Automated control of a pebble bed core thermal flow test unit

A dissertation presented to

The School of Electrical, Electronic and Computer Engineering

North-West University

In partial fulfilment of the requirements for the degree

Magister Ingeneriae

in Electrical and Electronic Engineering

by

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December 2006

Potchefstroom Campus

Abstract

The HTTF (Heat Transfer Test Facility) is a unique project verifying the only pebble bed correlations currently used by PBMR (Pty) LTD. They are developing a new concept nuclear power station and are at present in the preparation phase of the construction of the worlds first PBMR (Pebble Bed Modular Reactor).

The PBMR required the HTTF to be built at the North-West University in Potchefstroom. The HTTF consists of two separate test facilities: the HTTU (High Temperature Test Unit) and the HPTU (High Pressure Test Unit). The focus of this project will be on the HPTU.

The HPTU is a unique test plant making a high range of test and operating conditions possible. The plant's test vessel can be loaded with eleven types of separate test sections, enabling it to do these tests. Pressure ranges and mass flow conditions vary in every test that is conducted. A design like this requires a complex control system able to control the plant during these variable test conditions.

The HPTU has a very high safety requirement as it will be operated at extremely high pressures and, primarily because it will enable PBMR (Ltd) Pty to develop an inherently safe nuclear power plant. An automated control system needs to be developed to ensure the safety of this plant.

The purpose of this study is to develop and deliver this safe, automated and user friendly control system that will be able to control the HPTU throughout its operating ranges. Research had to be done on its design to determine the plant's operating criteria. Furthermore, an investigation of the HTPU's characteristics and behaviour is necessary to fully understand the operation arrangement of the plant in order for it to be controllable. For the development of a complex, but absolutely safe protection systems, the operating margins have to be gathered. The plant will be operated for many hours at a time with limited number of operating personnel, which underline the necessity of research in the development of a modern plant user interface, as it will be the only communication path between the highly complex HPTU and the newly trained operators.

It is not always possible to tune and simulate controllers for large plants because of their complexity. Additional tuning methods are required to do PID (Proportional Integral Differential) variable tuning. Most of these tests are conducted in the actual plant. A background study therefore had to be conducted on the development and tuning of industrial PID controllers.

A control system previously developed for PBMR project that was completed at the end of 2002. This plant is called the Pebble Bed Micro Model (PBMM) and was, up until now, one of PBMR's proudest achievements. This control system was investigated to determine the control and protection system criteria. It was used as a resource of information for an equally complex and similar in size plant's control systems.

The HPTU's automated control system consists of an OCS (Operational Control System) and an EPS (Equipment Protection System). The OCS will contain all the software necessary to control and protect the HPTU throughout all the operating conditions. It physically controls the plant by manipulating the actuators of the plant to perform the required functions. The EPS is a backup protection system for the OCS to ensure that critical plant operating parameters are not exceeded.

This system is developed to protect and control the plant throughout all the possible operating scenarios. Prior to the possibility to develop a protection system like this, it was essential to fully understand and analyse the HPTU's design. To determine the required operating conditions, the modes and states were investigated. High risk machines and equipment were then identified to determine whether extra backup protection hardware would be necessary for the specific equipment.

A simulator was developed for the HPTU to simulate and predict the operating behaviour of the plant and to design and test all the relevant PI controllers.

The control system was designed and developed during the construction of the plant. Tuning of the controllers was done during the commissioning of the HPTU and a study of the results determined the performance of the controllers.

The user interface is the interface between the operator actions and the plant. Modern engineering development like the HPTU required a modern user interface. Research was conducted to determine the effect that the conventional user interfaces had on operators in order to determine a optimum way to design and implement the system. Modern user interface was investigated to develop a control system that would allow good cooperation between operators and control systems. The hardware and control room setup was also designed to represent a quality control interface.

ACKNOWLEDGEMENTS

I would like to firstly thank M-Tech Industrial for granting me the opportunity to further my studies.

I would also like to acknowledge the following people, in no particular order, for their contributions during the course of this project.

- Professor George van Schoor, my supervisor, for his guidance, advice and support that stood central to the success of this project.
- Carl van Niekerk, my assistant supervisor, for his help, advice and support.
- Willem van Niekerk, my colleague, for his help and advice on thermal fluid systems.

Table of contents

ABBREVIATIONS AND ACRONYMS

Abbreviation or Acronym	**Definition**
HTTF	Heat Transfer Test Facility
PBMR	Pebble Bed Modular Reactor
GUI	Graphical User Interface
SCADA	Supervisory Control and Data Acquisition
HPTU	High Pressure Test Unit
BS	Blower System
HXCWS	Heat Exchanger Cooling Water System
HS	Heater System
BHS	Braiding Heater System
ICS	Inventory Control System
NWTS	Near Wall Test Section
CCTS	Convection Coefficient Test Section
PDTS	Pressure Differential Test Section
BETS	Braiding Effect Test Section
SAPB	Small Annular Packed Bed
SCPB	Small Cylindrical Packed Bed
PLC	Programmable Controller
PAC	Programmable Automation Controller
HMI	Human Machine Interface
CHI	Computer Human Interface
OCS	Operating Control System
EPS	Equipment Protection System

1. Introduction

This chapter provides introductory information on the high pressure test unit in general. The problem statement is supplied and followed by the issues to be addressed. A concise overview of the document is also presented

1.1 BACKGROUND

The Heat Transfer Test Facility (HTTF) consists of two clearly distinguishable test sections namely the High Temperature Test Unit (HTTU) and the High Pressure Test Unit (HPTU). This document will focus on the control design of the High Pressure Test Unit. The purpose of the heat transfer test facility is twofold:

- To validate the correlations that are currently used by PBMR (Pty) Ltd. to model the relevant heat transfer and fluid flow phenomena required for the integrated simulation of their nuclear pebble bed core, via a comprehensive set of separate effects tests.
- To generate results that may be used to validate the different simulation methodologies applied in the integrated models that represent the entire PBMR nuclear pebble bed core, via a comprehensive set of integrated effects tests

The HPTU will contribute to both of the objectives listed above since it will be used for the following [9]:

- Steady-state separate affects tests to validate the correlations used for the pebble-to-fluid heat transfer coefficient at different porosities.
- Steady-state separate effects tests to validate the correlations used for the reactor reflector surface-to-fluid heat transfer coefficient
- Steady-state separate effects tests to determine the total pressure drop through a homogeneous packed bed at different porosities
- Steady-state separate effects tests to determine the effective fluid heat conduction due to turbulent mixing at different porosities
- Steady-state integrated effects tests to determine the total pressure drop through an annular packed bed.
- Steady-state integrated effects tests to determine the effective fluid conductivity in an annular packed bed
- Steady-state integrated effects tests to determine the total pressure drop through a cylindrical packed bed.
- Steady-state integrated effects test to determine the velocity profile at the outlet of an annular packed bed

1.2 DESCRIPTION OF THE BASIC MACHINES AND THEIR PURPOSES

The schematic layout of the High Pressure Test Unit is shown in Figure 1.1

1. Test section

The main pressure vessel's purpose is to facilitate the test sections. The purpose of the test sections are briefly described in the next paragraph.

2. Blower

The blower's purpose is to circulate the nitrogen through the HPTU which is required to conduct the tests. The circulation system is discussed in detail in section 1.3.2

3. Orifice measuring station

The orifice measuring station is used to accurately measure nitrogen mass flow through the circulation system.

4. Nitrogen cooling system

The nitrogen cooling system consists of a shell and tube water cooler which is used to remove the extra heat caused by the blower and/or test section.

5. Heater system
6. The heater system is used to maintain the test pressure vessel inlet temperature at 35 °C. The braiding heater system (The braiding heater system is used to control the braiding inlet temperature at 75 °C)

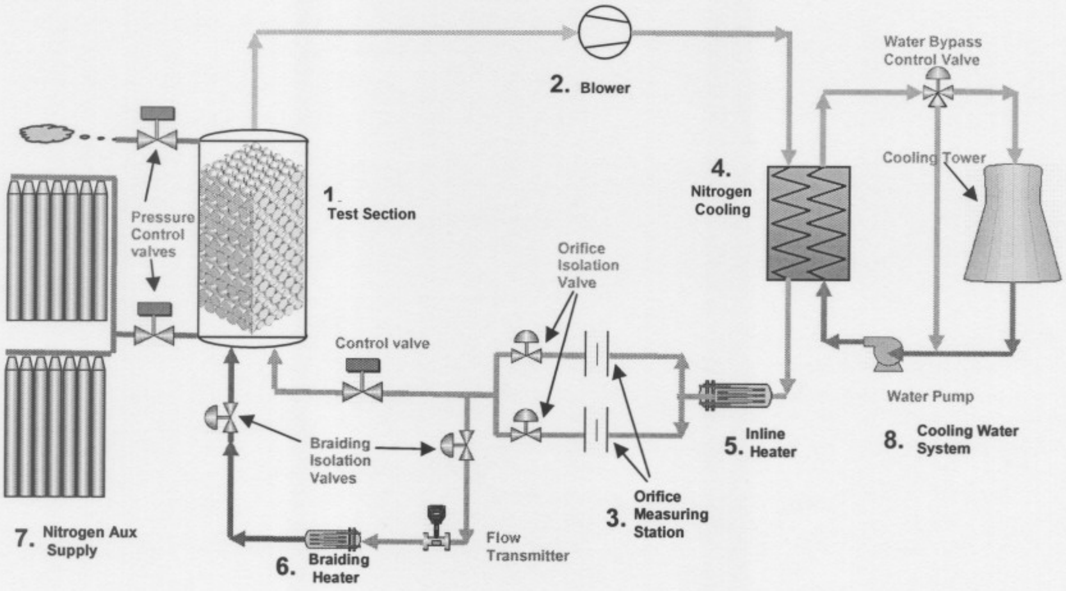


Figure 1.1 Schematic layout of the HPTU plant

7. Auxiliary gas supply system (Auxiliary gas supply system is used to maintain the HPTU system pressure at a constant specified pressure. The pressure varies from 100-5000 kPa)
8. Cooling water system (The cooling water system is used to supply the heat exchanger with a regulated water temperature [9].)

1.3 DETAIL DESCRIPTION OF THE PLANT

As shown schematically in Figure 1.2, the HPTU plant was designed to accommodate six different types of interchangeable test sections in one facility. For three of these, namely the PDTS, CCTS and the BETS, there are three different test sections each with a homogeneous porosity packed bed with a specific porosity of 0.36, 0.39 or 0.45. This results in a total of 14 interchangeable test sections.

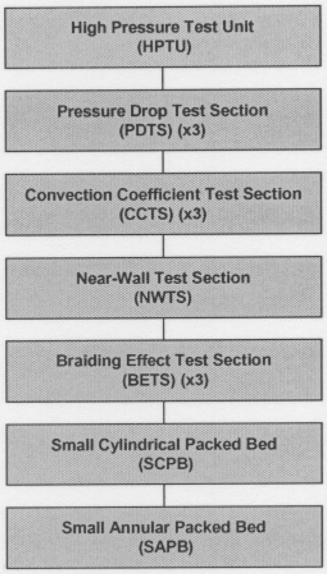


Figure 1.2 Schematic of the different test sections accommodated in the HPTU plant.

For all of the test sections, Nitrogen gas at controlled pressure and temperature is circulated through the packed bed within the test section in order to achieve forced convection flow rates representing a range of Reynolds numbers of up to 50,000.

1.3.1 Test sections

The PDTS, CCTS, NWTS and BETS consist of structured homogeneous porosity packed beds with spheres of either 60 mm or 30 mm diameter (as shown in Figure 1.3). In the PDTS the static pressures above and below the bed are measured in order to obtain the pressure drop through the bed. In the CCTS, a chrome-plated copper sphere that is heated internally via an electrical resistance heater, is positioned in the centre of the packed bed. Measurements of the sphere wall temperature, the surrounding gas temperature and the electrical heat input are taken in order to derive values for the sphere surface convection heat transfer coefficient.

Sspecific sections of the wall surrounding the packed bed are heated via electrical resistance heaters in the NWTS. By measuring the wall surface temperature, the surrounding gas temperature and the electrical heat input values can in this case be derived for the wall surface convection heat transfer coefficient.

In the BETS a hot gas stream with known temperature and mass flow is injected in the centre at the bottom of the packed bed. Due to the turbulent mixing within the bed, enhanced diffusion will take place between the hot gas stream and the surrounding colder gas flow. This phenomenon is also referred to as the 'braiding effect'. Measurements are made of the radial temperature distribution within the bed at approximately one third from the inlet at the bottom of the bed and one third from outlet at the top of the bed. Based on these temperature profiles the magnitude of the braiding effect can be evaluated [9].

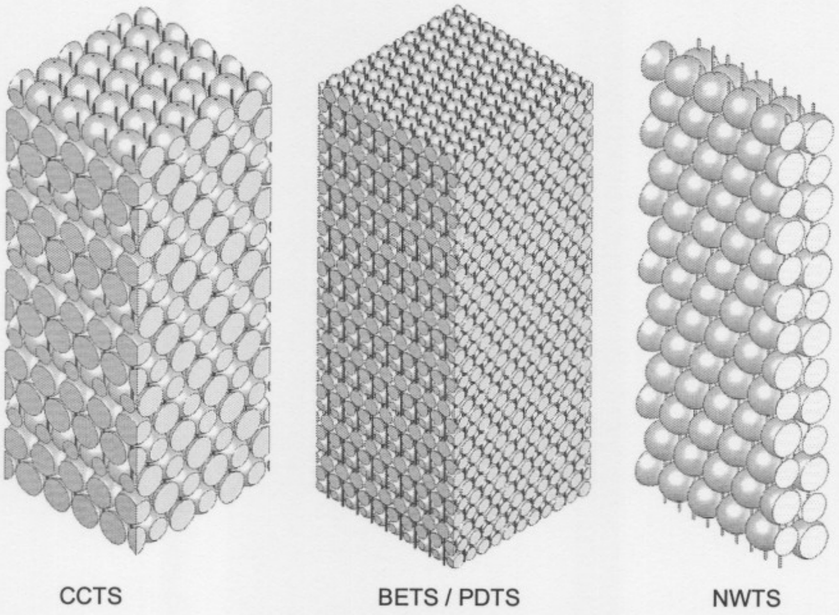


Figure 1.3 Illustration of the various homogeneous packed pebble bed structures

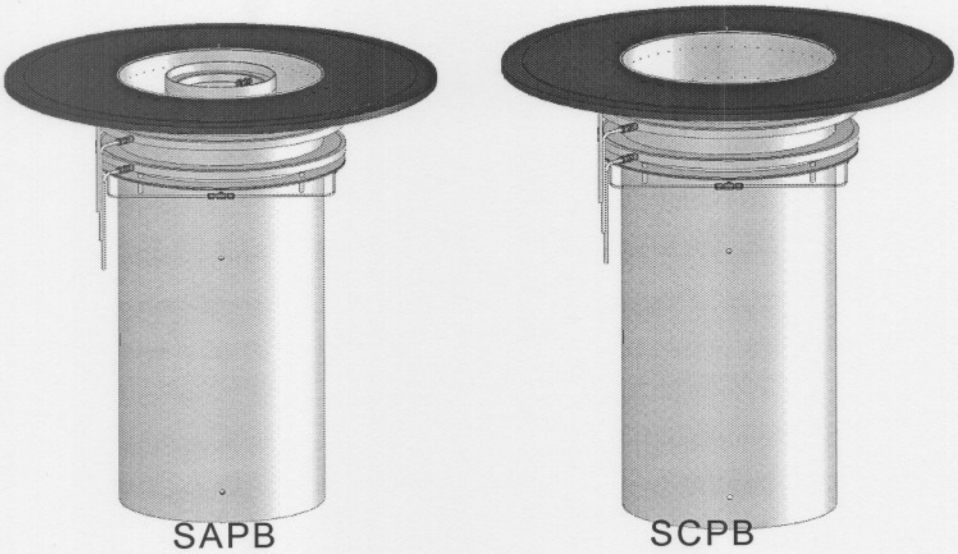


Figure 1.4 SAPB and SCPB test sections

In the case of the SAPB and CCPB shown in Figure 1.4, smaller spheres of approximately 6 mm in diameter are contained within either the annular or cylindrical cavity in an unstructured manner. Various tests are conducted on these unstructured packed beds. These include measurement of the pressure drop across the bed, measurement of the outlet velocity profiles as well as measurement of the braiding effect when hot gas is injected from different positions on the inner and outer walls through the manifolds that are visible in Figure 1.4.

1.3.2 Ventilation system

Figure 1.1 in section 1.2 shows a schematic layout of the HPTU plant ventilation system. The pressure level in the test section pressure vessel is regulated with the aid of a high pressure Nitrogen supply system by simply adding and extracting gas through a set of control valves. Gas is circulated through the test section in a closed-loop configuration via a two-stage positive displacement Roots-type blower. From the blower the gas is fed through a shell-and-tube heat exchanger and an electrical gas heater, that are used in tandem to regulate the gas temperature at the inlet of the test section. From the heater the gas is fed through either one or two ISO-standard orifice mass flow measuring stations, depending on the magnitude of the flow. From there it flows through the main control valve back to the inlet at the bottom of the test section.

The additional braiding gas loop shown underneath the test section in Figure 1.1 contains the braiding flow meter and the braiding gas heater. This loop is only employed for the BETS, SAPB and SCPB test sections. The main control valve is used in conjunction with the braiding flow meter to divert a specific fraction of the total flow through the braiding gas heater in order to supply the hot gas stream that is injected at the inlet of the packed bed for the braiding effect tests. The braiding flow meter is of the thermal type in order to allow for the measurement of very low mass flow rates. In the PDTS, CCTS, BETS and NWTS test cases the additional braiding gas loop is sealed off with the valve situated at the inlet of the braiding flow meter.

1.3.3 Auxiliary cooling system

The HPTU auxiliary cooling system consists of the cooling tower, the cooling water circulation pump and the three-way cooling water control valve. The pump supplies a nearly constant flow rate of water through the shell-side of the heat exchanger. The control valve is used to bypass a fraction of the total flow past the cooling tower in order to regulate the inlet water temperature to the heat exchanger. This in turn regulates the gas outlet temperature.

1.4 PROBLEM STATEMENT

An Automated control system is required for the high pressure test unit (HPTU) which is a pebble bed thermal flow test unit. This high pressure test unit requires separate complete and automated protection systems for each of the following sub-systems: Heat exchanger cooling water system (Nitrogen cooling system), inline heater system, braiding heater, blower system, near wall test section (NWTS) and the convection coefficient test section (CCTS). A total separate backup protection system needs to be implemented for the critical plant sub-systems to assist the main protection system. Controllers need to be developed to control the plant at required operator set-points. The controllers are: pressure controller, inline heater temperature controller, braiding heater temperature controller, Reynolds number controller, two near wall test section heater controllers and the convection coefficient test section's heated sphere temperature controller. A modern supervisory control and data acquisition system need to be developed to accommodate an easy to use human machine interface (HMI).

1.5 ISSUES TO BE ADDRESSED AND METHODOLOGY

In order to produce a safe controllable, operate able HPTU the following sub-problems need to be addressed.

1.5.1 Conceptual Analysis

The HPTU require a safe protection system that will be able to control the plant through any possible operating transition. In order to analyse the plant it need to be subdivided into separate protection and control systems. The main protection systems that need to be analysed are the cooling system, heater systems and ventilation systems. They need to be arraigned in order of importance. These systems must then be analysed separately to determine their required operating behaviour and requirements. The plant design teem need to be consolidated to gather all the necessary additional requirements that need to be incorporated into the control and protection systems. The modes and states need to be investigated to determine the required operating conditions. High risk machines and equipment need to be identified to determine if extra backup protection hardware is necessary. It must be determined what the requirements for the controllers are. The type of control, temperature, pressure and mass flow, need to be analysed in concept because of their completely different characteristics. A Literature study is essential to investigate the three possible plant control algorithms namely Proportional Integral (PID), Fuzzy Logic and neural networks. A graphical user interface (GUI) need to be developed to accommodate a safe and user friendly properties. In order to design a graphical user interface a literature study need to be conducted to determine all the issues involved in developing user interfaces and the human factors involved in human computer interfaces.

1.5.2 System Specification

The purpose is to generate a specification for the detail designs. All the protection systems operating specification need to be acquired to determine what the safe operating criterions are. In order to develop a protection system for each of the plant's sub-systems, the operating margins or limitation need to be acquired which include the maximum allowable pressures, temperatures and mass flows. The design teem need to be consolidated to acquire these information by either taking part in a Hazardous and operation (HAZOP) exercise or by studying such report. In such exercise all the possible operating scenarios and every possible operating condition are investigated to determine possible weak areas that require control and protection system.

The interaction of the protection systems need to be specified. It must be determined which sub-systems are dependant of each other. The type of control algorithm need to be specified by identifying the algorithm with the correct control properties for the specific control condition. The required control variables need to be specified together with the physical location of the controlled variable and the location of the actuator. The plant's design team need to be consolidated to gather information that will be used to develop a simulation model of the HPTU plant. All the operating conditions of the plant is of most importance to setup such simulation model. The user interface specification is of most importance to ensure that the designed user interface meets all the possible requirements. In order to do so a literature studies on previous SCADA systems need to be conducted.

1.5.3 Detailed Design

In order to complete the protection systems the background information regarding the HPTU operating conditions have to be combined with each of the HPTU's components operating margins or limits. Control or operating sequences need to be developed separately for the Heat exchanger cooling water system, Inline heater system, braiding heater system, heater wall test section two heaters system , convection coefficient heated sphere system and the blower system. These sequences will be the operating pathway of the software or it can be referred to as the intelligence of the protection programs. Their purpose will be to make corrective decisions during any possible operating conditions of the specific system. The sequences will guide the system through its modes by referring to the states of the plant. The operating margins and limits will be incorporated into some of the sequences modes for example the during a starting condition the program need to verify certain limits to make sure that the system is ready before it can be started and during running mode different limits need to be verified to determine if the plant is in safe operating condition. To do an intensive control loop design, simulations is required to do the initial setup and tuning of the controllers. A simulation model of the HPTU must be acquired from the thermal fluid design team. A simulation setup is then established between the HPTU model and the control software. All the plant's operating conditions is then used to setup a simulation for each operating condition from where the controller is then designed and tuned. A graphical user interface needs to be designed to accommodate all the required data logging, alarms and easy to use user interface.

1.5.4 Component / Sub-system procurement

Before the designing the control and protection system the software and hardware need to be selected. The requirements for an industrial controller need to be investigated to determine the amount of channels required for each of the type of signals. The suitable PLC (Programmable logic controller) or PAC (Programmable automation controller) needs to be specified to accommodate the amount of channels. Different types of PLCs have different control software which must be investigated to determine if the software are suitable for all the software requirements. It must be determined if it is necessary to buy additional software to for fill any addition needs if necessary. This must be kept in mind before selecting a PLC or PAC because industrial software comes with a big prise tag and requires additional programming training.

1.5.5 System Integration

At this point all the protection systems, control systems and graphical user interface system are separate programs that must be integrated into one control system. The integration of multiple programs can some times be a very complex task. The separate developed programs must thus be developed in such manner that integration of these systems is trouble-free and not time consuming. The integration of separate programs will most likely require additional communication software to e developed and programmed during integration. Time management of this project is thus a vital part to ensure that there is time to do such extra development.

1.5.6 System Evaluation

After the system integration is completed the protection systems must be tested without the hardware to ensure that it works under any condition. This will be achieved by programming a fault condition for every protection system and testing them separately. The control loops will be tested during the commissioning phase of HPTU and the results will then be compared to the simulated results to verify their performances. Meetings will be scheduled to evaluate the graphical user interface before and then during commissioning.

1.6 OVERVIEW OF DISSERTATION

Automation and the issues involved in the development of automatic control systems and the interactions between the operators and automated control systems are investigated to determine the effects of teamwork in modern industrial automated control systems. The user interface is the communication channel between the operator and the plant and is of most importance. The effect of visual and verbal feedback, which was used in the design process of the HPTU human machine interface, is introduced and discussed. This section includes a discussion on conventional interfaces versus modern improved interfaces. PID control is used in the control algorithm of the HPTU partly because of its robust performance in a wide range of operating conditions and partly because of its functional simplicity. It is implementable in a straight forward manner which made it the perfect choice for the HPTU. PID controllers are discussed in detail to provide a better understanding of the mathematical algorithms used in PID control. Values had to be set for the gain, integral and derivative times before a controller could be used. In theory, if a plant model is available, these values can be determined from a simulation model.

Usually, however, the plant's characteristics are unknown and the controller is tuned experimentally. A discussion of these tuning methods is provided.

The control philosophy of the HPTU is introduced in chapter 3, which includes the modes and states of the plant. The modes and states are the basic operating structures in which the plant operates. The basic terminology of modes and states is discussed, followed by a description of the HPTU modes and states. The protection and control requirements of the HPTU are proposed. This includes operator safety, protection systems and operating control systems.

The control system is split into the operational control system (OCS) and the equipment protection system (EPS). In Chapter 3 a discussion of the operating control system (OCS) and the backup equipment protection system (EPS) provide information regarding the safety of the HPTU. An introduction of the operating and control hardware follows, which includes the two programmable automation controllers (PAC's), the server computer and the client computer.
The interaction of the primary PAC, secondary PAC, SCADA server and the SCADA client together with their communication algorithms are described to provide an overview of the complete control and protection system hardware setup. A description of the purpose of each of these systems is also given. A HPTU simulator that was used for the designing of some of the controllers is introduced together with discussions of the simulated results.

In chapter 5 a detailed introduction of the HPTU equipment protection system is given. The chapter is divided into separate sections. Each section discusses a specific sub-system of the plant. All the operating margins and software control sequences are fully discussed. In each of the separate sections the operator interface is shown and described briefly.

Chapter 6 shows and discusses the operator control and client graphical user interfaces. The two main separate interfaces are displayed on two computers. The operator control interface, which is the primary interface, runs on a server. This interface is used by the operator to control the plant. The secondary client interface is displayed on a personal computer and is used by operators for observation purposes.

The HPTU controllers are illustrated in chapter 6. It shows how the controllers are tested to determine their ability to control the plant throughout any possible disturbances. During the commissioning of the plant the controllers were tested for the first time and the captured data where used in this chapter to illustrate their ability to control.

2. Literature study

2.1 AUTOMATION

This background study is conducted to determine whether an automatic control system is relevant and to be aware of the consequences of automated control systems. At the start of the HPTU project with the first preliminary design the plant would have been a small experimental plant that would have being operated manually. A pure data acquisition system would have done all the data logging although as the requirements for the plant developed the HPTU evolutes into a required automatic control system [22].

2.1.1 History of automation

Early machines were simple machines helped humans produce work more easily by still using physical human effort, as lifting a large weight with a system of pulleys or a lever. Later machines were also able to substitute natural forms of renewable energy, such as wind, tides, or flowing water, for human energy. The sailboat replaced the paddled or oared boat. Still later, early forms of automation were driven by clock type mechanisms or similar devices using some form of artificial power source for instance a wound-up spring, channeled flowing water, or steam which produced some simple, repetitive action, such as moving figures, making music, or playing games. Such early moving devices, featuring human-like figures, were known as automatons and date from perhaps 300 BC). In 1801, the patent was issued for the automated loom using punched cards. [22]

2.1.2 Automation in practice

Automation is present when a function that could be performed by a human operator is performed by a machine that may not be a computer [13].

Automation can be defined as: *The technique of making a system, process, or apparatus operate without human intervention (Dale R).*

Automation of equipment and the improved technology that has resulted from its acceptance ha caused industrial process control to become the fastest growing field in industry today [14].

The most visible part of modern automation can be said to be industrial robotics. Some advantages are repeatability, tighter quality control, and higher efficiency, integration with business systems, increased productivity and reduction of labor. Some disadvantages are high capital requirements, severely decreased flexibility, and increased dependence on maintenance and repair. For example, Japan had to scrap many of its industrial robots when they were found to be incapable of adaptation to substantially changed production requirements and so not necessarily able to justify their high initial costs.

By the middle of the 20th century, automation had existed for many years on a small scale, using simple mechanical devices to automate simple manufacturing tasks. However the concept only became truly practical with the addition (and evolution) of the digital computer, whose flexibility allowed it to drive almost any sort of task. Digital computers with the required combination of speed, computing power, price, and size first started to appear in the 1960s. Before that time, industrial computers were almost exclusively analog computers and hybrid computers. Since then digital computers have taken over control of the vast majority of simple, repetitive tasks, and ever more semi-skilled and skilled tasks, with some food production and inspection being a notable exception. As anonymous so famously remarked, "for very many rapidly changing tasks, it is difficult to replace human beings, who are so easily retrain able within a wide range of tasks and, moreover, so inexpensively produced by unskilled labor [17]."

Specialized hardened computers, referred to as programmable logic controllers (PLCs), are frequently used to synchronize the flow of inputs from (physical) sensors and events with the flow of outputs to actuators and events. This leads to precisely controlled actions that permit a tight control of almost any industrial process.

Human-machine interfaces (HMI) or computer human interfaces (CHI), formerly known as man-machine interfaces, are usually employed to communicate with PLCs and other computers, such as entering and monitoring temperatures or pressures for further automated control or emergency response. Service personnel who monitor and control these interfaces are often referred to as operators.

Greater than fifty percent of the nuclear industry's events which occur are attributable to human performance problems. A significant portion of these events is due to some breakdown in co-ordination among member of the nuclear control room teams. By implementing more and better automation these problems can be reduced [13].

Automation does not always suggest that no operators are required and it is now agreed that in automation systems humans are needed at least for two purposes as the last line of defense in hazardous operations and to improve productivity. During automation it is often possible to design a system to perform in a mathematically optimal way. However it can be shown that humans and machines when combined can sometimes exceed the performance of either, even if machines are fully optimized in a strong mathematically sense [13].

2.1.3 Social issues of automation

Automation raises several important social issues. Among them is automation's impact on employment. Some argue automation leads to *higher* employment. When automation was first introduced, it caused widespread fear. It was thought that the displacement of human workers by computerized systems would lead to severe unemployment but the freeing up of the labor force allowed more people to enter higher skilled jobs, which are typically higher paying.

It appears that automation does devalue labor through its replacement with less-expensive machines; however, the overall effect of this on the workforce as a whole remains unclear. Today automation of the workforce is quite advanced, and continues to advance increasingly more rapidly throughout the world and is encroaching on ever more skilled jobs, yet during the same period the general well-being of most people in the world has increased dramatically.

2.1.4 The current goal of Automation

Currently the purpose of automation has chanced from increasing productivity and reducing costs, to broader issues, such as increasing quality and flexibility in the manufacturing process. The old focus on using automation simply to increase productivity and reduce costs was seen to be *short-sighted, because it is also necessary to provide a skilled workforce who can make* repairs and manage the machinery. Moreover, the initial costs of automation were high and often could not be recovered by the time entirely new manufacturing processes replaced the old. Automation is now often applied primarily to increase quality in the manufacturing process and hazardous operations were the first processes to use automatic operations.

