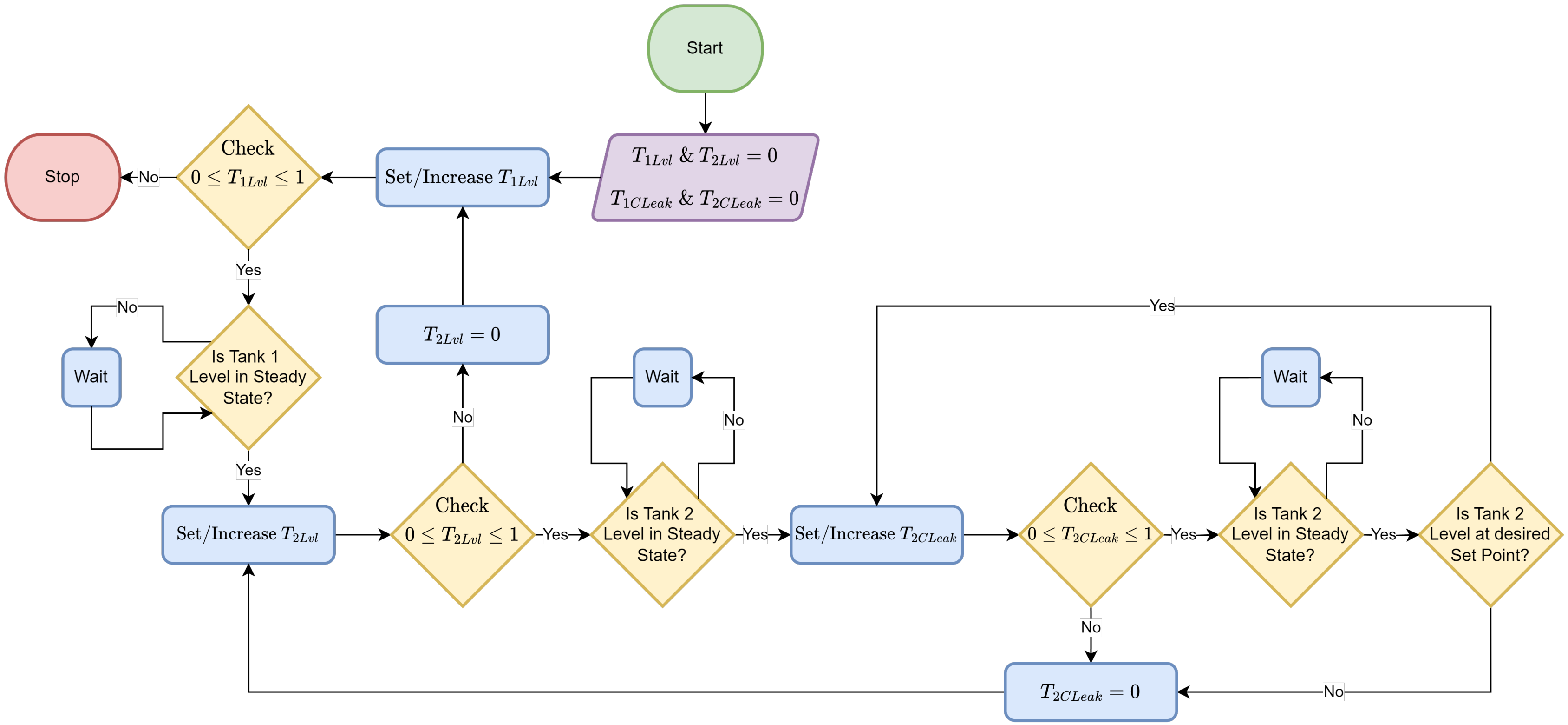


Figure 5.6: Tank 2 - Cold leakage fault characterisation process flow diagram

Tank 1 - Cold flow stuck valve: The level of Tank 1 is only dependent on its own input cold water flow rate. The characterisation therefore only has to account for the maximum allowed level within Tank 1. This is achieved by steadily opening the Tank 1 level control valve until the maximum level in Tank 1 is achieved. This is depicted in the flow diagram in figure 5.7.

The proposed characterisation method only contains a single iteration loop, that of Tank 1's level. It is therefore quite easy to construct a characteristic curve relating Tank 1's level control valve lift to Tank 1's level. Table 5.12 describes the initial and final values for the process variable setpoints to characterise Tank 1's cold flow stuck valve.

Table 5.12: Tank 1 - Cold flow stuck valve fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	10%	0%	0%
$T_{1_{Lvl}}$	Final	90%	100%	100%
	Step	40%	10%	10%

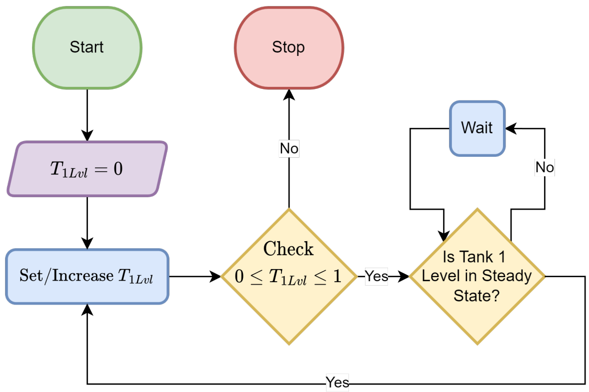


Figure 5.7: Tank 1 - Cold stuck valve characterisation process - Flow diagram

Tank 2 - Cold flow stuck valve: The level of Tank 2 is dependent on both its own input cold water flow rate and the output cold water flow rate of Tank 1. The characterisation of Tank 2's cold flow stuck valve fault, therefore, has to account for both the level in Tank 1 and the maximum allowed level in Tank 2. This is achieved by steadily opening the Tank 2 level control valve until the maximum allowed level in Tank 2 is achieved. This process is then repeated for various Tank 1 level setpoints. This is depicted in detail in figure 5.8.

The proposed characterisation method contains two iteration loops, that of Tank 1's level and Tank 2's level. The complexity of the process is fairly low allowing the characterisation to be done on the entire data set. Table 5.13 describes the initial and final values for the process variable setpoints to characterise Tank 2's cold flow stuck valve.

Table 5.13: Tank 2 - Cold flow stuck valve fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	10%	0%
$T_{1_{LVL}}$	Final	90%	90%	100%
	Step	0%	40%	10%
	Initial	10%	0%	0%
$T_{2_{LVL}}$	Final	90%	100%	100%
	Step	40%	10%	10%

5.4.5.2 Hot flow stuck valve (temperature control)

The hot flow stuck valve faults are characterised to determine the effect that a stuck temperature control valve has on the heated two-tank system. As mentioned previously the temperature, and therefore the hot flow valve lift, of both tanks are interlinked and affected by the level and temperature setpoint of each other. Therefore the effect of a stuck temperature control valve depends on the current water level in the tank as well as the level and temperature setpoint in the other tank.

Tank 1 & 2 - Hot flow stuck valve: The characterisation of a stuck temperature control valve in either of the tanks can be done simultaneously since the temperature control valve lift of both tanks is affected by the temperature and level setpoint of both tanks. This can be achieved by iteratively changing the temperature setpoint of Tank 1 until the desired temperature setpoint can no longer be maintained. This process is then repeated for various Tank 1 level setpoints as well as various Tank 2 level and temperature setpoints. This process is depicted in detail in figure 5.9.

The proposed characterisation method contains four iteration loops, Tank 1 and Tank 2's temperature and level setpoints. The characterisation will therefore also only be done for a subset of the entire data set. This subset is obtained by limiting both the level and temperature ranges of both tanks. Due to this limitation, the characterisation of Tank 1 and Tank 2's hot flow stuck valves are slit into two separate tests each with their own set of parameters. The proposed initial and final variable setpoints for Tank 1 are described in table 5.14 and for Tank 2 in table 5.15.

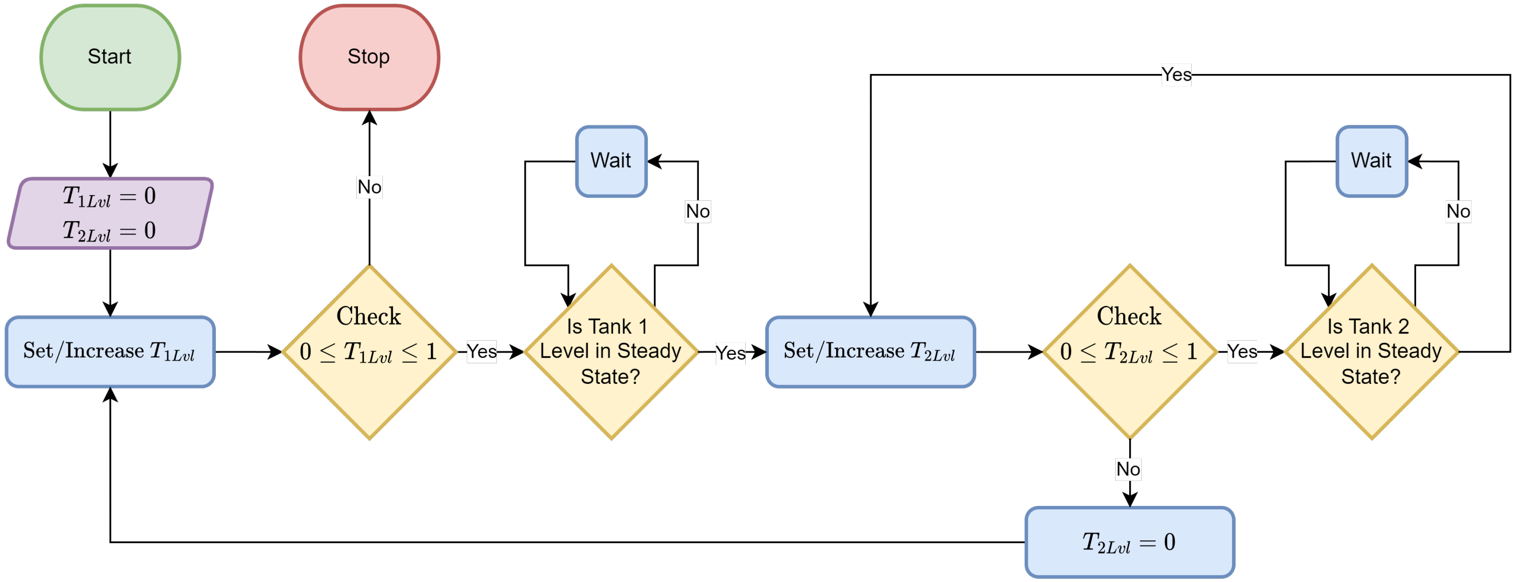


Figure 5.8: Tank 2 - Cold stuck valve characterisation process - Flow diagram

Table 5.14: Tank 1 - Hot stuck valve fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	27°C	20°C
$T1_{Temp}$	Final	28°C	29°C	30°C
	Step	0.0°C	0.5°C	1.0°C
	Initial	28°C	28°C	20°C
$T2_{Temp}$	Final	28°C	28°C	30°C
	Step	0.0°C	0.0°C	1.0°C

Table 5.15: Tank 2 - Hot stuck valve fault characterisation process parameters

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	80%	0%
$T1_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	90%	80%	0%
$T2_{LVL}$	Final	90%	100%	100%
	Step	0%	10%	10%
	Initial	28°C	28°C	20°C
$T1_{Temp}$	Final	28°C	28°C	30°C
	Step	0.0°C	0.0°C	1.0°C
	Initial	28°C	27°C	20°C
$T2_{Temp}$	Final	28°C	29°C	30°C
	Step	0.0°C	0.5°C	1.0°C

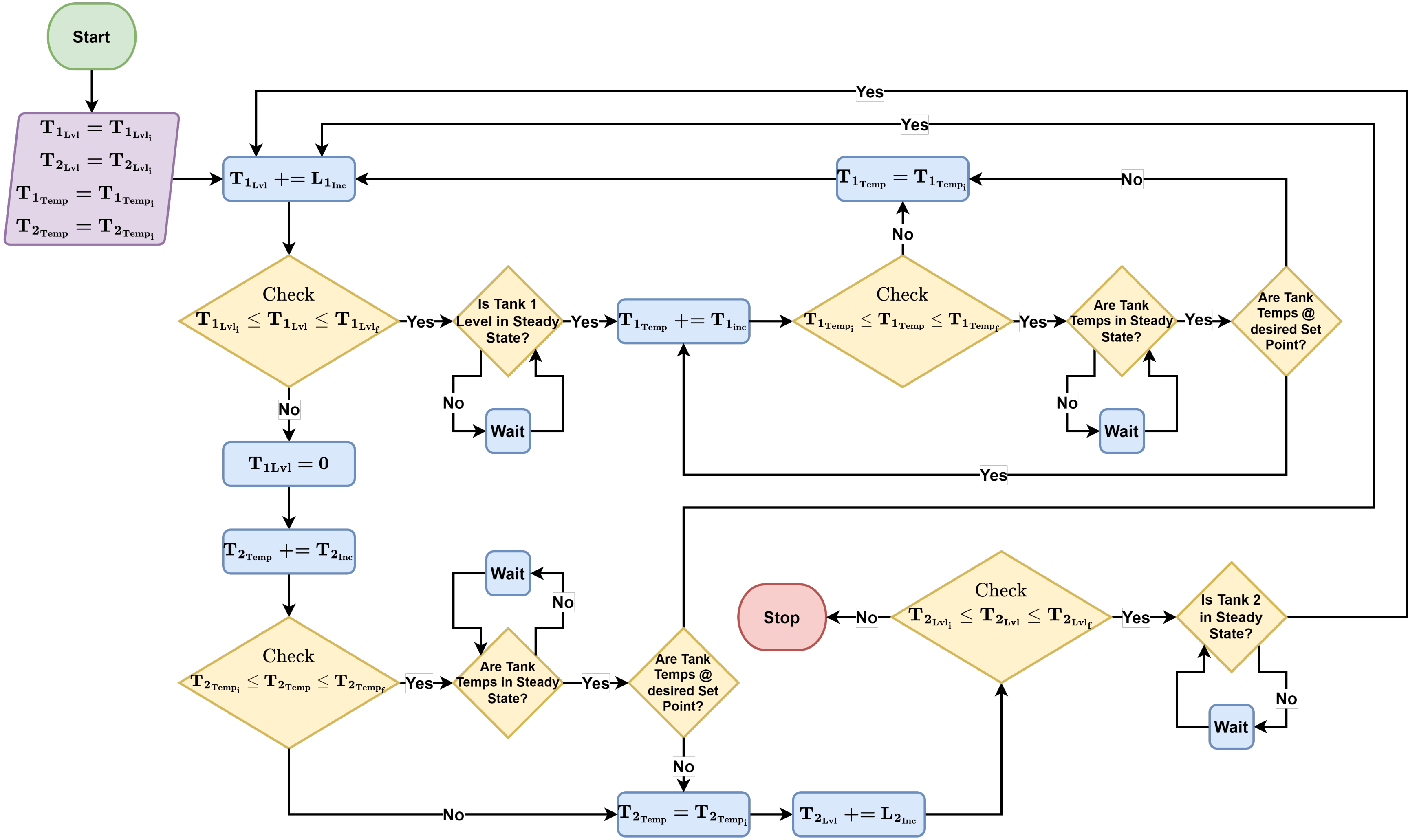


Figure 5.9: Tank 1 & 2 - Hot stuck valve characterisation process - Flow diagram

5.4.6 Blockage/obstruction emulation

The blockage fault emulates a blockage or obstruction within the piping network of the heated two-tank system. It is classified as a hardware-based fault since an additional valve is installed within the system to achieve the effect. Currently, the only blockage that can be emulated within the system is a blockage/obstruction at Tank 1's output.

Tank 1 - Output blockage valve: The output flow rate of Tank 1 is crucial to the normal operation of the heated two-tank system due to the fact that it directly dictates the mass flow rate of both tanks which affects both the level and temperature characteristics of the entire system. Decreasing the output flow rate of Tank 1 decreases the input flow rate of Tank 1 leading to an increase in the input flow rate of Tank 2 in order to maintain steady state. This also leads to a decrease in the hot input flow rate of Tank 1's heating coil since less heat has to be transferred due to a smaller mass flow rate. Decreasing the output flow rate of Tank 1 leads to an increase in the input cold water flow rate to Tank 2. The mass flow rate remains the same, however, in the case where the temperature setpoint of Tank 1 is higher than the temperature of the cold water reservoir the decrease in the output flow rate of Tank 1 results in less heat being transferred from Tank 1 to Tank 2. Therefore the input hot water flow rate of Tank 2's heating coil has to increase to satisfy the energy balance for Tank 2.

The characterisation of Tank 1's output blockage/obstruction fault can therefore be done by observing the steady state behaviour of the heated two-tank system at various combinations of Tank 1 and Tank 2 level and temperature setpoints. This can be achieved by iteratively increasing the blockage valve lift until either of the tank's level setpoints can no longer be maintained. This is then repeated for various Tank 1 and Tank 2 level and temperature setpoints. This process is depicted in detail in figure 5.10.

The proposed characterisation method contains five iteration loops, Tank 1 and Tank 2's level and temperature setpoints as well as the blockage valve lift. Therefore the characterisation will only be done for a subset of the entire data set. This subset is obtained by limiting both the level and temperature setpoint ranges for both tanks. The characterisation process is split into two separate tests in order to obtain a data set that simplifies the data post-processing while adhering to the set limitations of the process. The two tests are used to determine how the blockage valve fault affects the heated two-tank system when one of the Tank's level and temperature setpoints are held constant while the other Tank's level and temperature setpoints are varied. The proposed initial and final process variable setpoints for the two tests are described in table 5.16 Test variant 1 can be used to relate the Tank 1 output blockage/obstruction fault magnitude to the input cold water flow rate of Tank 1 as well as the input hot water flow rate of Tank 1's heating coil. The primary focus is however to determine the amount of flow blocked by the blockage valve at various valve lifts and Tank 1 levels.

Table 5.16: Tank 1 - Output blockage fault characterisation process parameters (variant 1)

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	10%	0%
$T1_{LVL}$	Final	90%	90%	100%
	Step	0%	40%	10%
	Initial	90%	90%	0%
$T2_{LVL}$	Final	90%	90%	100%
	Step	0%	0%	10%
	Initial	28°C	26°C	20°C
$T1_{Temp}$	Final	28°C	30°C	30°C
	Step	0°C	1°C	1°C
	Initial	28°C	28°C	20°C
$T2_{Temp}$	Final	28°C	28°C	30°C
	Step	0°C	0°C	1°C
	Initial	0%	0%	0%
$T1_{Block}$	Final	100%	100%	100%
	Step	25%	10%	10%

Table 5.17: Tank 1 - Output blockage fault characterisation process parameters (variant 2)

Variable	Condition	Minimum	Proposed	Full
	Initial	90%	90%	0%
$T1_{LVL}$	Final	90%	90%	100%
	Step	0%	0%	10%
	Initial	90%	10%	0%
$T2_{LVL}$	Final	90%	90%	100%
	Step	0%	40%	10%
	Initial	28°C	28°C	20°C
$T1_{Temp}$	Final	28°C	28°C	30°C
	Step	0°C	1°C	1°C
	Initial	28°C	26°C	20°C
$T2_{Temp}$	Final	28°C	30°C	30°C

Table 5.17 continued from previous page

Variable	Condition	Minimum	Proposed	Full
	Step	0°C	1°C	1°C
	Initial	0%	0%	0%
$T_{1_{Block}}$	Final	100%	100%	100%
	Step	25%	10%	10%

5.4.7 Sensor drift emulation

The sensor drift fault emulates a drift in the reported value of the sensors in the heated two-tank system. It is classified as a software-based fault since the reported value of each sensor is adjusted individually within the software to obtain a so-called drifted sensor value. The drifted value is then fed to the appropriate control system. The unadjusted sensor value is however still used for all of the control system's safety interlocks such as the tank overflow safety interlock. The heated two-tank system can currently emulate flow rate, level, and temperature sensor drift.

5.4.7.1 Flow rate sensor drift

The level and temperature setpoints of the heated two-tank system are controlled using a closed-loop control scheme. The level and temperature of each tank are controlled by feeding back the actual level and temperature of each tank and then comparing it to the desired setpoint. The error is calculated and fed into a PI controlled which in turn controls the level and temperature control valve lift. Therefore, the flow rate sensors are only used to provide additional information regarding the current state of the heated two-tank system and do not have to be characterised. The flow rate sensor drift maximum values can theoretically be described by the following range:

$$-100\% < \text{Drift} < \infty.$$

The flow rate drift value should not be less than or equal to -100% since that would result in either zero flow rate (Drift $= -100\%$) or a negative flow rate (Drift $< -100\%$) being reported to the system. The maximum positive flow rate drift can theoretically be infinite since this simply results in a very large reported flow rate. It is however limited to a maximum of 100% for practical reasons. This can however easily be adjusted within software should future research demand it.

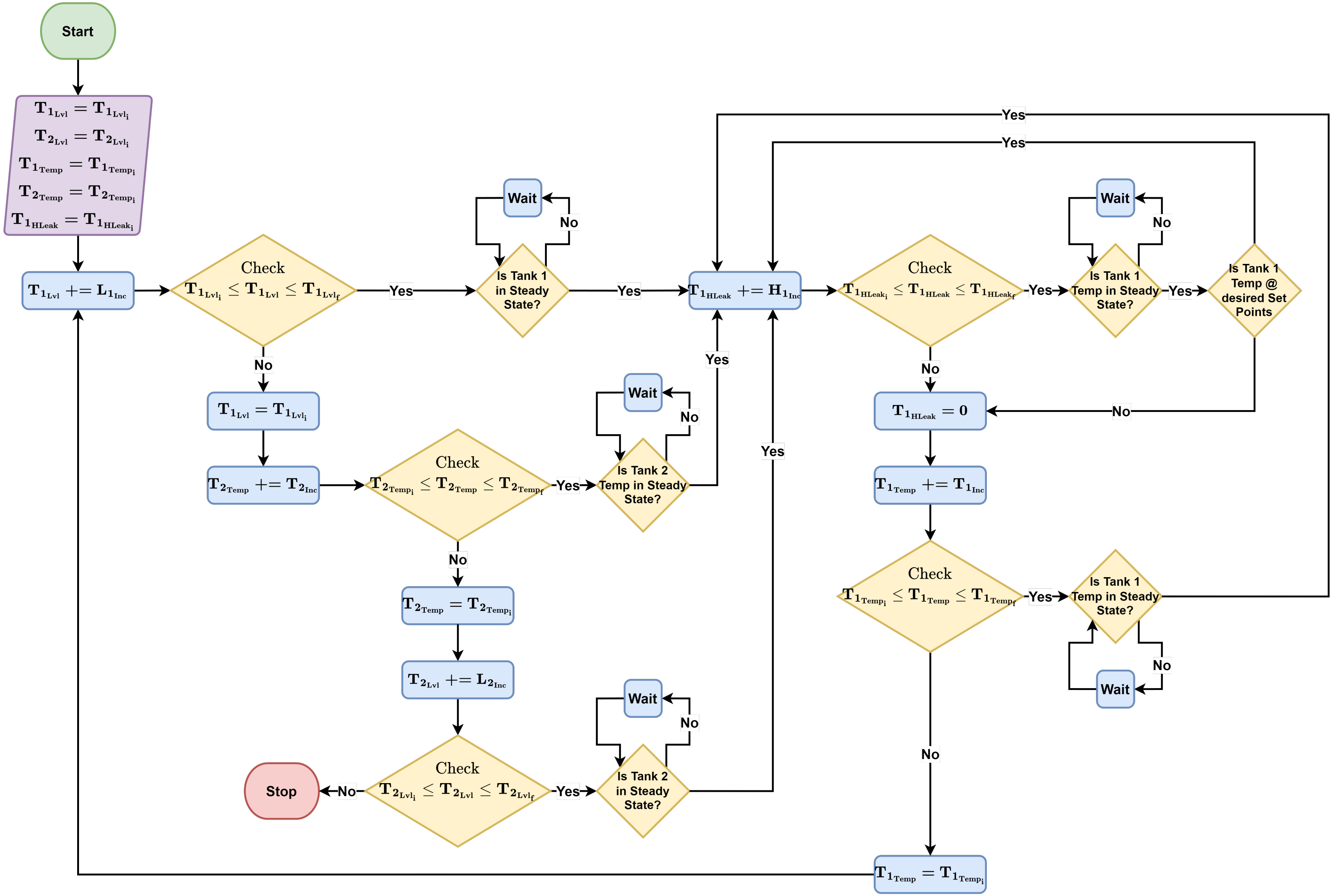


Figure 5.10: Tank 1 - Blockage valve characterisation process - Flow diagram

5.4.7.2 Level sensor drift

The reported level sensor values are used to control the level of each of the tanks; altering these values will therefore directly affect the actual level of a tank. Changing the level of a tank in turn affects the energy balance equations of the heated two-tank system. This means that the level sensor drift fault will change the operating point of the entire system. It should however be noted that a drift in the level of a tank will only shift the temperature and level characteristics of the system obtained previously as well as during the hot flow stuck valve fault characterisation. Therefore it is much more desirable to characterise the effect that the level sensor drift has on the actual level of a tank.

This can actually be done fairly easily by mathematically relating the actual tank level to the level setpoint of the tank and the level sensor drift value. The actual level that the heated two-tank system will settle at for a given level setpoint and level sensor drift value can therefore be determined using the following:

$$L = 100 \cdot \left[\frac{L_{sp}}{100 + D} \right], \tag{5.4.1}$$

with L the actual level of the system, L_{sp} the level setpoint of the tank, and D the level sensor drift value.

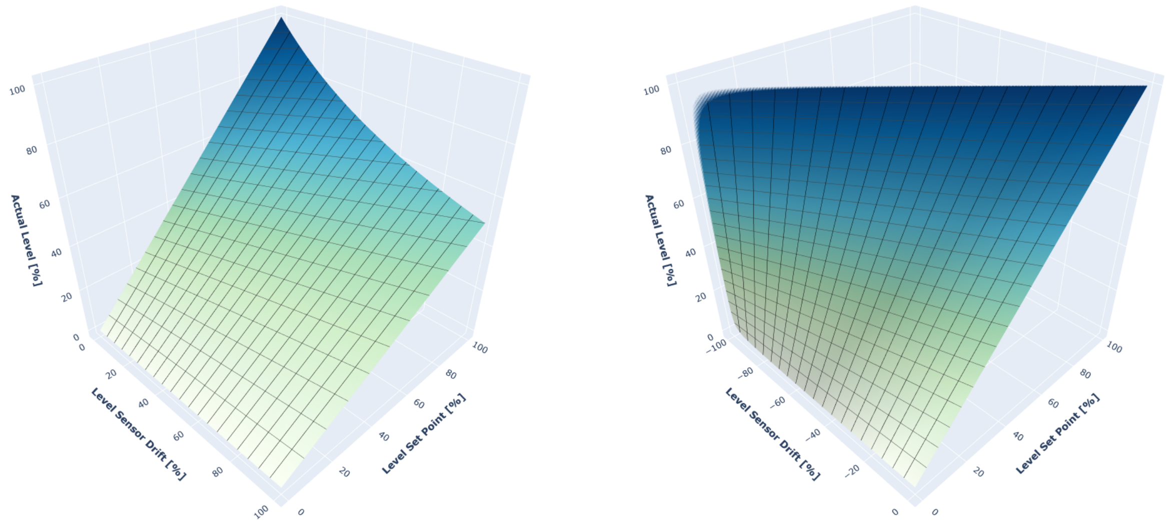
The maximum negative level sensor drift that can be emulated within the heated two-tank system without causing the actual tank level to exceed the maximum allowed level can be determined by altering (5.4.1) as follows:

$$D_{Max} = \left[1 - \frac{L_{sp}}{L_{Max}} \right] \cdot 100\%, \tag{5.4.2}$$

with D_{Max} the maximum allowed negative level sensor drift value and L_{Max} the maximum allowed level within a tank.

