
**A THERMO-HYDRAULIC MODEL OF THE
INVENTORY CONTROL SYSTEM FOR
LOAD FOLLOWING IN THE PBMR**

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I would like to dedicate this piece of work to Noah and Lizzie (my parents), who have and continue to show ineffable love and support throughout my endeavours.

ABSTRACT

This dissertation is aimed at the development of a thermo-hydraulic model of the Inventory Control System (ICS) for the Pebble Bed Modular Reactor (PBMR), which is a helium-cooled nuclear power plant. The model is used as a design and simulation tool. The ICS is a storage facility whose function is to perform load following through helium mass transfer to and from the PBMR power cycle. This mass transfer generally uses pressure differential as the driving force.

With a view to minimize the storage volume of the ICS, and hence improve the economics of the design, several concepts were investigated, many of which attain storage effectiveness by employing a heat transfer mechanism for cooling or heating the helium appropriately during mass transfer. From this, a suitable concept for the ICS was found to be a multi-tank arrangement, with a heat capacitance within each tank. This heat capacitance is in the form of perforated steel, and provides the heat transfer mechanism that aids mass transfer under pressure differential.

The thermodynamic model of the multi-tank concept, owes its foundation to the conservation principles of mass, energy and momentum, and includes a cost structure to address the economic aspect of the design. This model is developed in the Engineering Equation Solver (EES) software environment.

For a specified power reduction down to 45% of the full power (166 MW), the ICS must store at least 2.4 tonnes (from a total of 4.7 tonnes) of helium. To do this, the optimal design entails an arrangement of six similarly sized tanks with a total storage volume of 609 m³, 2.5% of which is occupied by the heat capacitance.

An alternative model developed in Flownex was used to validate the EES model. Good correlation was obtained overall, particularly with regards to the tank pressures during helium mass transfer. As a result, the thermo-hydraulic model was deemed suitable as a design and simulation tool.

SAMEVATTING

Die doel van die verhandeling is om 'n termo-hidrouliese model van die korrelbedkernreaktor (PBMR – Pebble Bed Modular Reactor) se inventarisbeheerstelsel (ICS – Inventory Control System) te ontwikkel. Helium word gebruik as koelmiddel vir die reaktor. Hierdie model word gebruik in die ontwerp en simulاسie van die ICS. Die kraguitset van die PBMR word deur die ICS beheer. Dit word gedoen deur meer of minder helium in die ICS te stoor en sodoende die heliuminventaris in die PBMR se kragopwekkingsiklus te beheer. Wanneer 'n lae kragvlak benodig word, word van die inventaris na die ICS oorgedra en omgekeerd. Inventaris word tussen die kragopwekkingsiklus en die ICS oorgedra deur die drukverskil tussen die stelsels.

Verskeie konsepte is geëvalueer om die storingsvolume van die ICS te minimeer vir ekonomiese oorwegings. Vir baie van hierdie konsepte is 'n ekonomiese storingsvolume verkry deur 'n meganisme wat hitte aan die helium in die ICS oordra of ontrek tydens die oordrag van helium tussen die stelsels. 'n Gepaste konsep is verkry en bestaan uit 'n multi-tenk stelsel met addisionele termiese kapasitasie in elke tenk. Die addisionele hittekapasitasie, bestaande uit geperforeerde staal, word dan gebruik as die hitteoordragmeganisme wat die oordrag van helium tussen die stelsels bevorder.

Die termo-hidrouliese model van die multi-tenk ICS is gebaseer op die behoud van massa, energie en momentum. Hierdie model sluit ook kostestrukture in om die ekonomiese oorwegings van die ontwerp te evalueer. Engineering Equation Solver (EES) is gebruik om hierdie model te ontwikkel.

Wanneer die maksimum krag produksie (166 MW) verlaag word tot 45% krag moet die ICS 2.4 ton helium (van die totale 4.7 ton) stoor. 'n Optimale ontwerp wat bestaan uit ses soortgelyke tenks met 'n totale volume van 609 m³ is hiervoor geselekteer. Die termiese kapasitasie beslaan 2.5% van die volume.

'n Alternatiewe model is in Flownex ontwikkel om die EES model se resultate te verifieer. Hierdie model gebruik soortgelyke randwaardes as die EES model. Die metodes vergelyk baie goed. Veral die tenkdrukke tydens heliumoordrag na die kragopwekkingsiklus het baie goed vergelyk. Gevolglik is die termo-hidrouliese model geskik vir ontwerp en simulاسie werk.

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ABBREVIATIONS

Abbreviation or Acronym	Definition
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
CV	Control Volume
DLL	Dynamic Link Library
GBP	Gas Cycle Bypass Valve
GBPC	Gas Cycle Bypass Control Valve
GUI	Graphical User Interface
HC	Heat Capacitance
HICS	Helium Inventory Control System
HP	High Pressure
HPB	Helium Pressure Boundary
HPC	High-pressure Compressor
HPT	High-pressure Turbine
IC	Intercooler
ICS	Inventory Control System
LCV	Low-pressure Coolant Valve
LP	Low Pressure
LPB	Low-pressure Compressor Bypass
LPC	Low-pressure Compressor
MCR	Maximum Continuous Rating
MCRI	Maximum Continuous Rating Inventory
MPS	Main Power System
OCS	Operational Control System
PBMR	Pebble Bed Modular Reactor
PC	Pre-cooler
PCU	Power Conversion Unit
PT	Power Turbine
RBP	Recuperator Bypass Valve
RC	Reactor Cavity
RD	Restrictor with discharge coefficient
Re	Reynolds number
ROT	Reactor Outlet Temperature

1 INTRODUCTION

1.1 Subject

This dissertation describes the development and simulation of a thermo-hydraulic model of the Inventory Control System (ICS) that is used for load following in the Pebble Bed Modular Reactor (PBMR).