2.1.5 Safety and automation

Since automation is used to make systems more efficient that those using manual control why is the role of human operators a concern? All too frequently accidents and systems failures are ascribed to human error rather than hardware faults, and therefore many engineers try to design out human operators, reduce the possibility of human error and increase productivity and safety [13].

On the other hand, safety issue with automation is that while it is often viewed as a way to minimize human error in a system, increasing the degree and levels of automation also increases the consequences of automated related error. For example, The Three Mile Island nuclear event was largely due to over-reliance on "automated safety" systems. With automation we have machines designed by people with high levels of expertise. These systems operate at speeds well beyond human ability to react although they are operated by people with relatively more limited education.

2.1.6 Teamwork transferred into the environment of human automation

This section will investigate the questions whether it is meaningful to transfer the idea of teamwork into the environment of human-automation within high-risk industrial production systems. Can the human-operator and the automatic system be said to share a set of goals and to seek to facilitate each other's performance?

The Human operators who works with highly automated production systems are fully aware that automatic systems work in accordance with a set of predefined specifications and that the activity of the system, when considered with reference to its underlying mechanisms, in principle is deterministic and predictable. They are also aware that automatic devices function in a different way than the basic process components for example tanks, valves pipe lines, ect. The automatic devices work to achieve something. For example a leaking tank will leak until the leakage is stopped or the tank is empty, where an automatic controller may respond to a tank leakage by starting to compensate for the outflow without human intervention. Thus the operators know that the intelligence and intentions which the automatic system appears to demonstrate reflect the intelligence and intentions of the system designers. This is concluded in the algorithms that the system designers implemented.

Still in many situations operators may nevertheless conceive of a system as having the will of its own. Reports show operators may perceive automatic systems as animated when confused about their activity and that some operators refer to automatic control systems as intelligent. In a study it was found that humans perceive a computer personality in much the same way than a human personality.

The reason why control room operators may sometimes refer to an automatic system as an agent relates to the characteristics of the operational requirements. When deviations occur in a highly automated plant, the operators will have to deal in real time with complex automatic systems, whose problem-solving behaviour resembles the behaviour of humans argues that physical systems, which behave intelligently sometimes are so complex and yet so organized that it is convenient to deal with them as if they have beliefs and desires and were rational when trying to predict their actions [16].

In for example, in a Nuclear power plant the human operator and the automatic system share the same goal and that is to maintain plant safety. This goal has been trained into the operators during education periods and is further contained within the general operating orders and operating procedures. On the other hand the automatic system acquired the goal from the system designer's specifications and the goal is programmed into the algorithms of the control system. The operator and the automatic system then communicate their goals to each other through the graphical user interface which present the situation. The human operator and the automatic control system can be said to share a set of temporary goals in addition to the overall goal. The goals are the operational orders which the operator receives and communicates to the automatic systems, by system entries and by entering the codes and information for automatic start-up of the plant. The automatic system will interpret these entries based on the knowledge contained in its algorithms. For example the start-up of the plant will involve series of part tasks, some that the operator will perform and some that the automatic control system will perform. When conflict arises in the completion of the final goal the agent which are either the operator or the automatic controller, whom detects the fault first will be expected to intervene with corrective actions for example to perform a reactor scram (STOP). In principle the human operator and the automatic control system will strive to facilitate each others activities in order to ensure that the joint performance of human-machine becomes as safe and efficient as possible. The human operator will facilitate the automatic systems performance based on knowledge on how the system works, and how to affect the state of the system using various code entries, acquired during training sessions. On the other hand the automatic system will be designed to support the performance of the human operator by presenting the information and control options, which the operator needs in a manner that he or she can understand.

Cooperative activity can be seen as reflected in the transactions between the human operators and the automatic system within modern industrial production systems. It now seems acceptable to transfer the cooperation concept into the human-automation transactions. However the human operator holds the overall responsibility for the performance outcome and the automatic system is expected to assist the operator. Given the limited cooperation capabilities of present day automation as compared to humans, a realistic approach to design cooperative systems could be to strive to ensure that the operator is provided with readily observable information about the goal and activities of the automatic system in a manner that allows him to manage the automated agent.

The following questions will help in the development and understanding of what an automatic control system should be designed to do.

1. **Relation:** To what extend does the automatic system provide relevant information about its activities?
2. **Quantity:** To what extend does the operator receive relevant information from the automatic system in time to benefit from it?
3. **Manner:** To what extend does the operator immediately understand the information that the automatic system provided?
4. **Quantity (Analogue):** To what extend does the automatic system perform the activities the operator request it to do?
5. **Relation (Analogue):** To what extend does the automatic system perform the activities the operator expect it to do?
6. **Overall:** How would the operator characterize the cooperation between him and the automatic system?

2.2 PROCESS CONTROL

2.2.1 Process control and automation

Process control has undergone significant changes since 1970 when the availability of inexpensive digital technology began a radical change in instrumentation technology. Modern Industrial processes have become now highly integrated with respect to material and energy flows, constrained ever more tightly by quality product specifications and subject to increasingly strict safety and environmental regulations. Pressure associated with increased competition, rapidly changing economic conditions and the need for more flexible yet more complex processes have given process control engineers an expanded role in the design and operation of processing plants. The design of effective, advanced process control and monitoring systems that can meet these demands however, can be quite a challenging undertaking the multitude of fundamental and practical problems that can arise in process control systems and transcend the boundaries of specific applications [14].

2.2.2 *Technical Process infrastructure*

The layer closest to the process installation consists of sensors and actuators. Sensors are devices which convert the physical characteristics of a process such as temperature, intensity of liquid flow, pressure, and revolution speed, into electrical signals.

Actuators are devices which, when driven by electrical signals, can effect the physical world in quite a literal way, by changing temperatures, valve positions, speed of movement or rotation, and so on. Examples of actuators are electric motors, pumps, and electromagnetic valves.

The normalize signals define the boundary between a control system and its environment. They can be connected to a control room (or to the nearest front-end processor) and coupled wit a control system through a process interface, which constitutes the last layer of the interface between a process and a control system.

The normalized signals which input to and output from a process interface fall, in general into two distinct categories: analogue and digital signals.

An analogue signal represents the value of a continuous process variable by the value of its voltage or current. In other words, the variations of a continuous process variable are represented by the amplitude modulation of a continuous signal. Typically, standard ranges of analogue signals in industrial applications are 0...+10 V and 4...20 mA. However the standards are not always kept and the voltage ranges.

It is worth nothing that the 4...20 mA current-based representation is superior to the others. First, because all valid values of a signal require some current flow, the opportunity is given to discover the most frequent cause of failure, i.e., when the circuit is broken and no current flow occurs [5].

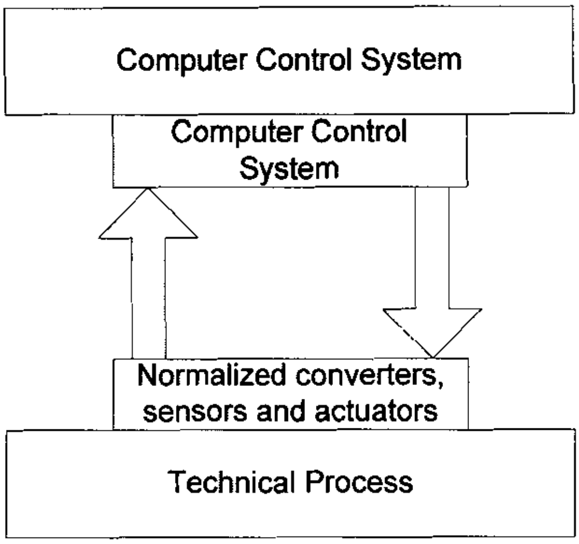


Figure 2.1 Interface between the process and a control system

2.3 PID CONTROL

PID Controlling In this section Proportional Integral Derivative controllers are investigated in detail because it is the algorithm that will be used for all the controllers.

2.3.1 Introduction

Currently, the Proportional-Integral-Derivative (PID) algorithm's the most common control algorithm used in industry. Examples of the conscious application of feedback control ideas have appeared in technology since very early times. Certainly the float-regulator schemes of ancient Greece were notable examples of such ideas. Much later came the automatic direction-setting of windmills, the Watt governor, its derivatives, and so forth. The first third of the 1900s witnessed applications in areas such as automatic ship steering and process control in the chemical industry. However, it was not until during, and immediately after, World War II that the fundamentals became recognized as a new engineering discipline [15].

Often, people use PID to control processes that include heating and cooling systems, fluid level monitoring, flow control, and pressure control. Often they are used as basis of more complex control schemes where couplings between simple control systems are exploited [15]. In PID control, you must specify a process variable and a set point. The process variable is the system parameter you want to control, such as temperature, pressure, or flow rate, and the set point is the desired value for the parameter you are controlling. A PID controller determines a controller output value, such as the heater power or valve position. The controller applies the controller output value to the system, which in turn drives the process variable toward the set point value [10].

2.3.2 PID Algorithms

The PID controller compares the setpoint (*SP*) to the process variable (*PV*) to obtain the error (*e*).

$$e = SP - PV \tag{1}$$

Then the PID controller calculates the controller action, $u(t)$, where Kc is controller gain.

$$u(t) = K_c\left(e + \frac{1}{T_i}\int_0^t edt + T_d\frac{de}{dt}\right) \tag{2}$$

If the error and the controller output have the same range, -100% to 100%, controller gain is the reciprocal of proportional band. T_i is the integral time in minutes, also called the reset time, and T_d is the derivative time in minutes, also called the rate time. The following formula represents the proportional action.

$$u_p(t) = K_c e \tag{3}$$

The following formula represents the integral action.

$$u_I(t) = \frac{K_c}{T_i}\int_0^t edt \tag{4}$$

The following formula represents the derivative action.

$$u_D(t) = K_c T_d\frac{de}{dt} \tag{5}$$

The following formula represents the current error used in calculating proportional, integral, and derivative action.

$$e(k) = (SP - PV_f) \tag{6}$$

Proportional Action is the controller gain times the error, as shown in the following formula.

$$u_P(k)=(K_c * e(k)) \tag{7}$$

Trapezoidal Integration is used to avoid sharp changes in integral action when there is a sudden change in *PV* or *SP*. Use nonlinear adjustment of integral action to counteract overshoot. The larger the error the smaller the integral action, as shown in the following formula:

$$u_I(k)=\frac{K_c}{T_i}\sum_{i=1}^{k}\left[\frac{e(i)+e(i-1)}{2}\right]\Delta t \tag{8}$$

Because of abrupt changes in *SP*, only apply derivative action to the *PV*, not to the error *e*, to avoid derivative kick. The following formula represents the Partial Derivative Action.

$$u_D(k)=-K_c\frac{T_d}{\Delta_t}(PV_f(k)-PV_f(k-1)) \tag{9}$$

Controller output is the summation of the proportional, integral, and derivative action, as shown in the following formula.

$$u(k)=u_P(k)+u_I(k)+u_D(k) \tag{10}$$

The PID functions that will be used use an integral sum correction algorithm that facilitates anti-windup and bump less manual to automatic transfers. Windup occurs at the upper limit of the controller output, for example, 100%. When the error *e* decreases, the controller output decreases, moving out of the windup area. The integral sum correction algorithm prevents abrupt controller output changes when you switch from manual to automatic mode or change any other parameters [25].

2.3.3 Stability

At first sight it would appear that perfect control can be obtained by utilizing a large proportional gain, short integral time and long derivative time. The system will then respond quickly to disturbances, alterations in load and set point changes. Unfortunately life is not that simple, and in any real life system there are limits to the settings of gain Ti and Td beyond which uncontrolled oscillations will occur. Like many engineering systems, the setting of the controller is a compromise between conflicting requirements [10].

Definitions and Performance criteria

Before the sufficiency of a control system can be assessed, a set of performance criteria is usually laid down by production staff. The most common definitions of systems response is illustrated in Figure 2.2.

The rise time is the time taken for the output to go from 10% to 90% of its final value, and is a measure of the speed of response of the system. The time to achieve 50% of the final value is called the delay time. This is a function of, but not the same as, any transit delays in the system.

The first overshoot is usually defined as a percentage of the corresponding set point change, and is indicative of the damping factor achieved by the controller. As the time taken for the system to settle completely after a change in set point is theoretically infinite, a settling band, 'tolerance limit' or maximum error is usually defined. The settling time is the time taken for the system to enter, and remain within, the tolerance limit. An under damped system may have a better settling time than a critically damped system if the first overshoot is just within the settling band. The shaded area is the integral of the error and this can also be used as an index of performance. Stable systems with integral action control have error areas that converge to a finite value [10].

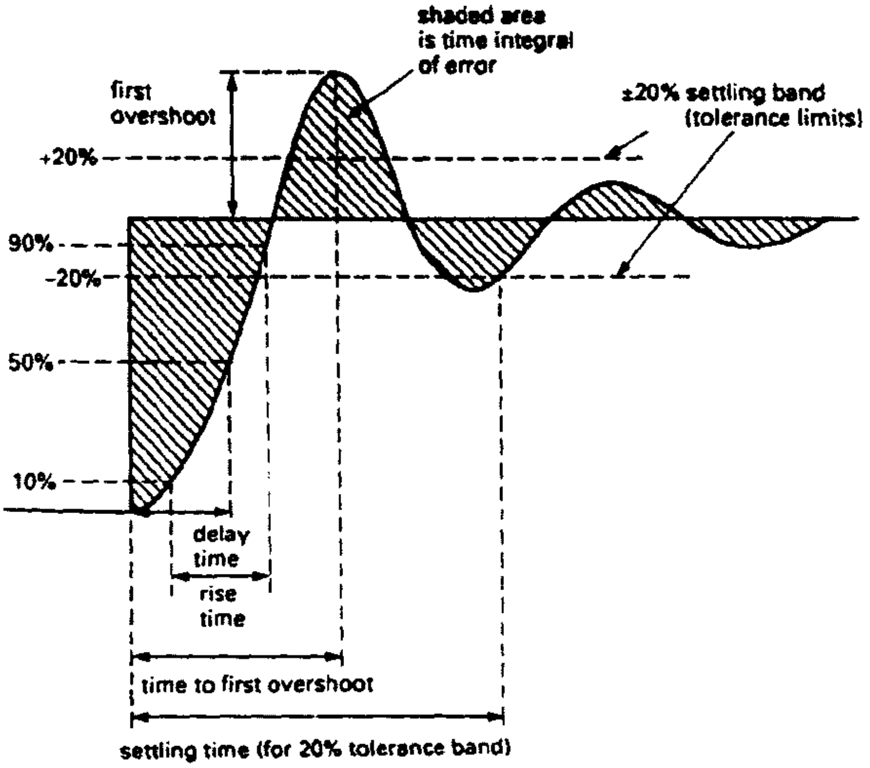


Figure 2.2: Common definitions of systems response

2.3.4 Scheduling Controllers

Many loops have properties which change under the influence of some measurable outside variable. The gain of a flow control valve, (i.e. the change in flow for change in valve position) varies considerably over the stroke of a valve.

A scheduling controller has a built-in look up table of control parameters (gain, filtering, integral time etc.) and the appropriate values selected for the measured plant conditions. The controller will then adjust the PID constants as predetermined for each operating condition [25].

2.3.5 Tuning Algorithms

The following controller tuning procedures are based on the work of Ziegler and Nichols, the developers of the Quarter-Decay Ratio tuning techniques derived from a combination of theory and empirical observations (Corripio 1990). For different processes, one method might be easier or more accurate than another [17].

Closed Loop (Ultimate Gain) Tuning Procedure

Although the closed-loop (ultimate gain) tuning procedure is very accurate, the process must be in steady-state oscillation. In order to perform closed-loop tuning the following steps needs to be followed:

1. Set both the **derivative time** and the **integral time** on the PID controller to 0.
2. Carefully increase the **proportional gain** (k_c) in small increments. Make a small change in **SP** to disturb the loop after each increment. As k_c is increased, the value of **PV** should begin to oscillate. Keep making changes until the oscillation is sustained, neither growing nor decaying over time.
3. Record the controller **proportional band** (*PBu*) as a percentage value, where $PBu = \frac{100}{K_c}$.
4. Record the period of oscillation (T_u) in minutes.
5. Multiply the measured values by the factors shown in
6. Table 1 and enter the new tuning parameters into your controller.

Table 1 provides the proper values for a quarter-decay ratio. In order to reduce the overshoot, increase the gain k_c [25].

Table 1: Closed loop Quarter Decay Ration Values

Controller	PB (%)	Reset (Minutes)	Rate (Minutes)
P	$2 \times PB$		
PI	$2.22 \times PB$	$0.83 \times T_u$	
PID	$1.67 \times PB$	$0.5 \times T_u$	$0.125 \times T_u$

Open Loop Step Test Tuning Procedures

The open-loop (step test) tuning procedure assumes that you can model any process as a first-order lag and a pure dead time. This method requires more analysis than the closed-loop tuning procedure, but your process does not need to reach sustained oscillation. Therefore, the open-loop tuning procedure might be quicker and more reliable for many processes. Observe the output and the process variable on a strip chart that shows time on the x-axis. Complete the following steps to perform the open-loop tuning procedure.

1. Put the controller in a manual mode, which will allow a change in the controller output directly, set the output to a nominal operating value. For example if it is a heater system set the heater to its process designed power (KW). Allow the process variable to settle completely.
2. Make a step change in the output.
3. Wait for the process variable to settle. From the data acquired, determine the values as derived from the sample displayed in Figure 2.3.

The variables represent the following values:

- T_d—Dead time in minutes
- T—Time constant in minutes
- K—Process gain

$$\Pr ocess\_Gain = \frac{Change\_in\_Output}{Change\_in\_PV} \tag{12}$$

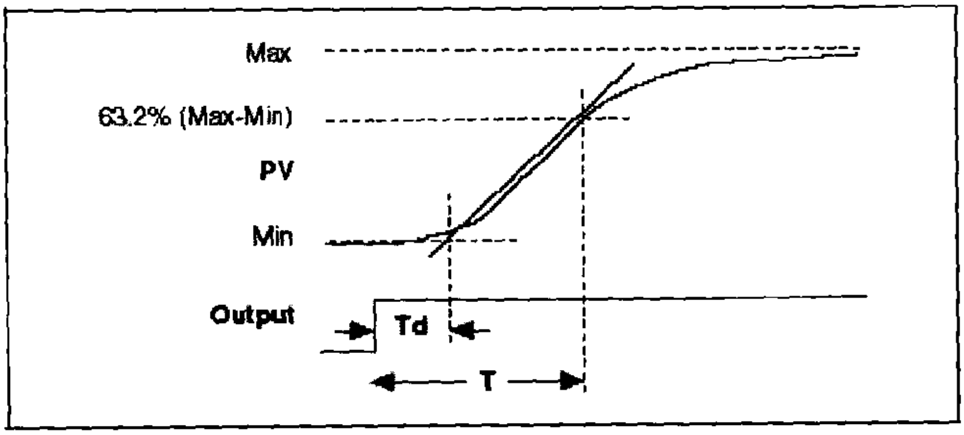


Figure 2.3: Experimental step test data

4. Multiply the measured values by the factors shown in Table 2 [25].

Table 2: Open loop Quarter Decay Ration Values

Controller	PB (percent)	Reset (minutes)	Rate (minutes)
P	$100\frac{KT_d}{T}$	—	—
PI	$110\frac{KT_d}{T}$	$3.33T_d$	—
PID	$80\frac{KT_d}{T}$	$2.00T_d$	$0.50T_d$

2.4 INDUSTRIAL GRAPHICAL USER INTERFACES

This section focus on the development of graphical user interfaces.

2.4.1 Background

The concept of personal computing has been pursued seriously since the late 1970s. However, the usage became widespread when the Personal Computer (PC) became more available and affordable [12]. The deployment of modern automation technologies in process control as well as in the enhancement of production processes promises considerable savings in actual costs and overheads. The operator is to some extent alienated from the process by automation systems in combination with computer-based visualization of information in centralized control rooms. Sensory experiences like tactile feedback by which the operator could deduce information about the status of and changes in the process are missing. Thus the process visualizations displayed on-screen are the only remaining access to the process. The operators are dependent on the early recognition of differences in the usual production process, which they have to detect only by means of process visualization, and furthermore must react to new, in critical cases mainly unknown situations. Visibility of system status allows the user to observe the internal state of the system [19]. Relevant process data have to be directly available to the operator eliminating the need for expending cognitive resources. Display formats need to be adjusted to human perception and information reception, as well as to the human way of problem solving and planning. The user interface is a critical part of any computer system and merits careful evaluation before it is released to users. The user interface is the interface between a human operator and the computer and is thus also referred to a Human Computer Interface (HCI) [20].

The operator's actions of monitoring and judging in both the control of technical production processes and other complex systems arc defined by the comparison of the system's present condition and the corresponding goal state. In case of any deviation from the goal state the operator has to intervene, so as to return the system to the desired state. In case of deviation from defined goal values, alternatives for action shall be made easily recognizable by an appropriate mode of presentation to ensure fast return of the sub process in question to a safe and productive state [21].

2.4.2 Designing Graphical User interfaces

Lewis (1992) indicates that developers should concentrate on how displays look, how they are controlled, and the quality of engineering that goes into them. One way to evaluate interfaces is to check them for compliance with standards and guidelines. However, this is not a simple or a fail-safe process. First, it is often difficult for designers to follow guidelines in the initial design phase [20].

Criteria for a successful HCI:

1. **Visibility of system:** It is important for the user to be able to status observe the internal state of the system through the HCI. This can be achieved by the system providing correct feedback within a reasonable time.
2. **Match between systems**: An HCI which uses real-world metaphors is and the real world easier to learn and understand. This will assist a user in figuring out how to successfully perform tasks.
3. **User control and freedom:** System functions are often chosen by mistake. The user will then need a clearly marked exit path.
4. **Consistency and standards:** Words, situations and actions need to be consistent and have the same meaning. A list of reserved words can assist in this area.
5. **Error prevention:** It is obviously best to prevent errors in the first place through careful design.
6. **Recognition rather:** The user should not have to remember than recall information from one session to another. Rather, the user should be able to 'recognise' what is happening.
7. **Flexibility and efficiency of use**: The system should be efficient and flexible to use. Productivity should be increased as a user learns a system. The system should not control the user; rather, the user should dictate which events will occur.

8. **Aesthetic and minimalist design:** Information which is irrelevant should not be displayed. The user should not be bombarded with information and options [6]

2.4.3 Verbal and Visual feedback

The most common way for automatic control systems to cooperate with operators are via the graphical user interface. The grade of cooperation between the operator and the automatic system can dramatically increase by increasing the quality of the feedback from the automatic control system to the operator.

In Nuclear power plants, an operator is often engaged in dual or multitasks. For example an operator can be occupied with a particular operation while monitoring the over all plant operation. The effect of negative interferences between multitasking can be reduced dramatically by introducing a combination of verbal and visual feedback in the automatic control system [16]. Verbal feedback can effectively be used during the initiating, stopping and deviations from normal operation in the automatic system. By using male and female voices in specific control areas the operator can clearly distinguish to which circuit the feedback was related without even looking at the control system.

2.4.4 Conventional interfaces vs. improved automatic systems interfaces

The Table 3 illustrate the differences between conventional and modern human-machine interfaces.

Table 3: Conventional interfaces vs. improved interfaces

	Conventional Interfaces	Improved automatic system interfaces
1.	No explicit representation of the key automation devices on the overview display	Representation of the key automatic devices on the overview display
2.	No verbal feedback	Verbal feedback
3.	No dedicated controller displays available, instead only overall activity of the controller	Dedicated displays with appropriate automatic controller feedback
4.	Logic diagrams available mainly on paper	Computer based logic diagrams available indicating the exact location of the automatic control system

Each of the above mentioned listings will now be discussed.

1. The representation of key automatic devices on an overview display enables the operator to immediately determine the state of the plant without switching between user interfaces or windows. Any fault condition can easily and immediately be detected which give the operator a time advantage to react on the fault or to determine if the automatic system reacted correctly.

2. Verbal feedback informs the operator of main plant states and deviations without the involvement of the graphical user interface. The operator could have being distracted from the graphical user interface for a small time although by using verbal feedback the operator can be informed of deviations in the plant activities. The operator then immediately knows appropriate information without struggling through user interface windows to acquire information regarding an alarm or deviation.

3. Dedicated controller displays for example, enable the operator to spot a controller struggling to control the system. The protection systems at that point are not able to determine any plant failure because the operating parameters are still maintainable by the controllers although this can be the start of a plant or component failure.

4. As discussed previously the operators sometimes refer to automatic systems having the mind of its own and this mostly occurs when the operator is not well informed of what the automatic system is currently doing or when operators are not familiar with the system. The confusing situation can be eliminated by supplying the operator with computer based logic diagrams indicating the exact state of the automatic control system.

Human-machine interface design guidelines stress that displays should be as simple as possible for example the lowest number of possible lines and objects should be applied. Although it was found that higher complexity of user interfaces does not reduce the ability of operators to benefit from the information provided. Operators ability to detect critical cues was higher in the improved automatic system interfaces as compared to conventional operating systems. It was also found that there is improved cooperation quality which increased the ability of the operators to detect critical plant occurrences. A balance needs to be struck by providing enough information for a first-time user while at the same time not providing too much information for an experienced user. Irrelevant information should not be displayed [19].

The following points are guidelines for the development of human-machines interfaces:

- The activity of the key automatic devices should be represented in overview displays

- The graphical representation should combine the key automatic devices and the associated plant components into meaningful presentation
- Verbal feedback should be associated with the key automatic devices activity to generally improve the operators ability to monitor the systems performance and to facilitate identification of deviations
- Verbal feedback should be associated with graphical feedback
- Verbal feedback should be short concise and delivered in a formal manner and should be designed to be as specific as possible
- Verbal feedback associated with different sub-systems should use a male and female voice.
- Hints using basic verbal feedback:
    - The key automation programs should inform on program initiation, completion and when deviations occur
    - Automatic programs that routinely calls upon other programs should inform when they start up and then only when deviations occur when it calls on other programs

2.4.5 SCADA Security

The increasing interconnectivity of SCADA (Supervisory Control and Data Acquisition) networks has exposed them to a wide range of network security problems. If processes are monitored and controlled by devices connected over the SCADA network then a malicious attack over the SCADA network has the potential to cause significant damage to the plant.

Therefore, security of SCADA networks has become a prime concern [2]. Security is usually not a primary activity for computer users, so their experience with security features needs to be pleasant and satisfying, otherwise they may neglect the security of their system [6].

Process control and SCADA systems are making use of, and becoming progressively more reliant on standard IT technologies. These technologies, such as Microsoft Windows, TCP/IP, web browsers and increasingly, wireless technologies, are replacing conventional proprietary technologies and further enabling the bespoke process control systems to be replaced with off the shelf software.

Firstly, process control systems were traditionally closed systems designed for functionality, safety and reliability where the prime concern was one of physical security. Increased connectivity via standard IT technologies has exposed them to new threats which they are ill equipped to deal with (for example, worms, viruses and hackers). As these processes control networks continue to increase in numbers, expand and connect so the risks to the process control systems from electronic threats continue to escalate.

The widely used standards and solutions for securing IT systems are often inappropriate for the process control environment. Although process control systems are now frequently based on standard IT technologies, their operational environments differ significantly from the corporate IT environment. While some standard security tools and techniques can be used to protect process control systems, they may need careful application or tailoring. Other security measures may be completely inappropriate or not available for use in a control environment [23].

2.4.6 Menu selection for user interfaces

Designers are faced with more and more difficult questions about how to design menus. Researchers are asking more probing questions about the relationship between design and performance. Finally, users are demanding more power, control and access to a wide variety of applications that are more consistent, intuitive and require less training.

Menu selection engages most aspects of human information processing. It involves visual scan and search, reading and comprehension, judgment and decision making, response selection and production, and over all that, thinking and task to perform.

The user must read and comprehend the alternatives, decide on the appropriate selection, implement the choice by making a response, and finally evaluate the outcome of the choice. However, over the entire component processes there must be a driving strategy or plan.

And finally how should menu selection systems differ in use by novice and expert users? The answer to these questions and many others are crucial in helping to determine how to design a usable and efficient human/computer interface [11].

2.5 PBMM (PEBBLE BED MICRO MODEL) CONTROL SYSTEM

This section will focus on the basic design of a previous developed PBMR demonstration plant namely the PBMM (Pebble Bed Micro Model)

2.5.1 Background on the PBMM

The PBMM are based on the same concept than the previous Pebble bed modular reactor design of PBMR (Pty) LTD. This plant was built in the same building in which the HPTU was build at the North-West University Potchefstroom.

A photo of the PBMM is shown in Figure 2.4

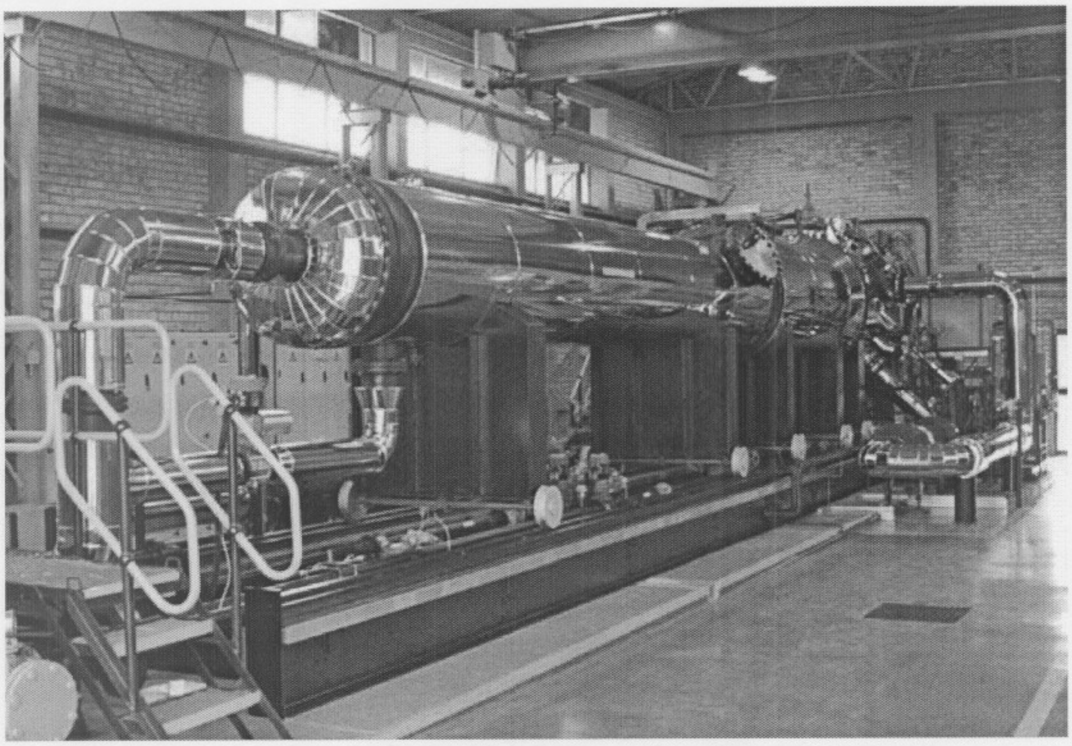


Figure 2.4: Pebble Bed Micro Model

2.5.2 PBMM Operating Control System and backup Protection System

The PBMM operating control system and the backup equipment protection system are shown in Figure 2.5. The OCS of the PBMM consists of a PLC and three control room computers. The PLC's main purpose is to protect the plant through unsafe conditions. The Control room computers interact with the plant via the PLC and are thus used to communicate measured values to the operator and to actuate the plants actuators as required from the operator. The three control room computers each have a different task and contain different control software. They are:

- Adroit SCADA system
- Unac (ProcessACT) control system
- I/O Interface

The PBMM backup protection system is a relay driven system which operates completely separate from the OCS. This backup system is used when the PLC doesn't recognise an unsafe condition or when the PLC malfunctions. This system has a higher priority than the OCS and will make sure that the plant is at all times protected. Each of the relays measures a single sensor and is set to trip if a configured parameter value is reached. The relays are connected to the power supply of electrical devices and will disengage the power during a trip. The PBMM is controlled via a series of valves. Some of these critical valves have a safe return position and will go to a safe position, either open or closed, when the instrument air supply fades. These valves can be forced into their safe position by the backup protection system [18].