The positive level sensor drift does not have a maximum value since adding a positive drift to the level lowers the actual level resulting in the level never being able to exceed the maximum level of a tank if the setpoint is never set above the maximum allowed level. It is however limited to a maximum of 100% for practical reasons. This can however easily be adjusted within software should future research demand it.

The level sensor drift fault characteristic curves can be constructed by using (5.4.1) and are depicted in figure 5.11.



(a) Positive level sensor drift (b) Negative level sensor drift

Figure 5.11: Level sensor drift - Characteristic curves

5.4.7.3 Temeprature sensor drift

The reported tank temperature sensor value is used to directly control the temperature of the tank. The actual temperature of the tank will therefore change if a drift is introduced to the tank temperature sensor value. A change in the tank temperature affects the energy balance equations of the heated two-tank system. This change will however only affect the temperature characteristics of the system since the cold water mass flow rate remains the same. Therefore the temperature sensor drift will only shift the temperature characteristics of the system obtained previously as well as during the hot flow stuck valve fault characterisation. It is therefore much more desirable to characterise the effect that the temperature sensor drift has on the actual temperature of a tank.

This can be done in the exact same way that the level sensor drift fault was characterised. Therefore (5.4.1) can be altered by simply swapping the actual level and level setpoint variables with the actual temperature and temperature setpoint variables. This results in the following:

$$T = 100 \cdot \left[\frac{T_{sp}}{100 + D} \right], \tag{5.4.3}$$

with T the actual temperature of the tank, T_{sp} the Temperature setpoint of the tank, and D the temperature sensor drift value.

The maximum negative temperature sensor drift, that can be emulated within the heated two-tank system without causing the actual tank temperature to exceed the maximum allowed temperature, can be determined by altering (5.4.3) as follows:

$$D_{Max} = \left[1 - \frac{T_{sp}}{T_{Max}} \right] \cdot 100\%, \tag{5.4.4}$$

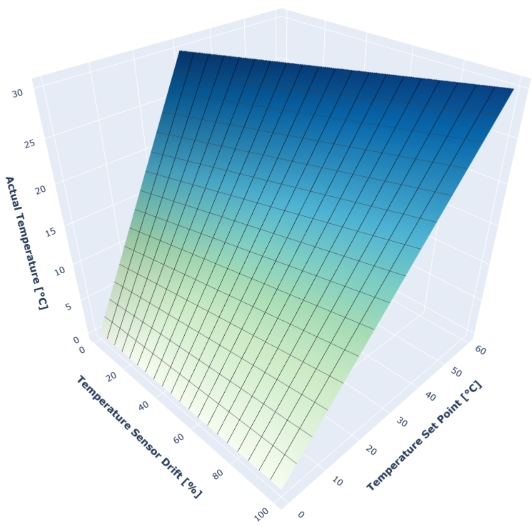
with D_{Max} the maximum allowed negative temperature sensor drift value and T_{Max} the maximum allowed temperature within a tank within a specific Tank 1 and Tank 2 temperature range set.

The maximum positive temperature sensor drift, that can be emulated within the heated two-tank system without causing the actual tank temperature to drop below the minimum allowed temperature, can also be determined by altering (5.4.3) as follows:

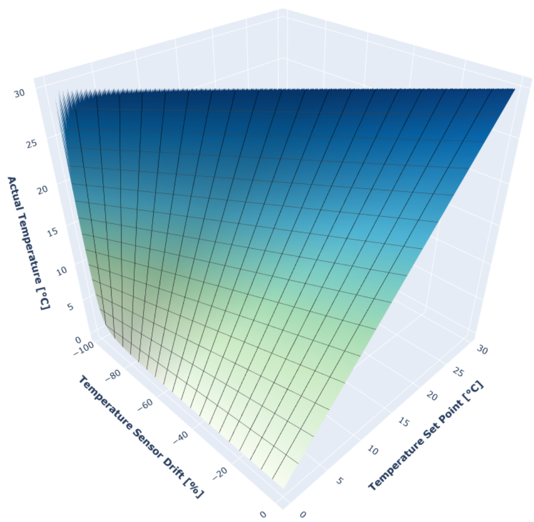
$$D_{Max} = \left[\frac{T_{sp}}{T_{Min}} - 1\right] \cdot 100\%, \tag{5.4.5}$$

with D_{Max} the maximum allowed positive temperature sensor drift value and T_{Min} the minimum allowed temperature within a tank within a specific Tank 1 and Tank 2 temperature range set.

The temperature sensor drift fault characteristic curves can be constructed by using (5.4.3) and are depicted in figure 5.12.



(a) Positive Temperature Sensor Drift



(b) Negative Temperature Sensor Drift

Figure 5.12: Temperature sensor drift - Characteristic curves

5.4.8 Fouling

Fouling is currently emulated within the heated two-tank system by enabling or disabling the agitators situated within each tank. The agitators are currently also being enabled automatically above a level setpoint of 70%. This means that a fouling fault can only be emulated within a tank with a level of 70% or higher. The fouling fault will therefore not be characterised since there is no variation in the extent that fouling is emulated resulting in the fault being binary, either ON or OFF.

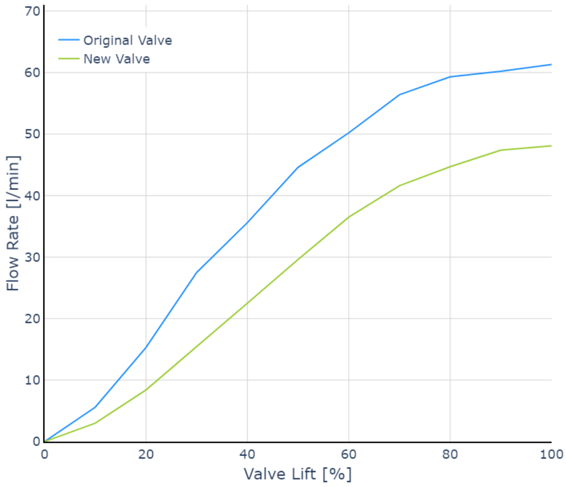
5.5 Experimental results - System characterisation

The system characterisation experimental results covered in this section have already been processed in order to obtain the desired system characteristic curves. The raw experimental data used during this section is briefly presented in Appendix C (Upgraded system data).

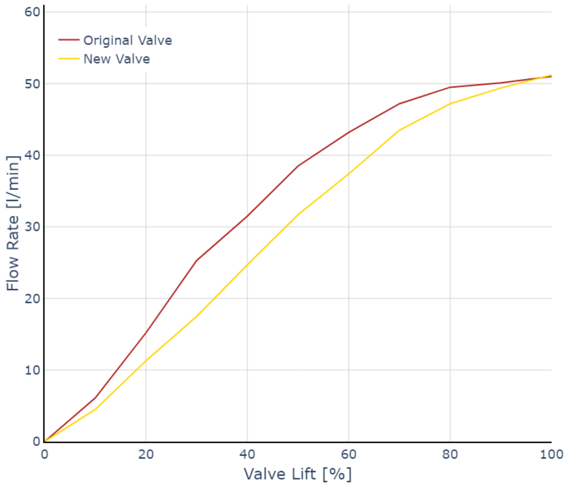
5.5.1 Control valves

5.5.1.1 Installed flow characteristics

The difference between the original control valves and the upgraded control valves' flow characteristics are depicted in figures 5.13 and 5.14 for the level control and temperature control respectively. The upgraded level control valves do appear to exhibit more linear flow characteristics than the original valves whereas the upgraded temperature control valves now clearly exhibit equal percentage flow. This can be shown more clearly by normalising the flow rates as done in figures 5.15 and 5.16.

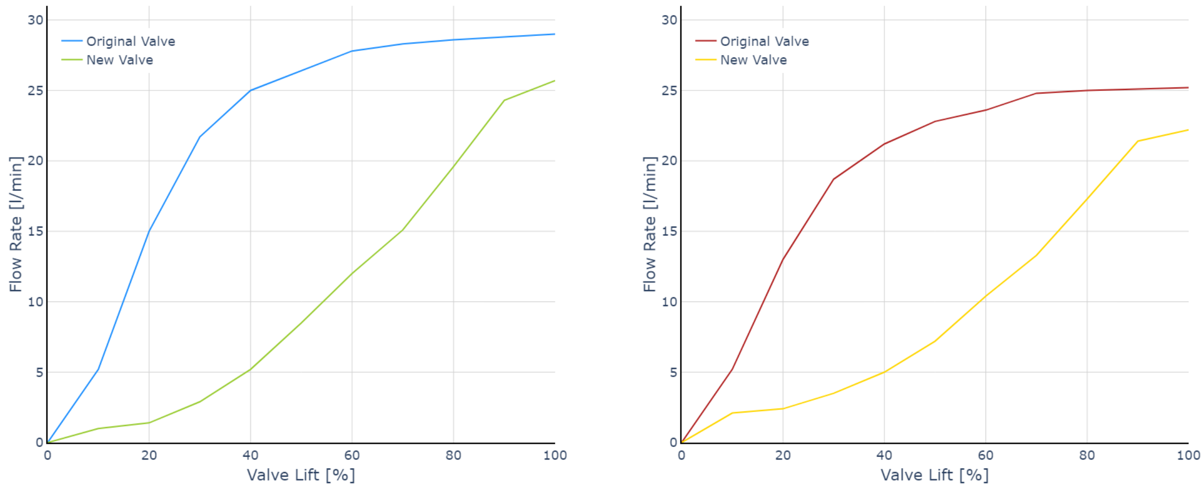


(a) Tank 1



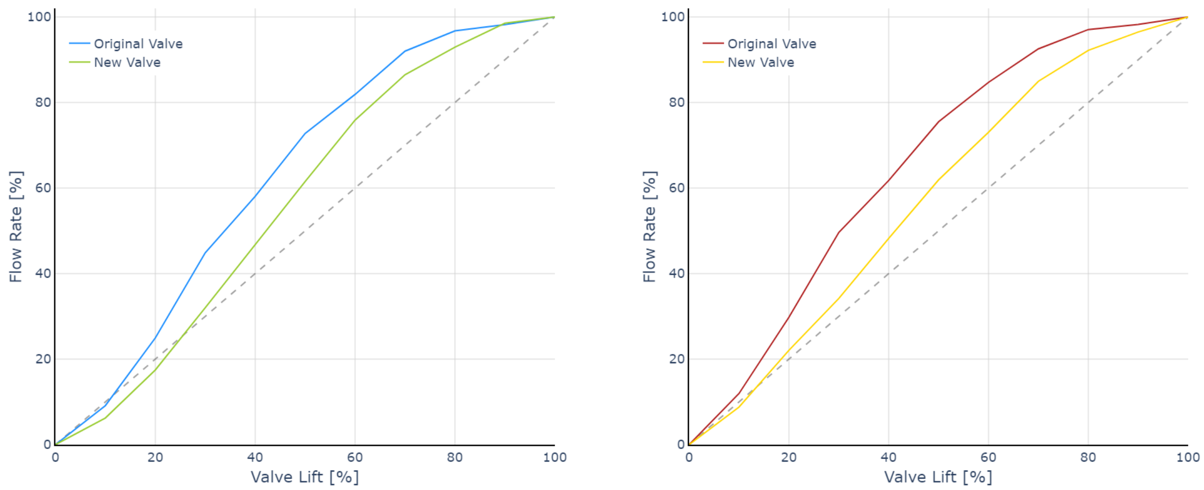
(b) Tank 2

Figure 5.13: Level control valve flow characteristics - Old vs. New



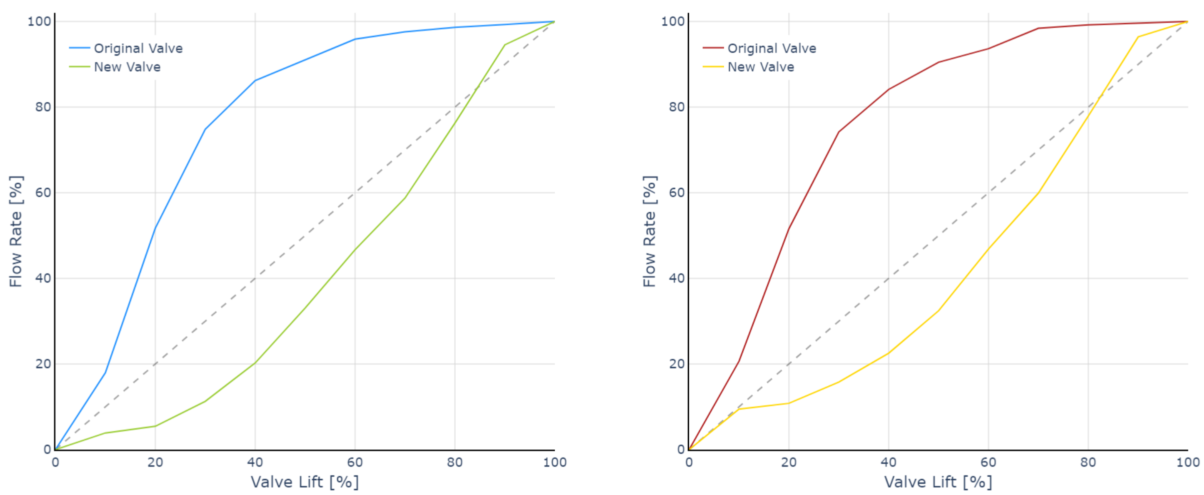
(a) Tank 1 (b) Tank 2

Figure 5.14: Temperature control valve flow characteristics - Old vs. New



(a) Tank 1 (b) Tank 2

Figure 5.15: Level control valve flow characteristics - Old vs. New (normalised)



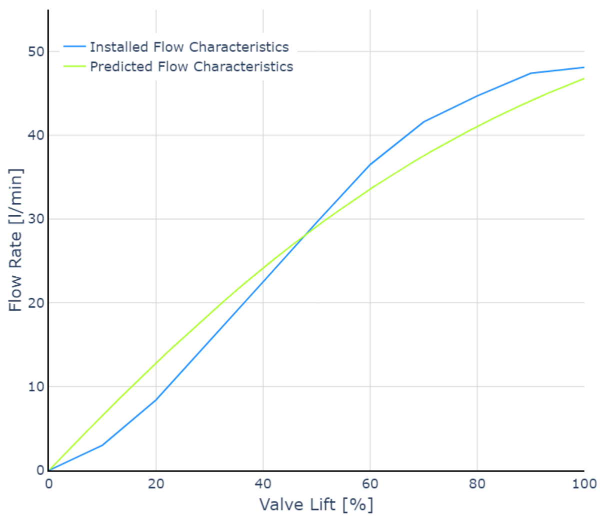
(a) Tank 1 (b) Tank 2

Figure 5.16: Temperature control valve flow characteristics - Old vs. New (normalised)

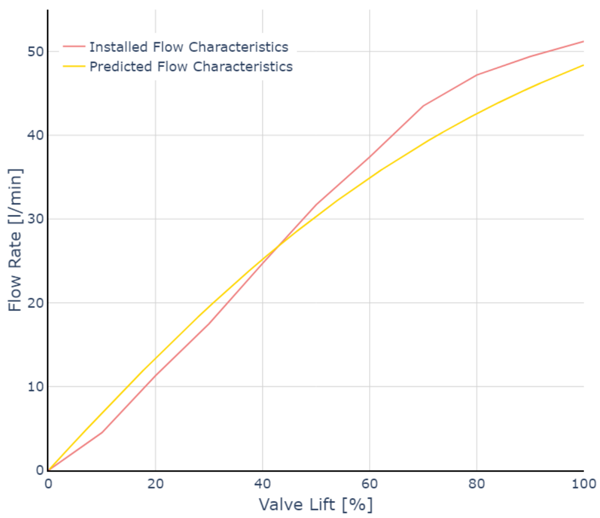
5.5.1.2 Valve sizing validation

The control valve sizing exercise done in Chapter 4 can now be validated by comparing the actual installed valve flow characteristics to that of the predicted installed valve flow characteristics. From figures 5.17 and 5.18 it can clearly be seen that the actual and predicted installed valve flow characteristics are fairly close to one another. The predicted maximum flow rates are within 6% of the actual maximum flow rates and the flow characteristics also match up. There are still some discrepancies. The actual level control flow characteristics however appear to tend towards a mix between that of a linear and a butterfly valve. This could be due to several sources of error such as inaccurate pump head curves or a damaged pump. It also seems to have a strong correlation with the measured Burkert 3285 valve seat area (figure 4.12) used during the data-driven valve sizing exercise. The inherent flow characteristic of the Burkert 3285 proportional valves might therefore not be entirely linear. It could therefore be possible to improve the predicted installed valve flow characteristics if the actual K_v vs. Valve lift curve was used during the calculations (if it were provided). The K_v curve can however be estimated by using a normalised version of the valve seat area from figure 4.12. The modified installed valve flow characteristics are depicted in figure 5.19 and clearly show an improved flow characteristic prediction.

It is however safe to say that the analytical valve sizing technique, given the fact that it purely relies on datasheet values for the pump head curves and sensor head loss curves; and assumes ideal inherent flow characteristics, is more than accurate enough to provide enough information regarding the installed valve flow characteristics to make an informed decision.

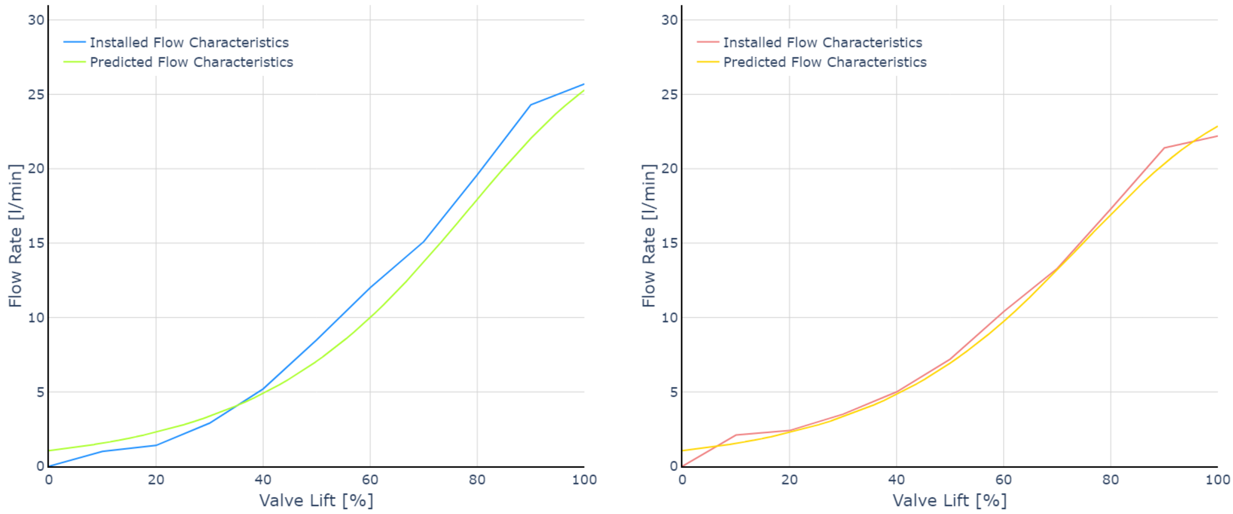


(a) Tank 1



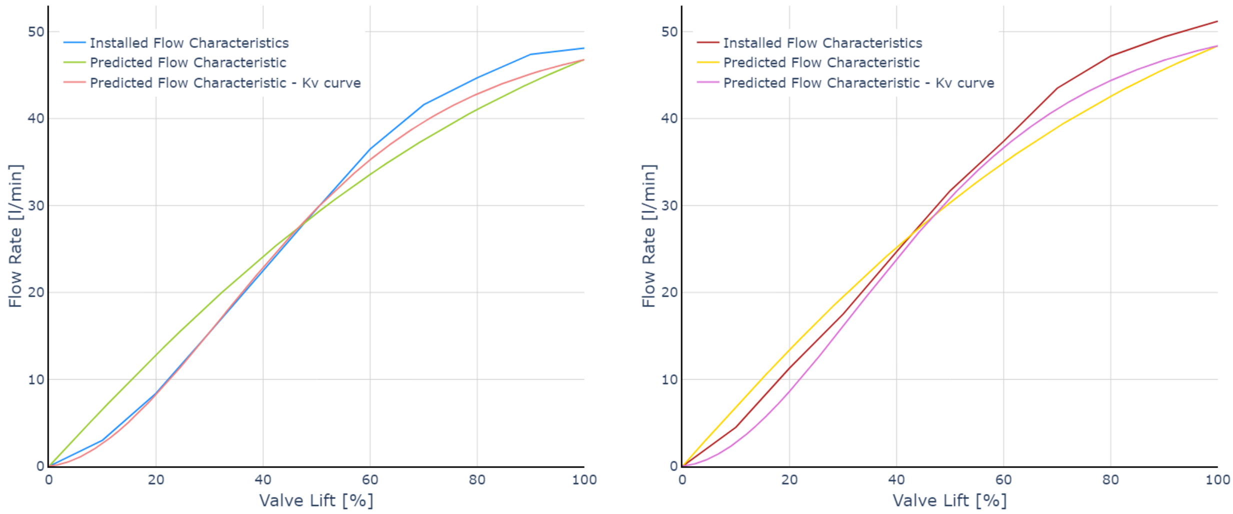
(b) Tank 2

Figure 5.17: Level control valve flow characteristics



(a) Tank 1 (b) Tank 2

Figure 5.18: Temperature control valve flow characteristics



(a) Tank 1 (b) Tank 2

Figure 5.19: Level control valve flow characteristics

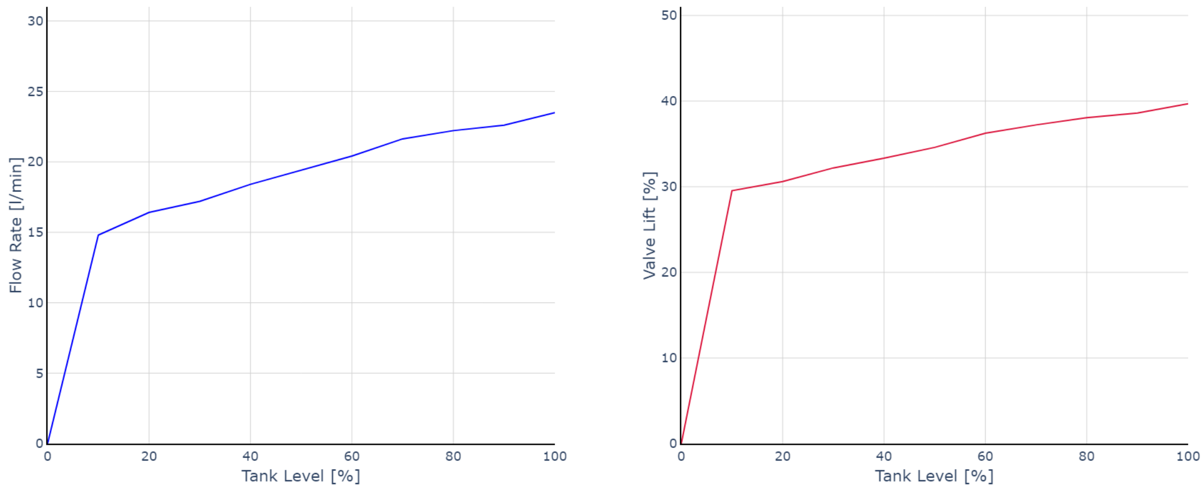
5.5.2 Level control

5.5.2.1 Operational range

The operational level control range experimental results are depicted in figures 5.20 and 5.21 along with the minimum and maximum input mass flow rates and corresponding valve lifts spanning the operational control range in table 5.18. These results show that the upgraded level control valves do in fact utilise their control range more effectively than that of the original control valves. This is however only due to the fact that the maximum desired input mass flow rates for both tanks were lowered from 60l/min to 45l/min. The control valve control range utilisation can therefore easily be improved by decreasing the difference between the desired maximum and nominal flow rates. This will however come at the cost of slower dynamic system behaviour.

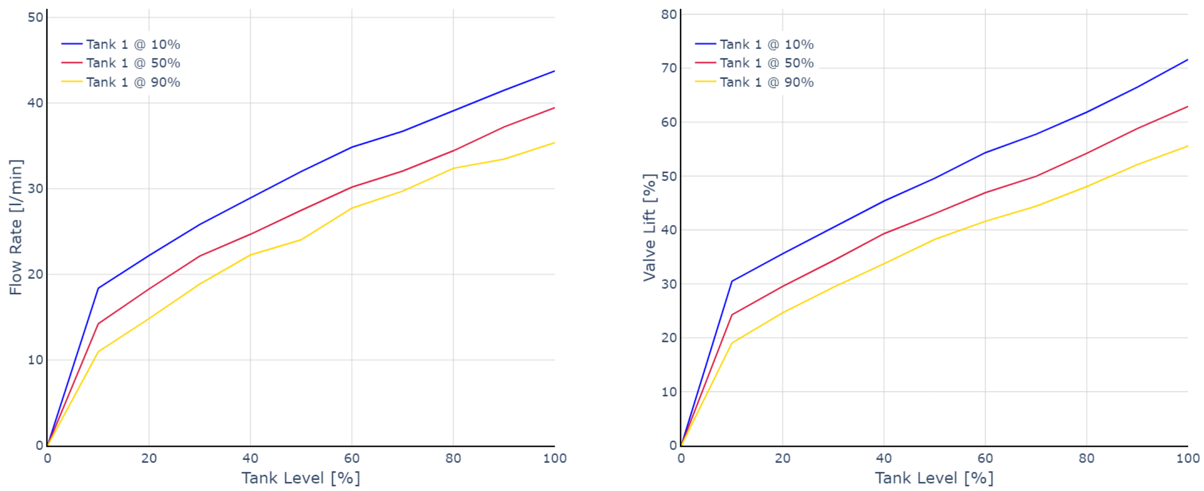
Table 5.18: Operational level control range - Results

Tank	Flow rate [l/min]		Valve lift [%]		
	Min	Max	Min	Max	Range
Tank 1	15	23	30	40	10
Tank 2	10	43	19	72	53



(a) Flow rate vs. tank level (b) Valve lift vs. tank level

Figure 5.20: Tank 1 - Operational level control analysis - Results



(a) Flow rate vs. tank level (b) Valve lift vs. tank level

Figure 5.21: Tank 2 - Operational level control analysis - Results

5.5.2.2 Controller effort

As mentioned in Chapter 3 the controller effort of the control valves can be determined by using either the standard deviation (3.2.1) of the control signal during steady state or the normalised variability of the controller (3.2.2) during steady state. The controller effort calculations and comparisons for Tank 1 are given in table 5.19 and Tank 2 in tables 5.20, 5.21, and 5.22. Both the Standard Deviation and Controller Effort comparisons clearly indicate that the upgraded level control valves for both tanks perform significantly better overall. The upgraded Tank 1 level control valves decreased the average level control valve lift standard deviation by roughly 33% and the controller effort by roughly 22%. The upgraded Tank 2 level control valves on the other hand decreased the average valve lift standard deviation by between 18% and 44% and the controller effort by between 11% and 39%.