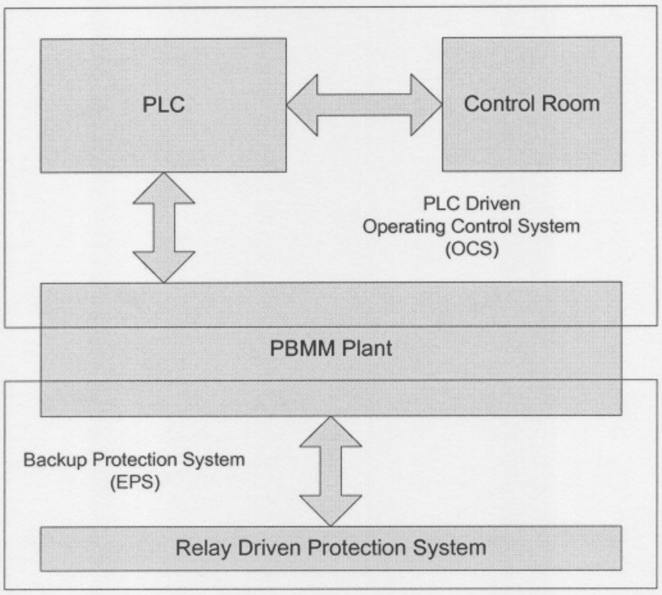


Figure 2.5: PBMM Operating Control system and Equipment Protection system

2.5.3 Adroit SCADA System

The operator uses the Adroit user interface to operate and control the PBMM. Adroit is specifically developed for SCADA (Supervisory Control and Data Acquisition) and graphical user interface purposes. The PBMM Adroit project also enables the user or operator to reads and change inputs into the system and is also responsible for all the data logging of all measured signals. The PBMM is fully controlled by the operator through the Adroit SCADA system.

2.5.4 UNAC (PROCESSACT) Control system

UNAC (ProcessAct) is typically used in conjunction with other control systems to add an environment to deal with challenging control problems. In this application it integrates into a PLC and SCADA systems to provide an extremely flexible and powerful total control solution and allow users to view systems and control loops in block diagram form. UNAC is similar to MATLAB Simulink with the difference that it was developed for industrial use with more stability. UNAC also has the ability to be manipulated during runtime which makes it a powerful control environment for systems that run in real time. In the case of the PBMM UNAC contains all the PID and logical control systems which is accessed by the operator via Adroit. UNAC then updates the OPC server from where the PLC acquires information to manipulate the PBMM. Refer to Appendix B section (11.3) for more background regarding OPC servers.

2.5.5 I/O INTERFACE

The I/O interface forms the interface between the PLC and the control room PCs. The I/O INTERFACE houses an I/Omap that manages the flow of data between the PLC and the control room. The I/Omap is accessible via the SIXNET OPC server on the I/O INTERFACE PC. The SIXNET OPC server allows any Windows application with an OPC client to access the variables in the SIXNET I/Omap.

2.5.6 PBMM control system remarks

The PBMM control system is a rugged system which has been in operation for the last four years. The protection systems of this plant were well designed and covered any unwanted plant operation, in fact there is no incident where the control system failed in its responsibility. There is however a few disadvantages in this control and protection system. They are:

- The control room is responsible for the interaction between the operator and the plant. The problem is that there are three normal personal computers which are dependent on each other. The chance is therefore three times higher for malfunction. If any of the three computers have an operating system failure or any malfunction, the link is broken between the plant and the operator.
- Two different operating systems is used which makes maintenance and problem identification very difficult.
- Three different operating control software packages are used. Two of the programs are from distant nationalities making after sales support virtually nonexisting
- The control engineer had to be trained in three software programs.

- The costs were high for the software.

These conditions can be prevented in the design of a modern control system such as the HPTU' control system.

3. HPTU Control Philosophy

This section will introduce the Modes and States of the HPTU and the control and protection requirements of the plant are discussed in concept.

3.1 GENERAL TERMINOLOGY

The following definitions are made to clarify the terminology:

Modes: Modes are defined as groupings of common function, logic and purpose. They are hierarchical in nature and have as goal the systematic reduction of overall plant function to simpler unambiguous logical constructs. A specific set of states will have a fixed value for any given mode. Other states may vary within a limited range for any particular mode.

Mode and state diagrams: These are event-driven logic diagrams that couple mode and states in an unambiguous fashion. Their goal is to describe the plant so that it is clear which events would trigger which functions. These functions are then allocated to operators, computer software and hardware components. Thus the mode and state diagrams encompass both the plant automation system and human interaction by plant operators.

States: States are plant characteristics or parameters of predetermined value or range. State definitions can be common to many modes of operation.

Transition Sequences: Normal operations taking the plant from one mode and state to the next.

Transients: Mode and state transition sequences that should be avoided, but the plant must still be designed to accommodate these transients. The transients result due to faults that arise externally or internally to the plant.

Fault Modes: Abnormal mode entered due to some fault condition in the plant. A specific fault mode transition sequence is associated with each abnormal mode. These transition sequences will be less frequent than transients, and will also be of a more complex nature. The rectification of a fault mode may require operator intervention.

The following section will discuss the control philosophy of the HPTU, with the Figure 3.1 indicating the proposed system conditions.

The following devices were considered to be parts of the automatic system:

Interlocks: They check the status of the specific plant components before a command is executed.

Limitations: It ensure that the predefined standard operating values are not exceeded.

Protections: Ensure that predefined safety critical values are not exceeded.

Controllers: Regulate, for example the temperature, the pressure and flow, in specific plant components to ensure that the set-point thresholds are not exceeded.

Automatic programs: Act to achieve a certain goal that involves a state change, e.g. to start-up or shutdown the plant. Automatic programs will switch on and off groups of components in a predefined sequence. In each sequence a set of commands will be initiated as soon as the pre-conditions for the commands are fulfilled. The commands may involve, e.g. the connection of a controller, or the opening of a valve. The group of components manipulated by automatic programs may contain interlocks, limitations, protections, and controllers, and they may call upon other automatic programs.

3.2 HPTU MODES AND STATES

The classical approach to the implementation of a control system is based on the concept of separate control loops. The key point of concept is an attempt to decompose the system into a set of independent clusters (loops), each of which is related to a single state variable and a single control variable. The HPTU operating control conditions was then decomposed into separate operating modes and states. This is the most basic description of the HPTU operating and control requirements.

The mode and state diagram of the HPTU is shown in Figure 3.1

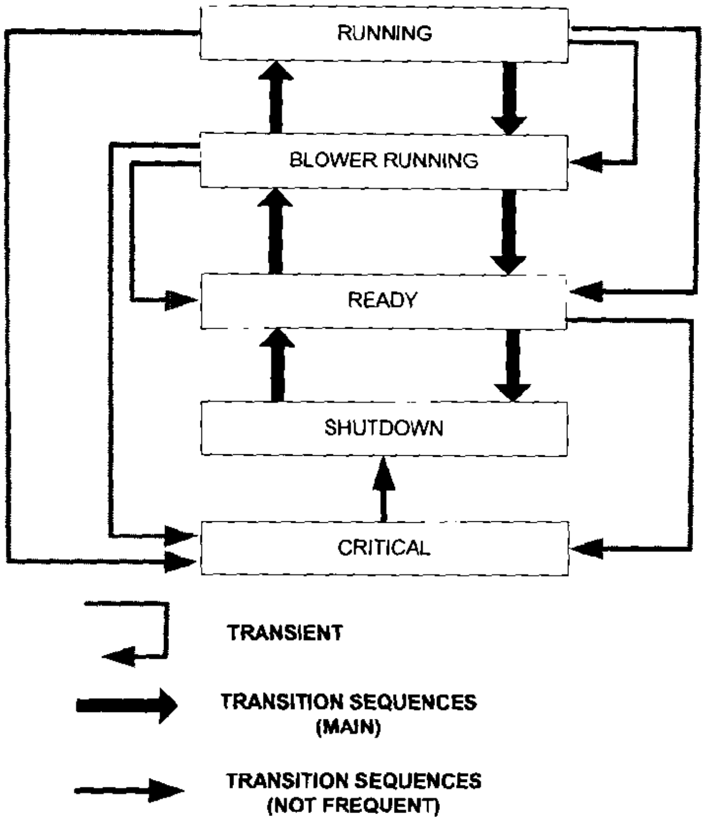


Figure 3.1: HPTU Modes & States

The transition sequences will mainly be used during the operation of the HPTU. Transients are unwanted but the HPTU control system is designed to accommodate any possible transient situation. Transition sequences can occur from the SHUTDOWN mode to the RUNNING mode and back. A less frequent transition can occur from the CRITICAL mode to the SHUTDOWN mode.

The Modes & States of the HPTU are as follows:

- **SHUTDOWN**
  - HEATER → OFF
  - CWS (Cooling Water System) → OFF
  - BLOWER → OFF
  - System → Barometric Pressure
  - Ventilation Fans → OFF
- **READY**
  - HEATER → OFF

  - CWS → ON
  - BLOWER → OFF
  - System → Pressurised
  - Ventilation Fans → ON

- **BLOWER RUNNING**
  - HEATER → OFF
  - CWS → ON
  - BLOWER → ON
  - System → Pressurised
  - Ventilation Fans → ON

- **RUNNING**
  - HEATER → ON
  - CWS → ON
  - BLOWER → ON
  - System → Pressurised
  - Ventilation Fans → ON

- **CRITICAL**
  - BUILDING OXYGEN CONTENT → LOW-LOW
  - VESSEL PRESSURE → HIGH-HIGH
  - Emergency STOP button is pushed

A **TRANSIENT** to the READY mode occurs if:

  - HEATER → TRIP or
  - BLOWER → FAULT or
  - CWS → FAULT

A **TRANSIENT** to the CRITICAL mode occurs if the CRITICAL mode conditions are met.

3.3 CONTROL REQUIREMENTS

The control philosophy for the HPTU was derived with the following order of importance as guideline (Also see Figure 3.2: Control Arrangement):

a. Operator safety

b. Equipment protection
c. Process or sub-system control

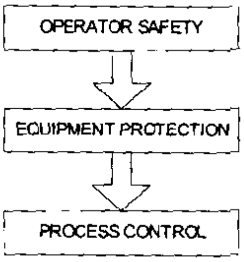


Figure 3.2: Control Arrangement

3.3.1 Operator Safety

Equipment protection and alarms need to protect the operator against the following unsafe conditions:

a. Abnormal high gas pressures in the system
b. Low oxygen in the building as a result of nitrogen leakage

3.3.1.1 Abnormal high pressures in the HPTU system

The following backup systems will be in place to protect the gas loop against any possible over pressure:

- Pressure controller system protects the system against high pressures.
- If the pressure controller fails or the pressure blow-off control valve fails, the pressure relief valves PRV200, PRV212 and PRV230 protects the system against over pressure.

3.3.1.2 Low oxygen content in building

The following safety systems will be in place to protect the operator against low oxygen levels as a result of nitrogen leakage:

- Oxygen analyzers will be installed in the building in possible high risk areas. The analyzers will be connected to the PAC as well as a separate warning system.

Interlocks will be implemented for the ventilation fans to be ON before the auxiliary system can supply gas to the building.

3.3.2 Equipment Protection

3.3.2.1 HPTU Systems

The following HPTU systems need to have equipment protection:

a. Inline Heater System (HS)
b. Braiding Heater System (BHS)
c. Blower System (BS)
d. Heat Exchanger Cooling Water System (HXCWS)
e. Nitrogen Inventory Control System (ICS)
f. Convection Coefficient Test Section (CCTS)
g. Near Wall Test Section (NWTS)
h. Vacuum Pump System (VPS)

3.3.3 Process Control

Process control requirements for the HPTU are as follows:

a. Inline-heater system gas temperature control
b. Braiding loop gas temperature control
c. Braiding loop gas flow control
d. Heat exchanger gas outlet temperature control
e. System pressure control
f. CCTS sphere surface temperature control
g. NWTS heated strips temperature control
h. Main loop gas flow control

The Equipment protection and process control is discussed in detail in section 1. Protection and Control will be handled separately for each sub-system.

4. HPTU Operating Control System (OCS) and Equipment Protection System (EPS) Setup

This section discusses the design and requirements of the operating control system and the backup protection system. The purposes of the different PAC (Programmable automation controller) are each discussed in detail together with the configuration of the control room computers.

The control system is split into the operational control system (OCS) and the equipment protection system (EPS). The OCS contains all the software which is necessary to control and protect the HPTU throughout all running and operating conditions. The OCS physically controls the plant by manipulating the actuators of the plant to perform the required functions. The EPS is a backup protection system for the OCS to ensure that critical plant operating parameters are not exceeded. These two control systems are completely separate and have the capability of acting independently from each other. The EPS is responsible for ensuring the safety of the HPTU under running conditions. Figure 4.1 shows a high level functional layout of the system as described.

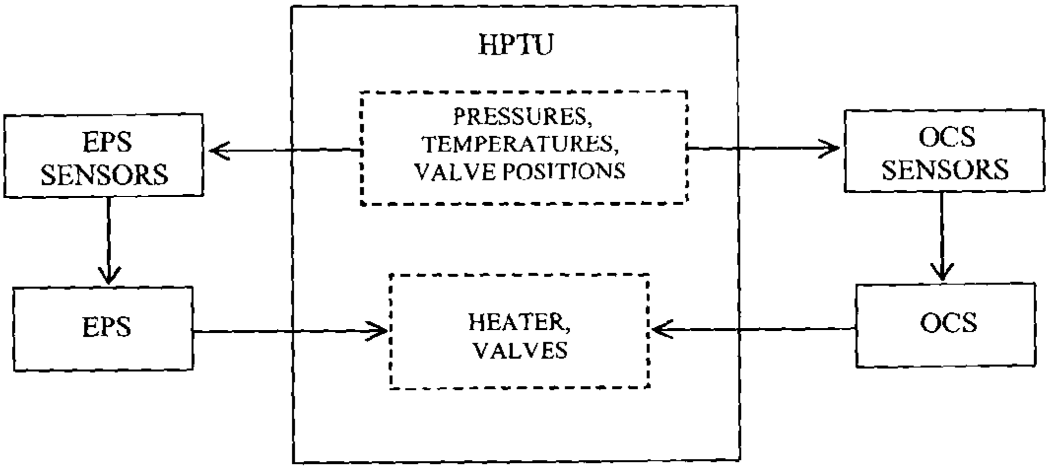


Figure 4.1: HPTU OCS and EPS Interaction

As shown the OCS and the EPS have the capability of acting independently. The controls of the heater and valves are configured in such a way that should an EPS trip occur, the EPS can reset the valve or heater state which effectively shuts down the plant.

4.1 HPTU OCS

The operational control system (OCS) is the main plant controller. The controller is implemented as a digital control system constituting one server and at this point one personnel computer with the appropriate software and a Programmable Automation Controller (PAC) interconnected with appropriate communications protocol. The HPTU uses a new more advanced type of PLC (Programmable Logic Controller) product and is more referred to as a PAC (Programmable Automation controller). For more information of the type of PAC refer to section 11.1 appendix B.

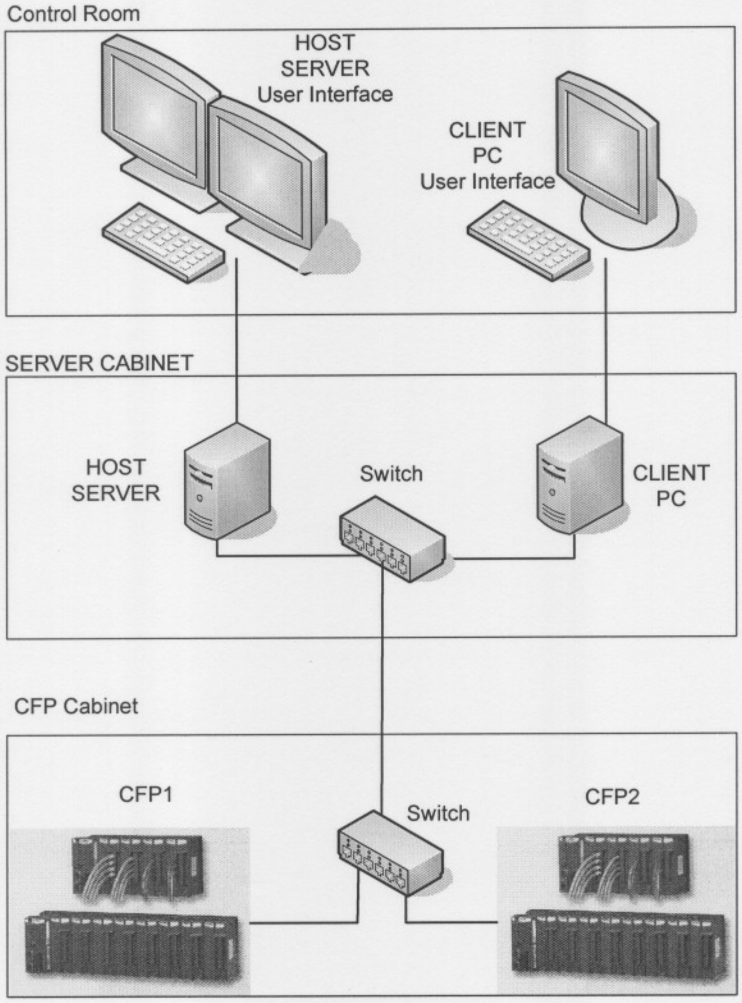


Figure 4.2: HPTU OCS Hardware setup

The OCS hardware setup is shown in Figure 4.2. The operator computers are located in a control room and the two PAC units on the plant floor next to the HPTU plant. The HOST server has a double view monitor system which is a much more convenient and easy to use operator plant interface system when compared to two separate computers operated by one operator. The server and client computers are installed in an air cooled server cabinet inside the control room. The two operator computers and the two PAC units are connected to an Ethernet network.

The HPTU OCS control system is developed in LABVIEW 7.1 and LABVIEW REALTIME. Labview 7.1 is used on the HOST server and Client computers and Labview Real time is used on the HPTU PAC units.

The HPTU OCS is currently configured on four hardware systems, which are:

- HPTU01, (PAC)
- HPTU02, (PAC)
- SCADA HOST Server (Control room)
- SCADA CLIENT Computer (Control room)

The four hardware systems works together to form the complete HPTU control system.

These systems are physically separated thus it was necessary to develop communication systems to merge them together as one control system. The flow diagram illustrating the communication algorithm of the HPTU OCS is shown in Figure 4.3. The arrows indicate the data communication paths and directions.

The secondary PAC unit perform thermocouple measurements which are sent to the HOST sever. This unit communicate a few selected thermocouple measurements directly to the primary PAC controller which contains all the HPTU control and protection software. This unit obtain and send required data to the SCADA which is located on the HOST SERVER. The operator sends commands and set-points through the SCADA to the primary PAC. As illustrated in figure Figure 4.3 all the measurement data passes through the HOST SERVER from where it is accessible to the CLIENT PC. The control system is developed in order to accommodate any amount of CLIENTS. The OCS hardware setup is illustrated in Figure 4.3. Detail information regarding the hardware systems mentioned is discussed in section 4.2-4.6

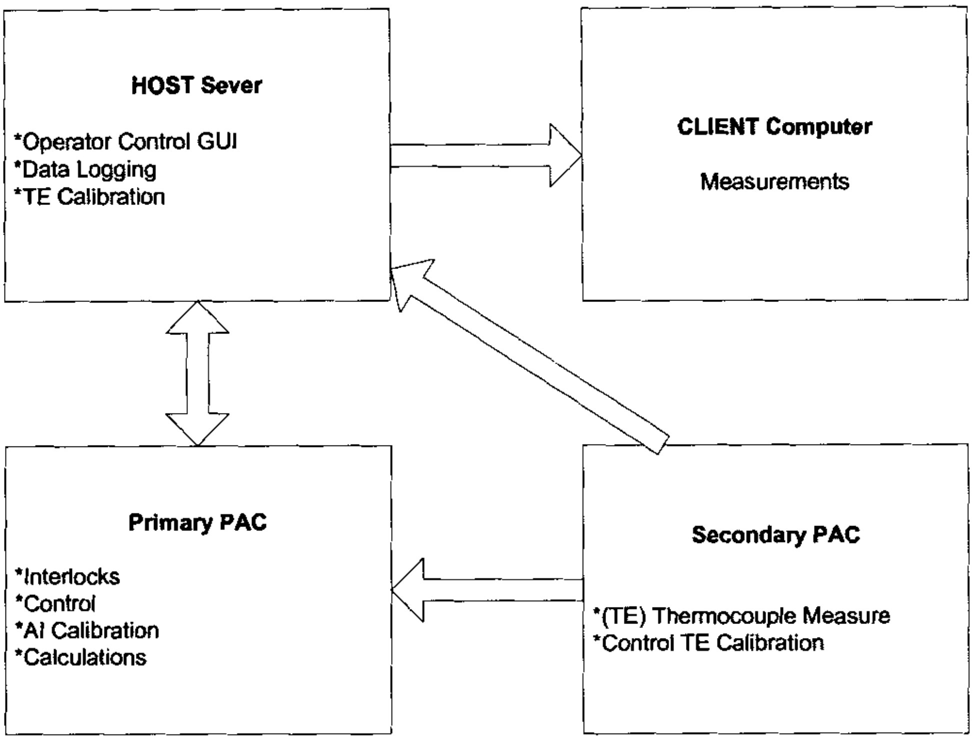


Figure 4.3: HPTU OCS (Operating control system) setup

4.2 HPTU EPS

The EPS (Equipment Protection system) are implemented in areas were additional backup protection where required. This will ensure that any possible PAC failure is covered in the HPTU protection system. The EPS works completely separate from the OCS. The EPS consists of separate components each responsible for the backup protection of its own hardware component. The units are each programmed manually via its own local interface. The units are basically programmable relays which work together. If the unit detects a fault condition it will disengage the specific hardware components main isolator breaker. The breakers are also fail open which imply that if a wire is damaged and the connection is lost the breakers will simply open which will also result the main breaker to disengage. The EPS is constructed into its own separate enclosure located next to the PAC enclosure. This makes it a very rugged and absolute stable system. In various situations more than one EPS unit is implemented which use different references or measurements to protect a single hardware component. The EPS is implemented on the following hardware:

- Inline Heater system
- Braiding Heater system
- CCTS

- NWTS

4.2.1 Inline Heater EPS

There are three EPS units implemented to protect the Inline heater. The only two scenarios where this heater could be damaged is when the heated fluid's temperature is to high or when inadequate nitrogen or air flow rate is present to absorb the heater element energy and to transfer the heat past the nearest temperature sensor. The two scenarios are thus:

- Sufficient flow rate is present although the temperature of the fluid is too high. The restriction is that the 55 bar piping has a temperature limit at these high pressures.
- Inadequate flow rate is present which will lead to incorrect temperature measurement and over heating of the heater elements. This will also result in the localised heating of the piping as a result of heat radiation.

Two of the EPS units are connected to the differential transmitters over the orifice measuring station and are set to trip the heater if a minimum differential pressure over the orifices is present. The other unit is connected to the nearest temperature which will disengage the main breaker at over temperature. The configuration of the units is wired in order to trip the heater if both the orifice differential transmitters have a low signal or when the gas outlet temperature is too high. The reason for this is that at some operating conditions a random orifice measuring station will be closed.

4.2.2 Braiding Heater EPS

There are two EPS units protecting this system. The braiding heater is the same type of heater system than the inline heater and that is the reason that it refer to the same protecting principles. The flow rate of the braiding loop is measured via a mass flow transmitter. The one unit monitors the braiding flow rate measurement directly and the other one the heater outlet temperature. They will disengage the main breaker if any of them measures a fault condition.

4.3 PRIMARY HPTU PAC

This PAC unit is responsible for most of the HPTU control which is:

1. HPTU Machinery and Components(Interlocks and Protections)
2. Control Systems (PI and PID control algorithms)
3. Analogue Inputs (AI) Calibration
4. Calculations

4.3.1 HPTU Machinery and Components (Interlocks and Protections)

The HPTU systems controllers are automatic programs that manage each of the HPTU machinery for example the heat exchanger cooling water system manage the water pump and cooling tower. These system controllers use operating sequences which guide them throughout the controlling process. Interlocks and Protections are incorporated in the operating sequences. They determine if it is safe to move from on sequence state to another. Refer to section 3.3.2 for a list of HPTU systems. The operating sequences, interlocks and protections are introduced in section 1. Almost all the HPTU interlock and protections measurements are done in the primary PAC unit.

The HPTU consists of the following machines:

- E201 - Blower
- E205 - Braiding heater
- E204 - Inline Heater
- Sphere Heaters
- E704 - Cooling tower Fan
- E206 - Cooling Water Pump
- E219 - Strip Heater 1
- E220 - Strip Heater 2

Each Machine has a separate control program which:

- Select between Engineer control or automatic control mode.
    - The Engineer control mode is used by an authenticated Engineer to override the automatic control and start or stop the machine via the Machines window in the SCADA. (refer to MACHINES WINDOW section 6.1.2)
    - Automatic control will always be used during HPTU operation. Automatic control implies that the machines are controlled by a sub-system program. For example the water pump and the cooling tower fan are controlled by the cooling water system.
- Check the machine running status from the contactor in the local electrical starter or actuate the contactor. The contactor supply a positive feedback to the PAC unit when it is actuated which implies that the machine is supplied with electrical power. The contactor also protects the load from over currents.
- Indicate a fault if the local starter trip during the ON and STARTING mode.

Figure 4.4. Illustrate how the automatic systems interact with the HPTU machines. The machine control sequences are separate programs that are externally controlled by the HPTU systems equipment protection programs. The systems programs send and receive data from the machines programs at all times during operation. For example if the cooling water pump trip as a result of a local motor problem, overload or short circuit, the pump machine program will inform the HXCWS (Heat exchanger cooling water system) that a pump fault had occurred. The HXCWS will then act automatically to control the system into a safe mode. All the information during the process will be communicated to the SCADA system which will inform the operator of the state of the system. The HPTU systems act automatically to protect and guide the machines in order to protect the plant.

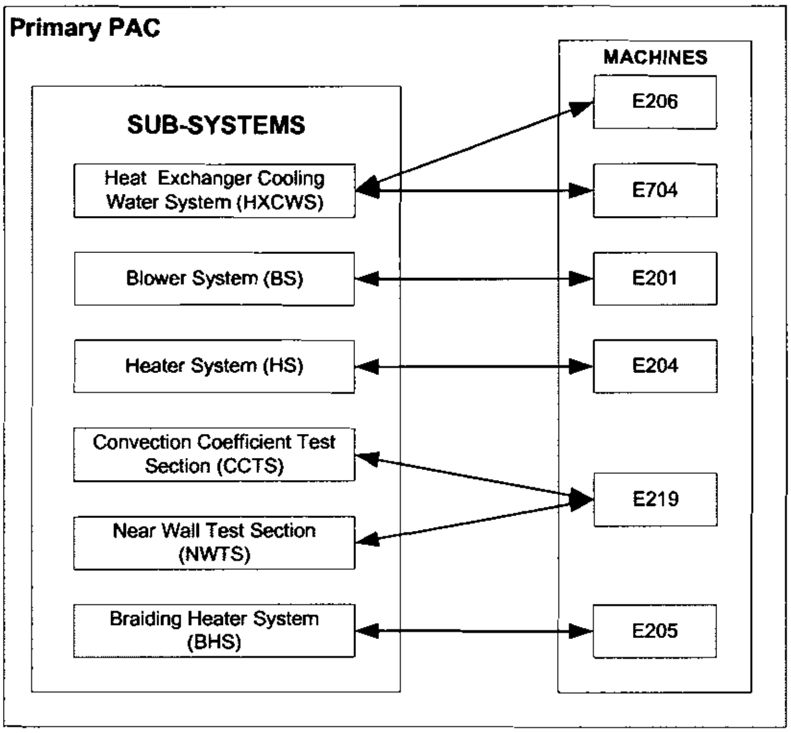


Figure 4.4: HPTU Primary PAC equipment protection program configuration

4.3.2 Control Systems (PI and PID)

All the HPTU protection and control systems are programmed on the primary PAC unit. The motive for this is that most of the control measurements are done with this PAC. The CCTS (Convection Coefficient Test Section) and NWTS (Near wall Test Section) surface temperature measurements are done on secondary HTPU PAC unit (refer to section 4.4) although its control software are located on the primary PAC unit. The HTPU controllers are listed in Figure 4.5.

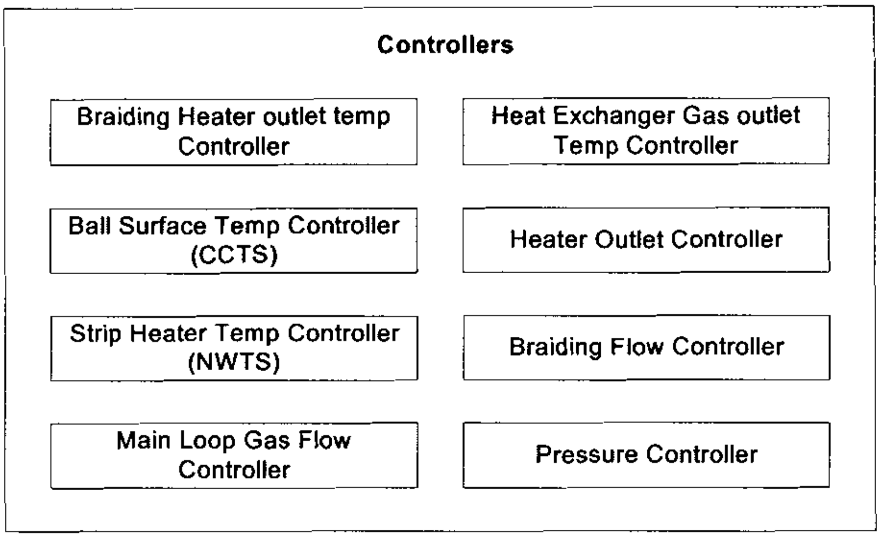


Figure 4.5: HPTU Controllers

4.3.3 Analogue Inputs (AI) Calibration

Loop calibrations from the sensor to the SCADA will be done before HPTU is commissioned. Corrections need to be applied to sensors with undesired error measurements. The National Instruments Compact FieldPoint Unit software doesn't include such capabilities. Program code was implemented to address these calibrations.

All the analogue Input channels are located on the primary PAC unit and that is the motivation for the AI calibration program to run on the same PAC unit.

The calibration is completed by applying a linear (y=mx+c) correction method. The values of m and c would be one and zero respectively for a perfect measurement. The calculated m and c values from sensors can be adjusted in the primary PAC calibration program. Figure 4.6 illustrate the basic calibration concept.

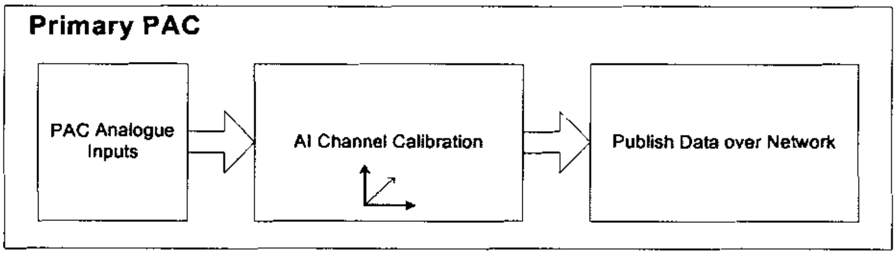


Figure 4.6: CFP Analogue Input (AI) Channel Calibration

4.3.4 Calculations

The following calculations are done on the PAC unit:

- HPTU main loop gas flow rate
- Reynolds Number

The Reynolds number is the reference point for all the tests.

- The Pressure Transmitters (PT) sensor selectors.

A single pressure transmitter didn't have the required accuracy to cover the complete pressure range. That is why a second transmitter is implemented at each measurement point. The selector program automatically selects the sensor which has the best accuracy for the specific range.

- Differential Pressure Transmitters (PDT) sensor selectors

The PDTs have the same accuracy problems and that is why three instruments were implemented at each measurement point. This selector program automatically selects the sensor which has the best accuracy for the specific range.

- Percentage Braiding flow rate

The braiding flow is controlled at a specific percentage flow rate of the main loop flow rate.

4.4 SECONDARY HPTU PAC

This PAC is used to:

- Measure all the HPTU thermocouples (TE)

This Unit is fitted with thermocouple measurement add-on cards ,which implies that the TEs are connected directly to the card.

- Calibrate eleven interlock and control thermocouples.

The interlocks and control TEs are used by the HPTU01 CFP unit. The HTPU02 CFP unit contains the calibration program. The calibrated values are then published from HPTU02 CFP to the HTPU01 unit. The basic TE channel calibration strategy are shown in Figure 4.7

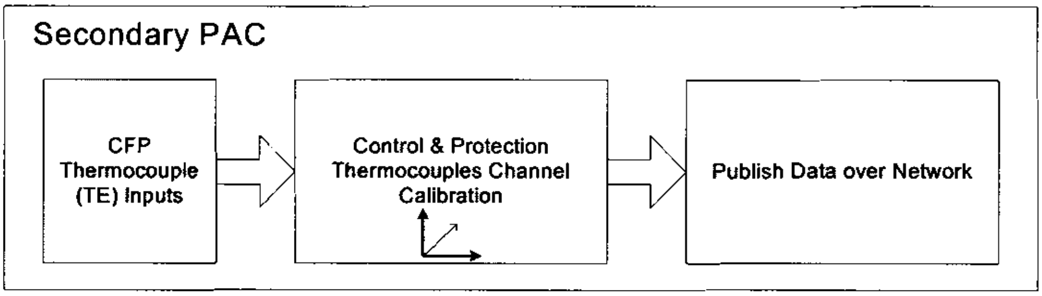


Figure 4.7: Thermocouple (Control & Protection) Input Channel Calibration

4.5 SCADA HOST COMPUTER

The SCADA HOST Computer is responsible for:

- Operator Control Graphical Interface
- Thermocouple calibration
- Data Logging

4.5.1 Operator Control Graphical user Interface

HPTU SCADA (Supervisory Control and Data Acquisition) is designed for the operator to control the HPTU from the HOST Computer and a secondary operator monitor any measurements from the Client Computer. The HOST computer uses a double screen display which creates a much more user friendly environment than two separate computers.

4.5.2 Thermocouple Calibration

The Secondary PAC unit is a much slower controller than the primary PAC unit and PACs are much slower than any personal computer. This was the motivation for the control and protection software to be distributed between the HOST, PAC1 and PAC2. More than three quarters of the thermocouples on the secondary PAC are for measurements and data logging only. Thus the calibration program for these sensors is located on the HOST computer. Some of the thermocouples are calibrated on the secondary unit (refer to 4.4).
The basic operating principle are illustrated in Figure 4.8

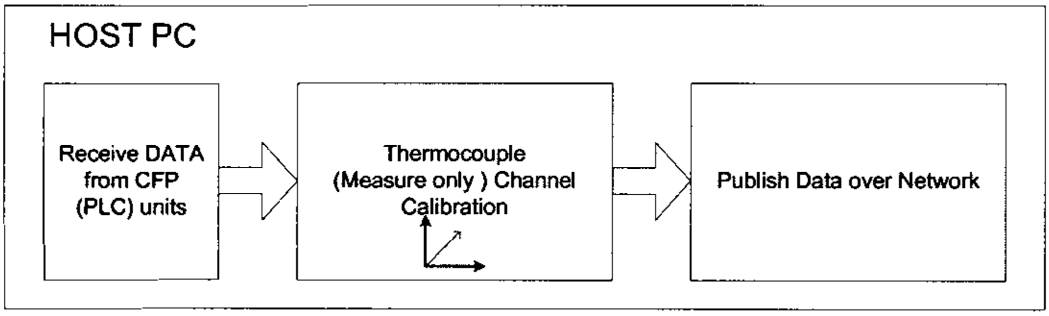


Figure 4.8: Thermocouple (Measure only) Channel Calibration

4.5.3 Data logging

All the data logging are done on the HOST computer. The storing of the data onto the hard disk of the HOST computer is done automatically although the data is in a raw format. A data retrieving program was created which can easily export all the logged data to Excel format. The operator only selects the start and end time to determine the time period and the sampling rate at which data should be exported. By selecting one button all the data is exported into a ready to use spreadsheet.

4.6 SCADA CLIENT COMPUTER

This system will be used to display the GPTU modes and states of all the machines and systems. Any analogue input instrument history data can be monitored for as long as a five day window period. This will be used to determine for example if the HPTU is running on the desired parameters. The Client PC is separate from the HOST SERVER which allows two operators to work simultaneously. The client PC will not be able to perform any control on the HPTU.

5. HPTU Equipment Protection & Control Systems

This section introduces the general working of the sequential protection system. The protection system order of importance and the design and operation of the equipment protection system are discussed in detail. The Controllers operating requirements are introduces with the design and testing of some of the controllers with the HPTU simulator.

5.1 GENERAL INFORMATION

5.1.1 Interlocks Functioning

The HPTU Interlock operating strategies are designed using a type block diagram of 'ladder' configuration as show in Figure 5.1. All the detail designed control strategies are included in APPENDIX C.

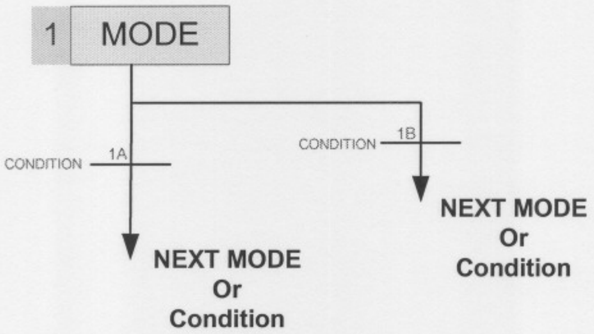


Figure 5.1: Operating Strategy illustration

During MODES the program will execute commands and will check interlocks and protections. When a condition is met the program will go from the current mode to the next condition or the next mode. In some scenarios more than one condition need to be met at the same time.

Any sub-system interlock or protection can be bridged by an authorised operator. This is mainly incorporated to assist the Site manager during commissioning.

Each sub-system has the following feedback which is used to indicate relevant information about the sub-system itself. This information is indicated on the graphical user interface. They are shown with a typical programming name:

- RUNNING status -> ON or OFF

- System MODE -> Each mode are identified by its name for example ON, OFF or FAULT
- FAULT status -> Indicates if the system is in the FAULT mode. This variable is incorporated into the graphical user interfaces to clearly indicates a FAULT condition
- TRIP status -> The trip status indicates if the system is in the TRIP mode on not and occurs when the Emergency button is pressed

Each of the sub-systems interlocks and protections are also feedbacks to the GUI

5.1.2 Interlock Alarms

Alarms are implemented to prepare the operator for a possible interlock or protection fault. This implies that the operator can be warned and an interlock trip can be prevented. These alarms where implemented on any possible measurement. The alarms FILL BAR is filled from left to right and the FILL COLOUR changes from Blue to green and then to red when the possibility for a trip is increased. All the alarms are programmed on the SCADA or HOST computer and not the PAC.

5.2 HPTU SYSTEMS ORDER OF IMPORTANCE

The different control and plant operating systems are running individually although in some cases some of the systems are dependent on other systems. These systems are operating in order of importance to insure the safe operation of the plant in terms of equipment protection. The HPTU systems order of importance is shown in Figure 5.2. The cooling water system is responsible to supply the heat exchanger with cold water which is then used to cool down the nitrogen gas which passes through the shell and tube heat exchanger. Circulation is then required to remove and transfer the plant's heat through the heat exchanger. These two systems are directly dependent on each other which imply that no excess heat of the plant can be removed without team work from the circulation and cooling systems. The pressure controller requires the Blower system to circulate the nitrogen through the plant during injection or blowing off of gas. This prevents isolation between the point of gas injection and extraction and the rest of the circulation path. As mentioned the blower is a positive displacement blower and the change exists that the seals of the blower will be damaged when instant pressure deviations occur. A percentage nitrogen mass flow is required to remove an amount kilojoule of heat energy. Mass flow is directly dependant on the gas density which is dependant on pressure. Referring to the amount of volume flow alone is not always sufficient in removing all the heat supplied by the heater. For example, the heater can overheat and damage the high pressure piping by turning the blower at top speed at the lowest pressure point. This in turn forces the heater to operate at maximum power output. The interlocks will therefore always refer to the measured mass flow in order to protect the plant. Thus the heater is also directly dependent on the safety systems which includes the water cooling system and the blower system.

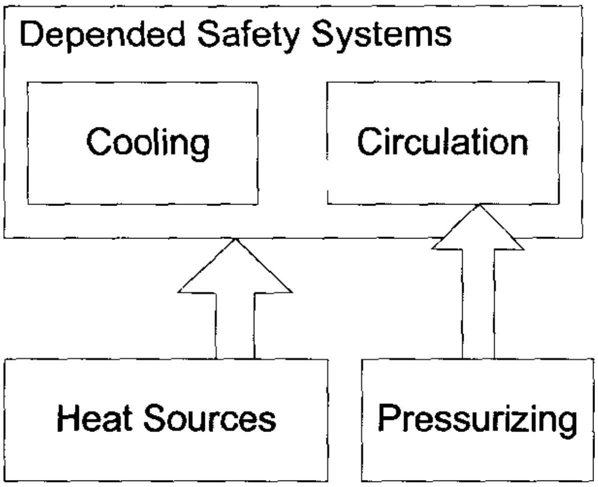


Figure 5.2: HPTU equipment protection systems order of importance

5.3 EQUIPMENT PROTECTION SYSTEM

5.3.1 Heat Exchanger Cooling Water System (HXCWS)

The protection system for the Heat Exchanger Cooling Water System will be discussed in detail. The basic principle is used in most of the systems with only a few changes.

5.3.1.1 Machines operating strategy

The HXCWS controls the water pump and cooling tower. These two machines are manipulated in two sub-systems that can run separately from the system controller (in this case the HXCWS). All the HPTU machine programs work on the same principle and have the following operating modes:

1. OFF
2. START
3. ON
4. FAULT

The machines of the HPTU are wired using a two wire system which implies that the there is a start and stop wire and a feedback wire that indicates the running status of the machine. In order to start a machine, the start signal need to be switched and held on its upper voltage level through the running duration which means that a FALSE signal will stop the machine and a (TRUE) feedback signal will indicate a running condition. The operating modes are illustrated in Figure 5.3 In the off mode of the machine the start signal are continuously held at its lower voltage level (FALSE). In the START mode, for instance the HXCWS, the start/stop signal becomes (TRUE) and if the feedback returns (TRUE) running status the HXCWS machine code will go to the on mode. If not the program will go to the fault mode where the program will continuously monitor the feedback. If the machine came back online it will go back to the ON mode otherwise if a stop signal is received the machine will go to the off mode.

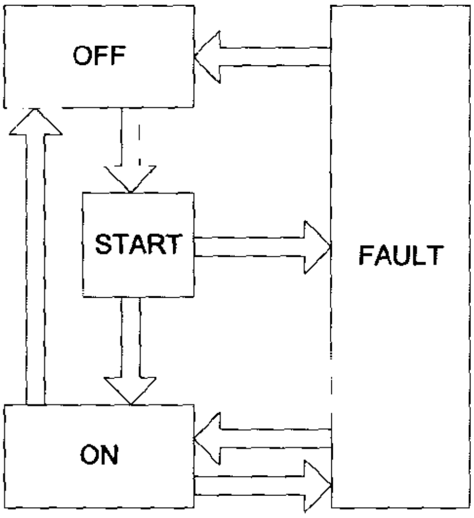


Figure 5.3: Machines operating sequences

5.3.1.2 Systems operating strategy

The HXCWS Interlocks program is divided into the following main operating MODES:

1. OFF
2. STARTING INTERLOCKS
3. START MACHINES
4. MACHINES INTERLOCK
5. ON
6. FAULT
7. TRIP

This paragraph will introduce the heat exchanger cooling water system operating strategy. The operating modes of the HXCWS are shown in Figure 5.4. All the machines receive a stop signal in the off mode to make sure that the machines remain in a non-operating condition. For this reason this is a safe mode. In the OFF mode all the previous faults are cleared. If the system receives a start signal from the SCADA when an operator triggers the start button, the system will verify the starting interlocks. These interlocks ensure that it is safe to start the machine. Some of the instruments are checked here for integrity for example a flow switch are checked to verify if it measures flow before the water circulation pump was started. If a fault is detected in this mode the system will go to the fault mode while indicating that the system was not running. The operator can then resets the fault and the system will then go to the off mode. This is a safe scenario because no heater systems in the HPTU can be started while the cooling water is in the off mode. This implies that no heat was supplied at this point and its safe to go back to the off mode.

If the starting interlocks pass the test the system will go to the start machines mode. In this mode the machines programs receive a start signal from the system program and they will go to the on mode if their running status signals are TRUE. The machines interlocks in the system program will continuously monitor the machines running status and will immediately go to the on mode if the machine has started. There is a timeout function build into this mode which will give a time out error if the machine was unable to start after 8 seconds which will shift the system to the fault mode. In this case also the operator can resets the fault and the system will go to the off mode. In the ON mode the running interlocks are monitored. These interlocks will ensure that the plant limiting margins are not exceeded. If a fault occurs in one of the interlocks the system will go to the fault mode and all the heaters will trip immediately. In addition the heat present in the system need to be removed.

When the HXCWS was in the ON mode before a FAULT occurred the heaters where most likely running and already supplied maximum amount of heat to the system. This heat is contained in the piping and the inertia of the plant as a result of the slow heat transfer of the heavy high pressure piping and pressure vessels. These trapped heat need to be removed after the heater has tripped to prevent the overheating of the heaters and piping. This implies that the cooling water system can not be stopped in the fault mode and must keep on running until the temperature of the heater is low enough.

The operating strategy of the FAULT mode is divided into three sub-modes (Refer to Figure 5.5):

1. RESET
2. HX FLOW RATE INTERLOCK
3. STOP MACHINES

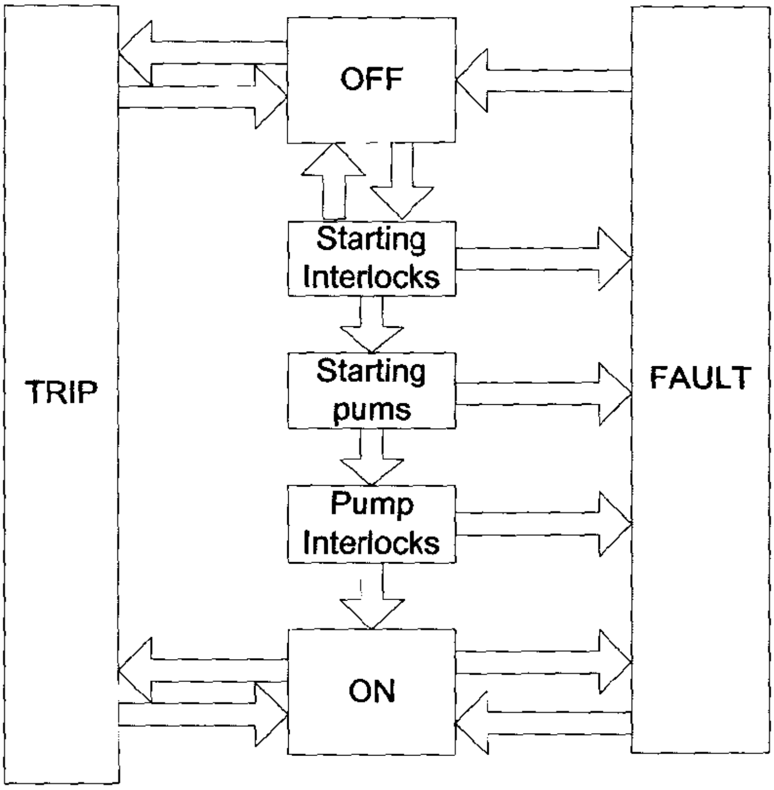


Figure 5.4: HXCWS control sequences

When the system is in the FAULT mode the operator can request a FAULT RESET. The RESET mode will clear all the FAULTS and the system will go to the ON mode if it was running and to the OFF mode when the running status was false. There is one condition that will stop the machines in the FAULT mode when the system was in the ON mode. This will occur when the HX flow rate interlock failed as a result of the water flow being insufficient. In this case there is no need for the pump and cooling tower to run because no cooling can take pace without water flow.

If the operator presses the emergency stop button the HX cooling water system will go to the TRIP mode.

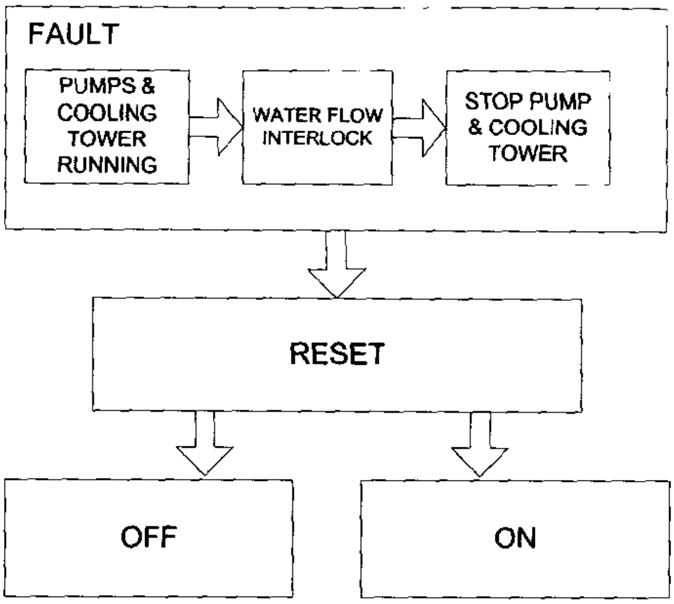


Figure 5.5: HXCWS FAULT mode control

5.3.2 Heaters and Blower systems

The heaters and blower systems uses the same sequences as the HX cooling water system with a few small differences. The heater systems include the inline heater system, braiding heater system, near wall test section (NWTS) with the two strip heaters and the convection coefficient test section (CCTS) with the heated sphere.

If a fault occurs and the heaters go to the FAULT mode the heaters will be immediately stopped. If the operator presses the emergency stop button the system will go to the trip mode and the heater will also be stopped.

When a fault occurs with the blower the system will go to the fault mode although the blower will only be stopped if the differential pressure over the blower is too high or when the water flow in the HX cooling water system is to low. If the operator presses the emergency button the system will go to the TRIP mode and the blower will be stopped.

5.3.3 Vacuum pump system

The vacuum pump system also uses the same starting and stopping sequences as the heater systems and blower system although it has exceptionally different control sequences when the system is in the ON mode. The ON mode will be discussed in this section.

The vacuum pump controls the two pressure control valves through the Injection Control system (ICS). The ICS monitor the vacuum pump system and when the vacuum pump system is in the ON mode the ICS give the control priority over the pressure control valves to the vacuum pump system. The vacuum system is isolated from the main plant by a sensing hand valve (SHV) and a pneumatic control valve (XV). As mentioned before, the plant is operated at 5000 kPa. The vacuum pump is not designed to handle pressure much higher that atmospheric pressure. This creates a great risk to connect a very low pressure system to a very high pressure system. The double valve system provides double safety. The PAC controls one valve and the operator the other and both need to be opened before the vacuum pump is connected to the plant. The SHV senses the position of the hand controlled ball valve and is used in interlocks in the ICS. The ICS will not supply nitrogen to the plant if the SHV is not in the closed position. The pneumatic control valve will not open if the pressure in the plant is too high. The vacuum ump can be operated manually which means that the operator must verify the vacuum pressure and stop the vacuum pump if the required vacuum pressure is reached. It is though recommended for the plant to be operated in automatic mode which is also the default mode for the vacuum pump system. In the automatic mode the operator simply select the amount of vacuum or purge cycles and the required vacuum pressure before the vacuum pump is started. The vacuum system will then complete the vacuum process automatically.

The automatic vacuum pump system has the following modes in the ON mode:

1. AUTO_OFF
2. OPEN SHV
3. PURGING
4. LINGER
5. PRESSURE-RISING
6. UPDATE COUNTER
7. AUTO_STOP

In the OFF mode the pressure control valves is closed because at this point the valves control are handed over to the vacuum system. In the OPEN SHV mode the control system inform the operator to open the valve and after the valve is opened the PAC will sense it and will go to the PURGING mode. In the purging mode the pneumatic control valve is opened by the vacuum system and the vacuum process is started. The purge pressure is constantly monitored and compared with the vacuum pressure. If the plant pressure is equal to the required purge pressure the vacuum system will go to the LINGER mode and inform the operator to close the sensing hand valve. While the control system waits for the operator to open the valve the pressures are constantly compared and if deviations larger than two kPa exist, as a result of a plant leak over time, the control system will go back to the PURGE mode to reduce the plant pressure. If the operator opens the SHV the controller will start the pressurising. The injection fluid depends on the choice of the operator to either EVACUTATE or INJECT. Evacuation will remove nitrogen and replace it with air and the injection option will remove air and inject the plant with nitrogen. If the plant pressure is larger than 85 kPa the purge counter will be updated and compared to the required purge cycles and the process will start all over again until the purge cycles are met.

5.4 CONTROL SYSTEM

5.4.1 Reynolds Number Controller

The Reynolds number will be controlled at a desired set point through a variable speed blower. The Reynolds number is a function of the following plant variables namely; pressure, temperature and mass flow rate. Pressure will be controlled at a specific steady state value although temperature will be controlled at a varying ambient temperature (refer to section 5.4.2). The Reynolds number controller will absorb the deviations in the temperature controller to provide a steady-state Reynolds number. This will easily be achieved by manipulating the mass flow rate by adjusting the blower speed. The changing of mass flow rate has a very fast response. The mass flow rate will be calculated in the PAC by using the temperature, pressure and differential pressure. The sum of the mass flow in each of the orifice flow measuring stations will be used to calculate the total mass flow. If any of the orifice stations is isolated by its hand valve that mass flow rate is ignored.

The flow measuring system is illustrated in Figure 5.6.

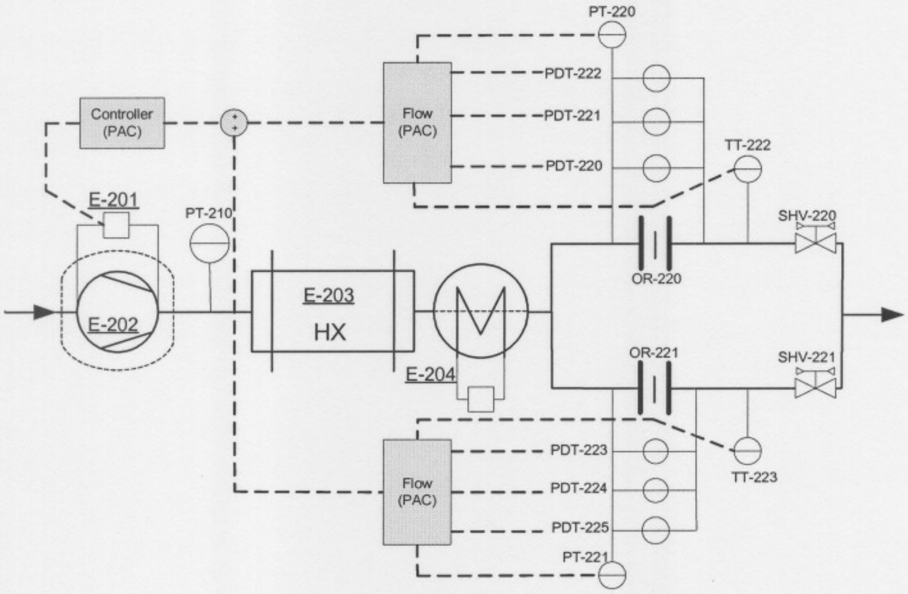


Figure 5.6: HPTU Flow control by means of variable speed blower

5.4.2 Vessel inlet temperature control

The purpose of the inline heater is to control the vessel inlet temperature at a steady value. This is a very important parameter and the function is to determine a good mean value for calculation purposes. The inline heater will control the pressure vessel gas inlet temperature by controlling the orifice temperatures (TT222 and TT223) at approximate ambient temperature. A steady state ambient temperature would be an ideal operating scenario although the ambient temperature changes rapidly during the day, thus an ambient temperature reference can't be used. The heat exchanger gas outlet temperature will be a few degrees below the ambient as a result of the cooling tower. This temperature is also not steady state because of the fluctuating ambient temperature. The reason for this is that the cooling tower transfers the oscillating ambient temperature to the gas cycle. The advantage is that this temperature has a very large time delay and is a very good damped signal. This is the heater inlet temperature and will be used in this control scenario.

The controller will follow the ambient temperature in 3 degrees steps and it will consist of two integrated control programs. The first program will do logical operations to determine the desired temperature set point for the second program, which is a proportional integral controller. The deviation between the ambient and the controlled temperature will vary from 3.5 degrees to 0.5 degrees. Data capturing during tests will be conducted during the steady state conditions.

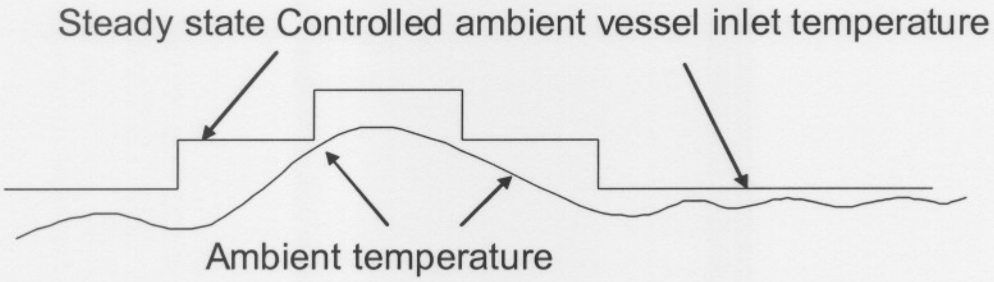


Figure 5.7: Vessel inlet temperature control theory

The heater will supply a small amount of energy during the experiments. The inline heater gas control is illustrated in Figure 5.8.

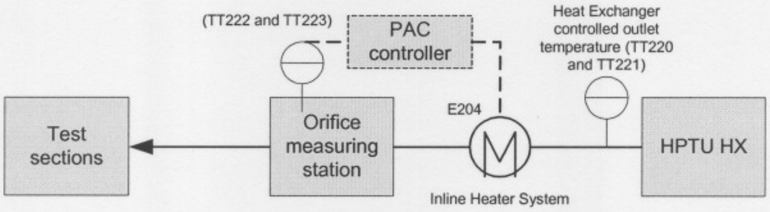


Figure 5.8: HPTU vessel inlet temperature controller

5.4.3 HPTU Sphere surface temperature control

The HPTU sphere surface temperature will be controlled at the desired temperature by varying the amount of electrical energy supplied to the sphere internal heater element. The purpose of this controller is to control the surface temperature to 50 ºC above the vessel inlet temperature and will not always be the same as the result of the different set points of the vessel inlet temperature controller. The rate of electrical energy supplied to the sphere need to be limited to prevent overheating and thermal shock on the heater element. Six thermocouple temperature sensors will determine the sphere surface temperature of each of the CCTS test sections. The sphere core temperature of each experiment is measured to protect the sphere heater element from over temperature. The three HPTU experiment test sections and respective temperature sensors are:

- 0.45 Porosity CCTS
    - Sphere surface temperatures (TT250A-TT255A)
    - Sphere core (relative heater element) temperature (TT256A)
- 0.39 Porosity CCTS
    - Sphere surface temperatures (TT250B-TT255B)

    - Sphere core (relative heater element) temperature (TT256B)
- 0.36 Porosity CCTS
    - Sphere surface temperatures (TT250C-TT255C)
    - Sphere core (relative heater element) temperature (TT256C)

The sphere surface temperature controller philosophy and Equipment Protection System (EPS) are illustrated in Figure 5.9.