From these results it can clearly be concluded that the first hypothesis was correct. The oversized control valves do have a direct impact on the amount of controller effort required in order to maintain a steady-state setpoint.

Table 5.19: Tank 1 - Level control controller effort comparison

Level [%]	**Flow rate** [l/min]		**STD** [l/min]			**Controller effort** [$\cdot 10^{-3}$]		
-	Old	New	Old	New	Diff	Old	New	Diff
10	15.50	14.70	1.05	0.70	-33%	4.68	2.46	-47%
20	16.36	16.41	1.03	0.68	-34%	3.88	2.56	-34%
30	17.29	17.21	1.09	0.63	-43%	4.92	4.57	-7%
40	18.35	18.41	1.14	0.64	-44%	3.15	2.90	-8%
50	19.34	19.41	1.00	0.64	-36%	3.64	3.32	-9%
60	20.23	20.42	0.81	0.86	6%	3.12	3.04	-3%
70	21.06	21.62	5.02	3.10	-38%	37.91	24.07	-37%
75	-	22.26	-	2.93	-	-	23.01	-
80	21.90	22.61	3.64	2.24	-39%	27.48	18.21	-34%
90	22.94	23.54	4.09	2.75	-33%	29.95	23.60	-21%
100	-	24.31	-	3.61	-	-	27.07	-

Table 5.20: Level control controller effort comparison - Tank 2 (T1 @ 10%)

Level [%]	**Flow rate** [l/min]		**STD** [l/min]			**Controller effort** [$\cdot 10^{-3}$]		
-	Old	New	Old	New	Diff	Old	New	Diff
10	17.99	18.20	1.10	0.56	-49%	3.96	3.77	-5%
20	21.34	22.20	0.77	0.56	-27%	2.22	2.20	-1%
30	25.26	25.83	2.36	0.67	-72%	2.82	2.53	-10%
40	28.56	28.93	1.85	0.56	-70%	3.25	2.71	-17%
50	31.45	32.01	0.88	0.48	-46%	2.99	1.92	-36%
60	34.30	34.86	0.68	0.64	-5%	1.52	1.46	-4%
70	36.12	36.79	3.14	2.56	-18%	22.99	16.13	-30%
80	38.25	39.09	2.10	0.90	-57%	13.48	5.98	-56%
90	40.75	41.38	2.74	1.39	-49%	17.39	8.52	-51%
100	-	43.74	-	2.61	-	-	8.53	-

Table 5.21: Level control controller effort comparison - Tank 2 (T1 @ 50%)

Level [%]	**Flow rate** [l/min]		**STD** [l/min]			**Controller effort** [$\cdot 10^{-3}$]		
-	Old	New	Old	New	Diff	Old	New	Diff
10	15.01	14.56	0.72	0.53	-26%	4.57	2.83	-38%
20	19.65	18.28	0.62	0.54	-14%	3.07	1.77	-42%
30	23.45	22.23	0.58	0.54	-7%	2.10	1.66	-21%
40	26.72	24.71	0.78	0.74	-6%	3.81	2.83	-26%
50	29.67	27.50	0.70	0.64	-8%	2.85	1.63	-43%
60	30.06	30.20	1.54	0.49	-68%	2.53	1.60	-37%
70	31.70	32.09	4.34	1.66	-62%	21.33	11.83	-45%
80	34.03	34.47	2.19	0.94	-57%	11.43	5.99	-48%
90	36.58	37.22	3.99	1.22	-69%	16.77	8.58	-49%
100		39.28		1.70	-	-	9.61	-

Table 5.22: Level control controller effort comparison - Tank 2 (T1 @ 90%)

Level [%]	**Flow rate** [l/min]		**STD** [l/min]			**Controller effort** [$\cdot 10^{-3}$]		
-	Old	New	Old	New	Diff	Old	New	Diff
10	11.78	11.05	0.64	0.41	-36%	3.63	2.29	-37%
20	15.29	14.77	0.65	0.54	-17%	2.24	2.02	-10%
30	17.97	18.69	0.60	0.54	-9%	2.15	2.14	-1%
40	20.65	21.64	0.61	0.53	-13%	2.73	2.69	-1%
50	23.66	24.03	0.77	0.59	-24%	2.09	1.96	-6%
60	26.81	27.64	0.95	0.61	-36%	1.66	1.62	-2%
70	28.47	29.70	1.50	1.52	2%	11.36	10.23	-10%
80	30.73	31.86	1.11	0.88	-21%	7.77	6.25	-20%
90	33.55	33.38	1.38	1.31	-4%	10.45	8.91	-15%
100	-	35.22	-	1.70	-	-	10.17	-

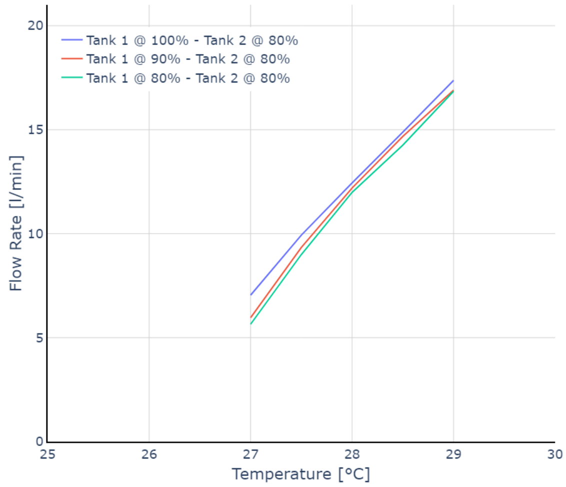
5.5.3 Temperature control

5.5.3.1 Operational range

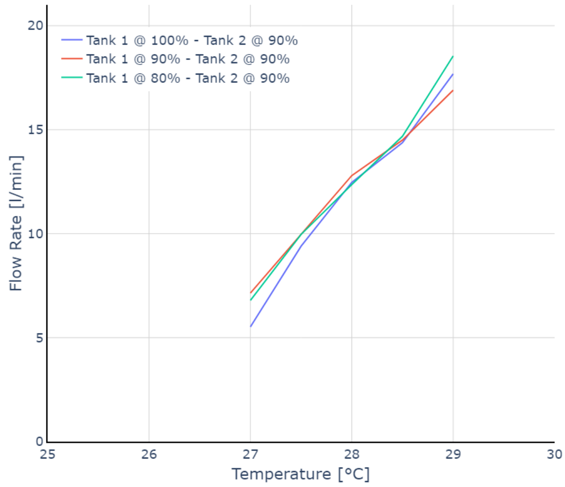
The operational temperature control range experimental results are depicted in figures 5.22, 5.23, 5.24, 5.25, 5.26, 5.27, 5.28, and 5.29 along with the minimum and hot input maximum flow rate and corresponding valve lifts spanning the normal operating conditions in table 5.23. From these results, it can be seen that the temperature control valves utilise a fair amount of their control range when the tank temperatures are within normal operating conditions.

Table 5.23: Operational temperature control range - Results

Tank	**Flow rate** [l/min]		**Valve Lift** [%]		
	Min	Max	Min	Max	Range
Tank 1	5	18	32	78	46
Tank 2	5	16	40	80	40



(a) Tank 2 level @ 80%



(b) Tank 2 level @ 90%

Figure 5.22: Temperature control - Flow rate vs. temp - Tank 1 (T2 @ 80 & 90)

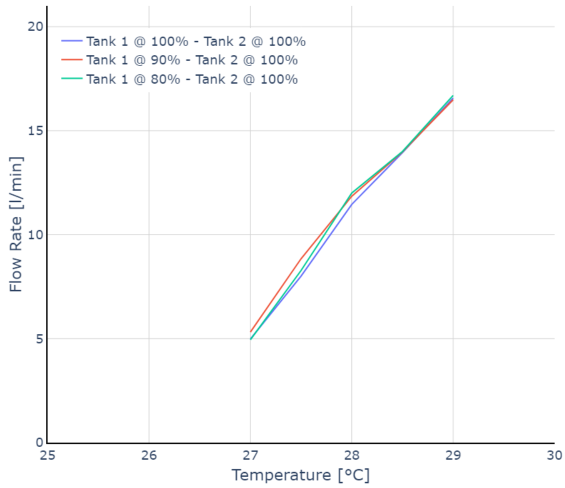
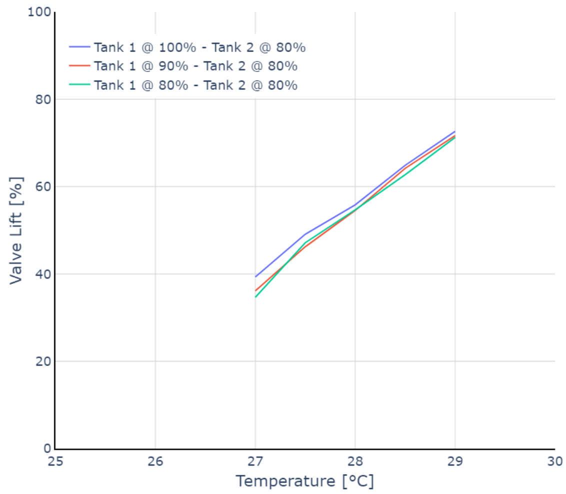
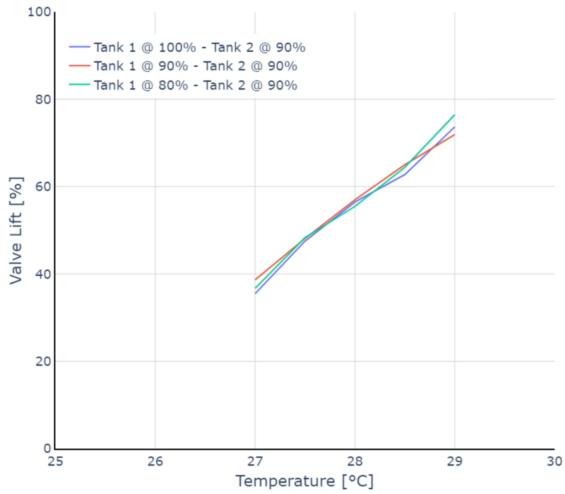


Figure 5.23: Temperature control - Flow rate vs. temp - Tank 1 (T2 @ 100)



(a) Tank 2 level @ 80%



(b) Tank 2 level @ 90%

Figure 5.24: Temperature control - Valve lift vs. temp - Tank 1 (T2 @ 80 & 90)

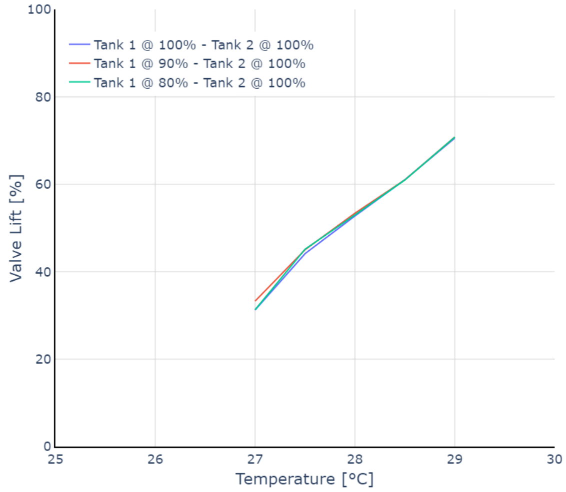
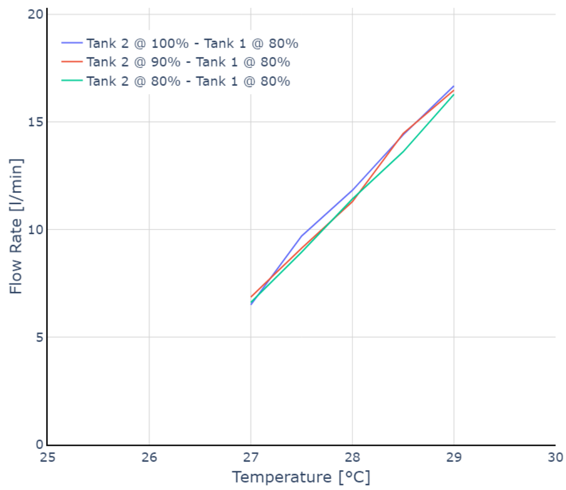
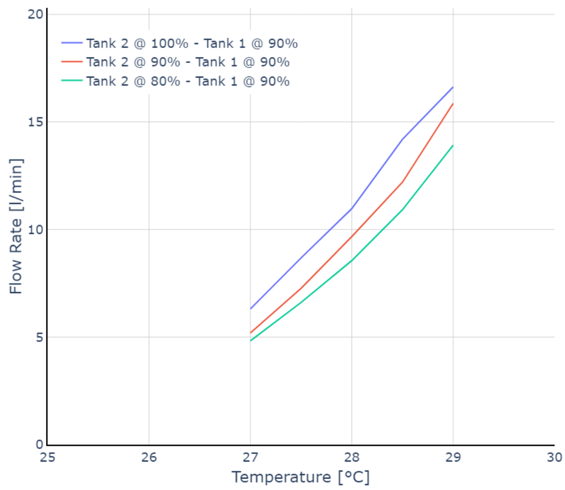


Figure 5.25: Temperature control - Valve lift vs. temp - Tank 1 (T2 @ 100)



(a) Tank 1 level @ 80%



(b) Tank 1 level @ 90%

Figure 5.26: Temperature control - Flow rate vs. temp - Tank 2 (T1 @ 80 & 90)

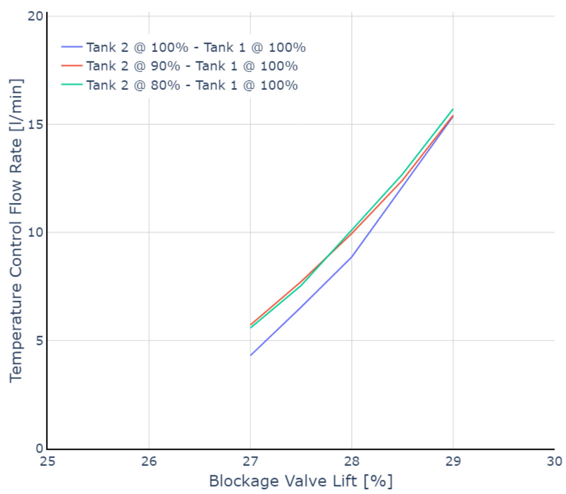
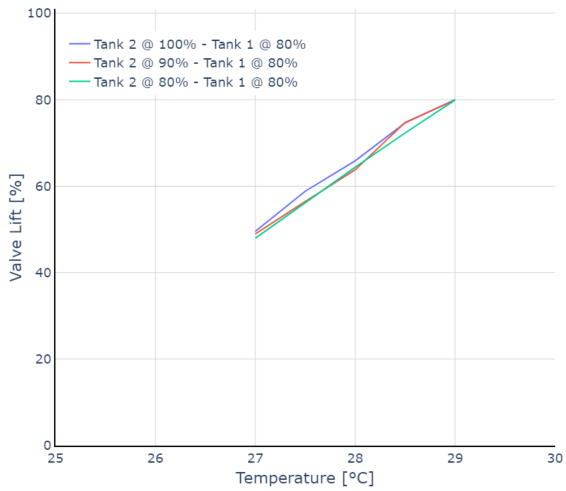
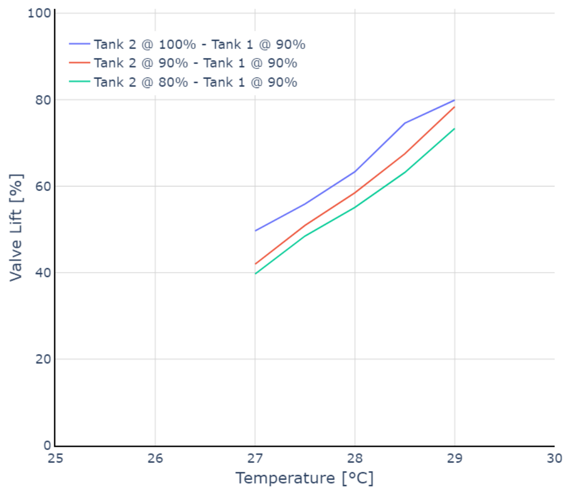


Figure 5.27: Temperature control - Flow rate vs. temp - Tank 2 (T1 @ 100)



(a) Tank 1 level @ 80%



(b) Tank 1 level @ 90%

Figure 5.28: Temperature control - Valve lift vs. temp - Tank 2 (T1 @ 80 & 90)

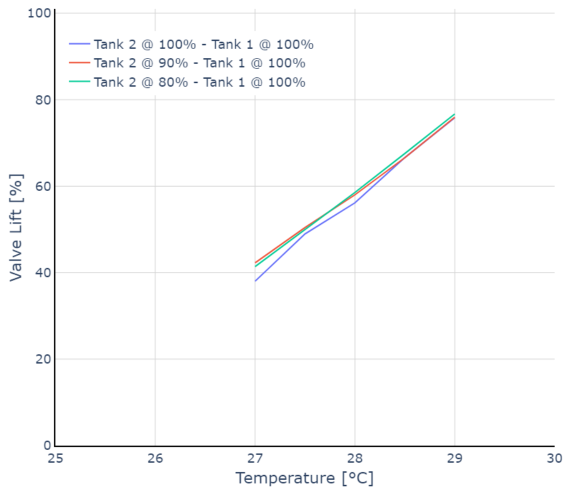


Figure 5.29: Temperature control - Valve lift vs. temp - Tank 2 (T1 @ 100)

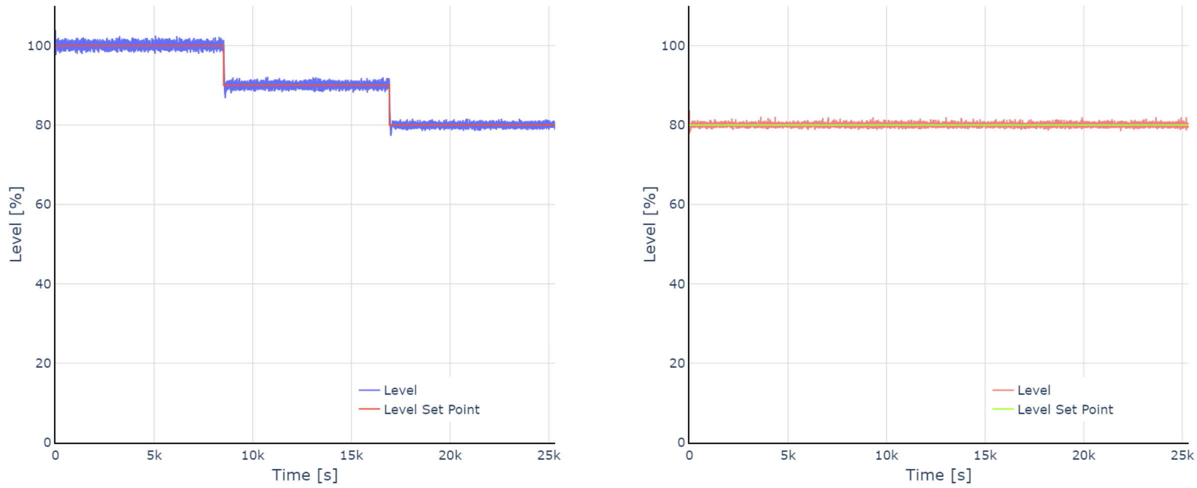
5.5.4 Cold water cycle heat exchanger

5.5.4.1 Cold reservoir temperature fluctuations

The third hypothesis postulated that the cold water cycle heat exchanger is undersized limiting the temperature control range of the system. It also stated that this could cause the temperature of the cold water reservoir to fluctuate based on the current temperature setpoints of the two tanks. The latter part can be investigated by analysing the data obtained during the operational temperature control characterisation. The first test set is obtained by controlling the Tank 1 temperature setpoint and level while maintaining the Tank 2 level and temperature at a constant setpoint. This data set is depicted by figures 5.30, 5.31, and 5.32. From figure 5.32 it can be seen that if the Tank 2 level and temperature setpoints are constant then the cold water reservoir temperature also remain fairly constant regardless of what is happening in Tank 1.

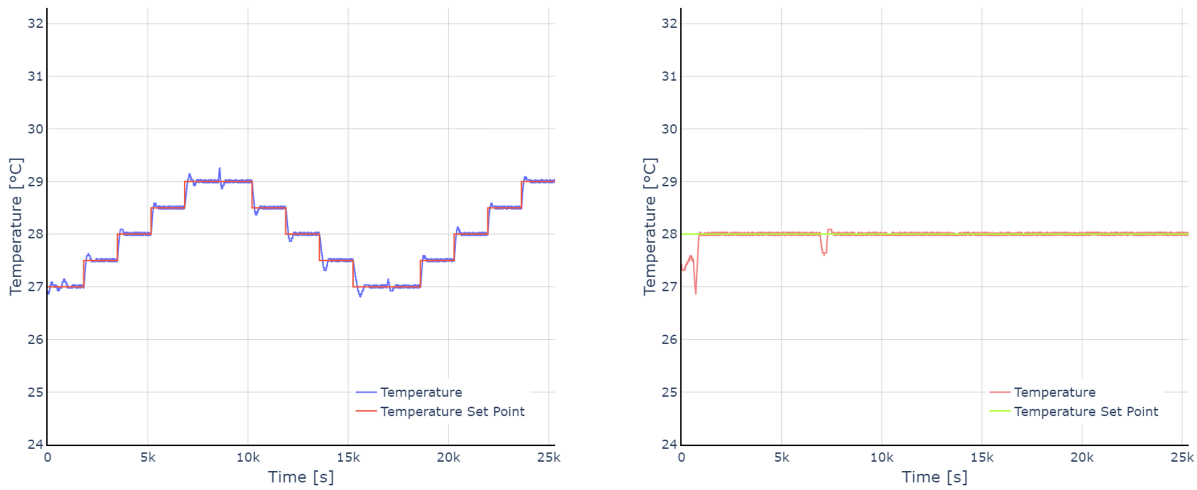
The second test set is obtained by controlling the Tank 2 temperature setpoint and level while maintaining the Tank 1 level and temperature at a constant setpoint. This data set is depicted by figures 5.33, 5.34, and 5.35. From figure 5.35 it can be seen that if the Tank 2 level and temperature setpoints are varied then the cold water reservoir temperature starts to fluctuate thereby proving the second part of the third hypothesis. The cold water reservoir temperature does in fact fluctuate when Tank 2 is operated at various temperature and level setpoints.

The cold water reservoir temperature fluctuates by almost the same amount as the temperature changes in Tank 2. This should be taken into account when running experiments on the system since the cold water input temperature to both tanks would also change. This would also affect the FDI-oriented nature of the system since this temperature fluctuation would have to be taken into account when the normal operation of the system is defined.