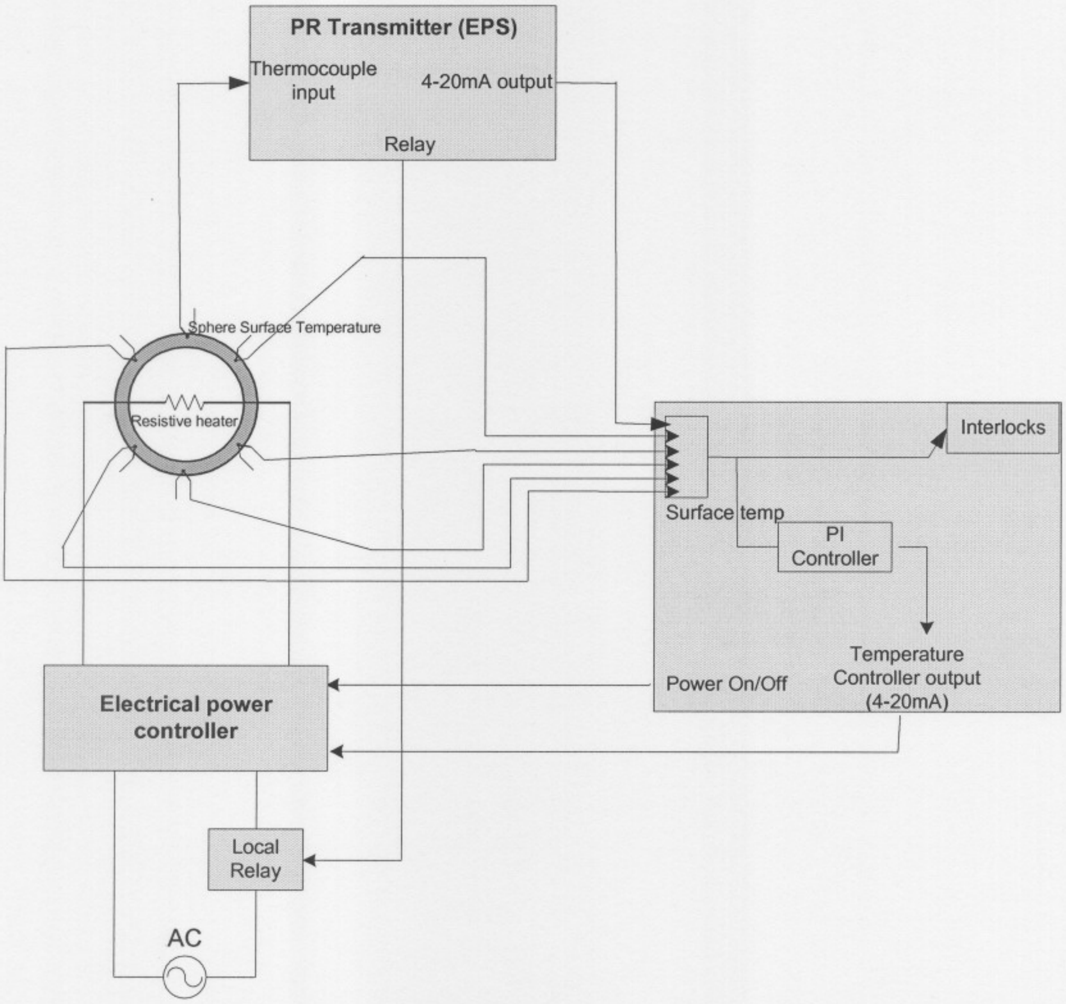


Figure 5.9: Sphere surface temperature controller

One of the surface thermocouples will be connected to a Shinko controller. The Shinko controller will be used to trip the local relay if the thermocouple detects surface over temperature. The Shinko will also be used to convert the mV signal from the thermocouple to a 4-20mA value, to the FieldPoint programmable automation controller (PAC). If the Shinko malfunction the PAC will receive either a zero value or a maximum output value which will trip the sphere heater service. If the thermocouple fails the open lead detection of the Shinko will trip the local breaker. The other five thermocouples will also be checked by the PAC for over temperature. The PAC will then switch OFF the Electrical Power controller.

5.4.4 Braiding loop gas temperature control

Heater E205 will control the pressure vessel gas braiding test section inlet temperature at 40 ºC above the vessel inlet temperature. There are three main lines which enters the test section and the temperatures of each of these lines are controlled separately. The operator will be able to select the appropriate line so that the controller uses the correct temperature sensor for reference.

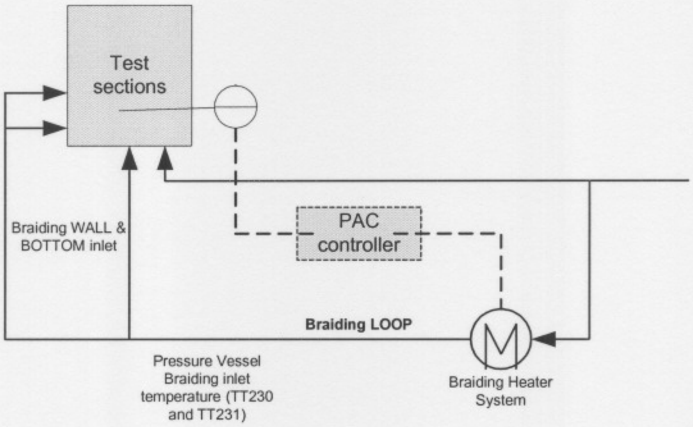


Figure 5.10: HPTU Braiding Heater gas temperature controller

5.4.5 NWTS Heated strip temperature control

The heated strip temperature controller works on the same principles as the sphere surface temperature control briefly described in section 5.4.3. The two strip heaters have complete separate power controllers, although the NWTS will be switched on with one interlock sequence. The power controller will also be controlled by two separate PID controllers as shown in Figure 5.11.

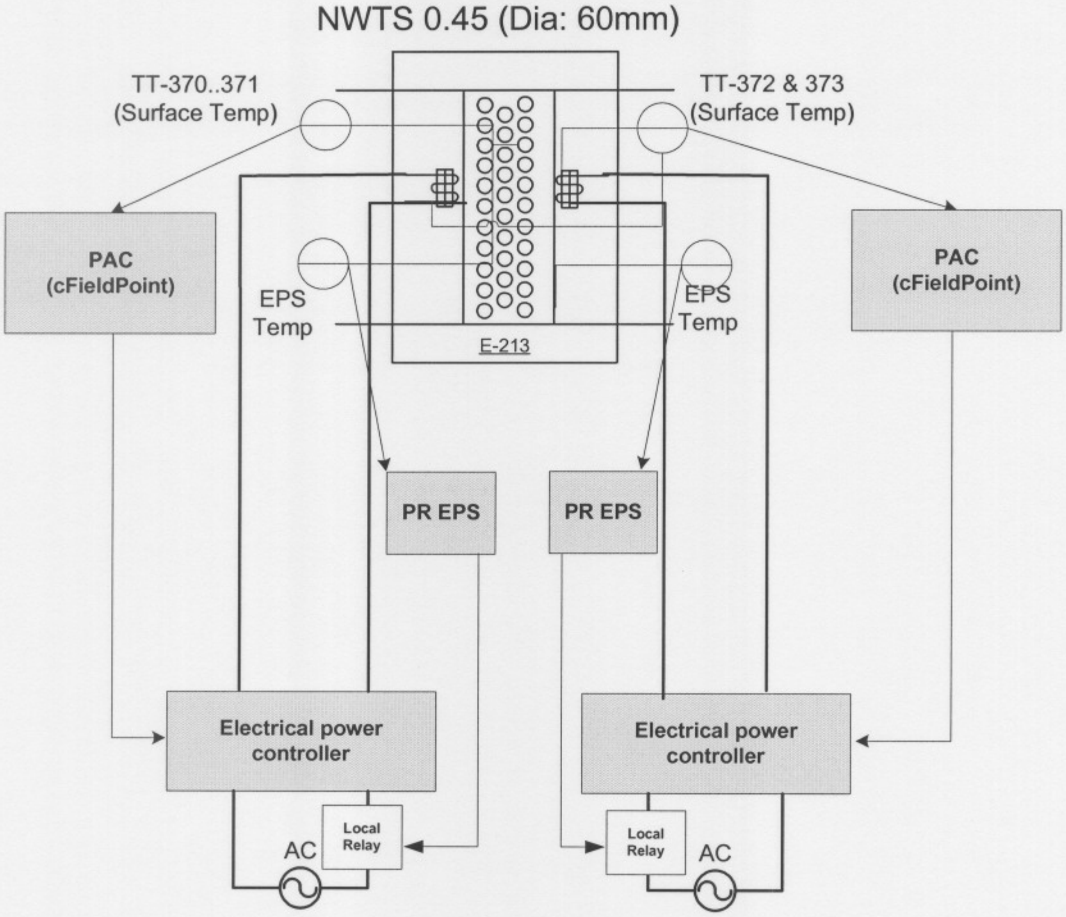


Figure 5.11: NWTS strip heaters temperature controllers

5.4.6 System pressure control

The HPTU pressure (PT200 and PT201) will be controlled at the desired pressures by injecting (CV200) nitrogen into the system and releasing nitrogen into the atmosphere through the blow-off control valve (CV201). The two control valves will be controlled by a bang-bang controller. This controller verifies the set-point pressure with the actual pressure and will make a decision on the required percentage valve opening. At least one of the control valves will always be in the close position. The System pressure control are shown in Figure 5.12.

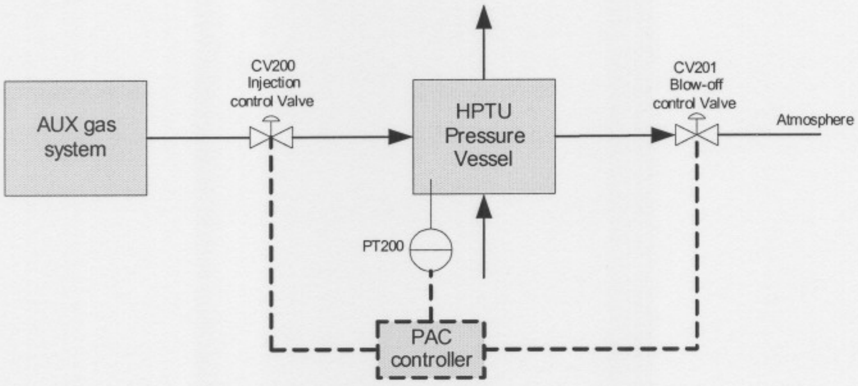


Figure 5.12: HPTU pressure controller

5.5 CONTROL SYSTEMS DESIGN AND SIMULATION

This section introduces the simulations that were conducted on the HPTU plant. Although it was not possible to simulate every controller on the plant, the Inline Heater controller and the braiding heater controllers were successfully simulated.

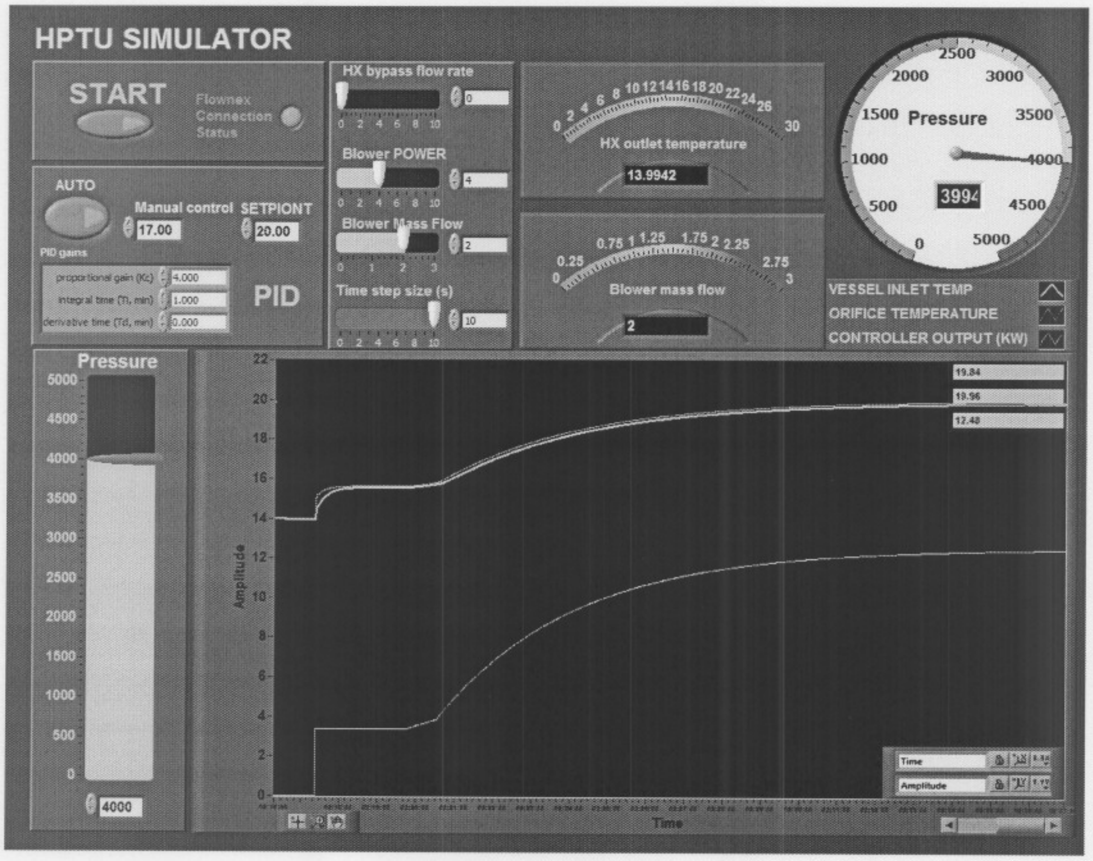
5.5.1 HPTU Simulator

A HPTU simulation model was provided by the thermo fluid design team that was developed in Flownex. Flownex is a thermal-fluid network analysis code that enables users to perform detail analysis of complex systems.

Flownex had the flexibility to connect to Matlab Simulink although this simulation configuration has very limitations. Inputs to the programmed user parameters can’t be changed in Simulink during simulation and the simulation had to stop after each user adjustment. One of the biggest problems was that the Flownex time step size couldn’t be adjusted during simulation. Large time steps can speed up the simulation in slow model responses although when faster responses occur large time steps reduce the simulations accuracy. The ideal would be to adjust the time step during simulation to get the optimum performance and accuracy. In order to do step changes in simulink every transient need to be pre-programmed be fore every simulation which was very time consuming. Another problem was that simulink uses different physical PID controller modulations than Labview because Labview has model configurations which were designed for industrial and experimental applications. Labview is used to develop the SCADA system and in order to simulate any control scenario correctly the simulator need to use Labview for its control applications and until now it wasn’t possible.

In order to resolve these limitations a different simulation configuration was developed for this project. The connection programs in Flownex and Labview was developed to establish a connection between the two programs. This configuration opened opportunities that were unimaginable and the simulation of the HPTU was done very successfully. This implies that the simulation model became a plant SIMULATOR and the simulations could all be done in series without restarting the simulation.

The HPTU simulator is shown in Figure 5.13. The PID controller has the ability to be on manual mode, where the operator specifies the percentage power that is supplied to the heater and an automatic mode where the controller controls the heater power to reach the user specified set-point. The following variables are adjustable; heat exchanger cooling tower water bypass flow, the blower electrical power, system mass flow and the Flownex time step change. The simulator indicates the actual system pressure, heat exchanger gas outlet temperature and Blower mass flow. The vessel inlet temperature Orifice temperature and the Heater power are shown on the trend.



Manual control 17.00

SETPIONT 20.00

proportional gain (Kc) 4.000

integral time (Ti, min) 1.000

derivative time (Td, min) 0.000

HX bypass flow rate 0

Blower POWER 4

Blower Mass Flow 2

Time step size (s) 10

HX outlet temperature 13.9942

Blower mass flow 2

Pressure 3994

Pressure 4000

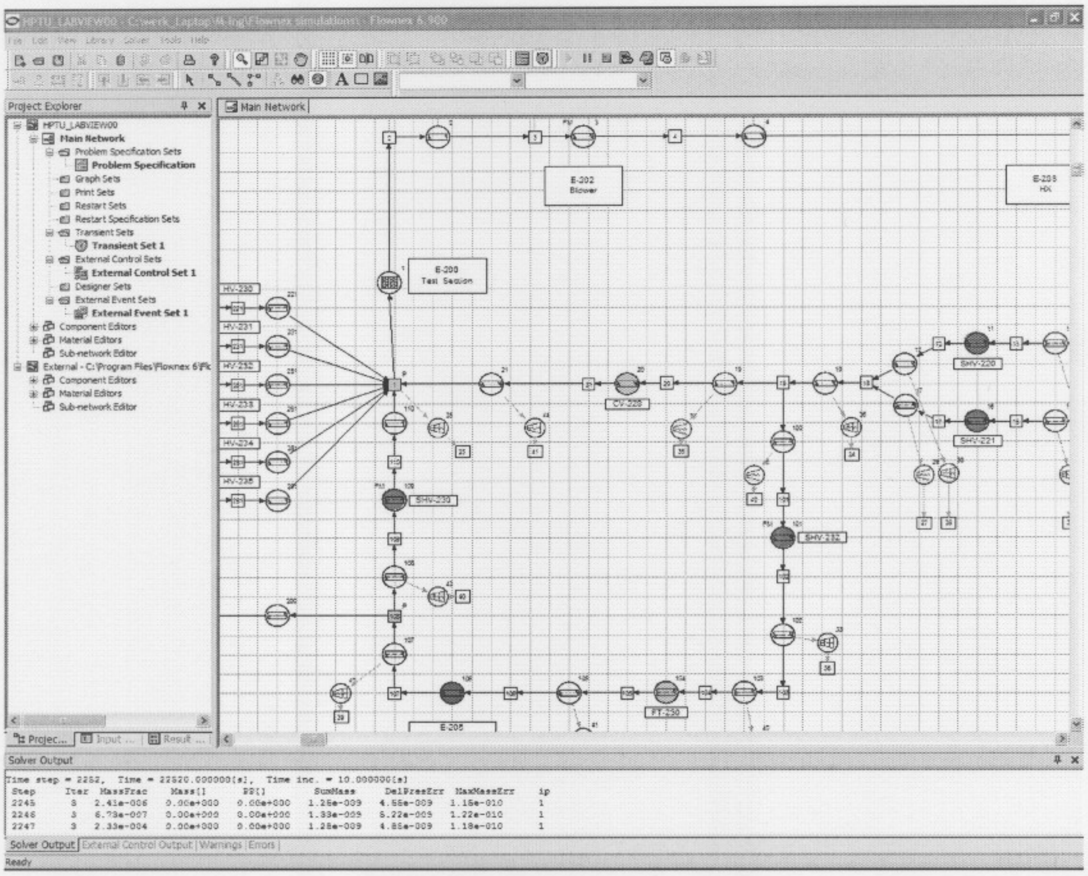
19.84

18.96

12.48

Figure 5.13: HPTU Labview-Flownex Simulator

The Flownex model which simulates the thermal hydraulic behaviours of the HPTU is shown in Figure 5.14.



```
Time step = 2252,  Time = 22520.000000[s],  Time inc. = 10.000000[s]
 Step      Iter  MassFrac    Mass[]      PP[]        SumMass     DelPresErr  MaxMassErr    ip
 2245       3   2.41e-006   0.00e+000   0.00e+000   1.25e-009   4.55e-009   1.15e-010     1
 2246       3   6.73e-007   0.00e+000   0.00e+000   1.33e-009   5.22e-009   1.22e-010     1
 2247       3   2.33e-004   0.00e+000   0.00e+000   1.28e-009   4.85e-009   1.18e-010     1
```

Figure 5.14: HPTU Flownex Model

5.5.2 Vessel inlet temperature Controller

A study was conducted in on different PID tuning methods in section 2.3.5 and these tuning methods was used in this section to estimate the PI constants. The open loop step test tuning procedure and the closed loop ultimate gain tuning procedure was used to tune the vessel inlet temperature controller. The open loop test procedure was first used to determine the proportional constant for the PI controller. The Closed loop tuning procedure sometimes provided small deviations in the PI constants and was an effective method to ensure the implementation of the most accurate constants.

The vessel inlet temperature controller, as discussed in section 5.4.2, was the first controller that was simulated and the control strategy of this controller is shown in section 5.4.2 Figure 5.7.

The open loop test procedure was conducted on the simulator at 100 kPa, 500 kPa, 700 kPa 1000 kPa, 3000kPa and 5000 kPa. The behaviour of the vessel inlet temperature was captured and is shown in Figure 5.15. The time response of the temperature is much faster at 5000 kPa and resulted in a rise time of approximately 50 seconds. A much slower rise time of 1000 seconds was measured at 100 kPa. The closed loop tuning procedure was used to verify and fine tune the vessel inlet temperature controller's constants.

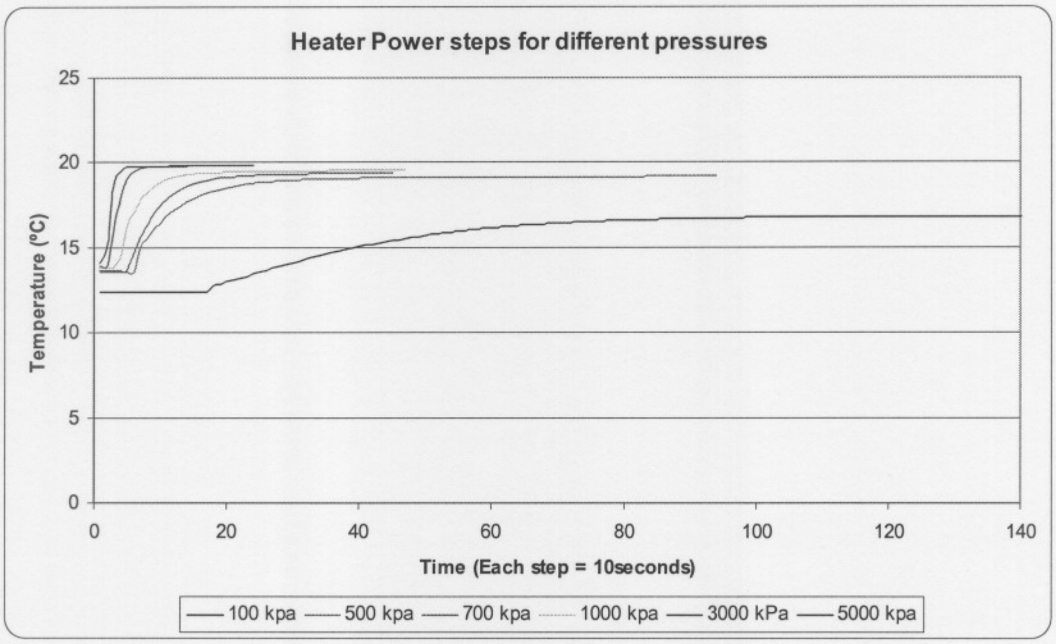


Figure 5.15: Open Loop Heater Power step test tuning

The temperature controller was tuned and then tested to confirm that the tuning parameters work correctly for every operating condition. Temperature controller step change was tested at 100 kPa as shown in Figure 5.16. To ensure the safety of the plant it was decided to design the controllers to be critically damped.

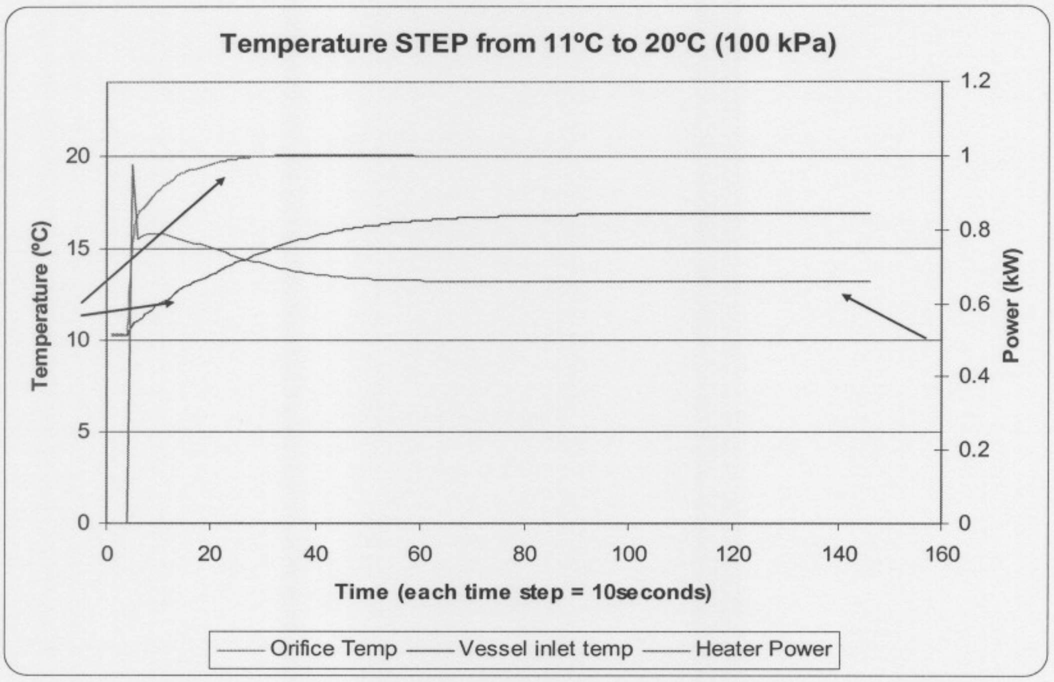


Figure 5.16: Temperature controller set-point step at 100 kPa

The stability of the controllers was tested by establishing any type of disturbance and in this case a mass flow disturbance was applied at 500 kPa as shown in Figure 5.17. The controller was able to recover very good from the disturbance without any ringing or overshoot.

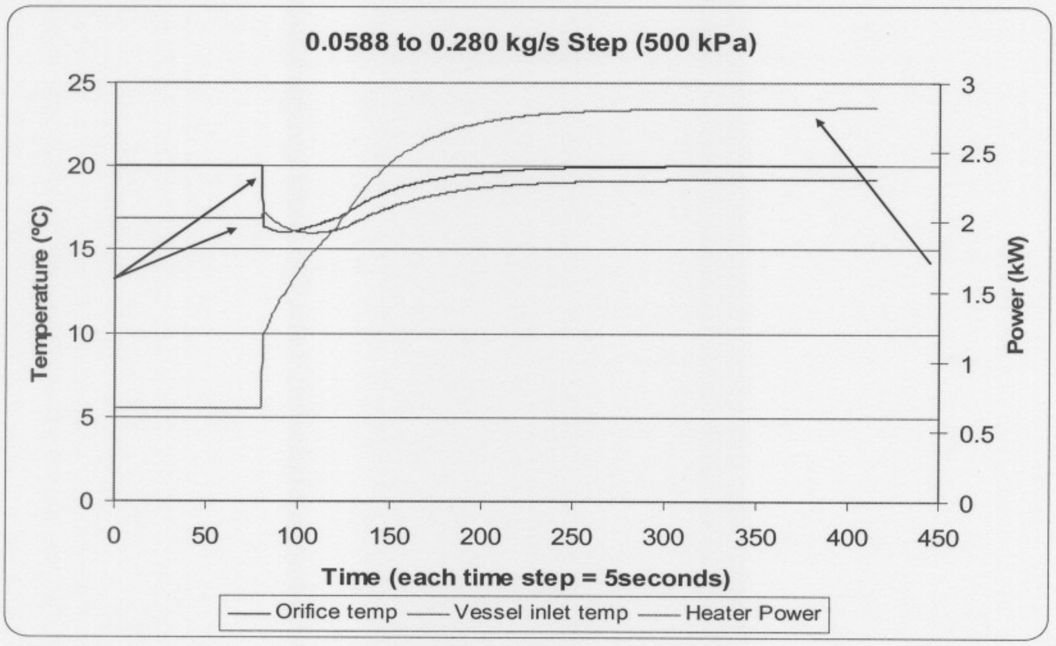


Figure 5.17: Mass flow step change at 500 kPa

A Mass flow step change was also applied at 5000 kPa to which the controller reacted very well as shown in Figure 5.18.

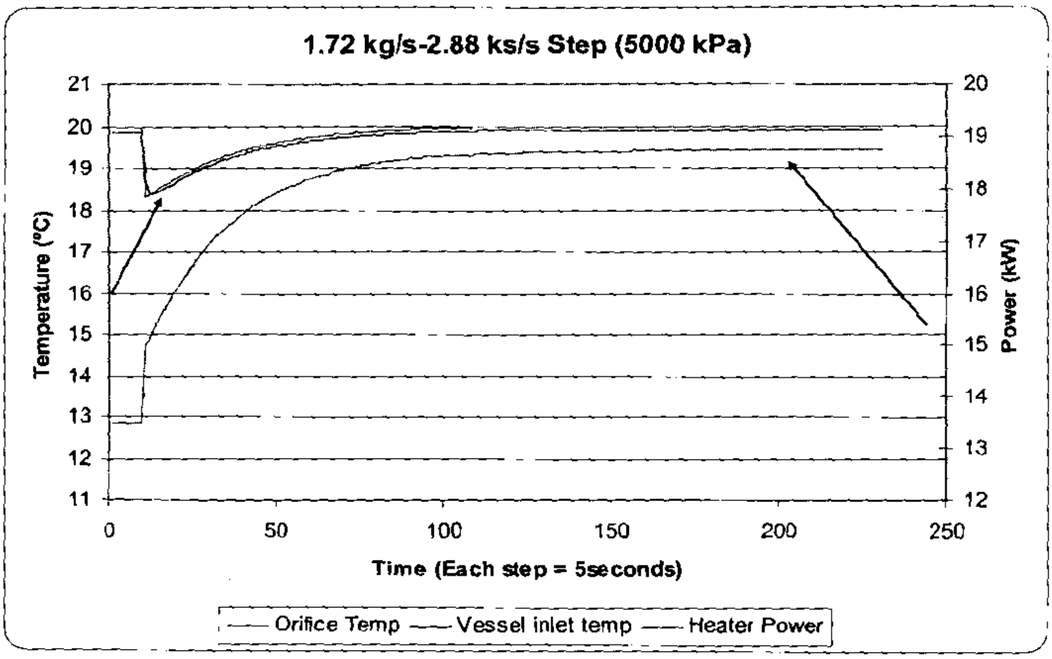


Figure 5.18: Mass flow step change at 5000 kPa

A pressure disturbance of 2000 kPa was tested at 1.71 kg/s as shown in Figure 5.19.