(a) Tank 1 (b) Tank 2

Figure 5.30: Cold water cycle heat exchanger - Tank levels



(a) Tank 1 (b) Tank 2

Figure 5.31: Cold water cycle heat exchanger - Tank temperatures

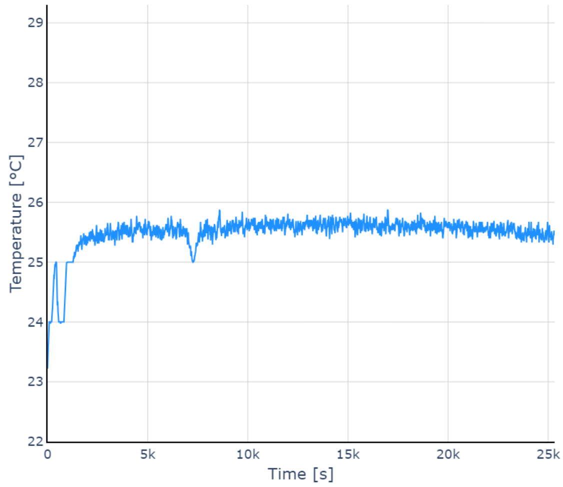
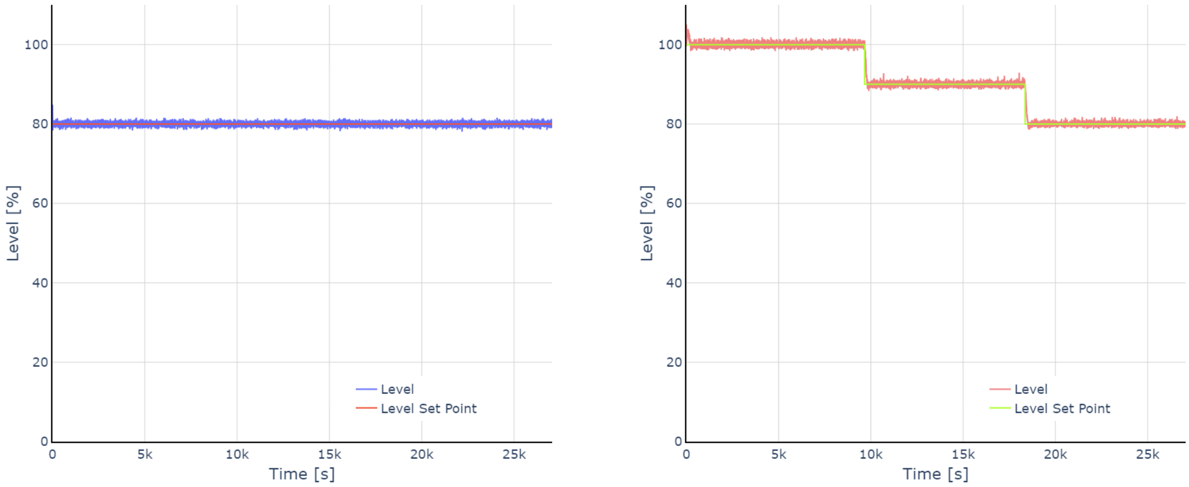


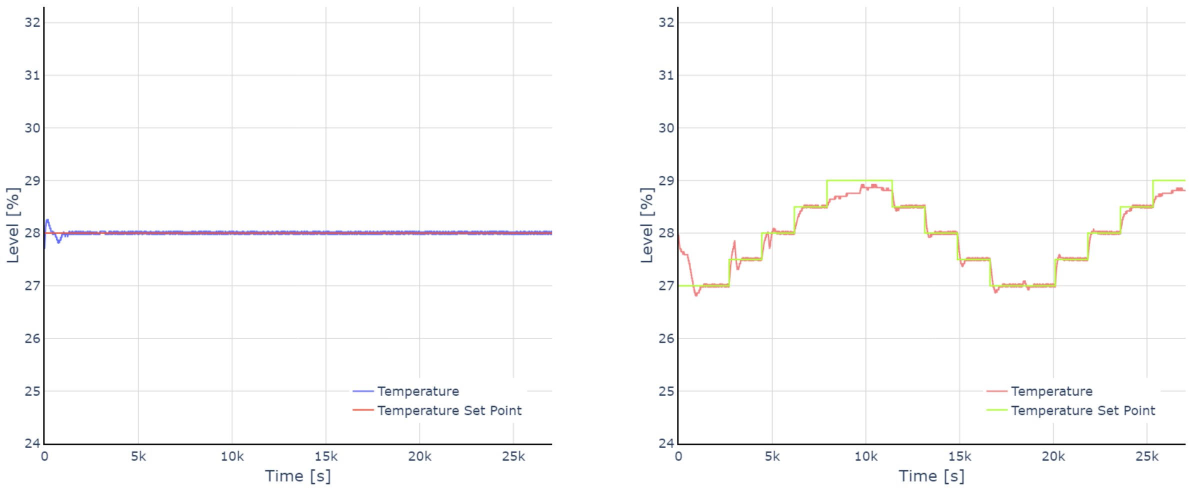
Figure 5.32: Cold water cycle heat exchanger - Cold reservoir temperature



(a) Tank 1

(b) Tank 2

Figure 5.33: Cold water cycle heat exchanger - Tank levels



(a) Tank 1

(b) Tank 2

Figure 5.34: Cold water cycle heat exchanger - Tank temperatures

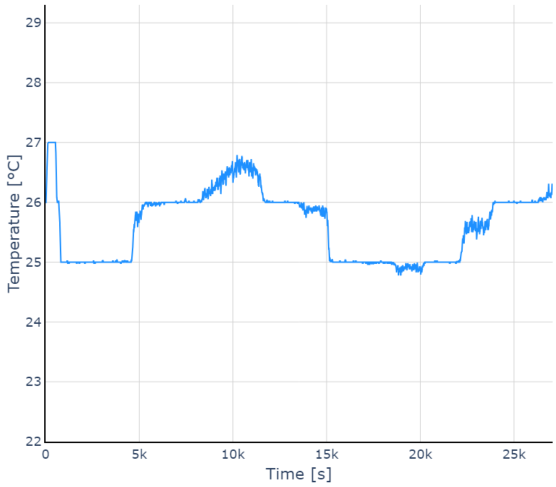
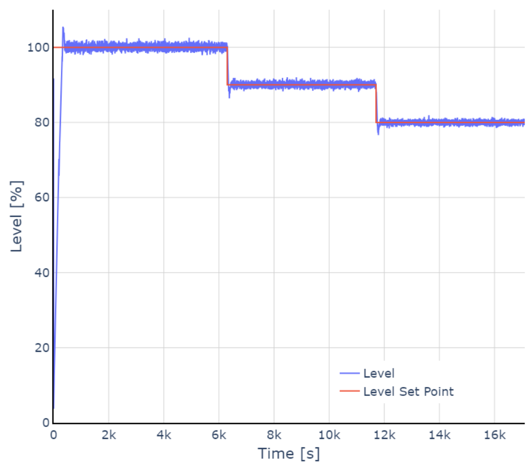


Figure 5.35: Cold water cycle heat exchanger - Cold reservoir temperature

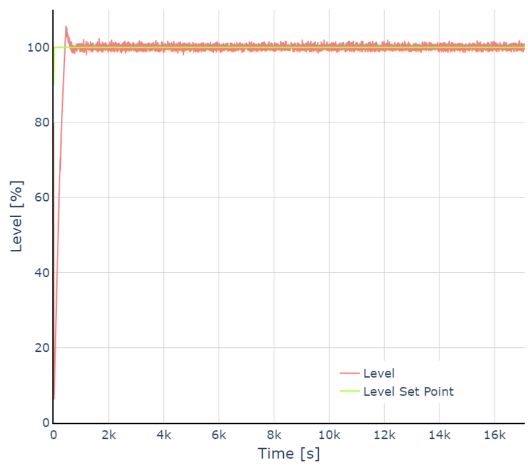
5.5.4.2 Maximum tank temperature difference

The maximum temperature difference that can be achieved between the two tanks is summarised in tables 5.24 and 5.25. One of the data sets used to obtain this data is depicted in figures 5.36 and 5.37. From figure 5.37b it can be seen that the Tank 2 temperature fluctuates along with the cold reservoir temperature despite having a setpoint of 0°C. The difference between the Tank 1 and Tank 2 temperatures therefore indicates the maximum temperature difference achievable since Tank 2's temperature is directly related to that of the cold reservoir meaning that no additional energy can be removed from the system.

The third hypothesis is therefore proven to be correct to a certain degree. From tables 5.24 and 5.25 it can be seen that on average the maximum temperature difference achievable between the two tanks will be at least 1.7°C. For a research system the larger the maximum temperature difference achievable the better. Therefore if a large temperature difference is desired then a larger heat exchanger will have to be installed.

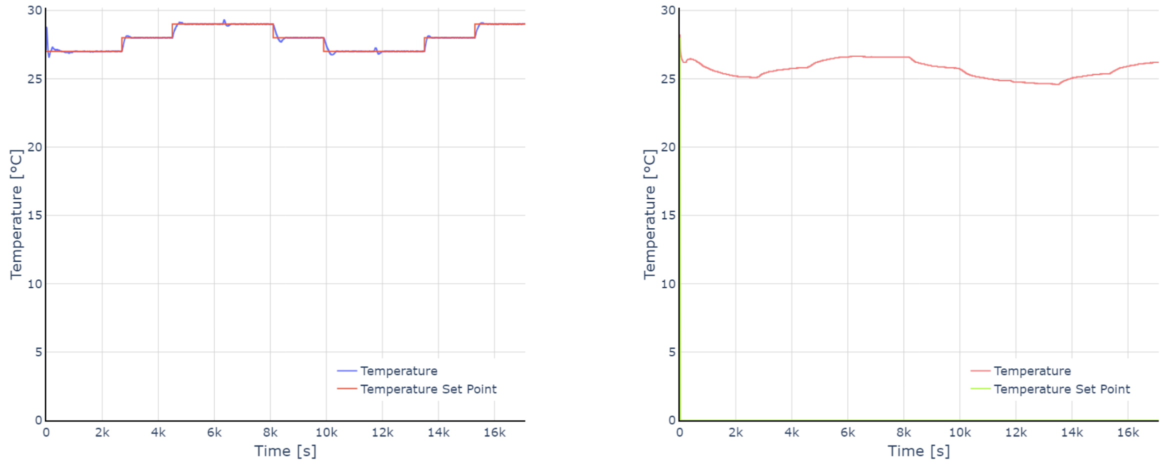


(a) Tank 1



(b) Tank 2

Figure 5.36: Cold water cycle heat exchanger - Max tank temp diff - Tank levels



(a) Tank 1 (b) Tank 2

Figure 5.37: Cold water cycle heat exchanger - Max tank temp diff - Tank temperatures

Table 5.24: Maximum tank temperature difference - T1 hotter than T2

Level [%]		**Temperature [°C]**		
Tank 1	**Tank 2**	**Tank 1**	**Tank 2**	**Difference**
		27.0	25.0	2.0
100		28.0	25.9	2.0
		29.0	26.7	2.3
		27.0	24.9	2.1
90	100	28.0	25.7	2.3
		29.0	26.6	2.4
		27.0	24.6	2.4
80		28.0	25.4	2.6
		29.0	26.3	2.7

Table 5.25: Maximum tank temperature difference - T2 hotter than T1

Level [%]		**Temperature [°C]**		
Tank 1	**Tank 2**	**Tank 1**	**Tank 2**	**Difference**
		25.3	27.0	1.7
	100	26.2	28.0	1.8
		27.1	29.0	1.9
		25.2	27.0	1.8
100	90	26.1	28.0	1.9
		27.0	29.0	2.0
		24.9	27.0	2.1
	80	26.0	28.0	2.0
		26.9	29.0	2.1

5.6 Experimental results - Fault characterisation

The fault characterisation experimental results covered in this section have already been processed in order to obtain the desired fault characteristic curves. The raw experimental data used during this section is briefly presented in Appendix C (Upgraded system data).

5.6.1 Leakages

5.6.1.1 Cold flow leakage

The leakage valve flow characteristics for Tank 1 are depicted in figure 5.38 and for Tank 2 in figures 5.39a, 5.39b, and 5.39c. The Tank 1 cold leakage valve shows consistent flow characteristics throughout the level control range of Tank 1 and is only limited to 77% valve lift when Tank 1 is at 100% level after which the level can no longer be maintained. The Tank 2 cold leakage valve flow characteristics however seem to vary with both tank's levels. Figure 5.39c however shows that it is fairly consistent when Tank 2's level is controlled within the normal operational range. This figure also indicates the Tank 2 cold leakage limitations within the normal operational level control range.

The cold leakage valve flow characteristics curves can be used to configure the heated two-tank system to emulate a cold leakage with a specific flow rate. Therefore the cold leakage faults will no longer have to be based on leakage valve lift and can instead be defined by leakage flow rate.

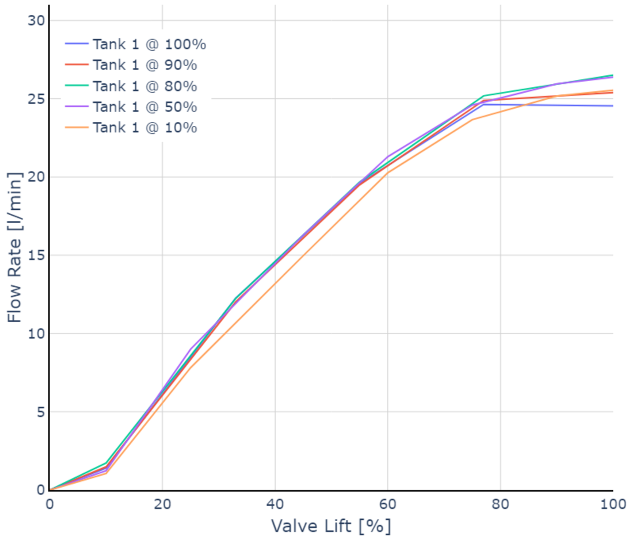
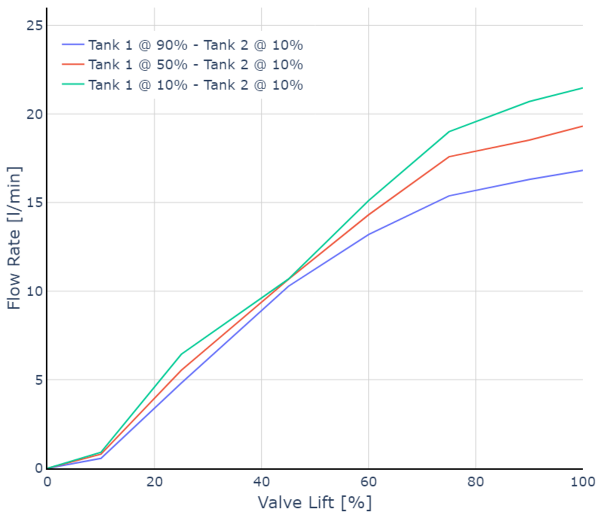
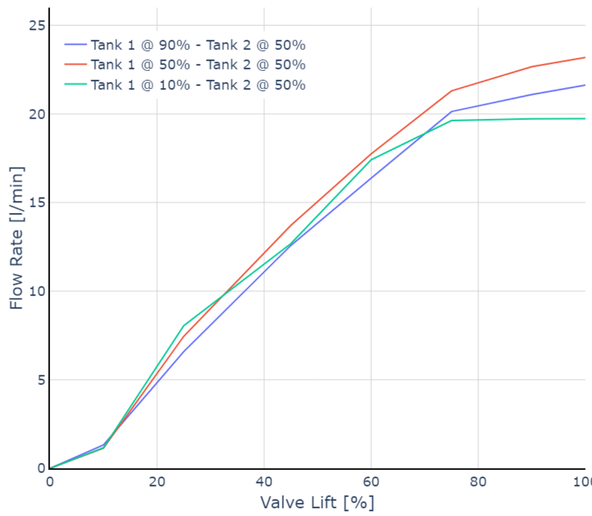


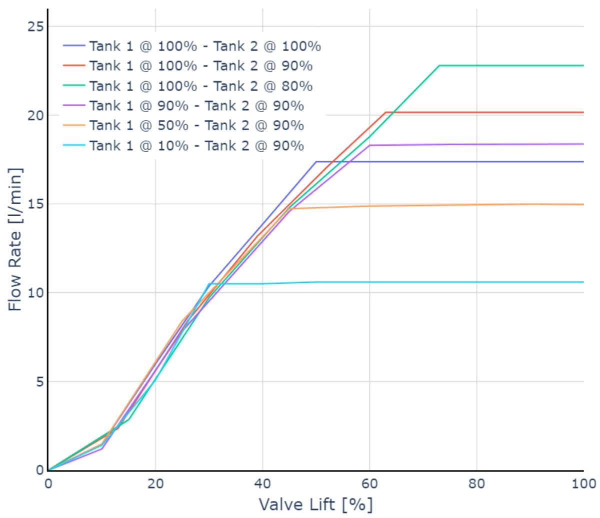
Figure 5.38: Cold leakage valve - Leakage flow rate vs. valve lift - Tank 1



(a) Tank 2 level @ 10%



(b) Tank 2 level @ 50%



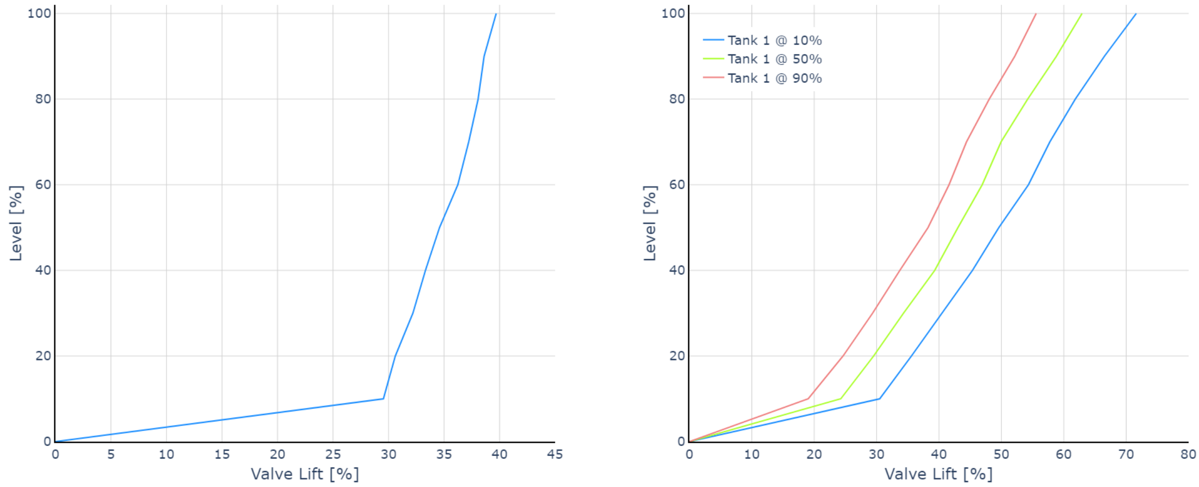
(c) Tank 2 level @ 90%

Figure 5.39: Cold leakage valve - Leakage flow rate vs. valve lift - Tank 2

5.6.2 Stuck valves

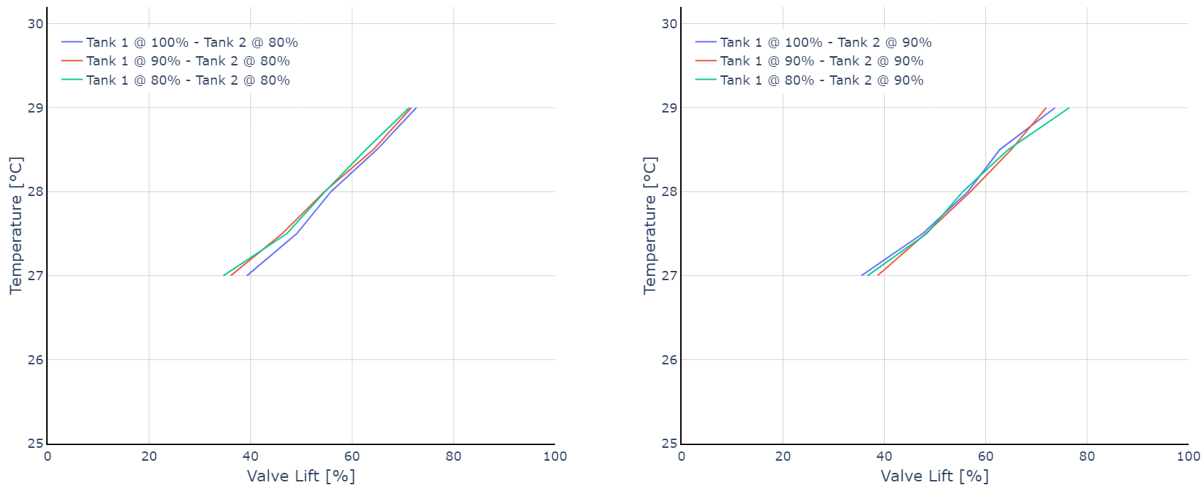
5.6.2.1 Level control

The level control stuck valve characteristic curves are obtained from the same data sets used to determine the operational level control range of both tanks and are depicted in figure 5.40. These curves can be used to determine how a stuck level control valve will affect the level of either one of the tanks.



(a) Tank 1 (b) Tank 2

Figure 5.40: Stuck valve fault - Level control



(a) Tank 2 level @ 80% (b) Tank 2 level @ 90%

Figure 5.41: Stuck valve fault - Temperature control - Tank 1 (T2 @ 80 & 90)

5.6.2.2 Temperature control

The temperature control stuck valve characteristic curves are obtained from the same data sets used to determine the operational temperature control range of both tanks and are depicted in figures 5.41, 5.42, and 5.43. These curves can be used to determine how a stuck temperature control valve will affect the system temperature within the system's normal operating range.

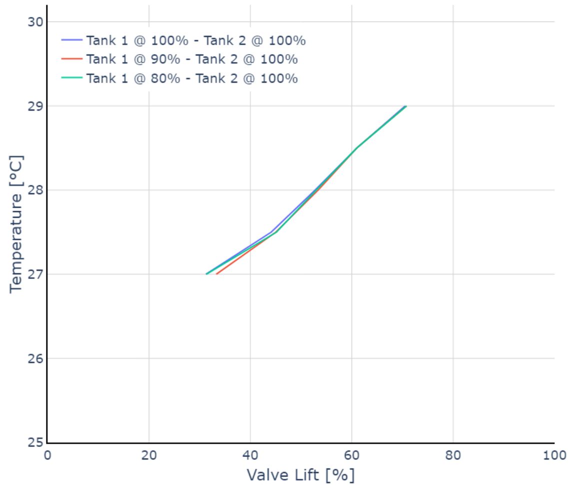
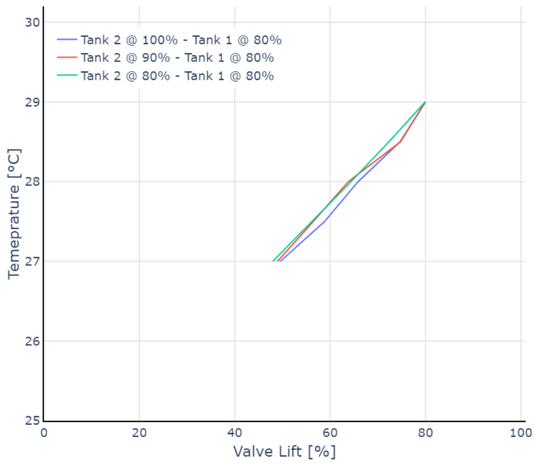
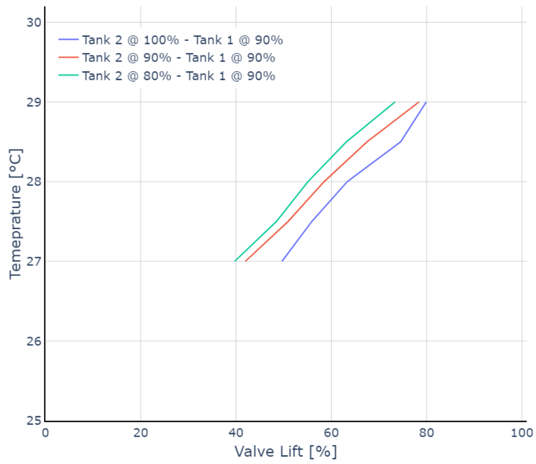


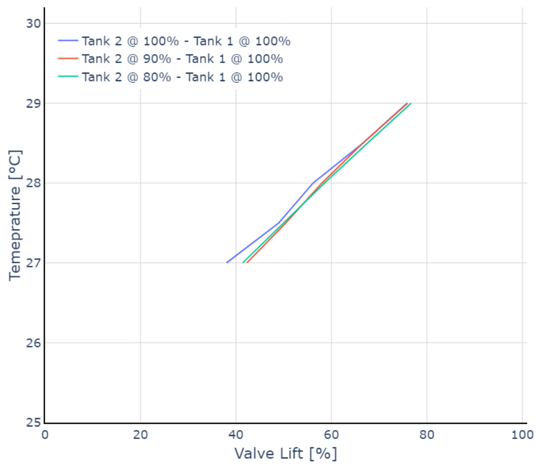
Figure 5.42: Stuck valve fault - Temperature control - Tank 1 (T2 @ 100)



(a) Tank 1 level @ 80%



(b) Tank 1 level @ 90%



(c) Tank 1 level @ 100%

Figure 5.43: Stuck valve fault - Temperature control - Tank 2 (T1 @ 80, 90, and 100)

5.6.3 Blockages

5.6.3.1 Tank 1 outlet

The Tank 1 outlet blockage valve characteristic curves are depicted in figure 5.44. These curves give an indication of the amount of flow blocked by the blockage valve and can be used to define the Tank 1 outlet blockage fault in terms of blocked flow instead of valve lift.

The effect that the Tank 1 blockage valve has on the temperature control flow rate and valve lift is depicted in figure 5.45. This clearly shows that a blockage in the Tank 1 outlet results in Tank 1 requiring a lower hot input mass flow rate to regulate temperature whereas Tank 2 now requires a higher hot input mass flow rate due to the increase in the Tank 2 cold input mass flow rate.

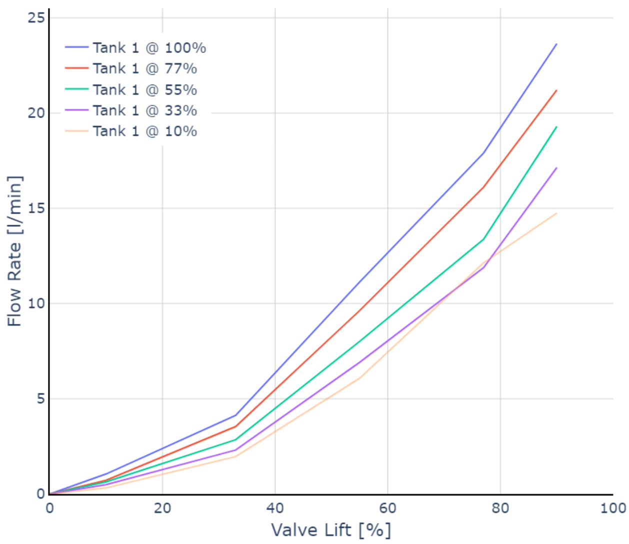
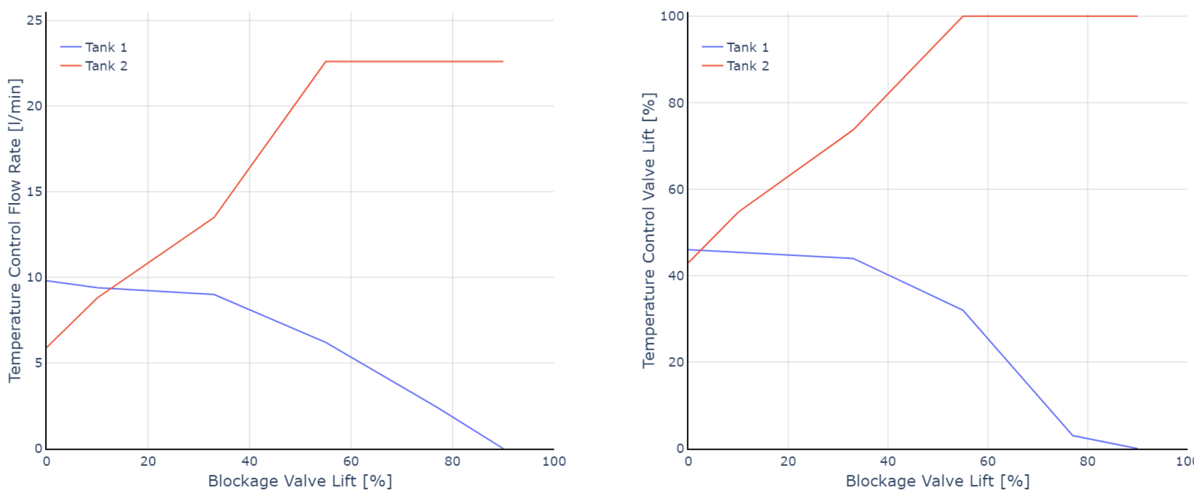


Figure 5.44: Blockage valve fault - Tank 1 outlet - Blocked flow rate vs. valve lift



(a) Hot input flow rate vs. blockage valve lift (b) Hot input valve lift vs. blockage valve lift

Figure 5.45: Blockage valve fault - Tank 1 outlet - Effect on temperature control

5.7 Conclusion

The upgraded system characterisation chapter covered the upgraded system's system and fault characterisation in detail. The experimental design section showed the intricacies and complexity of a multi-physics benchmarking system and how one might approach a practical characterisation thereof.

The analytical valve sizing technique and sizing exercise were validated by showing that the actual and predicted installed valve flow characteristics are close enough to one another to be able to make an informed decision based on the outcome of the valve sizing exercise.

The second hypothesis was proven correct by comparing the original and upgraded system's level control controller effort and showing that the upgraded level control valves lowered the controller effort. It was also shown that the upgraded level control valves significantly lowered the standard deviation of the control valve lift during steady state conditions.

The third hypothesis was also proven correct by showing that the cold reservoir temperature fluctuates when the level and/or temperature of Tank 2 is varied. The maximum tank temperature difference was also determined which showed that the heated two-tank system should be capable of maintaining a tank temperature difference of at least 1.7°C.

The system's operating level and temperature control ranges were determined providing significant insight on the operating conditions of the system.

Lastly, the faults were characterised and the characteristic curves for each fault were determined which can be used to determine how each fault will affect the system. These curves also allow some of the faults to be defined in terms of actual flow rates instead of arbitrary valve lift values. Most of these characteristic curves will be used during a follow-up study where the heated two-tank system's simulation model is updated to more closely simulate the actual behaviour of the system.