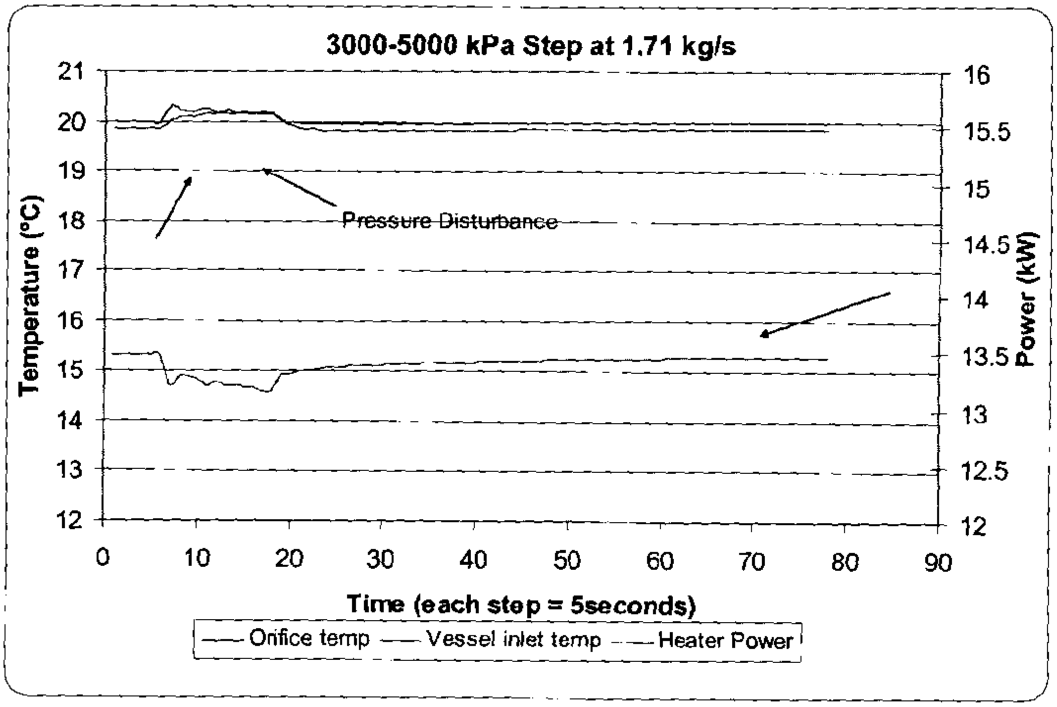


Figure 5.19: Pressure disturbance of 2000 kPa

5.5.3 Braiding Heater Controller

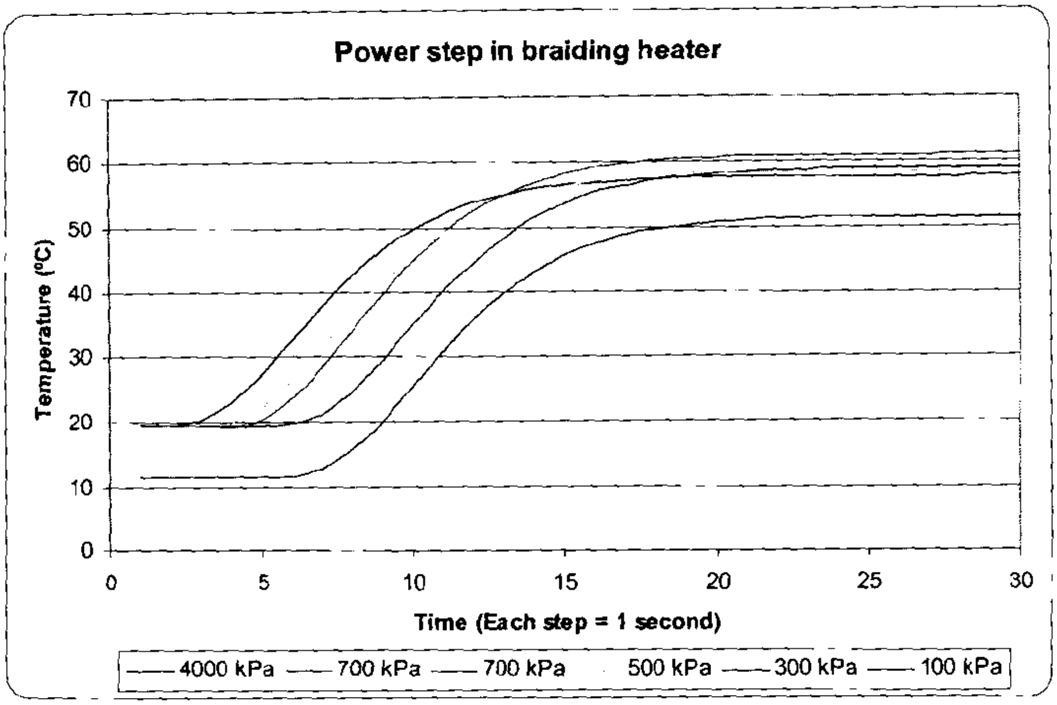


Figure 5.20: Braiding Heater power step change

The open loop step test tuning procedure and the closed loop ultimate gain tuning procedure was also used to tune the braiding inlet temperature controller. The tuning procedure that is used on the braiding heater controller is the same procedure that was used on the vessel inlet temperature controller.

After the controller was tuned it was tested to verify if it can withstand any possible disturbances. The first test was a step change in the controller set point, from room temperature measured in the winter, to 60°C at a pressure of 500 kPa. The controller, which is over damped, was able to control the plant to the desired set point value in about 60 seconds, as shown in Figure 5.21.

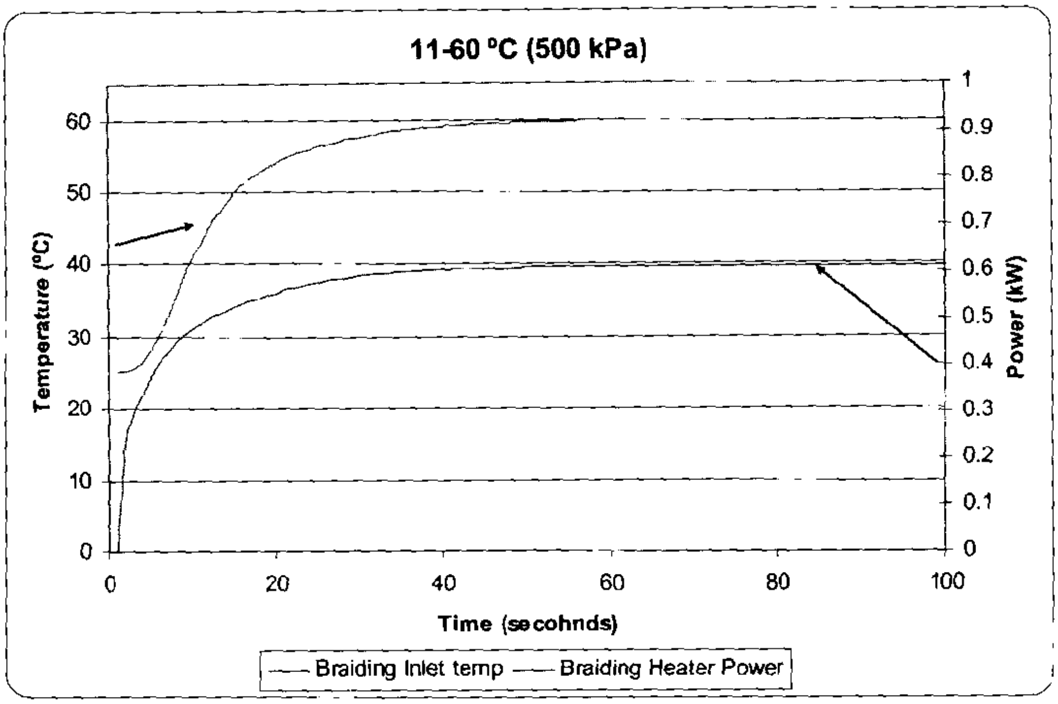


Figure 5.21: 11-60° Step at 500 kPa

The next test was conducted at 1000 kPa which implies that there is a much high mass flow through the braiding loop that resulted in a much faster temperature time response. The controller reached the set point value at 30 seconds.

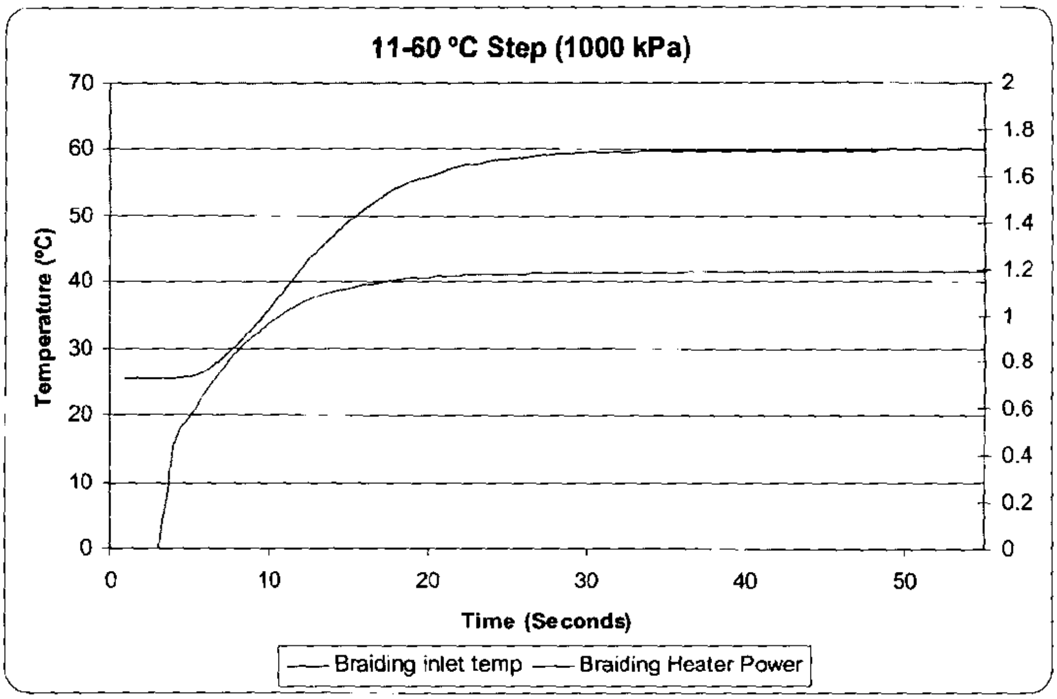


Figure 5.22: 11-60° Step at 1000 kPa

The last step change was at the highest pressure and mass flow and the controller reached required temperature in 25 seconds as shown in Figure 5.23.

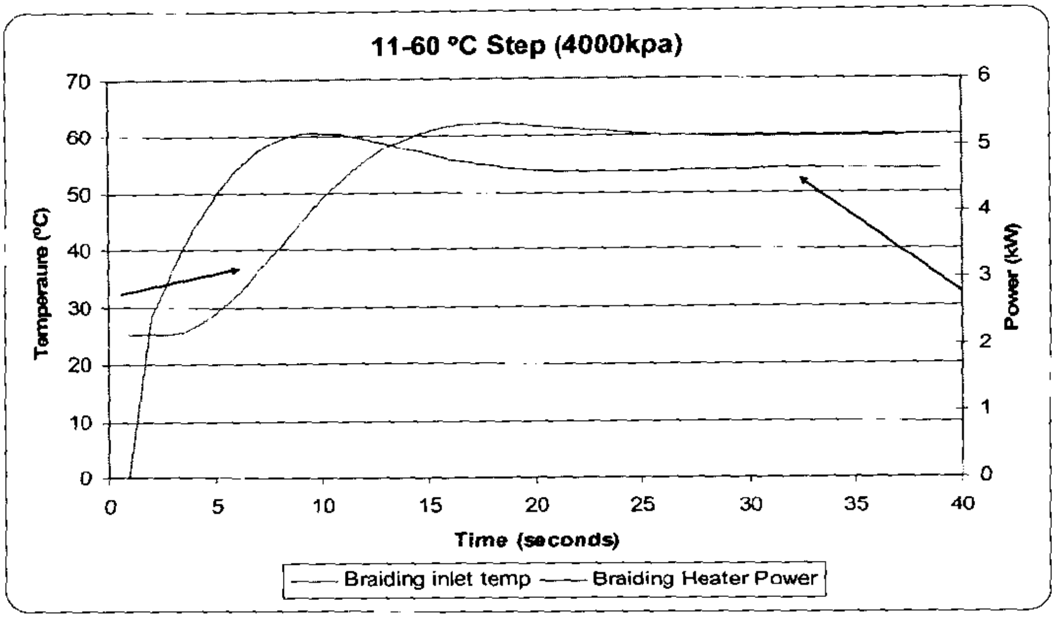


Figure 5.23: 11-60° Step at 4000 kPa

A pressure disturbance was applied at 100 kPa to verify if the controller can control through this scenario. The reason for this test is because the HPTU constantly changes the system pressure during operation and the controllers must be able to control through each pressure change.

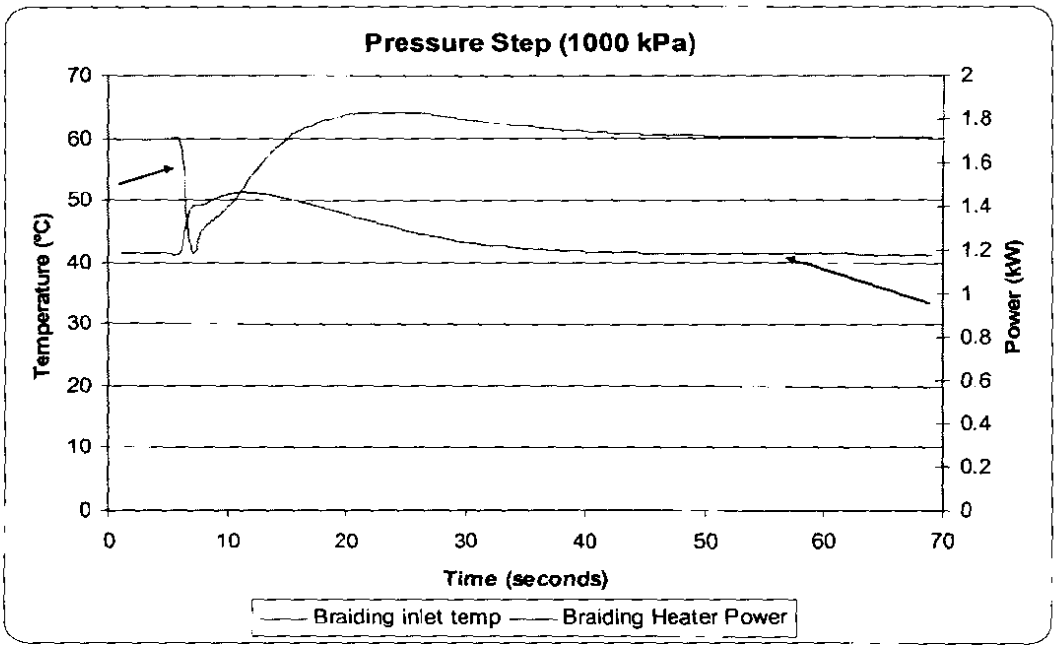


Figure 5.24: Pressure Step at 1000 kPa

The controller compensated for the change as shown in Figure 5.24 and the temperature was recovered in 50 seconds.

5.5.4 Contributions of the HPTU Simulator

During the test of the controllers the HPTU simulator identified a few problems with the design of the plant that was unforeseen. The problem was that in the lowest mass flow test conditions the heater would have to over heat itself in order to produce the correct vessel inlet temperature. The problem was that the heat losses in the pipes was too high and soaked up all the energy. The heater has a limitation on local temperature because the heater is build into one of the pipes and the pipes have a limit on the surface temperature at high operating pressures.

Pipe insulation was integrated into the Flownex simulator model and the simulation showed that the specific isolation would solve the problem. The result was that the pipes were isolated to reduce the energy losses in the system.

6. SCADA Graphical User Interface

The user interface is a critical part of any computer system and merits careful evaluation before it is released to users [20]. Before the designing of the HPTU user interface commence the designing tips, visual feedback implications and menu selections was studied in detail to implement and deliver a modern operator friendly user interface.

6.1 OPERATOR CONTROL USER INTERFACE

The operator control user interface was designed with the ability to control and adjust any operator required variable. This interface contains all the controls and feedback to easily control the plant.

The SCADA Control GUI consists of the following windows:

- SYSTEM MONITOR
- SUB-SYSTEMS
    - Heat Exchanger Cooling Water System (HXCWS)
    - Blower System (BS)
    - Heater System (HS)
    - Braiding Heater System (BHS)
    - Convection Coefficient Test Section (CCTS)
    - Near Wall Test Section (NWTS)
    - Vacuum pump system (VP)
- MACHINES
- CONTROLLERS
    - Pressure Controller
    - Inline Heater Controller
    - Braiding Heater Controller
    - Heat Exchanger gas outlet temp Controller
    - Main Loop Gas Flow rate Controller
    - Braiding Loop Flow rate Controller
    - NWTS Strip Heater Controller
    - CCTS Heated Sphere Controller

6.1.1 Systems Monitor window

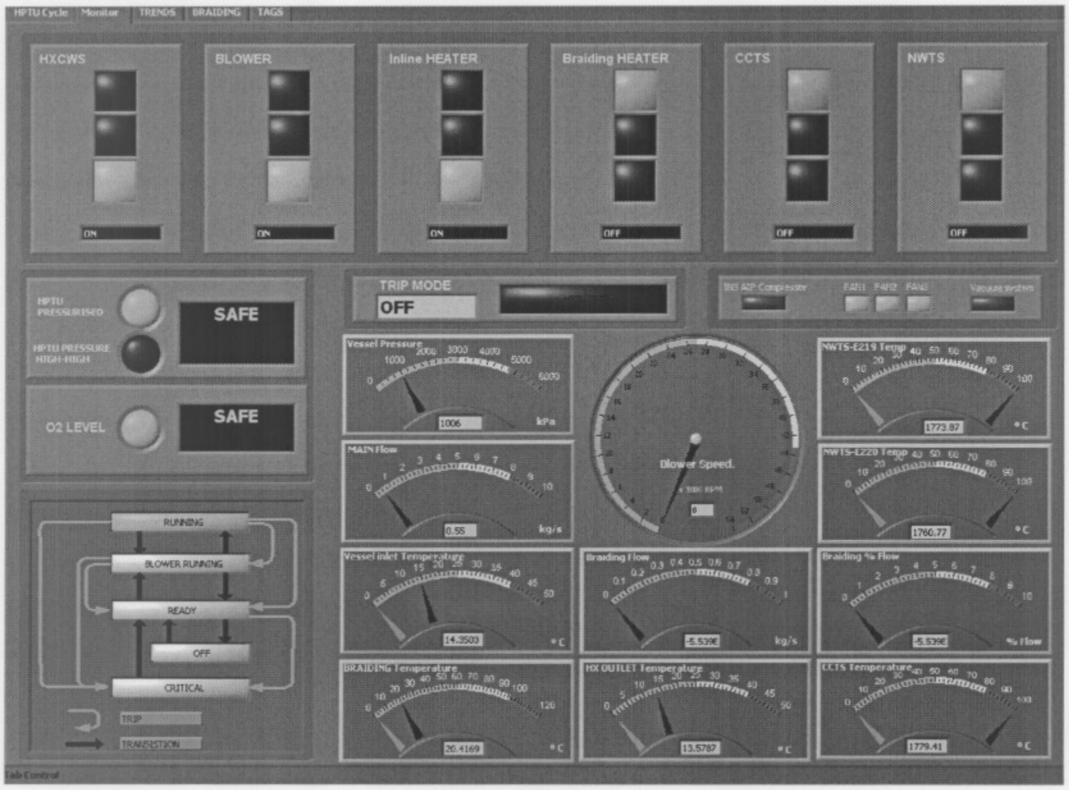
This window contains an over view of the operation of the whole plant and will warn the operator if any system went in to its fault mode as shown in Figure 6.1

The Systems Monitor Window display:

- HPTU Mode and Critical alarms
  - HPTU Modes (refer to 3.2)
  - Building Oxygen low level alarm
  - HPTU HIGH-HIGH pressure alarm
  - HPTU trip status and trip reset.

The trip status is indicated on all the subsystems.

- Sub-machines status
  - ON
  - FAULT
  - OFF
  - TRIP
  - Sub-system MODE
- Controlled variables



HXCWS: ON
BLOWER: ON
Inline HEATER: ON
Braiding HEATER: OFF
CCTS: OFF
NWTS: OFF
TRIP MODE: OFF
Vessel Pressure: 1006 kPa
MAIN Flow: 0.55 kg/s
Blower Speed: 0
NWTS-E219 Temp: 1773.87 °C
NWTS-E220 Temp: 1760.77 °C
Vessel inlet Temperature: 14.3503 °C
Braiding Flow: -5.539E kg/s
Braiding % Flow: -5.539E % Flow
BRAIDING Temperature: 20.4169 °C
HX OUTLET Temperature: 13.5787 °C
CCTS Temperature: 1779.41 °C

Figure 6.1: Systems Monitor Window

6.1.2 Machines Window

The machines window as shown in Figure 6.2 is used by and authorised operator to override and start the following machines:

- Blower E201
- Cooling water Pump E206
- Cooling tower fan E704
- Inline Heater E204
- Braiding Heater E205
- Export data

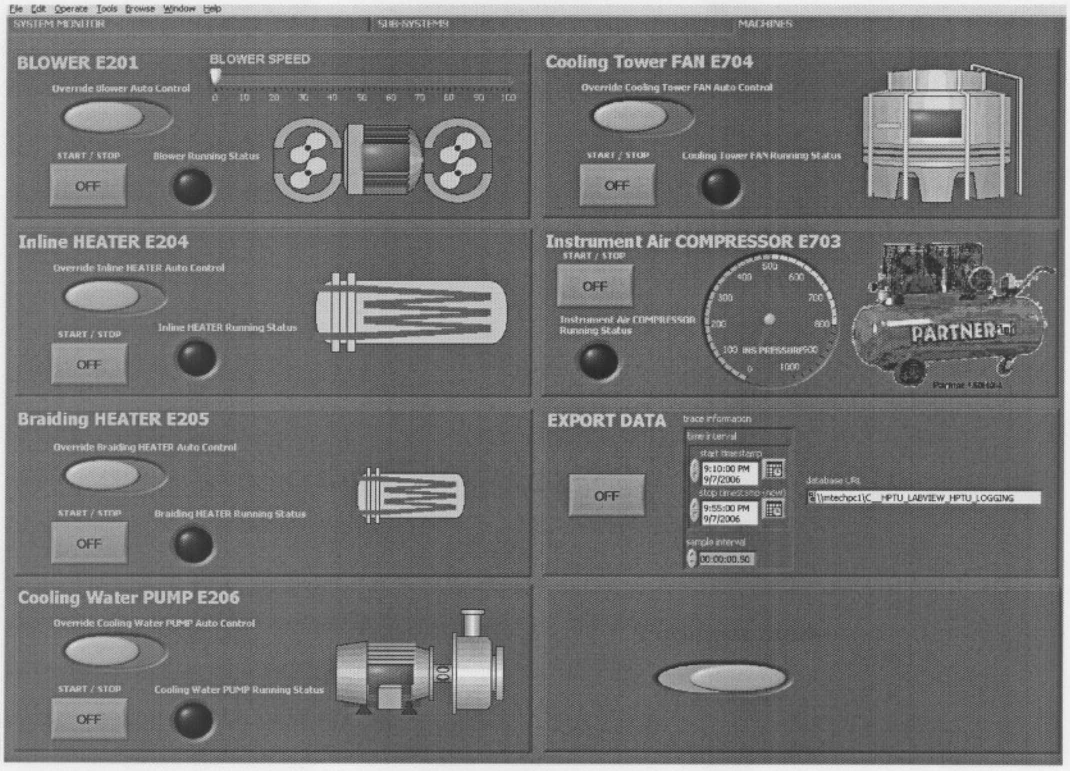
The task of exporting logged data is made very simple. The operator simply selects the beginning and end time together with the sample rate.

- Instrument air compressor

The Air compressor uses a basic START/STOP control. The air dryer and air cooler is started automatically when the Instrument Air compressor is started.

- Engineering mode selector

The engineering mode selector is used to select between operator authorities and engineer authorities. This disables the abilities for an operator to bridge any protection system or interlock and prevent the modification of any control parameters. It also disables the starting and stopping of machines in the machines window which was constructed for the engineer to help in the construction and commissioning phase of the SCADA. This engineer mode is password protected to prevent unauthorised access. It works on a simple principle which hides all the protected control buttons.



start timestamp: 9:10:00 PM 9/7/2006
stop timestamp (now): 9:55:00 PM 9/7/2006
sample interval: 00:00:00.50
database URL: \\mtechpc1\C__HPTU_LABVIEW_HPTU_LOGGING

Figure 6.2: Machines Window

6.1.3 Equipment protection SYSTEMS GUI

This section will illustrate the basic purpose of the equipment protection control user interfaces. The systems windows are similar to each other and only the HXCWS and the Vacuum pump system will be illustrated and discussed. The HXCWS SCADA user interface is shown in Figure 6.3.

Operator Controls

The operator controls are:

- Start
- Stop
- Reset
- Bridges for all interlocks (refer to section 1)

Indicators

Indicators which display feedback from PAC control system:

- OFF
- FAULT

- ON
- Fault and bridge status of all interlocks
- Alarms

The window supplies a basic layout of the heat exchanger cooling water systems. The purpose is to give the operator a better perspective of the physical system. The water pump and cooling tower running states is also shown in this user interface.

Alarms

The following alarms were implemented on the HXCWS:

- Cooling tower sump level LT480 (Percentage level indicator).
- Cooling tower sump temperature TT480 (ºC)
- Heat Exchanger gas outlet temperature TT220-TT221

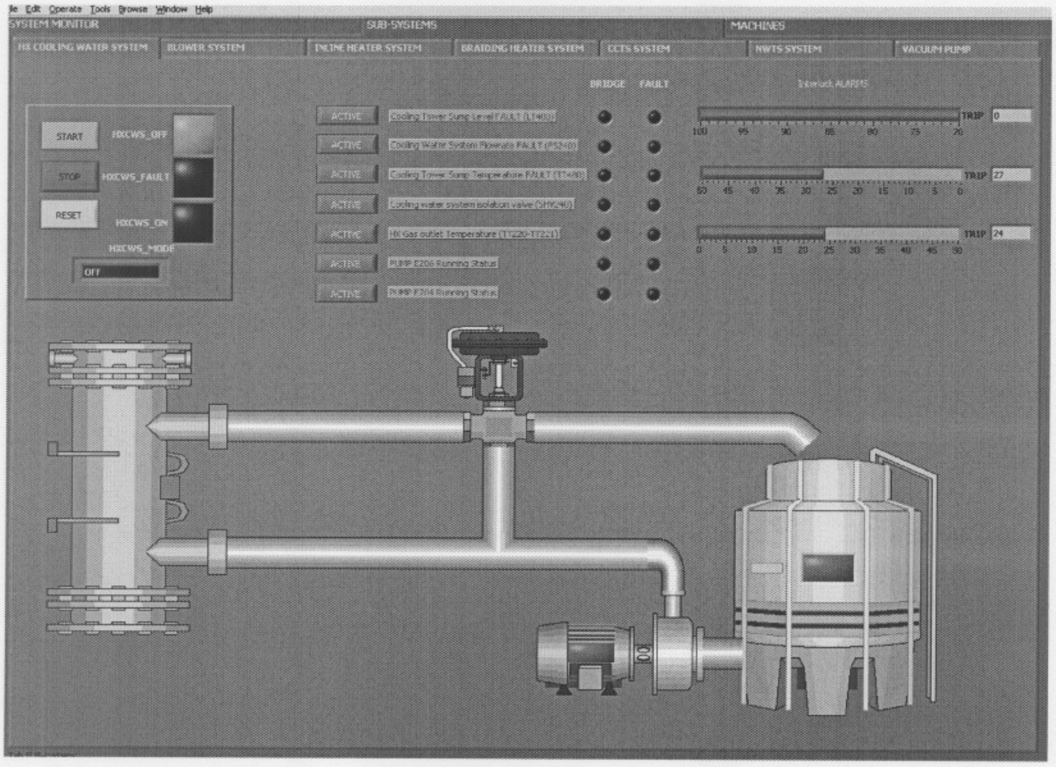


Figure 6.3: HXCWS Interlock SCADA user interface

6.1.4 Control system GUI

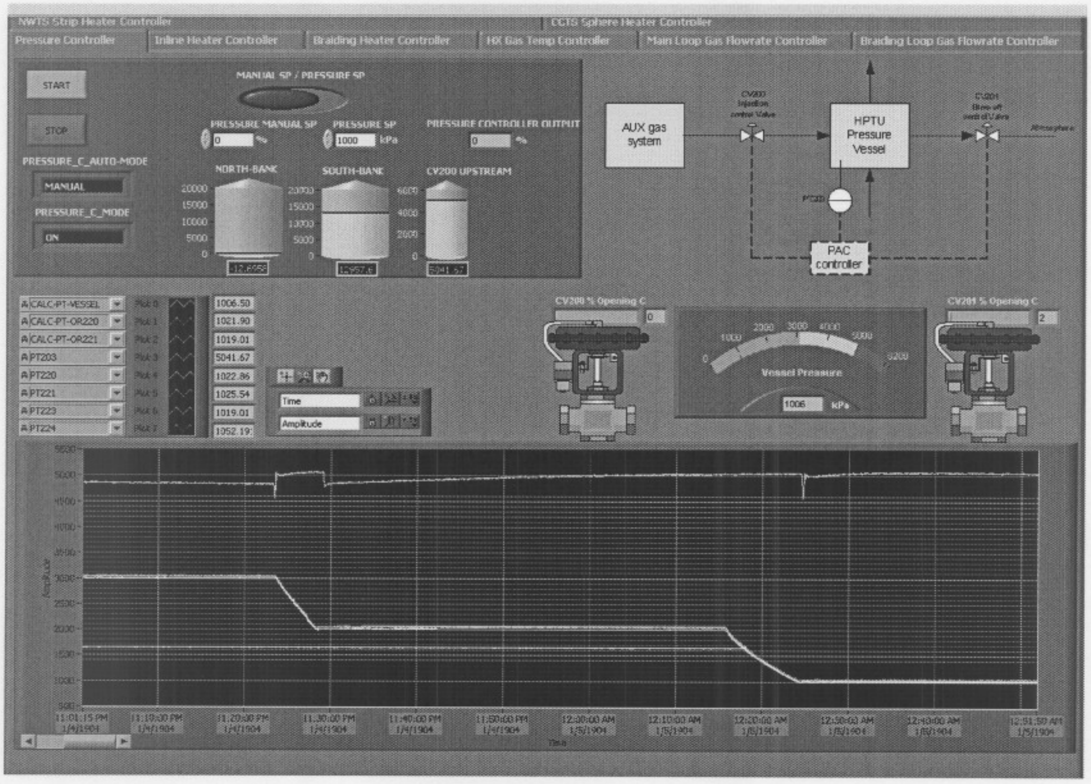
The control system graphical user interfaces will be discussed in this section

6.1.4.1 Pressure Controller GUI

Operator controls

The operator controls present in the pressure controller system are:

- START
- STOP
- MANUAL set point or AUTOMATIC set point selection
- Manual set point
- Automatic set point
- Eight simultaneous variables for the trend can be selected



PRESSURE MANUAL SP 0 %
PRESSURE SP 1000 kPa
PRESSURE CONTROLLER OUTPUT 0 %
PRESSURE_C_AUTO-MODE MANUAL
PRESSURE_C_MODE ON
NORTH-BANK 12.6958
SOUTH-BANK 12957.6
CV200 UPSTREAM 5041.67
CV200 % Opening C 0
CV201 % Opening C 2
Vessel Pressure 1006 kPa

CALC-PT-VESSEL	Plot 0	1006.50
CALC-PT-OR220	Plot 1	1021.90
CALC-PT-OR221	Plot 2	1019.01
PT203	Plot 3	5041.67
PT220	Plot 4	1022.86
PT221	Plot 5	1025.54
PT223	Plot 6	1019.01
PT224	Plot 7	1052.19

Figure 6.4: Pressure controller SCADA user interface

Indicators

The following information is displayed in the pressure controller window:

- Mode of the pressure controller
- Mode of the automatic controller
- North-Bank Nitrogen supply system pressure

- South-Bank Nitrogen supply system pressure
- Control valve upstream pressure
- PID controller output
- Control valve % opening for the injecting and blow-off valves
- HPTU pressure (gage indication)

A Trend window capable of showing 8 signals is present. The operator can modify channel selection during operation. The digital values are also displayed and a colour legend is present to identify signals on the chart. Time and date are indicated at the bottom of the Chart.