The next chapter will present an FDI-oriented data set to the FDI community.

6 Data in brief

6.1 Introduction

The data in brief chapter presents a couple of data sets obtained during the characterisation of the upgraded heated two-tank system to the FDI community. The value of the data is briefly discussed along with the data description and experimental setup used to obtain each data set.

This chapter is meant to serve as the first draft of a data in brief article to be submitted after the completion of the current study.

6.2 Data availability

The data sets presented in this chapter can be accessed at Data in Brief - Data.

6.3 Value of the data

Benchmarking systems are invaluable to researchers within the FDI and control systems communities. There is however a lack of data obtained from physical benchmarking systems since most benchmarking systems are only implemented within software and then simulated. This data set addresses this problem since all of the data were obtained from a physical benchmarking system. The heated two-tank system also provides a more complex and comprehensive benchmarking data set. It not only has both level and temperature control capabilities but also has the ability to emulate typical process faults.

Researchers within the FDI community can use this data to improve their own two-tank system simulation models and train their fault detection schemes. Additional experimental results can also be requested in the near future. This will allow researchers to obtain specific practical data sets that can be used in their own research.

6.4 Data description

In this data set, there are eleven different files which can be divided into 3 categories:

- Steady state data
  - *System_Characterisation_Steady_State_T1_80L_28C_T2_80L_29C.csv*
- Transient operational data
  - *System_Characterisation_Tank_1_Temperature_T1_80L_90L_100L_T2_100L.csv*

- *System_Characterisation_Tank_1_Temperature_T1_80L_90L_100L_T2_90L.csv*
- *System_Characterisation_Tank_1_Temperature_T1_10L_50L_90L_T2_90L.csv*
- *System_Characterisation_Tank_2_Temperature_T2_80L_90L_100L_T1_100L.csv*
- *System_Characterisation_Tank_2_Temperature_T2_80L_90L_100L_T1_90L.csv*
- *System_Characterisation_Tank_2_Temperature_T2_10L_50L_90L_T1_90L.csv*

- Fault emulation data
  - *Fault_Characterisation_Tank_1_Cold_Leak_T1_80L_90L_100L_T2_100L.csv*
  - *Fault_Characterisation_Tank_2_Cold_Leak_T2_80L_90L_100L_T1_90L.csv*
  - *Fault_Characterisation_Tank_1_Block_T1_100L_77L_55L_T2_50L.csv*
  - *Fault_Characterisation_Tank_1_Block_T1_33L_10L_T2_50L.csv*

The data set data fields and CSV header structure are given in table 6.1. The data can be visualised with the Jupyter Notebook provided at Heated two-tank system data visualisation.

Table 6.1: Data fields and CSV header structure

Header	**Description**	**Unit**
Record	Sample number	[·]
Date	Date	[mm/dd/yyy]
UTC Time	Time	[hh:mm:ss]
T1L	Tank 1 level	[%]
T2L	Tank 2 level	[%]
T1LS	Tank 1 level setpoint	[%]
T2LS	Tank 2 level setpoint	[%]
T1T	Tank 1 temperature	[°C]
T2T	Tank 2 temperature	[°C]
T1TS	Tank 1 temperature setpoint	[°C]
T2TS	Tank 2 temperature setpoint	[°C]
T1A	Tank 1 agitator status	[·]
T2A	Tank 2 agitator status	[·]
T1CF	Tank 1 cold flow rate	[l/min]
T2CF	Tank 2 cold flow rate	[l/min]
T1CT	Tank 1 cold input temperature	[°C]
T2CT	Tank 2 cold input temperature	[°C]
T1CV	Tank 1 level control valve lift	[%]
T2CV	Tank 2 level control valve lift	[%]
T1CVPI	Tank 1 level control valve inlet pressure	[bar]

Table 6.1 continued from previous page

Header	Description	Unit
T1CVPO	Tank 1 level control valve outlet pressure	[bar]
T1HF	Tank 1 hot flow rate	[l/min]
T2HF	Tank 2 hot flow rate	[l/min]
T1HT	Tank 1 hot input temperature	[°C]
T2HT	Tank 2 hot input temperature	[°C]
T1HV	Tank 1 temperature control valve lift	[%]
T2HV	Tank 2 temperature control valve lift	[%]
T1HVPI	Tank 1 temperature control valve inlet pressure	[bar]
T1HVPO	Tank 1 temperature control valve outlet pressure	[bar]
T1HCTI	Tank 1 heating coil input temperature	[°C]
T2HCTI	Tank 2 heating coil input temperature	[°C]
T1HCTO	Tank 1 heating coil output temperature	[°C]
T2HCTO	Tank 2 heating coil output temperature	[°C]
F	Fault status	[·]
1CL	Tank 1 cold leakage valve lift	[%]
2CL	Tank 2 cold leakage valve lift	[%]
1HL	Tank 1 hot leakage valve lift	[%]
2HL	Tank 2 hot leakage valve lift	[%]
1CS	Tank 1 stuck level control valve lift	[%]
2CS	Tank 2 stuck level control valve lift	[%]
1HS	Tank 1 stuck temperature control valve lift	[%]
2HS	Tank 2 stuck temperature control valve lift	[%]
1BV	Tank 1 outlet blockage valve lift	[%]
1CD	Tank 1 cold flow rate sensor drift	[%]
2CD	Tank 2 cold flow rate sensor drift	[%]
1HD	Tank 1 hot flow rate sensor drift	[%]
2HD	Tank 2 hot flow rate sensor drift	[%]
1TD	Tank 1 temperature sensor drift	[%]
2TD	Tank 2 temperature sensor drift	[%]
1LD	Tank 1 level sensor drift	[%]
2LD	Tank 2 level sensor drift	[%]
1FL	Tank 1 fouling status	[·]
2FL	Tank 2 fouling status	[·]

Table 6.1 continued from previous page

Header	Description	Unit
GT	Hot reservoir temperature	[°C]
GTL	Hot reservoir minimum temperature setpoint	[°C]
GTH	Hot reservoir maximum temperature setpoint	[°C]
CC	Cold circulation status	[·]
HC	Hot circulation status	[·]

6.4.1 Steady state data

The steady state data file contains data describing the steady state operation of the upgraded heated two-tank system, with Tank 1 at 80% level and 28°C, and Tank 2 at 80% level and 29°C. The 30 minutes of steady state operational data were obtained after the system had already reached steady state operation. All of the data contained within the data set are raw and have not been filtered.

6.4.2 Transient operational data

The transient operational data set contains the data that were used to characterise the temperature control functionality of the upgraded heated two-tank system. The data set is divided into the temperature characterisation data for Tank 1 and Tank 2. The characterisation data were obtained by varying one tank's temperature and level setpoints while maintaining a constant level and temperature within the other tank. All of the data contained within the data set are raw and have not been filtered.

6.4.3 Fault emulation data

The fault emulation data set contains the data that were used to characterise the cold leakage and outlet blockage fault emulation capabilities of the upgraded heated two-tank system. The data set includes the data for the leakage fault emulation in Tank 1 and Tank 2, as well as the data for the Tank 1 outlet blockage fault emulation. The leakage fault emulation data were obtained by varying the leakage valve lift at different tank level setpoints. The same methodology was followed in order to obtain the Tank 1 outlet blockage fault emulation data. All of the data contained within the data set are raw and have not been filtered.

6.5 Limitations

The original aim behind the fault emulation data was to characterise the fault emulation capabilities of the upgraded system and not to emulate a typical process fault. The leakage fault data set contains data on leakages ranging from 2 l/min to 24 l/min (8% - 99% of the corresponding normal operational flow rate). This means that a large portion of the fault emulation data describes fault conditions that are significantly larger than the typical faults found within the industry. This is not to say that these fault magnitudes are never seen within the industry but rather that they would not require a complex fault detection scheme to be detected or identified.

The data included within these data sets were also obtained over relatively short periods of time. On average the steady state conditions are only maintained for 15-20 minutes. With a sampling rate of 1Hz that equates to to only 900-1200 data points per process variable. The data sets should therefore ideally not be used as training or testing data sets for machine learning.

6.6 Conclusion

The data sets presented in this chapter provide significant insight into the operation of the upgraded heated two-tank system. The steady state and transient operational data sets describe the normal operational behaviour of the system. The fault emulation data describes the system behaviour when a fault is induced into the system.

Several additional data sets will however have to be obtained before the data in brief article can be submitted due to the limitations in the current data sets. These data sets will contain steady state operational data at several tank level and temperature setpoints. The fault emulation data will include faults with magnitudes comparable to those of typical process faults. Lastly, the data sets will include training and testing data over longer periods of time (the system is limited to roughly 450 minutes of continuous data capture) ensuring that they can be used to train a model.

7 Conclusion

7.1 Introduction

The conclusion chapter covers the closure of the study and concludes the dissertation. The objectives set out in Chapter 1 are reflected upon after which the shortcomings of the study are discussed. Possible future work is also identified. The chapter concludes by reflecting on the study as a whole.

7.2 Reflection on objectives

The original heated two-tank system was analysed in order to determine its shortcomings and potential upgrades. The five research objectives set out in Chapter 1 have been achieved thereby addressing the research problem:

1. **Analyse the current functionality of the heated two-tank system -** Three hypotheses were proposed based on a preliminary analysis of the original heated two-tank system These hypotheses were: 1) The control valves are oversized resulting in a smaller valve operating range, 2) The control valves exhibit inappropriate flow characteristics resulting in higher controller effort, 3) The cold water cycle heat exchanger is undersized limiting the temperature range of the system. The system was then analysed in order to prove or disprove these hypotheses and based on the results it was concluded that the control valves were oversized and exhibited inappropriate flow characteristics. Several other system shortcomings were also highlighted. This included the limited control and data acquisition capabilities of the system. A list of potential system hardware and software upgrades was also compiled.
   The original system's operational temperature control range could however not be analysed due to a malfunctioning pump. These results would have been a valuable resource and could have been used to analyse the upgraded heated two-tank system temperature control range and determine the effectiveness of the upgrades made to the system. The same goes for the analysis of the cold water cycle heat exchanger.
2. **Detail design of system upgrades -** Several upgrades were chosen from the list of possible system hardware and software upgrades. These included the upgrade of all of the control valves, additional fault emulation capabilities, improved process variable storage, an improved automated system control mode, and a redesign of the user interface on the HMI. A detailed control valve sizing exercise was done to ensure that the upgraded

valves would exhibit the correct flow characteristics. This included the use of several valve sizing techniques that were validated based on an analytical analysis of the system pressure and flow characteristics.

3. **Implementation of system upgrades -** The system upgrades were implemented.
4. **Upgraded system characterisation -** The upgraded system was characterised and based on the results it was shown that the upgrades did improve the functionality of the system. The valve sizing exercise was validated by showing that the installed control valve flow characteristics matched that of the predicted installed valve flow characteristics. It was also shown that the upgraded control valves lowered the controller effort thereby proving the second hypothesis. The operational level and temperature control ranges were also analysed and it was shown that the level control valves now utilised a larger operating range and the upgraded temperature control valves also utilised an acceptable operating range when the system is operated within the nominal level and temperature control ranges. Lastly, the cold water heat exchanger was also shown to be the limiting temperature control range factor. It was also shown that the cold water reservoir temperature fluctuated when the Tank 2 temperature and level setpoints were varied thereby proving the third and final hypothesis.

   The effectiveness of the upgrades made to the temperature control functionality of the system could not be quantified due to the fact that the original system's temperature control range could not have been analysed. If the cold water cycle heat exchanger was also upgraded then the temperature control range of the system could have been significantly improved. The additional temperature sensor upgrade list should have included temperature sensors that measure the temperature of the cold water reservoir in a higher resolution. The data obtained from these sensors could then have been used to accurately depict the temperature fluctuations in the cold water reservoir.
5. **Analyse the upgraded system fault emulation capabilities -** The fault emulation capabilities of the upgraded heated two-tank system were analysed. Each fault was experimentally characterised and from the experimental data, a characteristic curve was determined. The characteristic curves provide insight into the operation of each fault and allow the researcher to configure the heated two-tank benchmarking system with a specific fault magnitude as opposed to only being able to define a fault based on the fault valve lift value.

   The additional fault emulation capability upgrades should have included a blockage valve on Tank 2's output. This is a fairly easy upgrade to implement and would have provided more usable data than the hot leakage valves that were installed and never used. Some of the data obtained during the upgraded system characterisation could have provided more data if it was not for the fact that during the characterisation phase, a sum total of 3 centrifugal pumps, 2 control valves, and 4 48kg LP gas bottles had to be replaced. This led to several data sets that were obtained while either the hot/cold water circulation or the temperature control functionality was offline.

7.3 What could have been done differently?

The main problem with doing practically oriented research, especially on a system that changes during the research period, is the fact that as time progresses so does the researcher's knowledge and intuition regarding the system improve and evolve. Significant changes to the testing methodology were made during the upgraded system characterisation. These changes resulted in the original system analysis lacking certain data sets that could have come in quite useful during the upgraded system characterisation chapter. If the original system could have been analysed to the same degree as the upgraded system then the comparison between these data sets could have provided more insight.

7.4 Future work and recommendations

Several aspects were identified during the study that warrant further research and improvements. The possible system upgrades and recommended future work are listed below.

System upgrades:

- The heat exchangers can be upgraded to allow for better fouling fault emulation. This can be done by installing several heat exchanger coils that have different heat transfer coefficients. Another possible solution could be to construct a heating coil that is enclosed by a second heating coil. The outer heating coil can then be used to alter the heat transferred from the inner heat exchanger to the water in the tank.
- An additional blockage valve should be installed on the output of Tank 2. This blockage will have a significant effect on the system's overall behaviour and will add value to the fault emulation capabilities of the system.
- Additional blockages can be emulated by installing additional oversized valves in series with existing level and temperature control valves. In their default state, they would be completely open and have a nominal valve orifice diameter equal to or bigger than the pipe it is connected to. The blockage/obstruction is then emulated by slightly closing these valves thereby effectively narrowing the nominal pipe diameter.
- The cold water cycle heat exchanger should be upgraded in order to increase the temperature control range of the system. It will also be beneficial to be able to directly

control the temperature setpoint of both the cold water cycle heat exchanger and the gas heater. This will allow the system to regulate the hot and cold water reservoir temperatures and maintain a constant temperature setpoint. This will mitigate the large temperature fluctuations of the cold water reservoir.

- The cold reservoir temperature should be measured with higher resolution temperature sensors to allow for a more accurate estimation of its temperature.
- The leakage faults can be improved by installing leakage flow rate sensors that would allow the leakage flow rate to be controlled using a feedback controller.

Future work:

- Improved simulation model - The current Simulink model can be further improved upon by utilising the system characterisation data obtained during this study. This will allow the simulation model to include the actual control valve and fault valve flow characteristics. The additional heat exchanger coil temperature sensors can be used to verify the heat transfer coefficients of the heat exchanger coils. The simulation model should also model both the cold and hot water reservoir dynamics. This can be done by modelling the cold water cycle heat pump and the gas heater used to regulate the hot water reservoir temperature.
- The effect of component sizing on FDI performance - It would be interesting to evaluate the difference between the FDI performance of the original and upgraded heated two-tank system. The overall variation in the systems process variables has been decreased since the controller effort and standard deviation of the control valve control signals were decreased by properly sizing the control valves. This could therefore allow an FDI scheme, such as PCA, to detect a fault condition more easily.

7.5 Closure

During the study and throughout the dissertation it has been shown that all of the objectives set out during Chapter 1 have been met. The original system's functionality was adequately analysed and from the analysis, a comprehensive list of required upgrades was constructed (some of which required some assumptions due to a lack of data).

The upgraded system design provided significant insight into the workings of the control valves and the complexity associated with determining the installed valve flow characteristics.

The system was successfully upgraded especially with regards to the PLC and HMI. The automatic mode and sequencer functionality saved hundreds of hours that would have had to be spent in the lab constantly monitoring the system. After the sequencer was validated the system could be configured to run 8 hours of consecutive tests without supervision. The system characterisation provided significant insight into the workings and behaviour of the upgraded heated two-tank system.

Even though the characteristics curves obtained from the upgraded system characterisation were not used during the study itself, they will be of significant value when the heated two-tank system's Simulink model is updated. Overall it can be concluded that the original heated two-tank system has been successfully upgraded and a comprehensive characterisation data set was obtained.

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Appendices

A Original system data

A.1 Introduction

The original system data chapter briefly covers the data used during Chapter 3 (Original system analysis). These data sets provide real-world system data of a heated two-tank benchmarking system with oversized level and temperature control valves. The data is hosted at Heated two-tank system data - Original system.

The CSV file header structure for the data sets is given along with a Jupyter notebook that visualises the data. This will allow any interested parties to analyse the data themselves.

A.2 System data

A.2.1 Data structure

The original system data was obtained before the final PLC and data acquisition upgrades were made to the system. Therefore the CSV file header structure of the original system analysis data files only contains some of the improvements made on the upgraded system. The original system data CSV file header structure is given in table A.1.

Table A.1: Original system - CSV header structure

Header	**Description**	**Unit**
Record	Sample number	[·]
Date	Date	[MM/DD/YYYY]
UTC Time	Time	[HH:MM:SS]
T1Level	Tank 1 level	[%]
T2Level	Tank 2 level	[%]
T1Temp	Tank 1 temperature	[°C]
T2Temp	Tank 2 temperature	[°C]
T1ColdFlow	Tank 1 cold flow rate	[l/min]
T2ColdFlow	Tank 2 cold flow rate	[l/min]
T1HotFlow	Tank 1 hot flow rate	[l/min]
T2HotFlow	Tank 2 hot flow rate	[l/min]
T1HotTemp	Tank 1 hot input temperature	[°C]
T2HotTemp	Tank 2 hot input temperature	[°C]

Table A.1 continued from previous page

Header	Description	Unit
T1ColdTemp	Tank 1 cold input temperature	[°C]
T2ColdTemp	Tank 2 cold input temperature	[°C]
T1InValve	Tank 1 level control valve lift	[%]
T2InValve	Tank 2 level control valve lift	[%]
Tank1HotValve	Tank 1 temperature control valve lift	[%]
Tank2HotValve	Tank 2 temperature control valve lift	[%]
Tank1Block	Tank 1 outlet blockage valve lift	[%]
T1Leak	Tank 1 cold leakage valve lift	[%]
T2Leak	Tank 2 cold leakage valve lift	[%]
T1LSS	Tank 1 level setpoint	[%]
T2LSS	Tank 2 level setpoint	[%]
T1TSS	Tank 1 temperature setpoint	[°C]
T2TSS	Tank 2 temperature setpoint	[°C]
Fault	Fault status	[·]
Geyser	Geyser temperature	[°C]

A.2.2 Jupyter Notebook

This Jupyter Notebook is intended to simplify the process of visualising the data obtained from the original heated two-tank system and can be found at Jupyter Notebook - Original system. The data visualisation is divided into the following sections:

1. Tank variables (figure A.3)
    - Tank level and level setpoint
    - Tank temperature and temperature setpoint
2. Cold water cycle (figure A.1)
    - Cold input flow rate
    - Cold input temperature
    - Level control valve lift
3. Hot water cycle (figure A.4)
    - Hot input flow rate
    - Hot input temperature
    - Temperature control valve lift
4. Faults (figure A.5)

- Fault status
- Cold leakage valve lift
- Blockage valve lift

5. System parameters (figure A.2)
    - Cold reservoir temperature
    - Hot reservoir temperature

The Jupyter Notebook has the following package dependencies: python3.11, NumPy [pip install numpy], Pandas [pip install pandas], Plotly [pip install plotly], SciPy [pip install scipy], and nbformat [pip install nbformat]. It is recommended that the Jupyter Notebook be used within Visual Studio Code.

Figure A.1: Cold water cycle

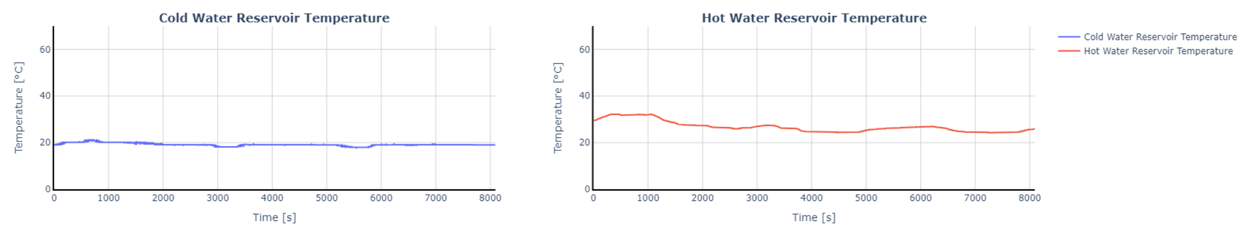


Figure A.2: System parameters

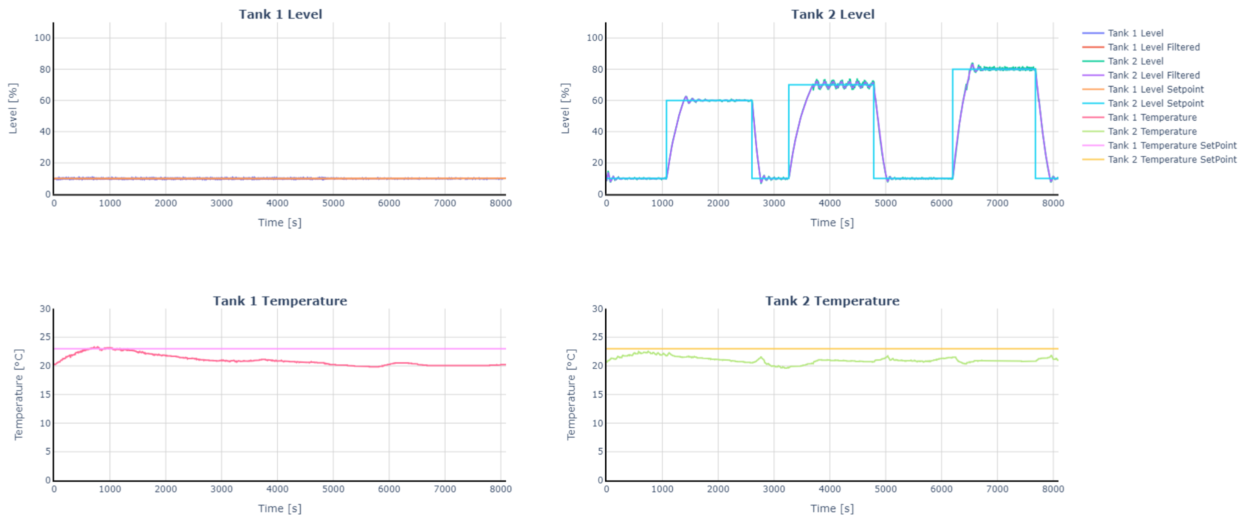


Figure A.3: Tank variables

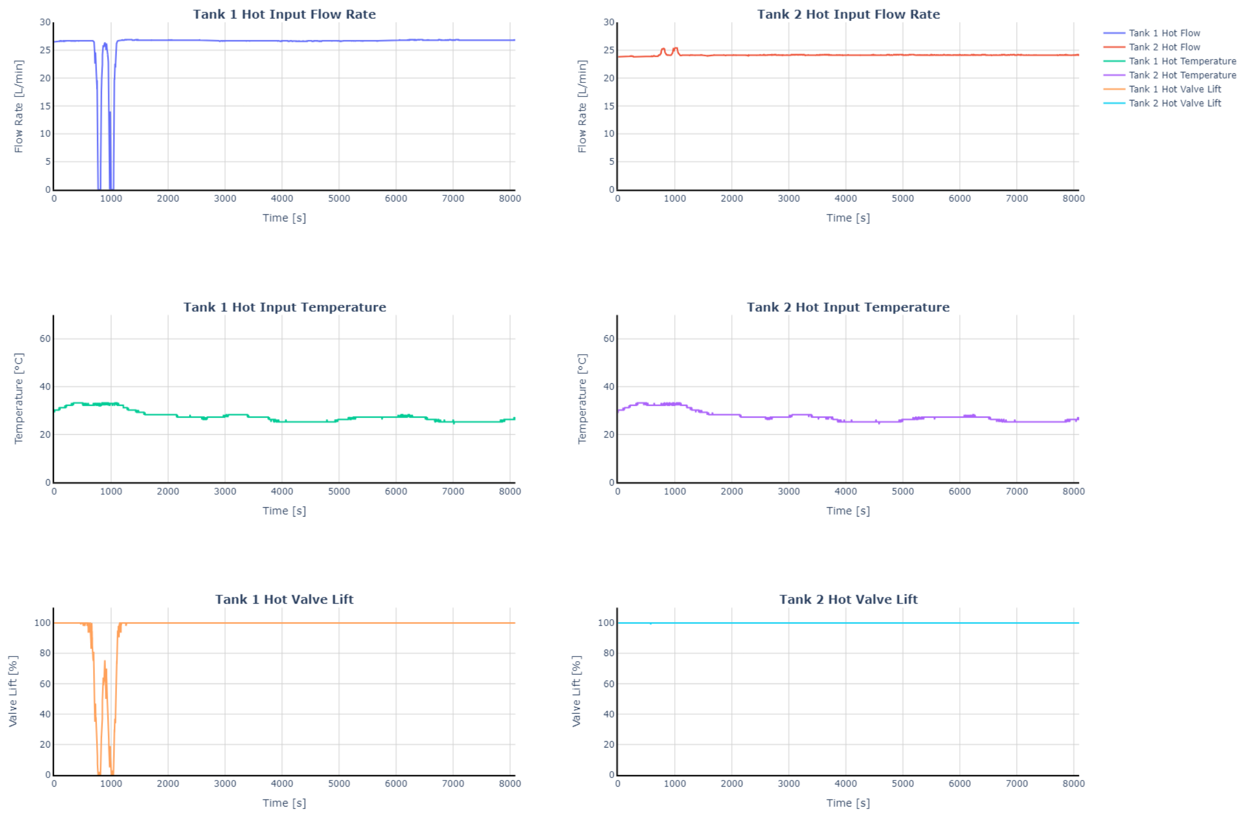


Figure A.4: Hot water cycle

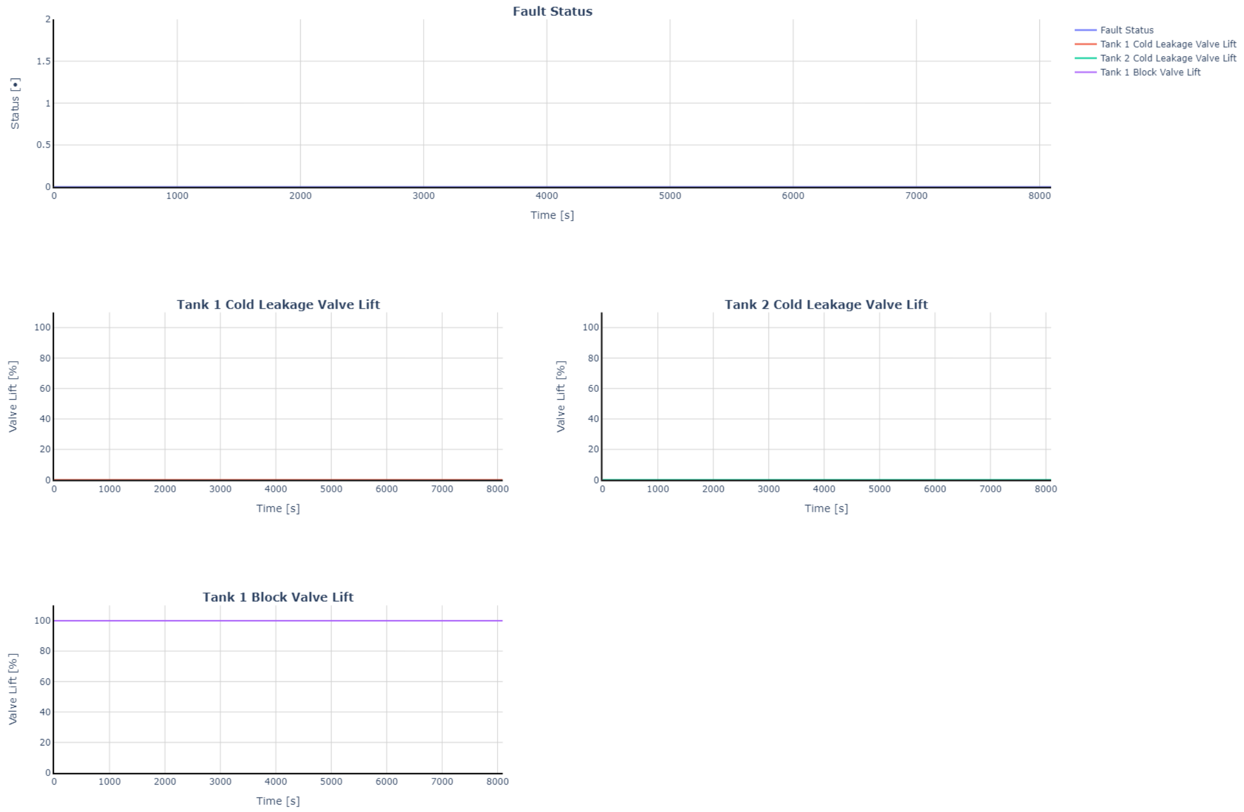


Figure A.5: Faults

B System design

B.1 Introduction

The system design chapter briefly covers the mechanical design and implementation of the system upgrades. The improvements made to the data acquisition capabilities of the system along with the improvements made to the control system and HMI are also covered. The HMI improvements are also compared to the original system HMI.

The valve sizing Excel calculations are also provided.

B.2 System design and implementation

The system design and implementation section briefly covers the mechanical design and practical implementation of the upgraded heated two-tank system.

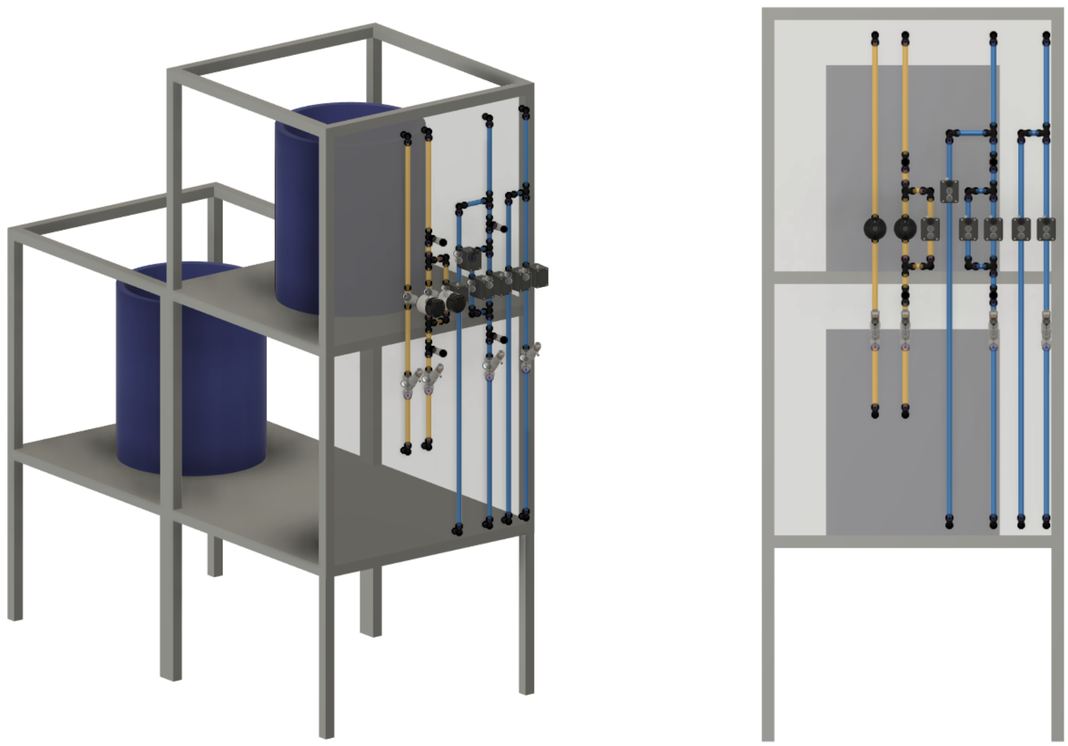
B.2.1 System design

The original heated two-tank systems piping and instrumentation diagram was updated to reflect the upgrades made to the system. The original piping and instrumentation diagram can be found on page 136 and the updated piping and instrumentation diagram can be found on page 137.

The physical valve and piping placements were designed within Fusion 360. This was done to ensure that the implementation would go smoothly and ensured that there was enough space for all of the valves and sensors to be installed. The 3D renderings of the valve and piping placement design are depicted in figure B.1.

A system pressure board was added to give the system operator an overview of the system pressures (figure B.2). These can be used to ensure that all of the centrifugal pumps are operating correctly and that the hot water reservoir is not over-pressurised.

The hot circulation centrifugal pump was upgraded from the Pedrollo CP100 to the Leo ACm75 according to the gas heater installation manual specifications (Bosh OptiFlow 26L). The Leo ACm75 will be able to provide the required 3 bar operating pressure at a flow rate of at least 26 l/min. This should allow the gas heater to operate at maximum performance according to its installation manual.



(a) Original system (b) Upgraded system

Figure B.1: Piping network

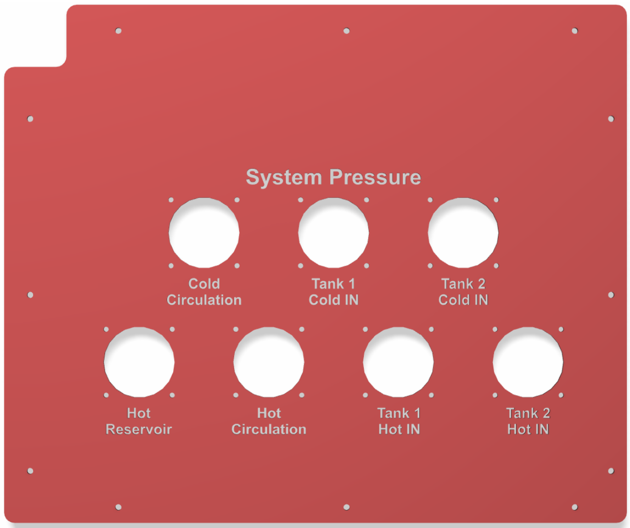
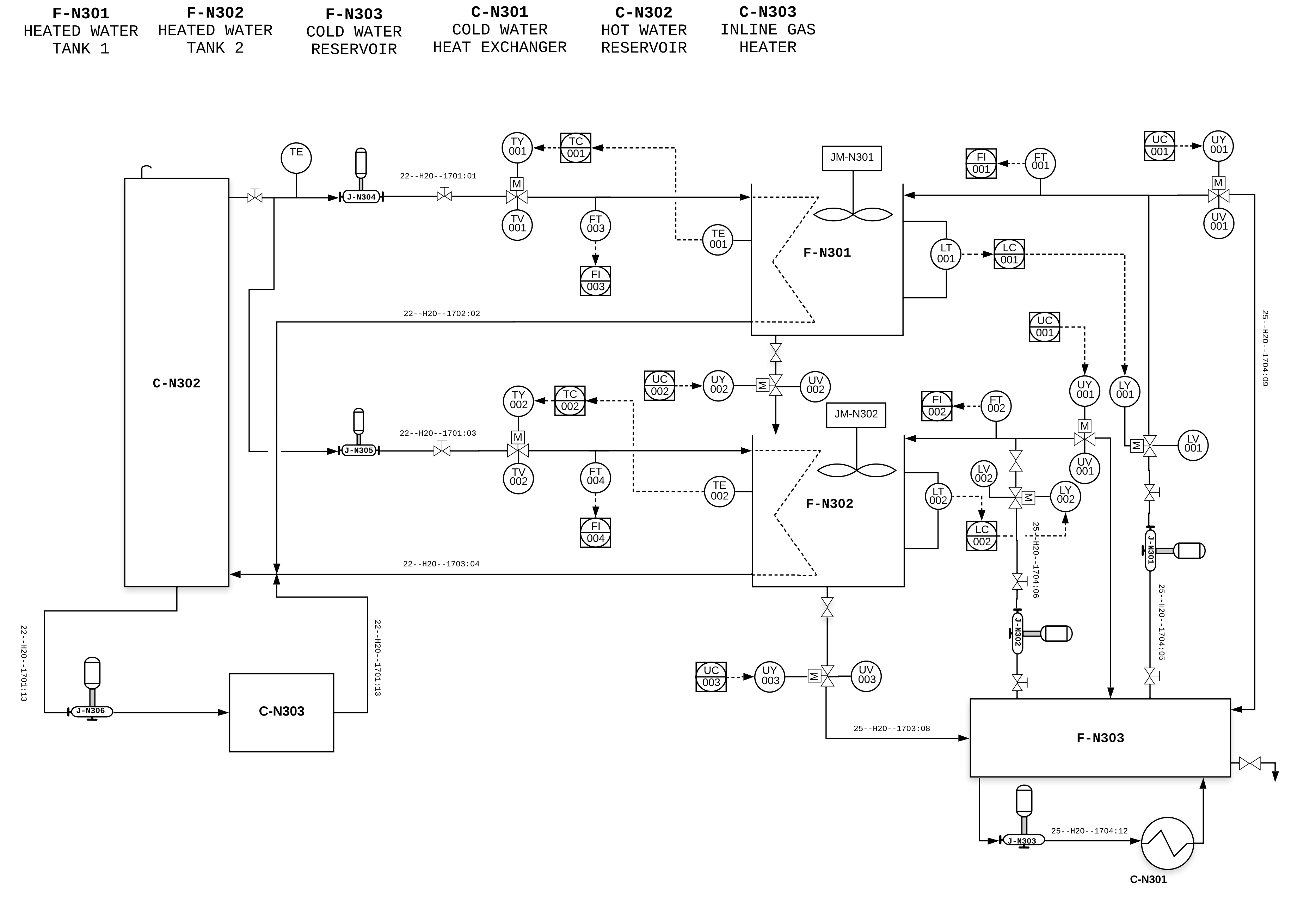


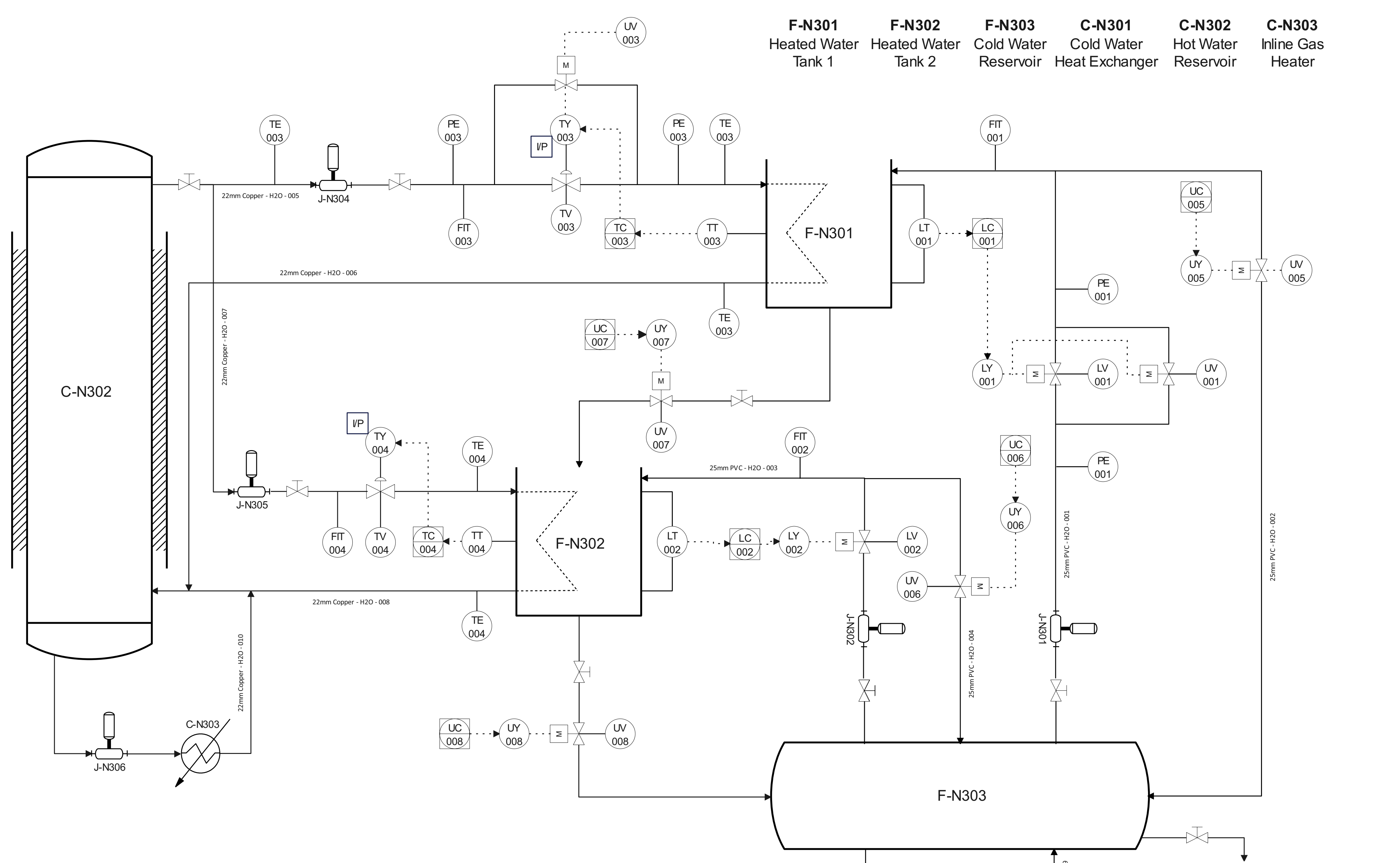
Figure B.2: Pressure Board



GENERAL NOTES

1. VALVE N3-UV-002 TO BE USED FOR CLOG EMULATION ON THE OUTLET OF TANK F-N301
2. VALVE N3-UV-003 TO BE USED FOR CLOG EMULATION ON THE OUTLET OF TANK F-N302
3. VALVE N3-UV-001 TO BE USED FOR PARTIAL LEAK EMULATION ON THE FEED TO TANK F-N301
4. STUCK VALVE FAULT TO BE IMPLEMENTED BY SOFTWARE FUNCTION ON N3-LV-001 AND N3-LV-002
5. SENSOR FAULT TO BE IMPLEMENTED BY SOFTWARE FUNCTION ON N3-TC-001.
6. FOULING FAULT TO BE IMPLEMENTED BY MEANS OF SOFTWARE MODIFICATION ON N3-TC-002
7. SYSTEM OPERATION ONLY ALLOWED IN THE PRESENCE OF OPERATOR

REV 1 PO 2019/09/05	REV 3 WW 2020/01/25	REV 5 PO 2020/11/02		DRAWN BY: P. OBERHOLZER	PROCESS PIPING & INSTRUMENTATION DIAGRAM OF
ISSUED FOR P&ID REVIEW AS PER 2019-001 CHK: WW APPR:	POST MFD REVIEW UPDATE AS PER 2019-001 CHK: PO APPR: WW	POST MFD REVIEW UPDATE AS PER 2019-001 CHK: PO APPR: WW		CHECKED BY: W. WOLMARANS	**HEATED TWO-TANK SYSTEM**
REV 2 PO 2019/10/17	REV 4 WW 2020/02/08			APPROVED BY: W WOLMARANS	NWU ENGINEERING WORKSHOP N3
VALVES ADDED AS PER 2019-001 CHK: PO APPR: WW	MODIFIED TEMPERATURE LOOP AS PER 2019-001 CHK: PO APPR: WW			PROJECT NO. 2019-001	DRW NO: PID2019001 REV.4



DRAWN BY	ESTIAN CHAMBERS	PROCESS PIPING & INSTRUMENTATION DIAGRAM OF
CHECKED BY	BEANZ INC	**HEATED TWO-TANK SYSTEM**
APPROVED BY		
PROJECT #	420-42	

The hot water reservoir piping network was also upgraded adhering to standard geyser installation protocol. The hot water outlet was moved to the top of the hot water reservoir thereby ensuring that the hottest water gets pumped out first. The cold water inlet was moved to the bottom of the hot water reservoir to minimise its effect on the temperature of the hot water outlet. Lastly, the hot water circulation was also moved to ensure that the hot water circulation pump inlet is situated at the bottom of the hot water reservoir and the return from the gas heater is situated at the top of the hot water reservoir on the opposite side. This ensures that the hot circulation pump causes most of the water stored within the hot water reservoir to be circulated and mixed thereby allowing the hot water reservoir to have a more uniform temperature gradient. A pressure relief gauge was also installed to ensure that the hot water reservoir could not be over-pressurised. The upgrades made to the hot water reservoir piping are shown in figure B.3.

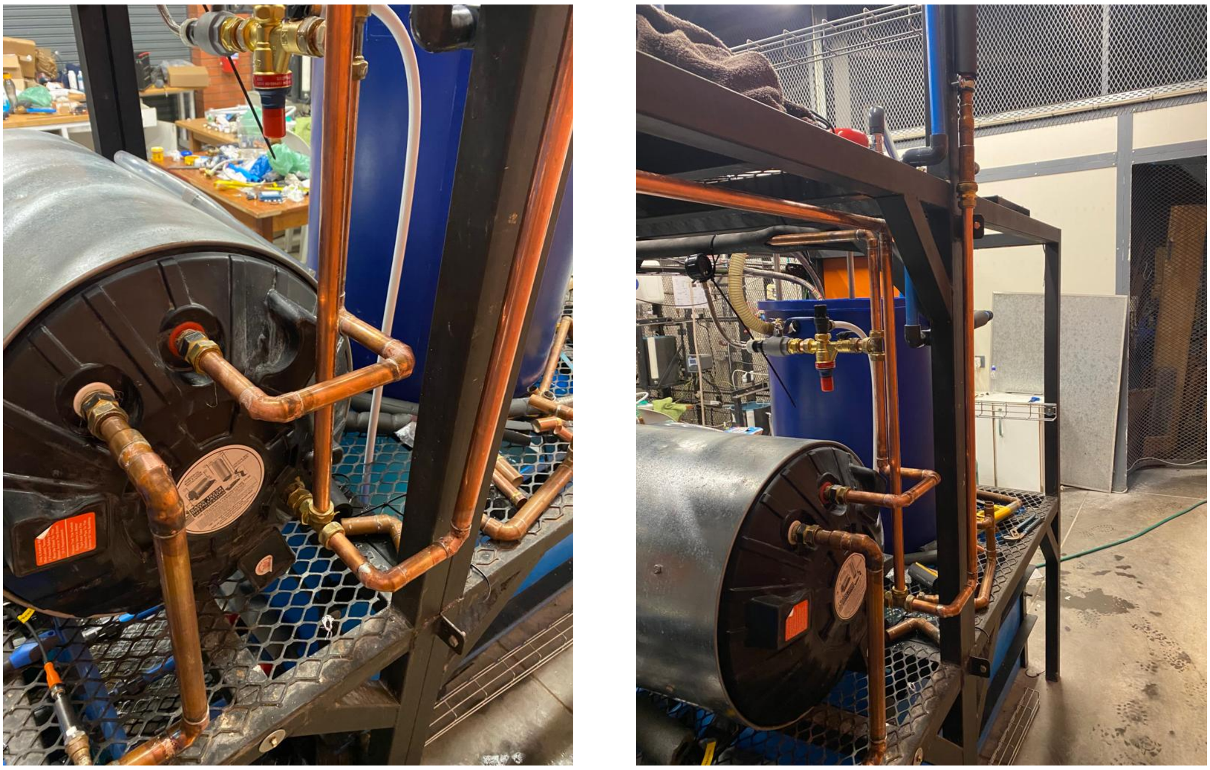


Figure B.3: Hot reservoir - Flow improvements

B.2.2 System implementation

The implemented system upgrades are shown in figures B.5 and B.4

Figure B.4: Implementation - Upgraded System

Figure B.5: Implementation - Upgraded System valves

B.3 Data acquisition

The original system only exported a limited subset of the heated two-tank system's process variables and parameters. This resulted in a severe lack of information contained within an exported data set. Without an accompanying experimental setup description, the data set would lose a lot of its value since the unknown variables could not be accounted for. The data acquisition and export functionality of the system are therefore upgraded in such a way as to ensure that all of the system parameters and process variables are stored and that the intent behind each data set will be apparent without an experimental setup description.

Table B.1: Comparison between original and upgraded system stored system data

Description	Original system	Upgraded system
Setpoints	-	Level
	-	Temperature
Level sensors	Tank 1 & 2	Tank 1 & 2
Temperature sensors	Tank 1 & 2	Tank 1 & 2
	Cold in [T1 & T2]	Cold in [T1 & T2]
	Hot in [T1 & T2]	Hot in [T1 & T2]
	-	Heating coils [T1 & T2]
	-	Hot water reservoir
Flow sensors	Cold in [T1 & T2]	Cold in [T1 & T2]
	Hot in [T1 & T2]	Hot in [T1 & T2]
Valve lift	Cold in [T1 & T2]	Cold in [T1 & T2]
	Hot in [T1 & T2]	Hot in [T1 & T2]
Pumps & motors	-	Agitators [T1 & T2]
	-	Cold circulation status
	-	Hot circulation status
Pressure sensors	-	T1 cold in valve
	-	T1 hot in valve
Faults	-	Fault status
	Cold leakage [T1 & T2]	Cold leakage [T1 & T2]
	T1 blockage	T1 blockage
	-	Cold flow drift [T1 & T2]
	-	Hot flow drift [T1 & T2]
	-	Level drift [T1 & T2]
	-	Temperature drift [T1 & T2]
	-	Cold stuck [T1 & T2]
	-	Hot stuck [T1 & T2]
	-	Fouling status [T1 & T2]

B.4 PLC and HMI

The PLC and HMI section briefly cover the improvements made to the PLC and HMI.

B.4.1 PLC

Several improvements were made to the overall control of the system. The most noteworthy of these improvements is the addition of the automatic control mode and sequencer. The original system required the system operator to manually change system parameters throughout the duration of an experiment. This led to the failure of several experiments due to the inconsistent timing between setpoint changes. The solution to this was to automate the entire experimental setup and procedure process by means of a sequencer. The sequencer will, as the name suggests, sequentially update the system set points as defined by each sequence step's durational setpoint. The sequence steps are defined numerically in the order in which they should occur. The following parameters can be adjusted for each step: step number, step duration, final step status (is the step the final step that should be run), system parameters (tank level and temperature setpoints), fault status (should a fault be induced into the system during this step), fault parameters (leakages, stuck valves, blockages, and sensor drift). The system operator can configure the sequencer by entering the parameters for each step on the "Automatic Mode" HMI screen (figure B.6).

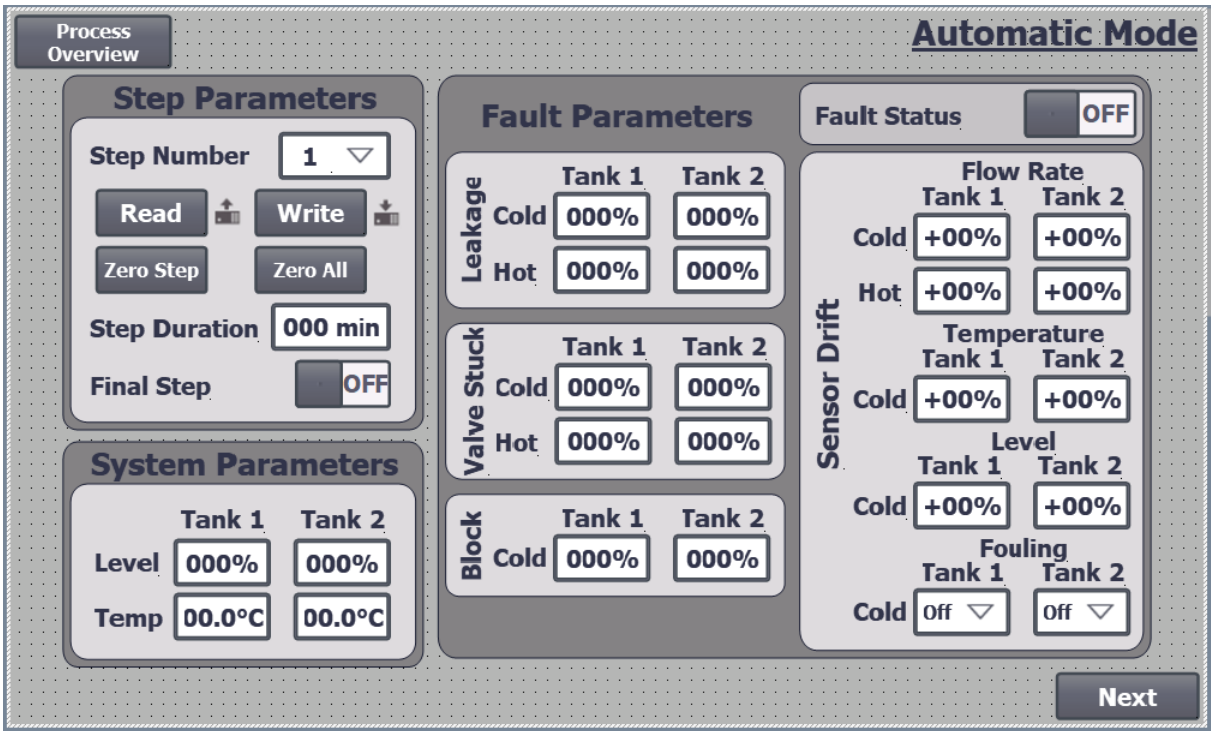


Figure B.6: Upgraded HMI - Automatic Mode

B.4.2 HMI

The user interface implemented on the HMI was completely redesigned for the upgraded system. The original system HMI consisted of the following screens: process overview (home screen), process setup, fault setup, commissioning, and hot reservoir setup. The upgraded system HMI consists of the following screens: process overview (home screen), dashboard, manual mode, automatic mode, circulation, and commissioning.