6.2 CLIENT INTERFACE

The client user interface was designed to be a second operator interface and with only the ability to verify and monitor any feedback from the plant.

The Client interface consists of the following main windows:

- HPTU CYCLE window
- Monitor window (Similar than the control interface)
- Trends window
- Braiding
- Tags

6.2.1 HPTU CYCLE window

The SCADA HPTU CYCLE window illustrate the basic HPTU piping layout with most of the basic used information. The information displayed in this window is:

- Nitrogen auxiliary gas levels (North-Bank and South-Bank)
- Cooling tower sump level indication, pump status and water flow status.
- Vessel Pressure
- Blower Speed (RPM)
- Inline Heater power indication
- Braiding Heater Power Indication
- Main Loop gas Flow rate (kg/s)
- Braiding Loop Flow rate (%)
- Vessel Braiding Inlet temperature
- Vessel Inlet temperature
- Control valves positions

- Sensing hand valves positions

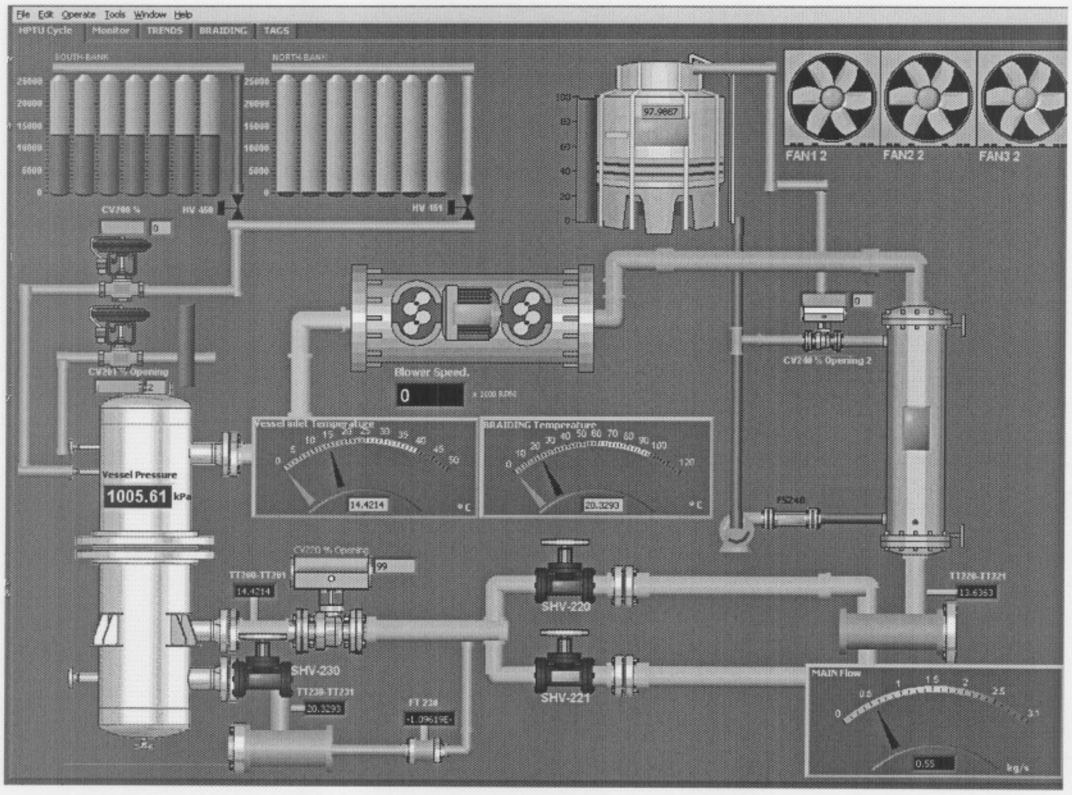


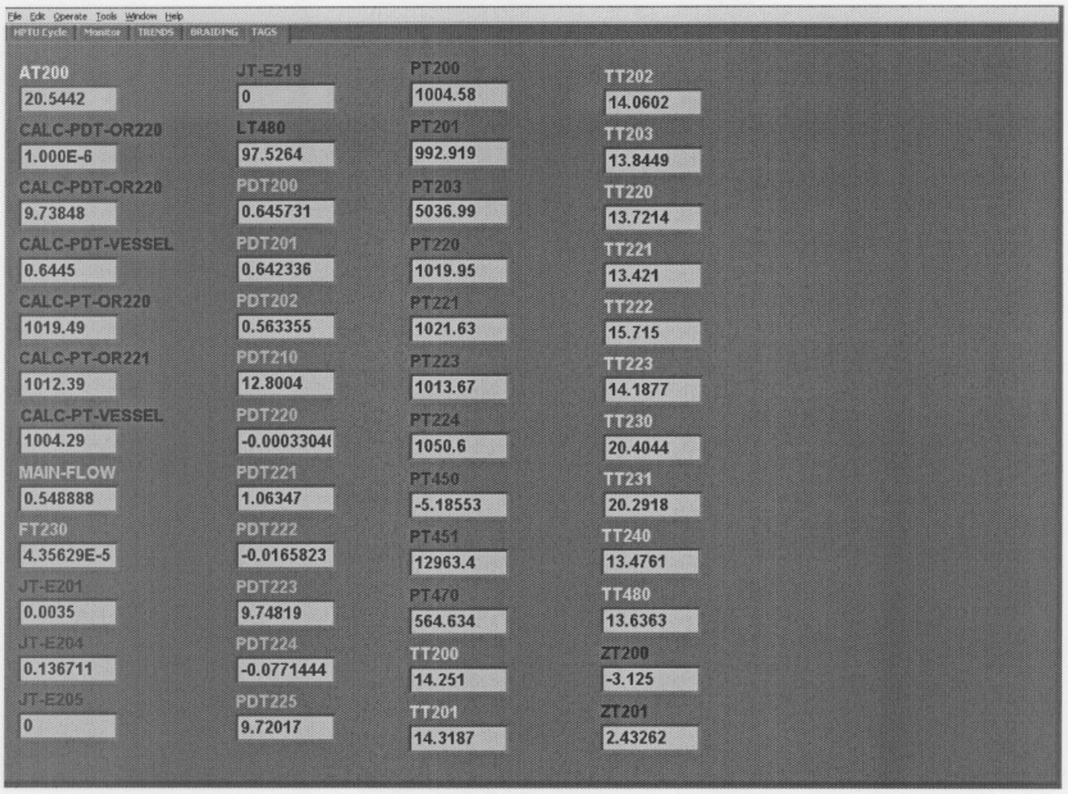
Figure 6.5: HPTU CYCLE Window

6.2.2 *Trends Window*

The trend window indicates a list of temperatures, pressures or flow rate related data. The list is pre-programmed although it is possible for the operator to modify existing tags and it is also possible to add and remove tags as required during runtime.

6.2.3 *TAGS Window*

This window displays a list of the most common used tags during operation. This is a quick reference for the operator to verify measurements.



AT200	20.5442
CALC-PDT-OR220	1.000E-6
CALC-PDT-OR220	9.73848
CALC-PDT-VESSEL	0.6445
CALC-PT-OR220	1019.49
CALC-PT-OR221	1012.39
CALC-PT-VESSEL	1004.29
MAIN-FLOW	0.548888
FT230	4.35629E-5
JT-E201	0.0035
JT-E204	0.136711
JT-E205	0
JT-E219	0
LT480	97.5264
PDT200	0.645731
PDT201	0.642336
PDT202	0.563355
PDT210	12.8004
PDT220	-0.00033046
PDT221	1.06347
PDT222	-0.0165823
PDT223	9.74819
PDT224	-0.0771444
PDT225	9.72017
PT200	1004.58
PT201	992.919
PT203	5036.99
PT220	1019.95
PT221	1021.63
PT223	1013.67
PT224	1050.6
PT450	-5.18553
PT451	12963.4
PT470	564.634
TT200	14.251
TT201	14.3187
TT202	14.0602
TT203	13.8449
TT220	13.7214
TT221	13.421
TT222	15.715
TT223	14.1877
TT230	20.4044
TT231	20.2918
TT240	13.4761
TT480	13.6363
ZT200	-3.125
ZT201	2.43262

Figure 6.6: Tags Window

7. Controllers Performance

This section discusses the testing of the HPTU PID controllers. All the controllers were tested during the commissioning phase of the HPTU plant and the results shown in this chapter was gathered to verify the performance of the specific controllers.

7.1 VESSEL INLET TEMPERATURE CONTROLLER

The mass flow through the HPTU has a direct effect on the temperature controllers and it is the variable that has the largest disturbance on the controller. The reason for this is that the mass flow removes the energy from the heater element and transports the temperatures through the piping systems pass the required temperature control point. When the mass flow increases the heater needs to supply more power in order to maintain the controlled temperature and when the mass flow decrease the heater need to reduce the amount of energy supplied to prevent the controlled temperature from overshooting the required value. The time it takes to change the controlled temperature also changes causing the controller to react faster and slower to prevent the controller to become unstable.

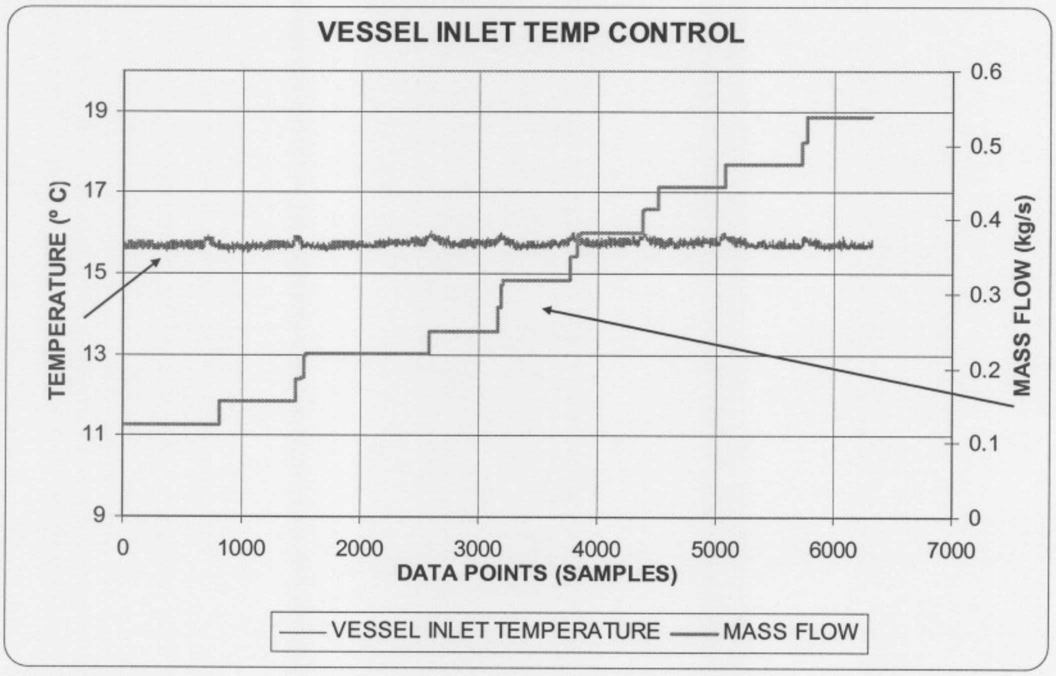


Figure 7.1 Vessel inlet temperature controller

The temperature controlled therefore has a set of PID constants that are used and changed automatically to maintain stability throughout the mass flow range. As a result of the large variety of tests at different pressures and mass flows the temperature controller will be tested to its limits by the step changes in these variables. Figure 7.1 illustrates the ability of the vessel inlet temperature controller to respond to disturbances.

The vessel inlet temperature controller requires to be controlled a few degrees above the heat exchanger outlet temperature. The set point is thus always different as a result of the changing ambient temperatures. The temperature controller uses a stepping control strategy and is demonstrated in Figure 7.2. This figure illustrates that the stepping control strategy is working very well and it is clear from the chart that the temperatures for each new mass flow is controlled to a new steady sate temperature.

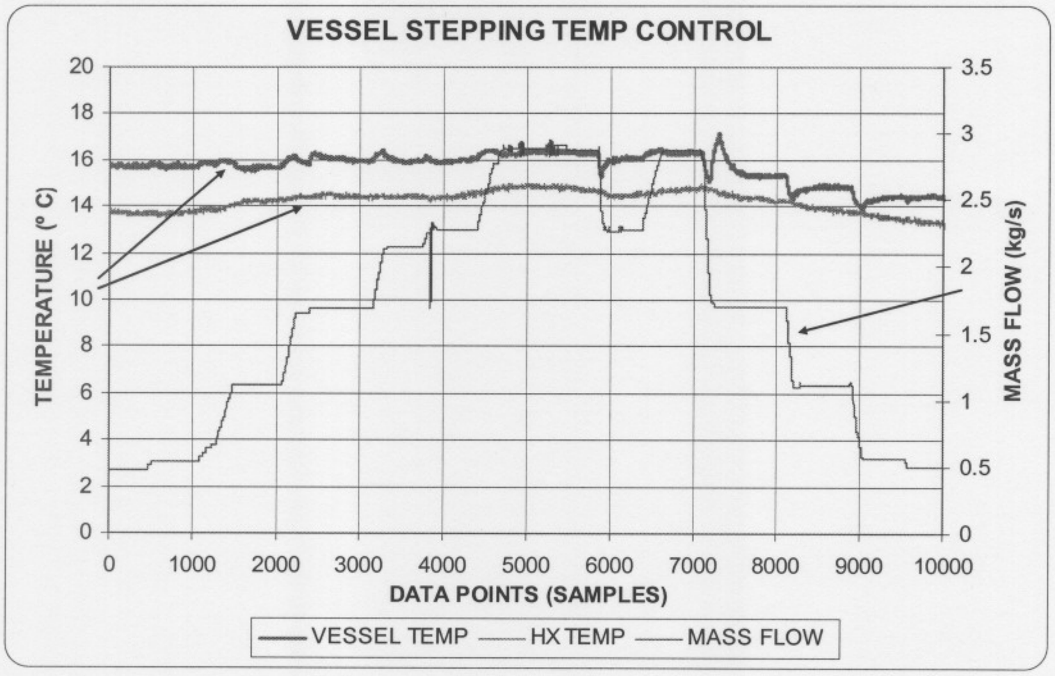


Figure 7.2 Vessel inlet temperature stepping controller

7.2 VESSEL PRESSURE CONTROLLER

The vessel pressure controller does not use an ordinary PID controller and has a different strategy (refer to section 5.4.6). A PID controller was tested at first but didn't manage to control the pressure. The problem was that the pressure control valve's upstream pressure was always relatively large when referring to the system pressure and the reason for this is the large variety of system pressures that need to be achieved during testing. The current controller open and close the valve very fast and prevent the pressure to overshoot. Figure 7.3 illustrates the ability of the pressure controller to control the pressure. Its clear from the chart that the controller has zero overshoot and the controller is much faster as indicated.

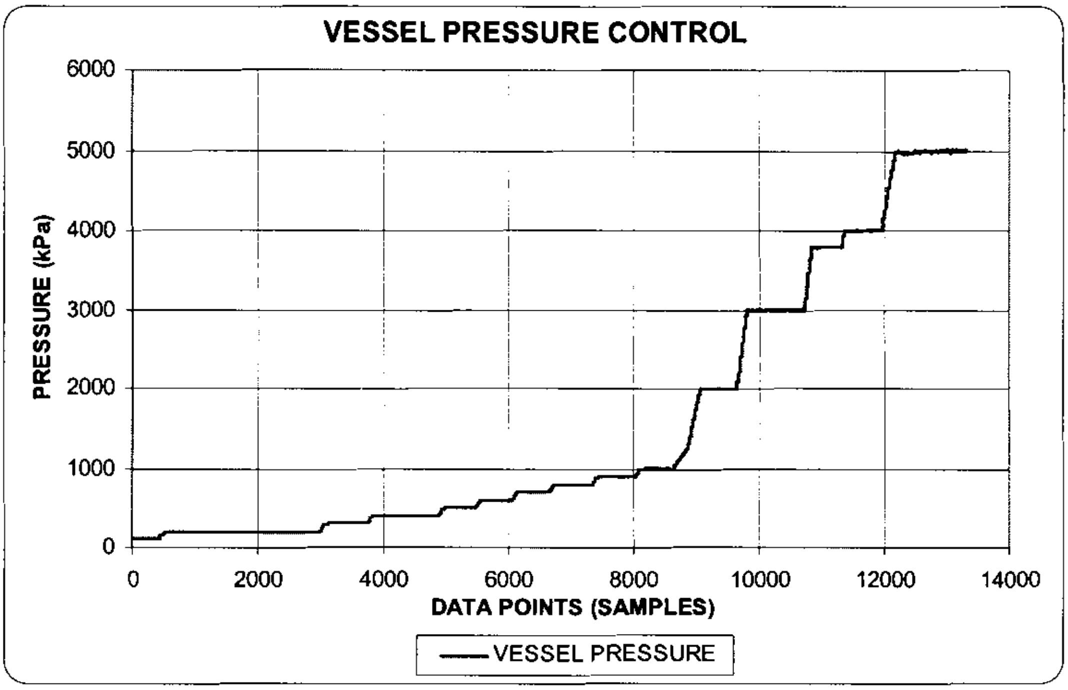


Figure 7.3 Vessel Pressure controller

7.3 HPTU REYNOLDS NUMBER CONTROLLER

The Reynolds number controller uses the variable speed blower to control the Reynolds number. This is the fastest PID controller in the HPTU, because from the moment the blower speed is changed the effect is almost immediately measured on the mass flow. This controller also has a large variety of control set points which varies from 1000 to 50 000 (Reynolds numbers). The PID constants were tuned manually for each set point during commissioning of the plant and programmed in such manner that the controller updates the PID constants automatically during operation. The results of the tested controller are shown in Figure 7.4 and Figure 7.5. There is though a small oscillations in the controller at 40 000 Reynolds number as shown. Some of the controller's PID constants are on the edge of being too aggressive and each of them needs to be reduced in order to properly control the Reynolds number.

The reason for this adjustment is that the mass flow calculation was upgraded after commissioning of the plant. The controller worked perfectly on the previous mass flow calculation which was calculated slower. When the calculation was upgraded to a much faster solution the response time of the plant's mass flow measurement was decreased and the effect is that the measurement is less damped. This was the first test run after the mass flow calculation upgrade and the new improvements will be tested during a second HPTU start-up.

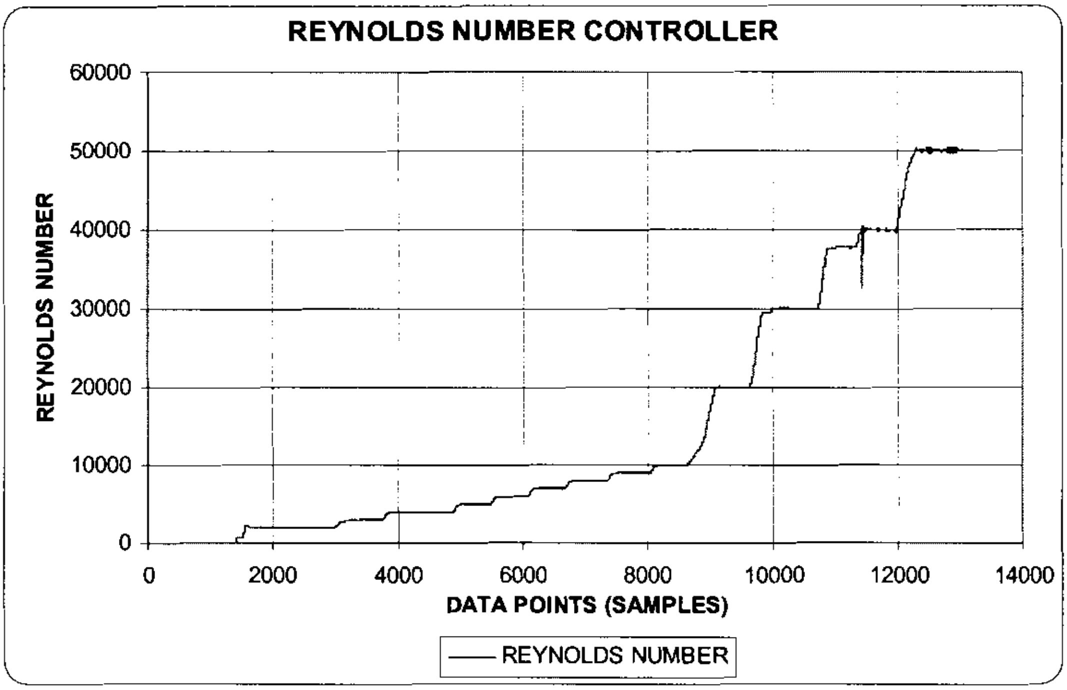


Figure 7.4 Vessel Reynolds number controller

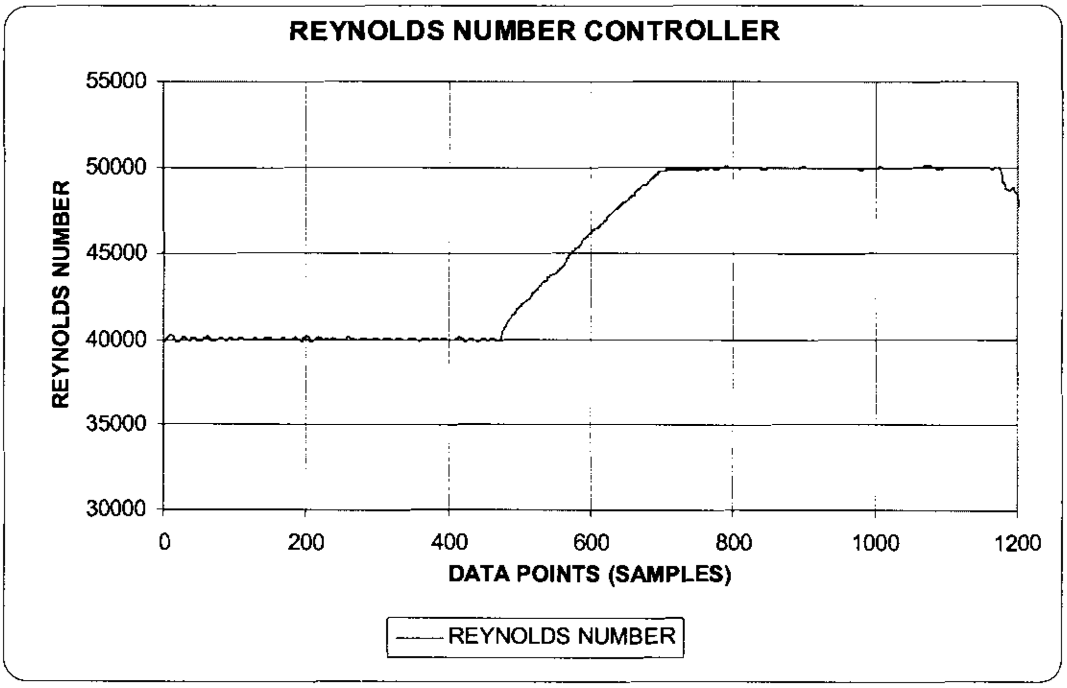


Figure 7.5 Vessel Reynolds number controller zoomed

7.4 CCTS SPHERE SURFACE TEMPERATURE CONTROLLER

The Convection Coefficient Test Section (CCTS) has a sphere heater controller that controls the surface temperature at a required set point. The time response of this controller is also relatively slow when referring to the size of this sphere, because the heat is transferred from the heater element to the surface by conduction. This sphere is by far the most sensitive component in the HPTU and it would be very expensive and time consuming to replace the sphere if it is damaged and that is why it should be operated cautiously. The sphere is controlled using an over damped control system to prevent the sphere heater element from overheating as a result of the controller over shooting.

The data shown in Figure 7.6 was produced during the commissioning of the CCTS test section and at that point the mass flow was not yet exported. The differential pressure over the orifice mass flow measuring station is proportional to mass flow and is used to illustrate the sphere surface temperature controller's ability to operate during a disturbance as a result of a change in mass flow. Figure 7.6 illustrates the over damped controller's performance with a mass flow disturbance.

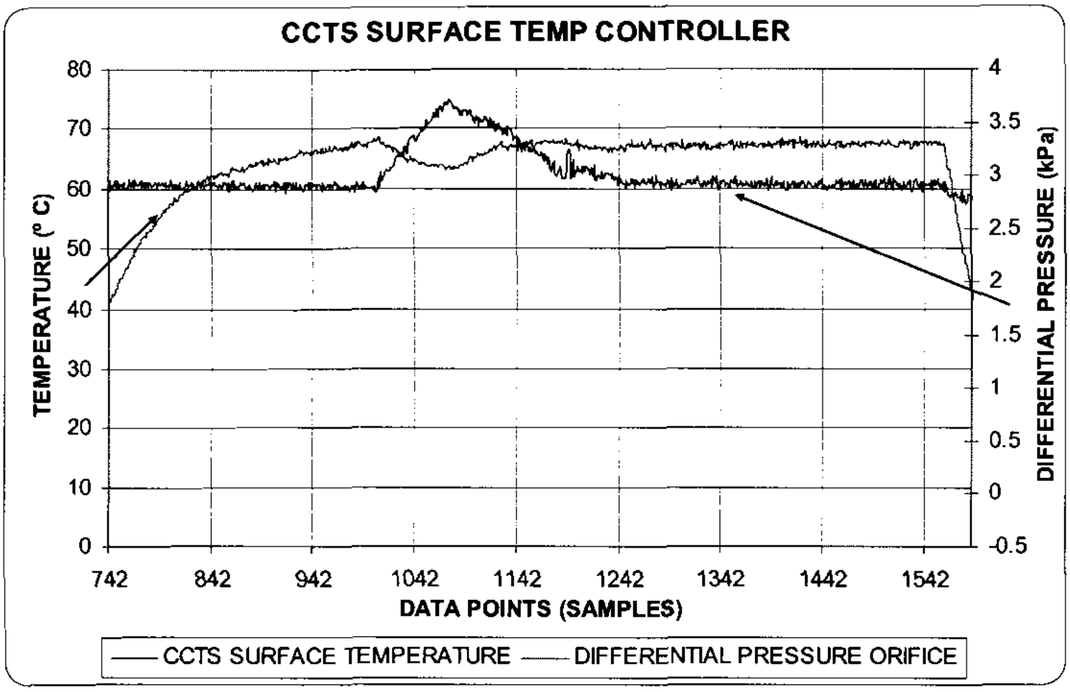


Figure 7.6 CCTS surface temperature controller

7.5 NWTS SURFACE TEMPERATURE CONTROLLER

The Near Wall Test section consists of two separate strip heater systems that are controlled by two separate PID controllers. The controller's purpose is to control the surface temperatures of the strip heaters at desired temperatures. The NWTS strip heaters has a surprisingly slow time response. The heaters also rely on conduction to transfer the heat from the heater element to the surface of the combined aluminium and copper structure. The surface temperatures are measured at two locations on each strip heater surface and the average of each heater are shown in Figure 7.7. The differential pressure indicates a decrease in mass flow to which the controller reacted very well. The full scale operation of the NWTS has not started yet and the controller can be fine tuned when this testing commences.

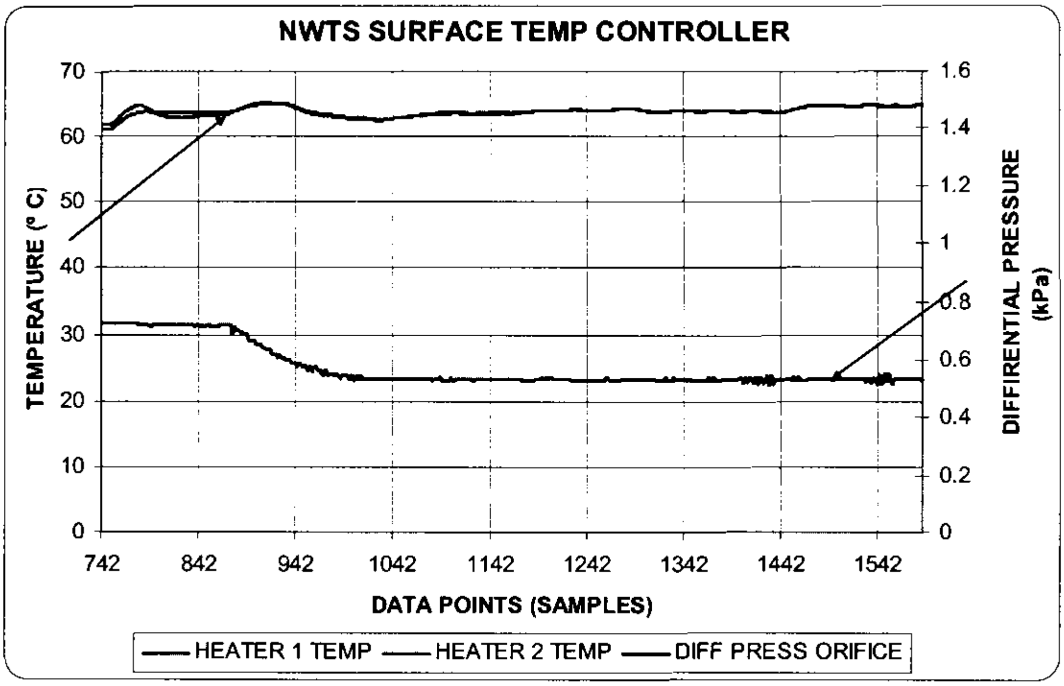


Figure 7.7 NWTS strip heater controllers

7.6 BRAIDING HEATER TEMPERATURE CONTROLLER

The braiding heater controller controls the braiding vessel inlet temperature. The controller controls the braiding temperature to 40°C above the vessel inlet temperature. The controller's inlet temperature are affected by the inline heater outlet temperature and when the inline heater receive a new set point, the braiding heater will be affected by this change in inlet temperature. This controller thus needs to out perform these deviations in temperature and compensate for it. Figure 7.8 illustrates the braiding heater controller performance together with the mass flow.