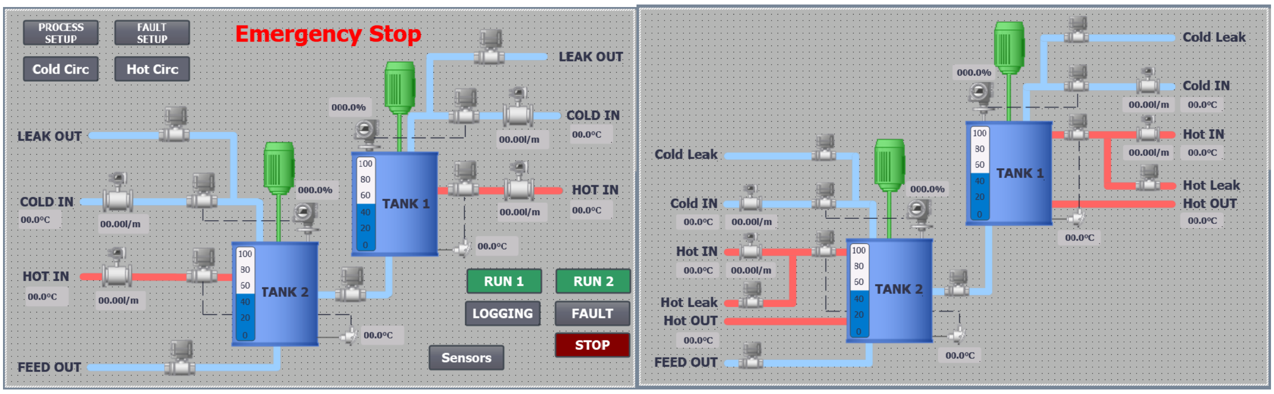
The original system process overview was cleaned up and a drop-down menu was added that allows the operator to access any other screen directly from the home screen. The dropdown menu along with the manual and automatic mode versions of the upgraded system process overview HMI screens are shown in figure B.8. The process overview screen is a graphical depiction of the heated two-tank system that provides some insight into the system's operation. The industry norm is however to have a dashboard that provides all of the required system information without any visual clutter thereby minimising any potential distractions when an actual fault does occur. The original and upgraded system process overview HMI screens are compared in figure B.7. The upgraded system dashboard HMI screen is shown in figure B.10.

The original system process setup and fault setup HMI screens have been combined into a single interface representing the manual mode configuration HMI screen of the upgraded system. Manual mode allows the system operator to define two sets of operating conditions (Run 1 and Run 2) along with a set of fault conditions that can be activated at any point while the system is operated within manual mode. The manual version of the process overview HMI screen allows the system operator to select between the two sets of operating conditions as well as the ability to activate the fault parameters. The screen also shows the current system parameter setpoints along with status indicators for which one of the parameter set are active and whether or not the faults are active or not. The original system process setup and fault setup HMI screens are shown in figure B.13. The upgraded system manual mode HMI screen is shown in figure B.9.

The automatic mode HMI screen allows the system operator to configure the sequencer parameters as described above. The screen allows the system operator to select the current sequence step number from a drop-down list. The "Read" and "Write" buttons can be used to either read the current sequence step's corresponding sequencer parameters or write the sequencer parameters currently present on the screen to the sequencer data block. The "Zero Step" and "Zero All" buttons allow the system operator to either change all of the sequencer parameters present on the screen to zero or zero all of the sequence steps sequencer parameters. Lastly, the "Fault Status" toggle switch can be used to indicate whether or not the current sequence step will allow the use of the fault parameters or not. The automatic mode version of the process overview HMI screen shows the current sequence step number, total number of sequence steps, current sequence step time remaining, total time remaining before the sequencer is finished, and the current system parameter setpoints.

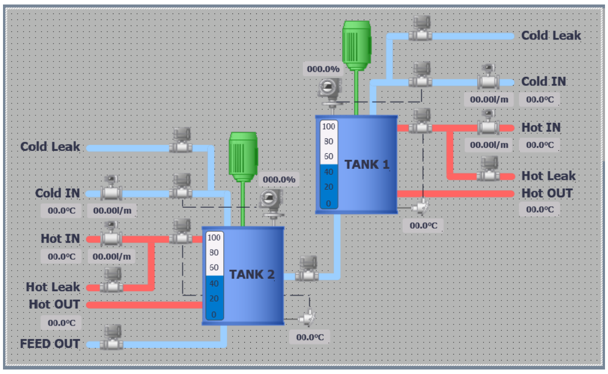
The original commissioning HMI screen was completely redesigned to improve readability. The upgraded commissioning HMI screen also features a button leading to the dashboard HMI screen allowing the system operator to see all of the system parameters while in commissioning mode. The original system commissioning HMI screen is shown in figure B.11. The upgraded system commissioning HMI screen is shown in figure B.12.

Lastly, the original system hot reservoir setup HMI screen was replaced with a circulation HMI screen on the upgraded system. The circulation HMI screen allows the system operator to enable or disable both the cold water and hot water circulation pumps. The hot water reservoir can also be set to automatic temperature control mode in which the temperature is regulated by means of a bang-bang controller between the minimum and maximum temperature setpoints. The original system hot reservoir setup HMI screen and upgraded system circulation HMI screen is shown in figure B.14.

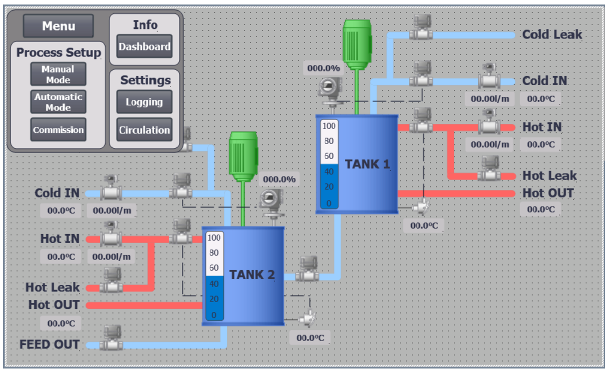


(a) Original (b) Upgraded

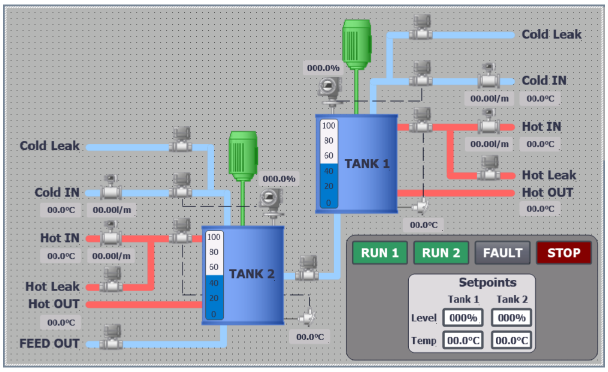
Figure B.7: HMI - System home screen



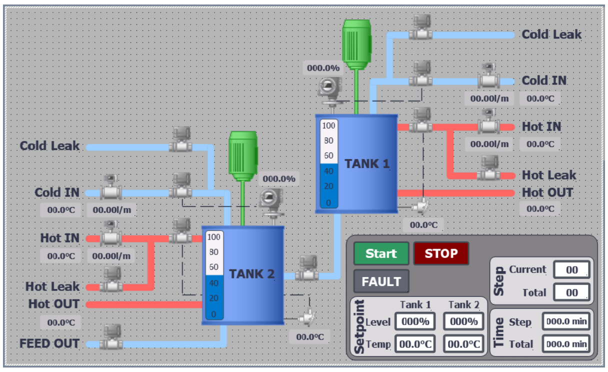
(a) Home screen



(b) Drop down menu



(c) Manual mode menu



(d) Automatic mode menu

Figure B.8: Upgraded HMI - Home screen

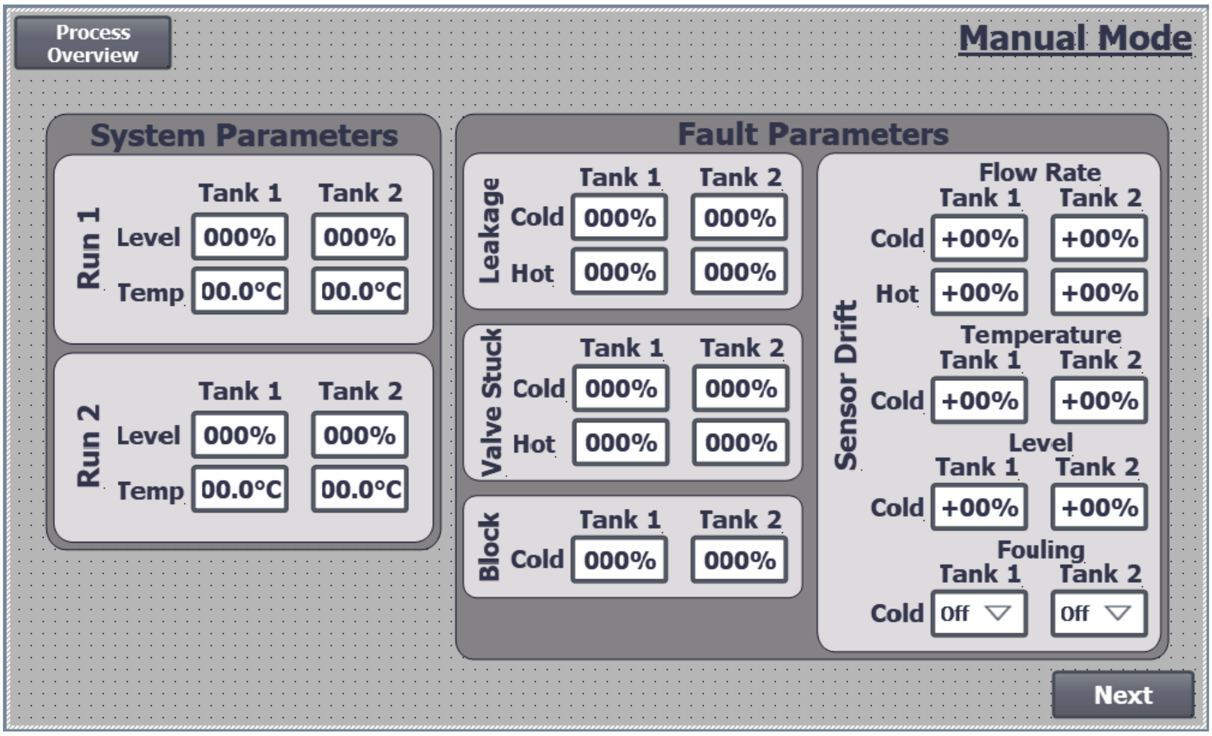


Figure B.9: Upgraded HMI - Manual mode

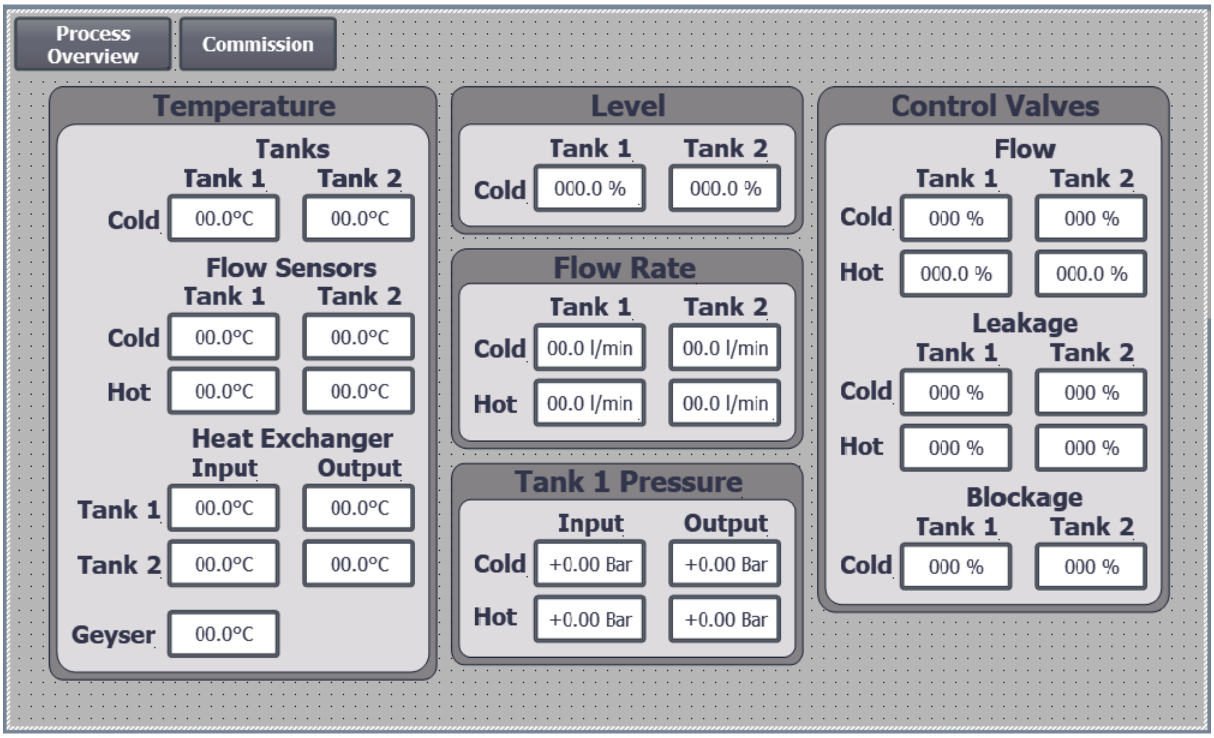


Figure B.10: Upgraded HMI - Dashboard

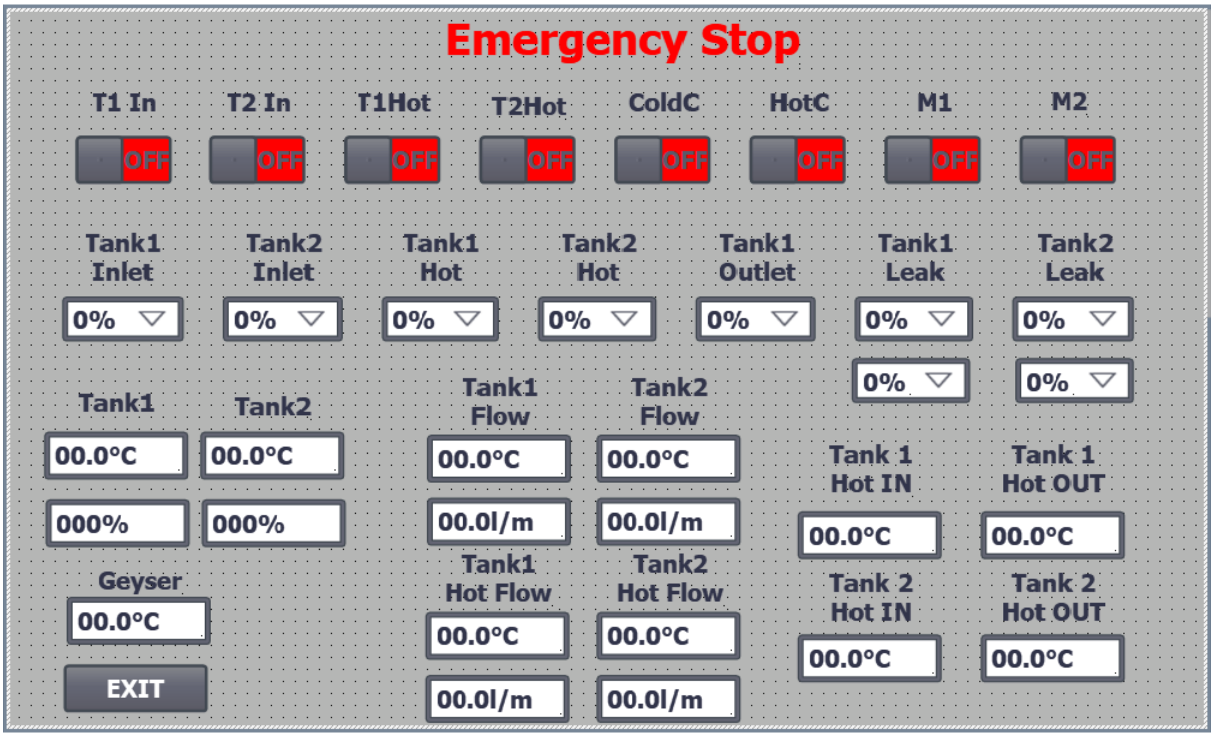


Figure B.11: Original HMI - Commission Mode

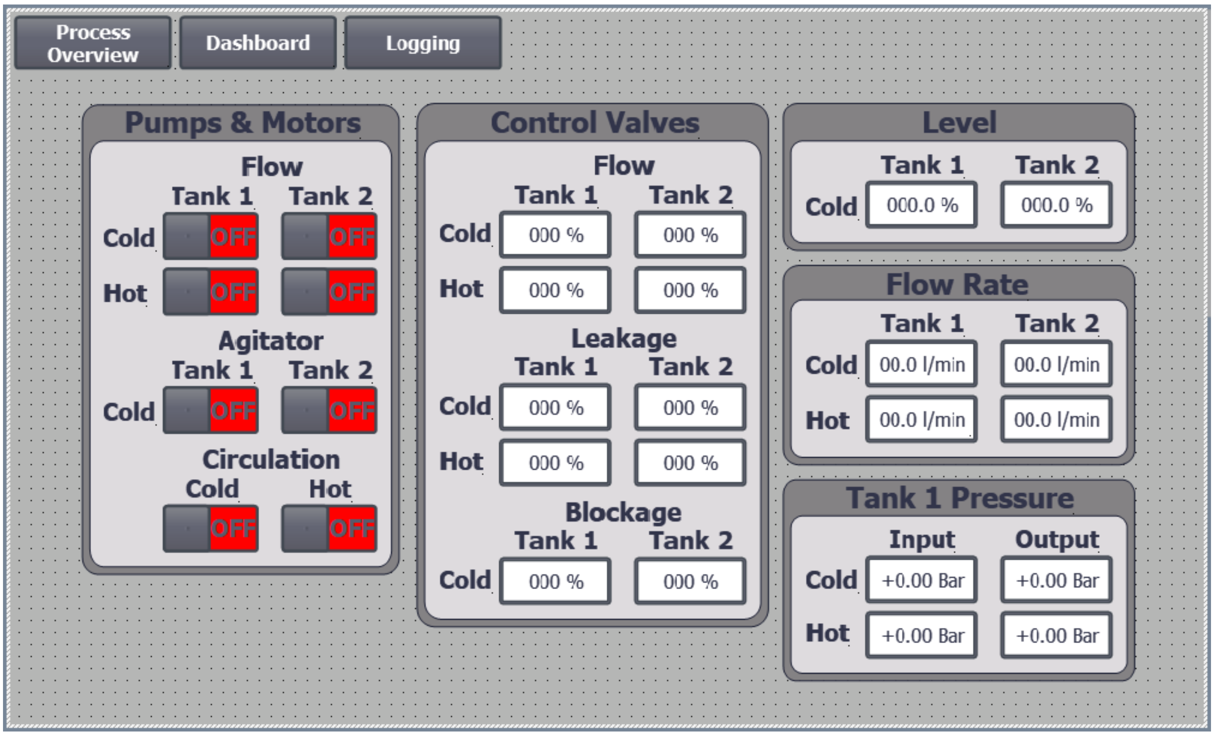
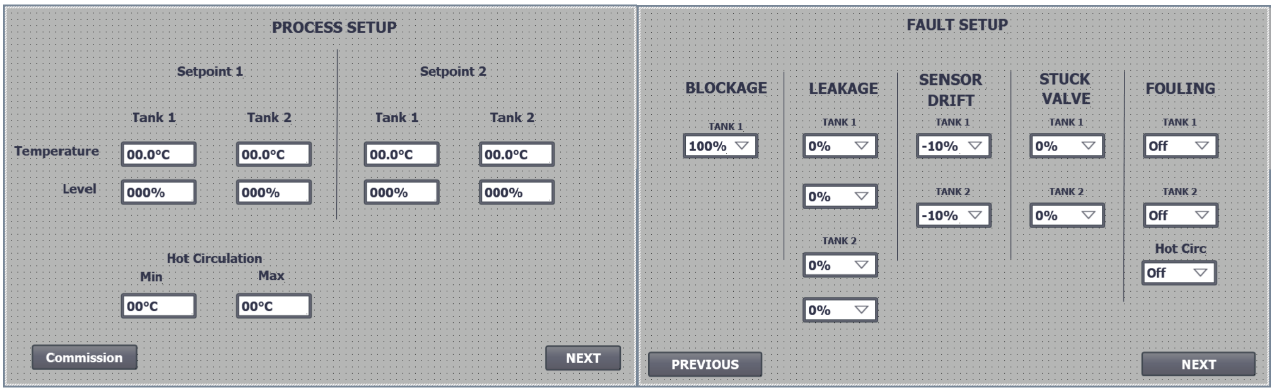


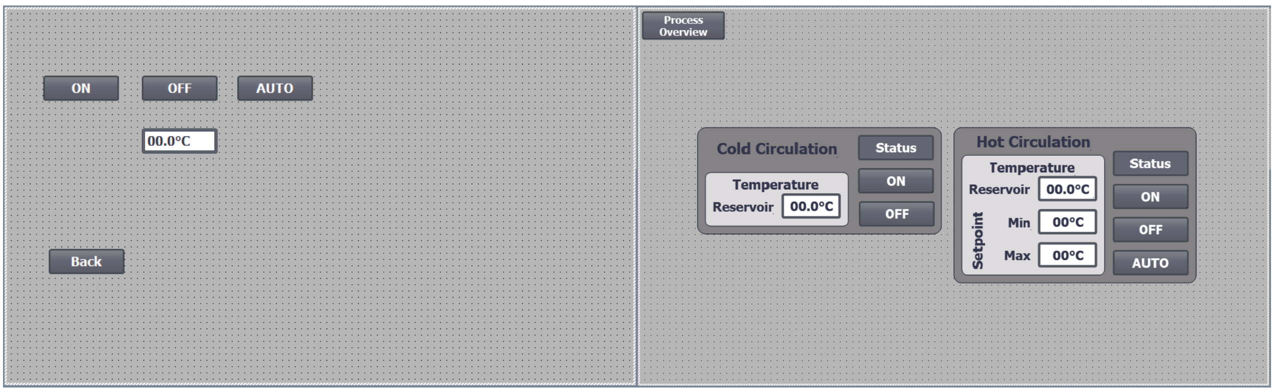
Figure B.12: Upgraded HMI - Commission Mode



(a) System configuration

(b) Fault configuration

Figure B.13: Original HMI - Manual mode



(a) Original

(b) Upgraded

Figure B.14: HMI - Hot and cold water cycle circulation control

B.5 Valve sizing

B.5.1 Valve sizing - Excel calculations

Tank 1 Cold Input

Qmean [l/min]	Qmax [l/min]	Dpipe [mm]	Wall [mm]	P @ Tank [bar]	ε [mm]
23	45	25	1.7	0.02	7.00E-03
23	40	21.6		1.15	4.00E-03
35	60				

Elbow L/D
30

Before Valve

Horizontal [m]	Vertical [m]	elbows
0.37	0.45	3
0.33	1.18	

Total Length [m]	4.27
Total Height [m]	1.63

After Valve

Horizontal [m]	Vertical [m]	elbows
0.36	0.83	4
0.08	-0.2	
0.31		
0.19		

Total Length [m]	4.56
Total Height [m]	0.63

Head losses

Before Valve		After Valve	
ΔPe [bar]	0.16	ΔPe [bar]	0.06
ΔPf (min) [bar]	0.027	ΔPf (min) [bar]	0.029
ΔPf (max) [bar]	0.091	ΔPf (max) [bar]	0.097
ΔPloss (min) [bar]	0.187	ΔPloss (min) [bar]	0.091
ΔPloss (max) [bar]	0.251	ΔPloss (max) [bar]	0.159

Pressure at end points

Pinlet (min) [bar]	2.354	Poutlet (min) [bar]	0.111
Pinlet (max) [bar]	2.105	Poutlet (max) [bar]	0.179

Valve Pressure Drop

ΔP (min) [bar]	2.243	ΔP (max) [bar]	1.926

30	0.766
35	1.116
40	1.04
50	0.848
60	0.597

Control Valve

Kvs
2.5

Kvr (min)	0.920	Kvr (max)	1.942
Lift (min)	37%	Lift (max)	78%

Kvs (rec)	2.137	
Qmax (pred)	57.915	[l/min]

Constants

ρ		μ				ε	
997	kg/m³	0.00100	N·s/m²	20 °C	min	58.80E-6	inches
0.997	g/cm³	0.00089	N·s/m²	25 °C	max	276.00E-6	inches
0.997	g/mL	0.00080	N·s/m²	30 °C	min	1.50E-6	m
		0.00072	N·s/m²	35 °C	max	7.00E-06	m

g	
9.81	m/s²

Head loss Calculator

Q [l/min]	Dp [mm]	finit	ε [mm]	L [mm]
40	21.6	0.021726667	1.50E-03	150
0.000666667	21.6		3.50E-03	4270
				4560

Re	44.07E+3	A	366.44E-6

Xleft	6.78427
Xright	6.78467
diff	-0.00040

f	21.7241E-3	21.6486E-3
Δp	2.489E-3	[bar]
h	25.451E-3	[m]
Rf	3.734	[bar/(m³/h)]

Figure B.15: Excel Calculations: Piping Network

Valve Sizing Calculations

Input Parameters

Q [l/min]	D [mm]	Valve Set	L [mm]	Dp [mm]
23	15	27%	200	23.3
23		27		

Constants

ρ		μ			
997	kg/m³	0.00100	N·s/m²	20 °C	
0.997	g/cm³	0.00089	N·s/m²	25 °C	
0.997	g/mL	0.00080	N·s/m²	30 °C	
		0.00072	N·s/m²	35 °C	

	ε	
min	58.80E-6	inches
max	276.00E-6	inches
min	1.50E-6	m
max	7.00E-06	m

Conversions

Q	0.00038333	[m³/s]	L	0.2	[m]			
	1.38	[m³/h]						
Dp	23.3	[mm]	D	15	[mm]	d	7.794	[mm]
	23.30E-3	[m]		15.00E-3	[m]		7.79E-3	[m]
Ap	426.385	[mm²]	An	176.715	[mm²]	Av	47.713	[mm²]
	426.38E-6	[m²]		176.71E-6	[m²]		47.71E-6	[m²]

Calculations

ß	0.11		Cd	972.23E-3	Flow Nozzle			
				0.7	Estimate			
Re	36.49E+3	D		0.6	Datasheet			
	70.22E+3	d						
Δp	64.85E+3	N/m²	Δp	65.67E+3	N/m²	Δp	752.53E+0	N/m²
	648.45E-3	bar		656.67E-3	bar		7.53E-3	bar
Kv	1.711	m³/h	Kv	1.700	m³/h	Kv	15.884	m³/h

$$Q = C_d A_0 \sqrt{\frac{2|\Delta p| \cdot \frac{1}{\rho}}{1 - \left(\frac{A_0}{A_1}\right)^2}}$$

$$\Delta p = \frac{1}{2} \cdot \rho \cdot \left(1 - \left(\frac{A_0}{A_1}\right)^2\right)\left(\frac{Q}{C_d A_0}\right)^2$$

$$Q = C_d A_0 \sqrt{\frac{2|\Delta p|}{\rho}}$$

$$\Delta p = \frac{1}{2} \cdot \rho \cdot \left(\frac{Q}{C_d A_0}\right)^2$$

$$Q = \frac{\pi \cdot D^4}{128 \cdot \mu \cdot L} \Delta p$$

$$\Delta p = \frac{128 \cdot \mu \cdot Q \cdot L}{\pi \cdot D^4}$$

Figure B.16: Excel Calculations: Shorthand Valve Sizing

Constants			
Absolute Vapor Pressure		Abs Thermodynamic crytical Pressure	
Pv		Pc	
0.2	[psi]	22058453	[Pa]
0.023	[bar]	220.58453	[bar]

Emerson Standardized Method

Kv	Q [l/min]	Sg	N_1	N_2	Nom valve d [mm]	Nom pipe D [mm]	Δp [bar]
3.751	45	0.998	0.865	0.00214	12	21.6	0.6743

Q	2.7	[m³/h]
Cv	4.336	

Piping Geometry Factor

Fp	0.876	Σk	0.717

$$F_p = \left[1 + \frac{\sum K}{N_2} \cdot \left(\frac{C_v}{d^2}\right)^2\right]^{-1/2}$$

$$\Sigma K = K_1 + K_2 + K_{B1} - K_{B2}$$

$$K_1 + K_2 = 1{,}5\left(1 - \frac{d^2}{D^2}\right)^2$$

Valve Sizing Coefficient

Cv	4.336
Kv	3.751

$$C_v = \frac{Q}{N_1 F_p}\sqrt{\frac{\rho}{1000\,\Delta p}} \qquad C_v = \frac{Q}{N_1 F_p \sqrt{\frac{\Delta p}{SG}}}$$

Max Flow Rate and Pressure

Qmax [l/min]	Kv	P_1 [bar]	Pv [bar]
60	5.4	1.1	0.023
3.60	6.24	2.3	

			globe	0.87-0.92
FF	0.957		FL	0.900
			FLreq	0.644
Qmax	5.0456	[m³/h]		
	84.0941	[l/min]		
Pmax	0.873	[bar]		

$$F_F = 0{,}96 - 0{,}28\sqrt{\frac{P_v}{P_c}} \qquad F_L = \frac{1{,}16\,Q_{max}}{C_v\sqrt{P_1 - 0{,}96\,P_v}}$$

$$Q_{max} = N_1 F_L C_v \sqrt{\frac{P_1 - F_F P_v}{SG}}$$

$$\Delta p_{max} = F_L^2 (P_1 - F_F P_v)$$

Figure B.17: Excel Calculations: Standardised Valve Sizing

C Upgraded system data

C.1 Introduction

The upgraded system data chapter briefly presents the data used during Chapter 5 (Upgraded system characterisation). These datasets provide real-world system data of a heated two-tank benchmarking system. The data is hosted at Heated two-tank system data - Upgraded system.

The CSV file header structure for the data sets is given along with a Jupyter Notebook that visualises the data. This will allow any interested parties to analyse the data themselves.

C.2 System data

C.2.1 Data structure

Significant improvements were made to the data acquisition capabilities of the original system. The upgraded system data CSV file header structure is given in table C.1. From the upgraded CSV file header structure it is possible to fully reconstruct the experimental procedure used to obtain the dataset. This is due to the fact that every process variable, setpoint, disturbance, and control signal is being saved allowing the researcher to know exactly what the system was doing at any given time.

Table C.1: Upgraded system - CSV header structure

Header	**Description**	**Unit**
Record	Sample number	[·]
Date	Date	[MM/DD/YYYY]
UTC Time	Time	[HH:MM:SS]
T1L	Tank 1 level	[%]
T2L	Tank 2 level	[%]
T1LS	Tank 1 level setpoint	[%]
T2LS	Tank 2 level setpoint	[%]
T1T	Tank 1 temperature	[°C]
T2T	Tank 2 temperature	[°C]
T1TS	Tank 1 temperature setpoint	[°C]
T2TS	Tank 2 temperature setpoint	[°C]
T1A	Tank 1 agitator status	[·]

Table C.1 continued from previous page

Header	Description	Unit
T2A	Tank 2 agitator status	[·]
T1CF	Tank 1 cold flow rate	[l/min]
T2CF	Tank 2 cold flow rate	[l/min]
T1CT	Tank 1 cold input temperature	[°C]
T2CT	Tank 2 cold input temperature	[°C]
T1CV	Tank 1 level control valve lift	[%]
T2CV	Tank 2 level control valve lift	[%]
T1CVPI	Tank 1 level control valve inlet pressure	[bar]
T1CVPO	Tank 1 level control valve outlet pressure	[bar]
T1HF	Tank 1 hot flow rate	[l/min]
T2HF	Tank 2 hot flow rate	[l/min]
T1HT	Tank 1 hot input temperature	[°C]
T2HT	Tank 2 hot input temperature	[°C]
T1HV	Tank 1 temperature control valve lift	[%]
T2HV	Tank 2 temperature control valve lift	[%]
T1HVPI	Tank 1 temperature control valve inlet pressure	[bar]
T1HVPO	Tank 1 temperature control valve outlet pressure	[bar]
T1HCTI	Tank 1 heating coil input temperature	[°C]
T2HCTI	Tank 2 heating coil input temperature	[°C]
T1HCTO	Tank 1 heating coil output temperature	[°C]
T2HCTO	Tank 2 heating coil output temperature	[°C]
F	Fault status	[·]
1CL	Tank 1 cold leakage valve lift	[%]
2CL	Tank 2 cold leakage valve lift	[%]
1HL	Tank 1 hot leakage valve lift	[%]
2HL	Tank 2 hot leakage valve lift	[%]
1CS	Tank 1 stuck level control valve lift	[%]
2CS	Tank 2 stuck level control valve lift	[%]
1HS	Tank 1 stuck temperature control valve lift	[%]
2HS	Tank 2 stuck temperature control valve lift	[%]
1BV	Tank 1 outlet blockage valve lift	[%]
1CD	Tank 1 cold flow rate sensor drift	[%]
2CD	Tank 2 cold flow rate sensor drift	[%]

Table C.1 continued from previous page

Header	Description	Unit
1HD	Tank 1 hot flow rate sensor drift	[%]
2HD	Tank 2 hot flow rate sensor drift	[%]
1TD	Tank 1 temperature sensor drift	[%]
2TD	Tank 2 temperature sensor drift	[%]
1LD	Tank 1 level sensor drift	[%]
2LD	Tank 2 level sensor drift	[%]
1FL	Tank 1 fouling status	[·]
2FL	Tank 2 fouling status	[·]
GT	Hot reservoir temperature	[°C]
GTL	Hot reservoir minimum temperature setpoint	[°C]
GTH	Hot reservoir maximum temperature setpoint	[°C]
CC	Cold circulation status	[·]
HC	Hot circulation status	[·]

C.2.2 Jupyter Notebook

This notebook is intended to simplify the process of visualising the data obtained from the upgraded heated two-tank system and can be found at Jupyter Notebook - Upgraded system. The data visualisation is divided into the following sections:

1. Tank variables (figure C.1)
   - Tank level and level setpoint
   - Tank temperature and temperature setpoint
   - Agitator status
2. Cold water cycle (figure C.2)
   - Cold input flow rate
   - Cold input temperature
   - Level control valve lift
   - Tank 1 level control valve pressure drop
3. Hot water cycle (figure C.3)
   - Hot input flow rate
   - Hot input temperature
   - Temperature control valve lift
   - Heating coil input temperature

    - Heating coil output temperature
    - Tank 1 temperature control valve pressure drop

4. Faults (figure C.4)
    - Fault status
    - Cold leakage valve lift
    - Hot leakage valve lift
    - Cold stuck valve lift
    - Hot stuck valve lift
    - Blockage valve lift
    - Cold flow sensor drift
    - Hot flow sensor drift
    - Temperature sensor drift
    - Level sensor drift
    - Fouling status
5. System parameters (figure C.5)
    - Cold reservoir temperature
    - Hot reservoir temperature
    - Hot reservoir minimum temperature setpoint
    - Hot reservoir maximum temperature setpoint
    - Cold circulation status
    - Hot circulation status

The Jupyter Notebook has the following package dependencies: python3.11, NumPy [pip install numpy], Pandas [pip install pandas], Plotly [pip install plotly], SciPy [pip install scipy], and nbformat [pip install nbformat]. It is recommended that the Jupyter Notebook be used within Visual Studio Code.

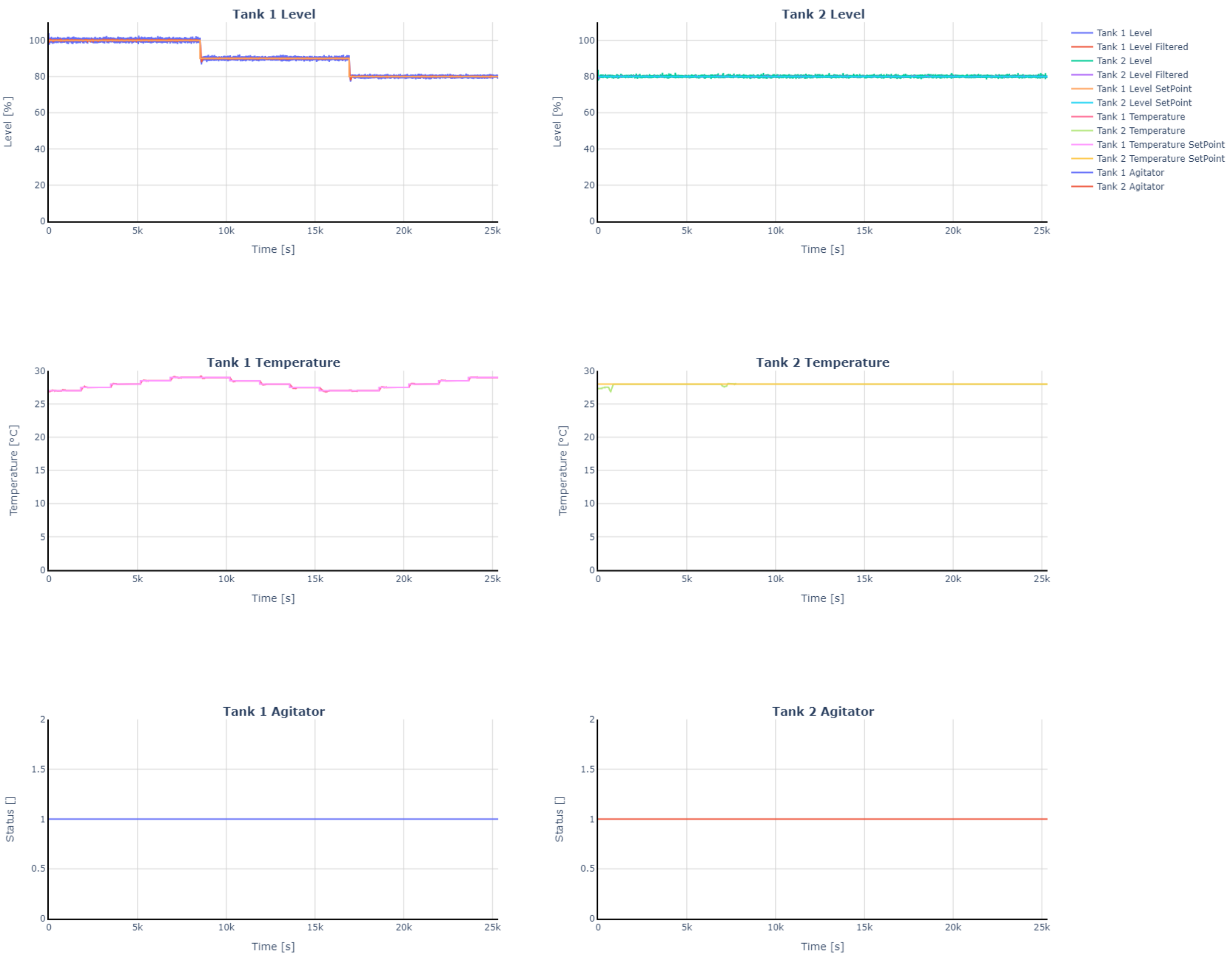


Figure C.1: Tank variables

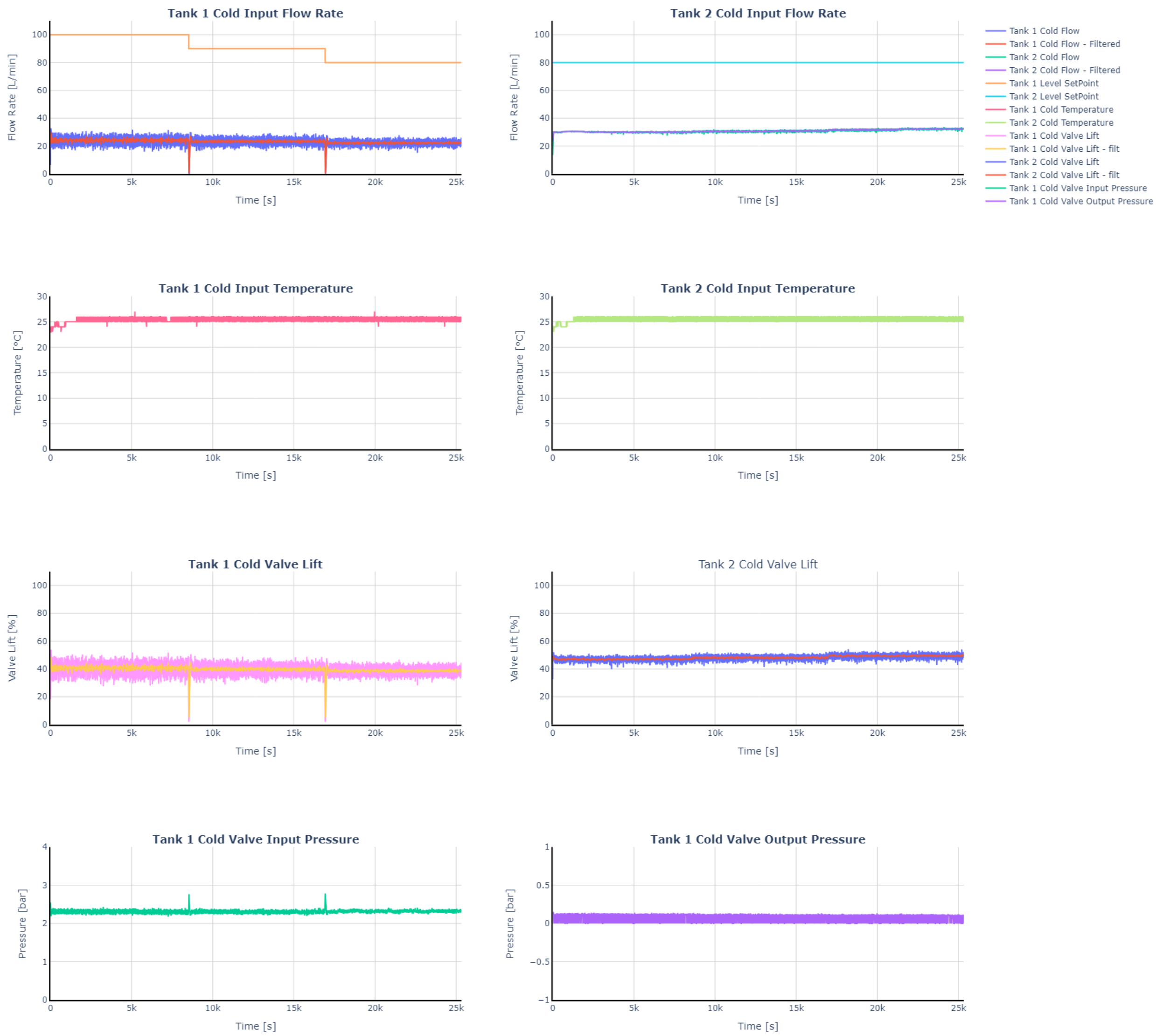


Figure C.2: Cold water cycle

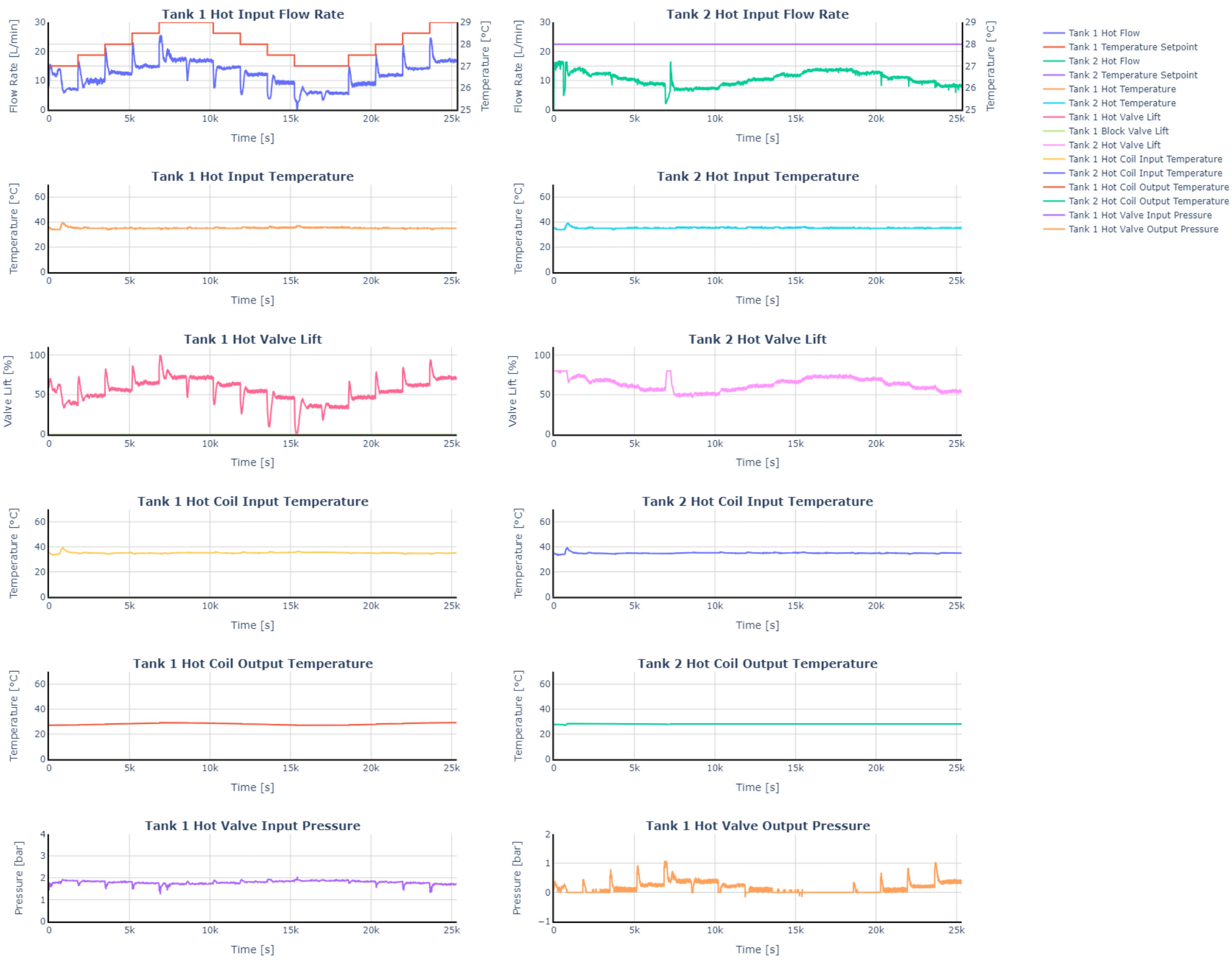


Figure C.3: Hot water cycle

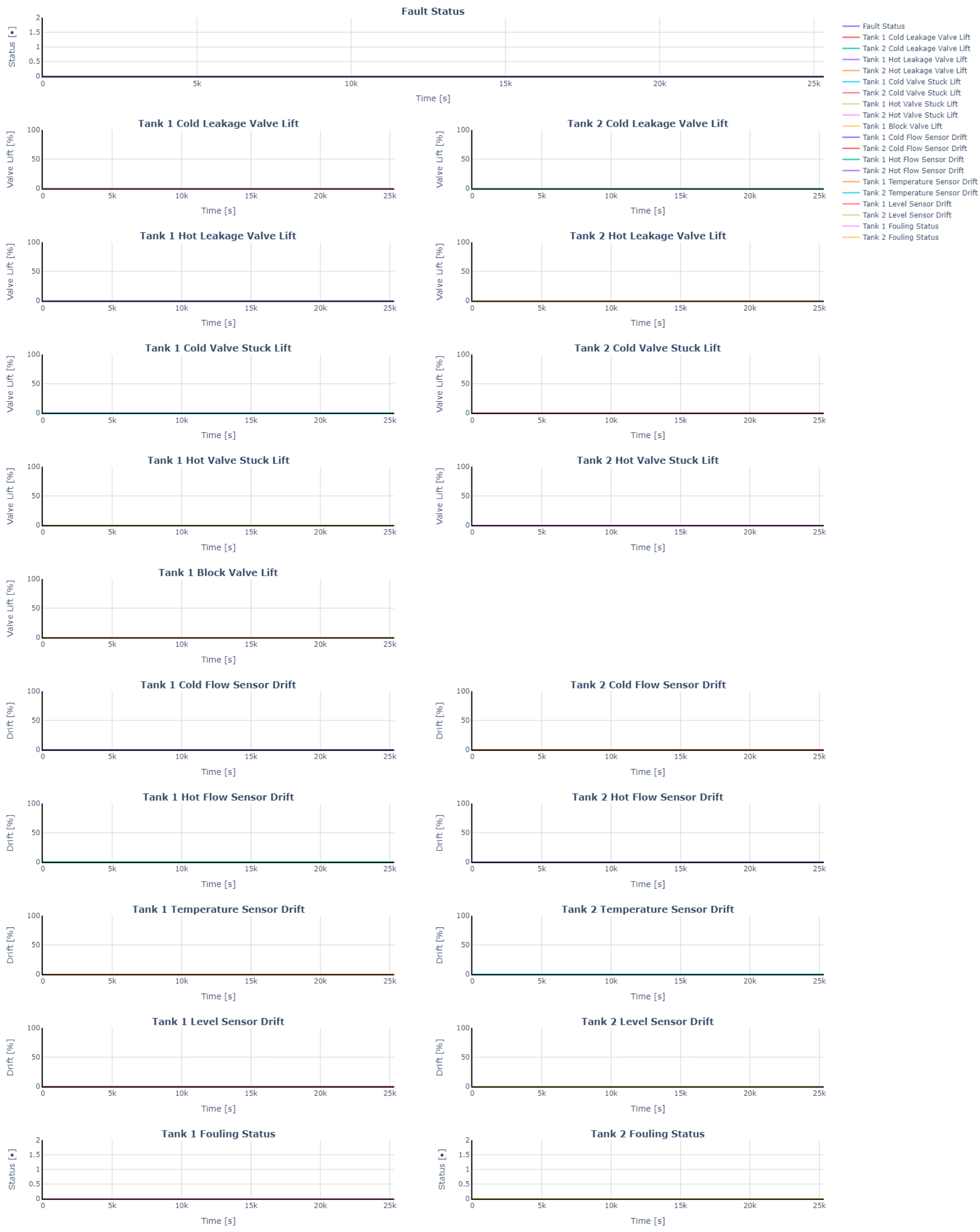


Figure C.4: Faults

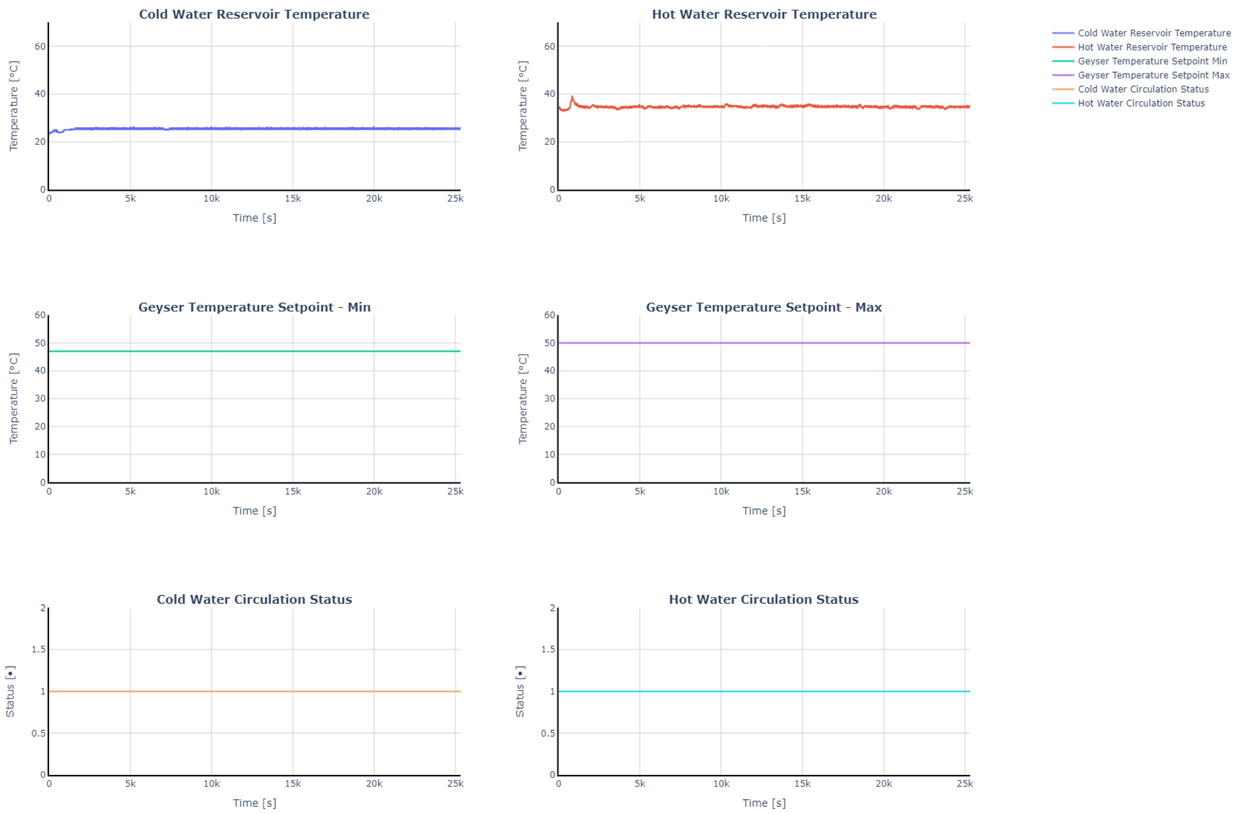


Figure C.5: System parameters