As previously mentioned, the mass flow was calculated very slowly as a result of PAC performance although this measurement was upgraded. The slow measurement is visible in the chart.

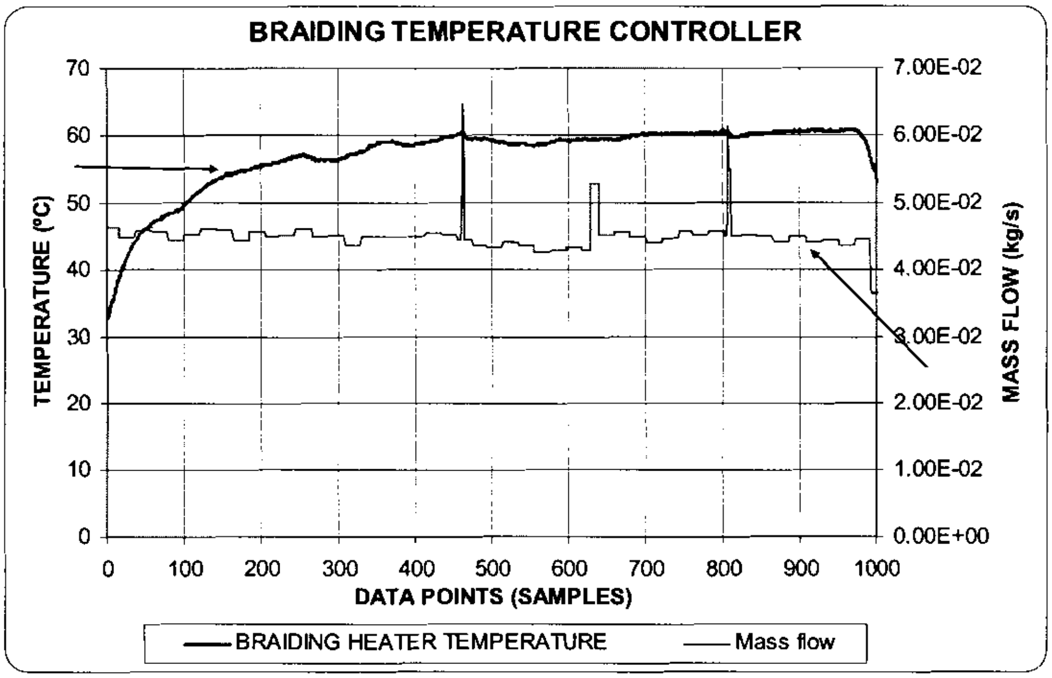


Figure 7.8 Braiding heater temperature controller

7.7 COMPARING PRACTICAL AND SIMULATION RESULTS

The HPTU simulator was the primary contribution to the control design of the inline heater temperature controller and the braiding heater temperature controller of the HPTU plant.

The simulations indicated that deviations in mass flow and pressure created large disturbances on the inline heater temperature controller. This implied that an automatic adjusting proportional integral variable controller would be required in order to control the plant through its operating ranges. This design was tested during simulations and various control PI variables was obtained for different operating scenarios. The response of the controller was then simulated in Figure 5.16 (temperature set-point step), Figure 5.17-Figure 5.18 (mass flow disturbances) and Figure 5.19 (pressure disturbances). These simulations indicated that the controllers are able to withstand any possible plant disturbances. The controller variables that were contained from the simulator worked very well when it was tested during the plant operation (Figure 7.1 and Figure 7.2). The variables were fine tuned during operation to optimize the controller's performance.

During the simulation of the braiding heater it became clear that the heater is also affected by mass flow and pressure changes. The design also incorporated automatic adjustment of the proportional and integral constants. The braiding heater temperature controlled was then tested with temperature set-point changes (Figure 5.21) and pressure deviations (Figure 5.24) to confirm controller performance.

The braiding heater controller was only tested during the commissioning of the plant. Some fine tuning might be required during the operation of the braiding heater to improve the performance of the controller.

8. Conclusion and Recommendation

8.1 CONCLUSION

The HPTU is a unique test plant making a high range of test and operating conditions possible. The plant's test vessel can be loaded with eleven types of separate test sections, enabling it to do these tests. Pressure ranges and mass flow conditions vary in every test that is conducted.

A design like this required a complex control system that would be able to control the plant during these variable test conditions.

Research was done on automation systems, process control, PID control, Industrial User Interfaces and on the PBMM control and protection system (a previous PBMR (Pty) Ltd developed plant). This information was used to design the ultimate safe and controllable plant possible. The user interface is the only communication between man and machine. It encouraged a large part of this project to be in the research, design and implementation of an easy to use and safe modern industrial user interface.

The modes and states were introduced to supply the reader with the required basic information regarding the operation of the HPTU plant. This information was then used to design the protection system in concept. The modes of the plant were implemented into the graphical user interface to constantly supply the operator with information regarding the current plant mode. This was a very useful tool during the testing and operation of the HPTU plant.

The protection system is split into the operational control system (OCS) and the equipment protection system (EPS). The OCS contains all the software which is necessary to control and protect the HPTU throughout all running and operating conditions. The OCS physically controls the plant by manipulating the actuators of the plant to perform the required functions. The heat exchanger cooling water system (HXCWS), which is part of the OCS, contains most of the controlling strategies and was discussed in detail. The heater and Blower systems have basically the same operating structures although the vacuum pump has a relatively large operating and protection system. The reason for this is that it is a very sensitive system because it is a low pressure system connected to the dangerously high pressure plant. This system is also fully automated to establish a very easy to use vacuum system and reduces the possibility of human error.

The protection systems where tested during construction with simulated scenarios and succeeded their first official tests during the commissioning of the plant.

The EPS is a backup protection system for the OCS to ensure that critical plant operating parameters are not exceeded. The operation of the backup protection system was tested throughout the commissioning of the plant. The OCS and even the EPS protected the plant during this commissioning phase and the importance of automatic control and protection systems was proven. There were even situations where the EPS had to interrupt and protect as a result of incorrect settings in the OCS and the importance of the HTPU backup protection system was confirmed. After minor adjustments to the OCS and EPS the operation of the protection system was fully operational and successful.

A HPTU simulation model was provided by the thermo fluid design team that was developed in Flownex. In order to do simulation a specific simulation configuration was developed for this project which includes the use of Labview that was used to develop the HPTU SCADA system. A connection between Flownex and Labview was established. This configuration opened opportunities that were unimaginable and the simulation of the HPTU was done very successfully. This implies that the simulation model became a plant SIMULATOR and the simulations could all be done in series without restarting the simulation. The operation of this simulator was very useful in the designing process of the controllers. The controllers were tuned with this simulator and the behaviour and characteristics of the plant were available. The simulator also helped to identify limitations in the design of the plant before the plant was completed and helped to correct the design without delaying the delivery date of the plant.

The simulations indicated that deviations in mass flow and pressure created large disturbances on the inline heater temperature controller and braiding heater temperature controller. This implied that an automatic adjusting proportional integral variable controller would be required in order to control the plant through its operating ranges. The designed controllers were tested and the simulations indicated that the controllers were able to withstand any possible plant disturbances. The results obtained during the commissioning of the plant clearly indicated that the inline heater temperature controller and braiding heater temperature controller worked very well.

The operators are dependent on the industrial user interface to detect, only by means of process visualization, and to react to unknown situations. Visibility of system status allows the user to observe the internal state of the system and to control required machines or PAC controlled systems for example the HPTU cooling water system.

The user interface was designed according to information acquired during research on industrial user interfaces. The issues involved when developing high redundancy and critical application user interfaces were studied to ensure that the HPTU user interface is a redundant high quality interface. Menu selections were also investigated to develop an easy to use human machine interface. Alarms where implemented, in the form of filling sliders which are located at all the local systems' windows, to warn the operator of a developing problem before it occurs. This is a very useful tool and many plant trips have already been prevented with this alarming indication. This was also useful during the commissioning phase of the project to identify trip margins that were at unreasonable values.

The HPTU controller's ability to control and maintain controlled conditions during operation was tested and confirmed. The HPTU plant is operated by running at least three controllers at once. The HPTU has a closed cycle and therefore all the controllers affect each other and these controllers continuously receive very different set point values which contribute to the complexity of the HPTU control systems.

The controllers performances was illustrated and the conclusion is that all the controllers are working perfectly when kept in mind that the controllers are exposed to very high disturbances from the other controllers during testing.

The data shown was collected during the commissioning of the plant through a very short testing period. This implies that most of the test sections were tested only once or twice and the ability to fine tune all the controllers was not of the highest importance at that time, thus only the performance was tested. The controllers will be more closely investigated during the long operating periods in order to fine tune controllers if necessary.

8.2 RECOMMENDATIONS

There are a few recommendations that could help in the development of future modern industrial control systems. The first one is that the EPS consists of separate components each responsible for the backup protection of its own hardware component. The units are each programmed manually via its own local interface. The units are basically programmable relays which work together. If the unit detects a fault condition it will disengage the specific hardware component's main isolator breaker. The breakers are also "fail open", which implies that if a wire is damaged and the connection is lost the breakers will simply open. This will cause the main breaker to disengage. The EPS is constructed into its own separate enclosure located next to the PAC enclosure. The disadvantage of this system is that the operator does not immediately know what the problem is when the EPS engages a fault condition and needs to open the EPS

enclosure to identify possible engaged interlocks. This was confusing at times because the OCS is supposed to handle every possible problem. This implies that the operator almost forgets about the EPS operation and when the EPS engages the operator tends to run around before identifying the problem. The recommendation is that a more automatic protection system, that will have communication to the graphical user interface, should rather be used in future. This will warn the operator that the EPS has engaged, and the operator then knows that the plant is in a safe mode. Feedback from the EPS is thus required. There is, however, no problem with the redundancy and ability of the current EPS to protect the plant under any circumstances. The current EPS is less expensive for the current amount of channels that requires protection, although for a larger number of channels it is advised to opt for a backup type of PLC or PAC.
The simulator for the HPTU project was only available at a very later stage of the project. This simulator had identified problems that could have been identified earlier. This would have been much less stressful on the design team.

The HPTU project is an enormous milestone for PBMR and Mtech Industrial. It produced a lot of interests amongst the staff and partners of both companies. There were visitors to the plant, almost constantly. The visitors caused the operators to experience a lot of stress, especially during maiden start-up exercises. The operators constantly needed to switch between menus to operate the plant. The problem can be solved by modifying the control room design to accommodate the visitors. One way to accomplish this is to implement more static displays. However, the available space was limited for extra displays for the HPTU project.

Most of the HPTU's controllers were tuned and tested during commissioning, although there were a few of them that were not tested throughout their working ranges. They are the Near Wall Test Section (NWTS), the Convection Coefficient Tests Section (CCTS) and the braiding heater. It is recommended that the controllers are tuned throughout their working ranges to ensure that they are stable during all possible disturbances.

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10. APPENDIX A

10.1 HPTU MEASUREMENT & CONTROL REQUIREMENTS

10.1.1 HPTU I/O Requirements

The HPTU inputs/outputs requirements are shown in Table 4. The table includes the number of (4-20mA) analog inputs and outputs and the number of (0-24vDC) digital inputs and outputs together with the amount of Thermocouples.

Table 4: Number and type of I/O for the HPTU test system

HPTU						
PAC (C)						
I/O Type	**Part Name & Number**	**cFieldPoint I/O Amount**	**CFIELDPOINT channel p/u**	**QTY. CFieldPoint I/O units**	**Spare ports**	**MAX**
Analogue Inputs 4-20mA	cFP-AI-111	45	16	3	3	48
Analogue Inputs Thermo couples	cFP-TC-120	n/a	8	n/a	n/a	0
Analogue Outputs	cFP-AO-200	10	8	2	6	16
Digital Inputs	cFP-DI-301	29	16	2	3	32
Digital Outputs	cFP-DO-401	13	16	1	3	16
	Total	**97**		**8**		**112**

PAC (D)						
I/O Type	**Part Name & Number**	**cFieldPoint I/O Amount**	**CFIELDPOINT channel p/u**	**QTY. CFieldPoint I/O units**	**Spare ports**	**MAX**
Analogue Inputs 4-20mA	cFP-AI-111	0	16	0	0	0
Analogue Inputs Thermo couples	cFP-TC-120	64	8	8	0	64
Analogue Outputs	cFP-AO-200	0	8	0	0	0
Digital Inputs	cFP-DI-301	0	16	0	0	0
Digital Outputs	cFP-DO-401	0	16	0	0	0
	Total	**64**		**8**		**64**

11. APPENDIX B

11.1 CONTROL SYSTEM EQUIPMENT

In this section the hardware selection and configuration of the PAC (Programmable automation controllers) are discussed. An Introduction to Labview and Flownex are supplied together with a description of OPC servers.

11.1.1 Measurement and CONTROL Hardware configuration

The HPTU will use a PAC (Programmable Automation Controller) The HPTU measurement and control hardware configuration is shown in Figure 11.1

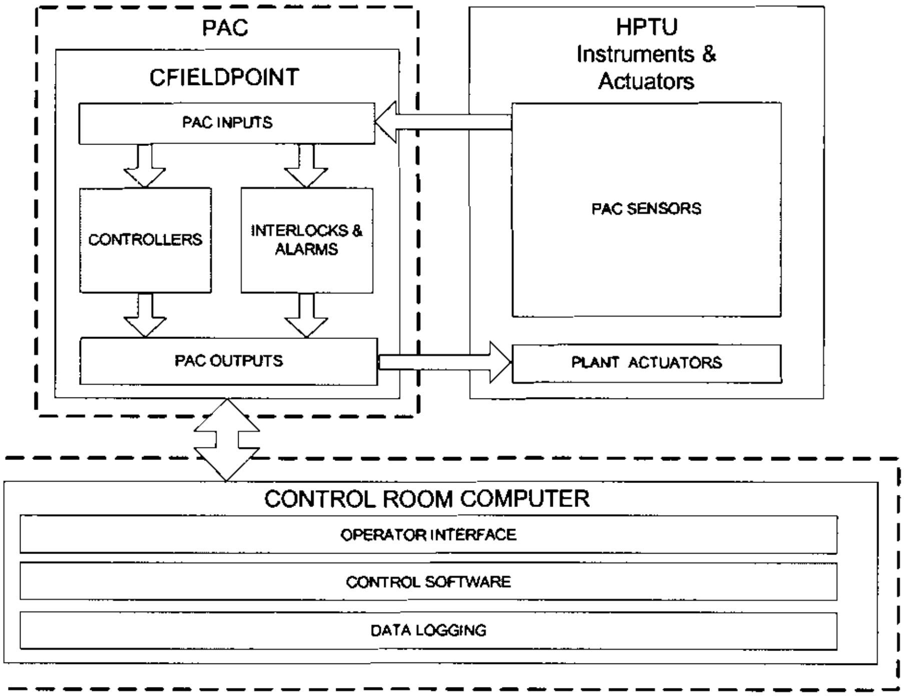

Figure 11.1: HPTU Measurement & Control Hardware Configuration

11.1.2 Measurement and control hardware selection

NI CompactFieldPoint is a modular distributed I/O system for PC-based measurements, control and data logging applications that demand high accuracy industrial grade I/O. CompactFieldPoint is designed to be mounted on DIN rails in static applications where the CompactFieldPoint bank is connected to a PC for data collection, analyses, display and storage. CompactFieldPoint system has I/O control units that incorporate real-time embedded control.

A single CompactFieldPoint setup constitutes up to 8 I/O devices and one CompactFieldPoint embedded controller. The figure below illustrates a scenario where a combination of embedded CompactFieldPoint controllers is used together with the Ethernet interface units.

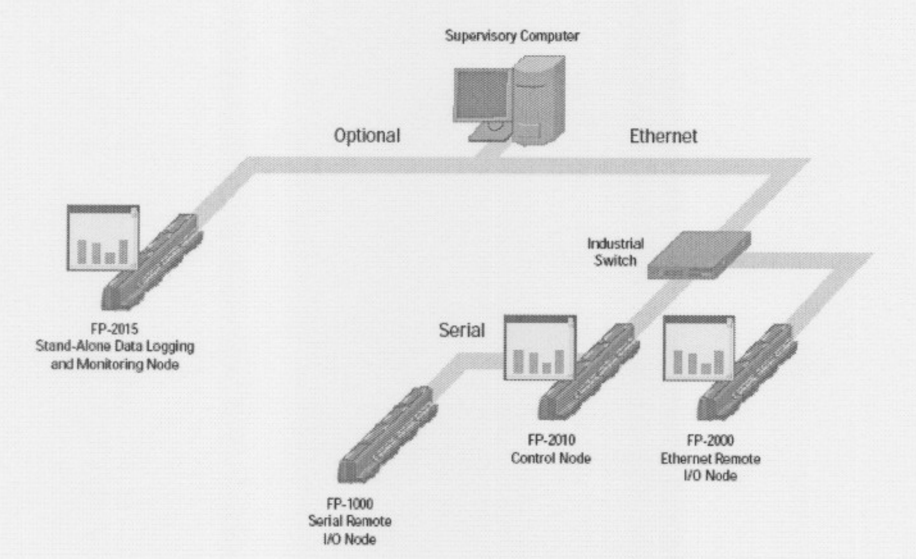

Figure 11.2: Real-time Labview embedded control together with I/O Ethernet interface

Figure 11.3 shows a picture of this component while the typical configuration for a large amount of I/O can be seen in Figure 11.4.

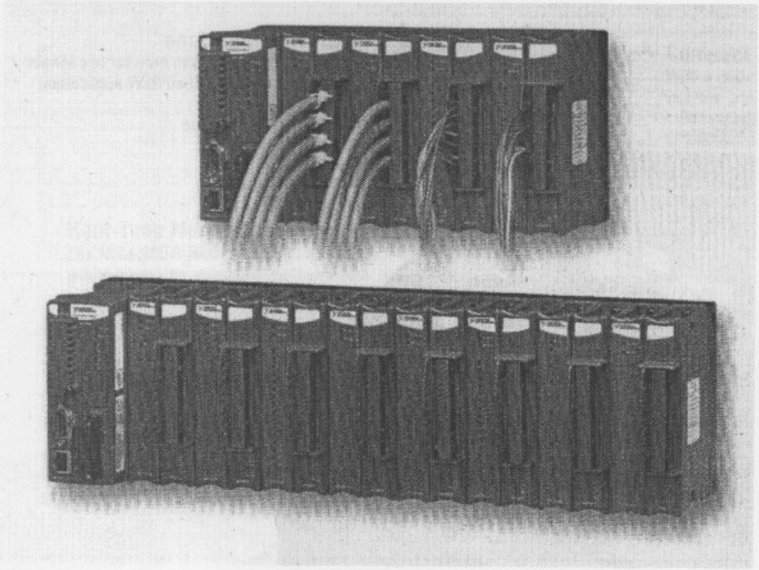

Figure 11.3: Compact Fieldpoint Chassis

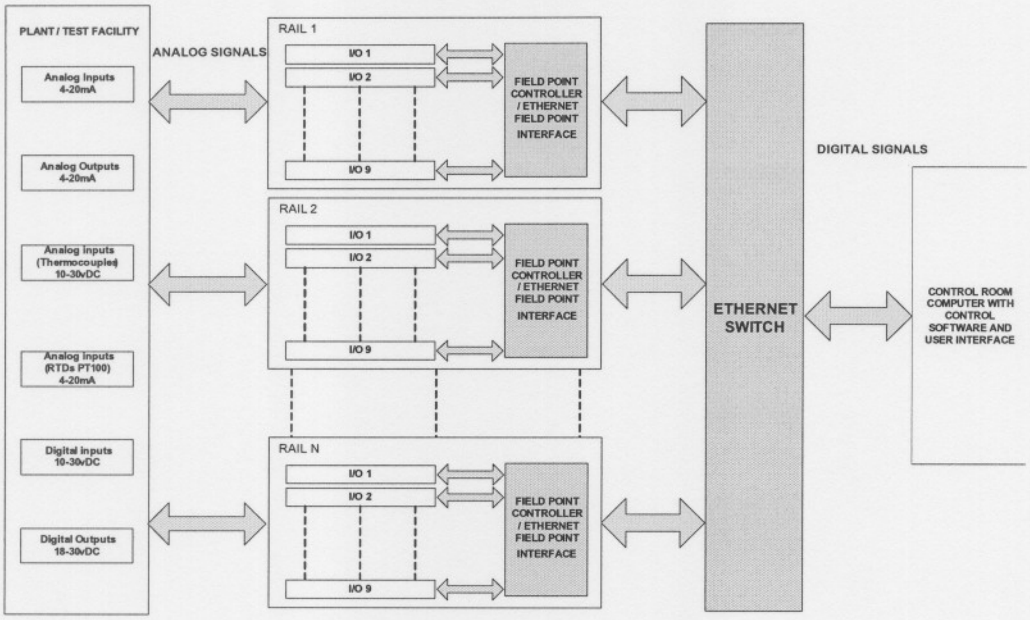

Figure 11.4: NI CompactFieldPoint configuration for large amount of I/O

A disadvantage of the CompactFieldPoint system is that the sampling rates of certain I/O modules are relatively low (Approx the same as PAC systems).

11.2 INTRODUCTION TO LABVIEW

LabVIEW is a graphical programming language that uses icons instead of lines of text to create applications. In contrast to text-based programming languages, where instructions determine program execution, LabVIEW uses dataflow programming, where the flow of data determines execution.

In LabVIEW, you build a user interface by using a set of tools and objects. The user interface is known as the front panel. You then add code using graphical representations of functions to control the front panel objects. The block diagram contains this code. In some ways, the block diagram resembles a flowchart.

The Labview programs for the cooling water system's starting mode are show in Figure 11.5.

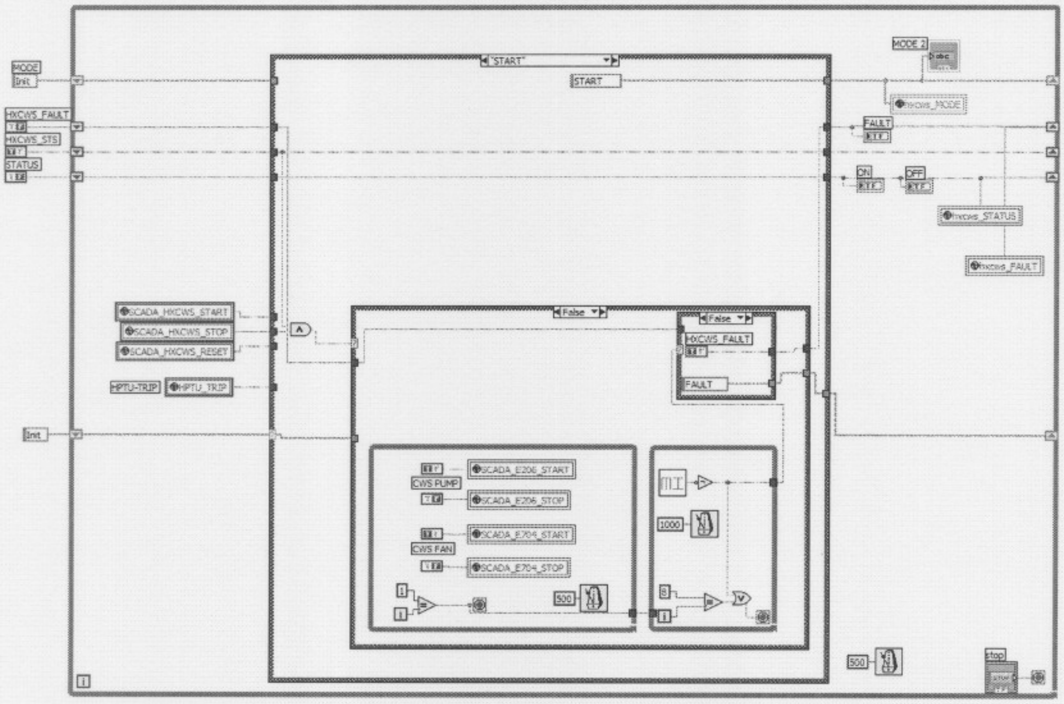

Figure 11.5: The Labview Heat exchanger cooling water system starting mode

11.3 OPC SERVER

OLE for Process Control (OPC) is a protocol for communication between Windows programs. The SIXNET OPC Server allows any Windows application with an OPC client to access SIXNET I/O registers in the SIXNET I/Omap. Once the SIXNET OPC server is running, all I/O registers in the I/Omap database are available to any OPC-compatible program. The I/O registers are referenced by the tag names assigned using SIXNET Windows programs such as the SIXNET I/O Tool Kit. All data passed to the OPC Client will be date and time stamped.

11.4 FLOWNEX

Flownex is a thermal-fluid network analysis code that enables users to perform detail analysis of complex systems such as:

- High temperature gas-cooled nuclear power plants
- Thermal power plants
- Heat exchanger networks
- Jet engine combustion systems
- Air cycle cold air units
- Gas distribution networks

- Compressed air systems
- Ventilation systems
- Water or fuel distribution networks

12. APPENDIX C

This section shows photos taken of the HPTU plant.

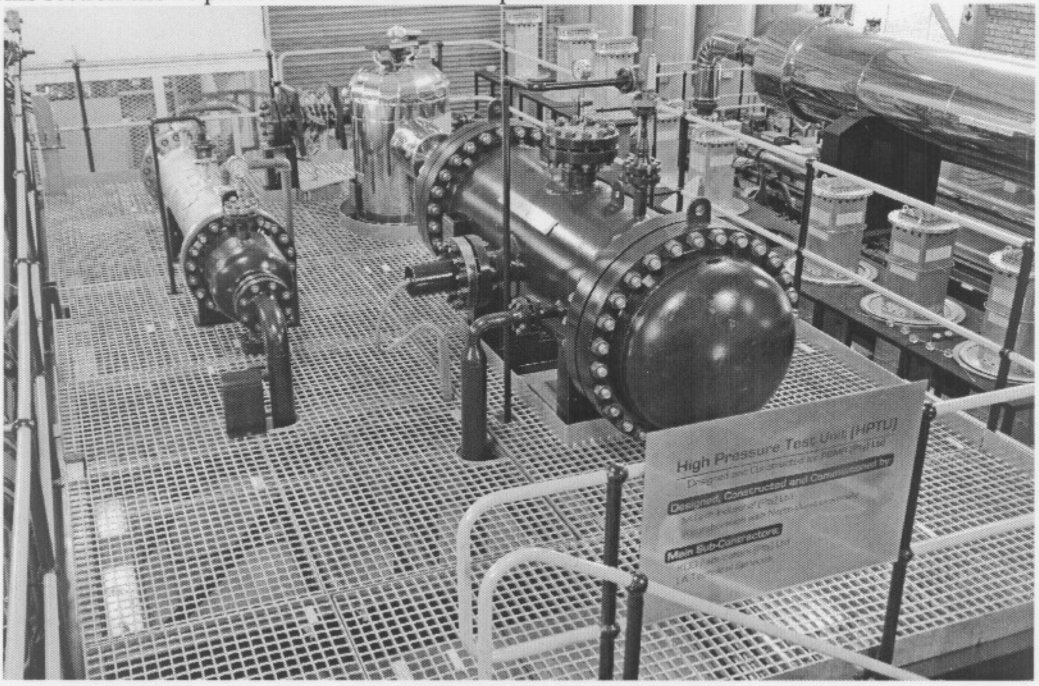

Figure 12.1: Top view of the HPTU plant

Figure 12.2: Top view from the North

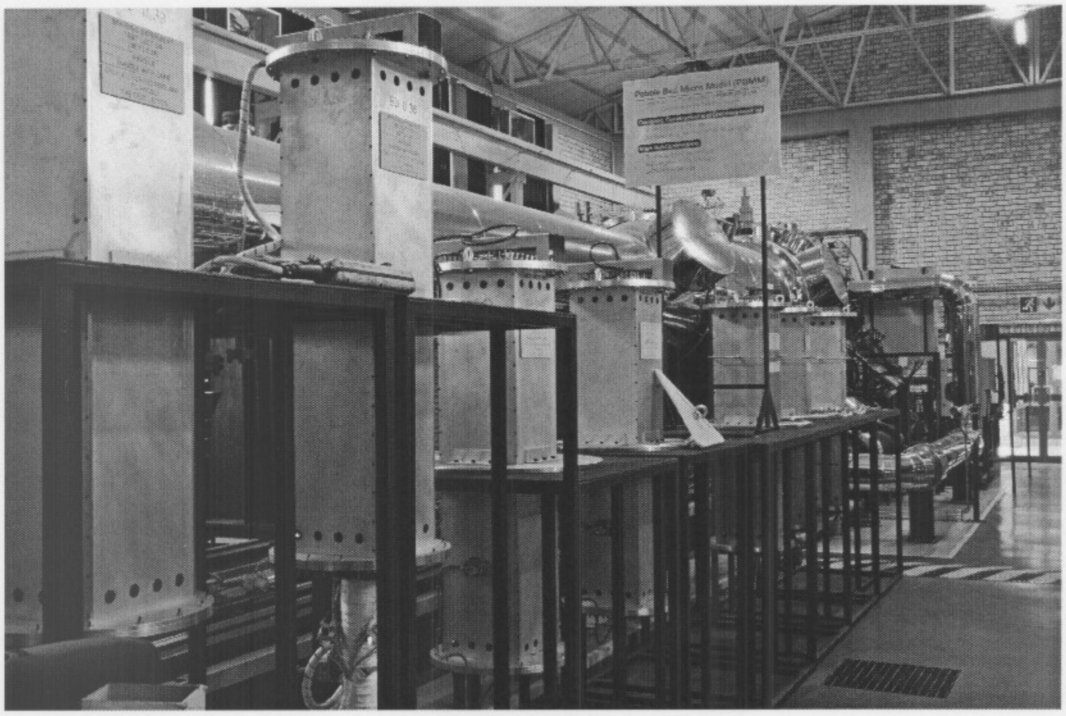

Figure 12.3: HPTU test sections