1.2 Background to load following

With regards to power plant engineering, load following can be understood as the ability of the plant to respond to a fluctuating power demand. In the case of electricity generation, consumption or demand may vary dramatically over a 24-hour period, with very high consumption - peak demand, at certain periods and very low consumption - off peak, at other periods. The idea in general, is for the plant to be able to store, or save energy during off-peak periods and replenish this energy during peak demand periods.

1.3 Objective

This exercise is aimed at;

- i. Developing a comprehensive thermo-hydraulic model of the ICS for load following, through research and thermodynamic applications. This model will be used as a design tool for determining a suitable ICS design that can achieve a specified performance. Sensitivity analyses will be used to rank the design parameters on a scale which reflects the cost to benefit ratio.
- ii. Generating simulations of the model as a way of verifying the thermo-hydraulic model and to characterize the response of the PBMR due the ICS operation.

1.4 Sources of information

Sources of information included research into patents and journals for known techniques of load following. The conservation principles of mass, energy and momentum formed the basis of the thermo-hydraulic model.

1.5 Scope of the research and development of the ICS

The scope of the research and the development of the ICS investigates load following primarily in the context of transferring the working fluid medium across the boundary of the power conversion unit (PCU) of a gas cycle.

1.6 Plan of development

Following an overview of the PBMR, the document presents a survey of known techniques for load following in the context of transferring a working fluid across the PCU of a gas power cycle. The emphasis of the survey is directed towards minimising the storage volume of the ICS which will effect the load following. A technique that is suitable to the PBMR is chosen as the basis of the ICS design. Thereafter the development of the ICS thermo-hydraulic model is described, before an optimal solution resulting from the model, is presented. A validation is made on the model before characterising the response of the power plant due to the ICS operation. Finally a set of conclusions and recommendations is drawn.

2 LITERATURE SURVEY

2.1 Background to the PBMR power cycle

The Pebble Bed Modular Reactor (PBMR) offers a safe, clean and cost effective means of converting nuclear energy for the purposes of electricity production [1]. The current PBMR power plant concept features a single shaft, two-stage, recuperative Brayton cycle. Helium gas [20] is the preferred working medium owing to its chemical and radioactive inertness. The Main Power System (MPS) of the PBMR, which runs on the Brayton cycle, circulates helium through the core of the reactor and through a configuration of turbo-machinery, the latter of which constitutes the Power Conversion Unit (PCU).

With reference to Figure 1, the helium flow-path [39] can be explained as follows:

- **1-2:** Helium gas enters the Reactor at 1, at a temperature of approximately 500°C. As the gas flows through the core of the reactor, it absorbs heat from the nuclear reaction within the pebbles and exits and point 2.
- **3-4:** The gas enters the Power Turbine (PT) at point 3, where the gas expansion drives the shaft onto which the Power Turbine (PT) is mounted. The fluidic power produced by the PT is partially transmitted to the Low Pressure Compressor (LPC) and the High Pressure Compressor (HPC), both of which are downstream in the flow-path. The rest of the power is transmitted to the electrical grid network via a gearbox. At 4, the expanded helium exits the PT.
- **5-6:** The gas leaving the PT enters the recuperator (RX) at 5, through which heat is exchanged with cooler gas further downstream. At 6 the helium exits the recuperator at approximately 130 °C.
- **7-8:** The helium gas enters the Pre-Cooler (PC) at 7, where it exchanges heat with water at ambient conditions, and leaves the PC at 8 before entering the LPC.
- **9-10:** Between points 9 and 10, compression takes place, and at the latter, the compressed helium is conveyed to the Inter-Cooler (IC) downstream.
- **11-12:** Further cooling occurs in the intercooler between points 11 and 12.

- **13-14:** Further compression at the HPC, which lies between 13 and 14, is carried out. At 14 the helium leaves the HPC at 90bar and approximately 100°C before entering the recuperator again, but this time, to absorb heat from the upstream side of the circuit.
- **15-16-1:** At 15 the gas enters the recuperator to absorb heat from upstream gas. Point 16 sees the completion of the gas cycle as the helium is conveyed back to the inlet of the reactor at 1.

The Gas Cycle Bypass valves (GBP and GBPC) are used to bypass the flow to the RX, RC and PT. The Low Pressure compressor Bypass Valve (LPB) and Recuperator Bypass Valve (RBP) are used to bypass the LPC and the RX respectively. The Low Pressure Coolant Valve (LCV) directs cooling flow from the HPC outlet, to the downstream side of the PT.

Within the PBMR, **load following** is performed by withdrawing gas at the HPC outlet (14) (See Figure 1), if the need is to reduce power output to the grid, and by injecting the gas at the PC inlet (7), if the need is to increase power output to the grid. With the Brayton Cycle [9] in operation, the power output to the grid is nearly proportional to the amount of helium gas in circulation, provided all gas bypass valves are closed and the Reactor Outlet temperature (ROT) is maintained at its design point of 900 °C.

The facility that is responsible for storing and replenishing the helium as it is transferred to and from the MPS power cycle is known as the **Inventory Control System (ICS)**. Helium mass transfer between the MPS and the ICS is performed using pressure differential as the driving force. The HPC outlet is chosen as the extraction point, as this is the highest pressure point in the PCU, and so will provide the highest potential relative to the ICS which will initially be at a low pressure. On the other hand the PC inlet serves as the injection point as this is almost the lowest pressure point in the MPS. As such, stored helium in the ICS will see a low potential through the PC inlet when replenishing the helium to the MPS. The use of pressure differential to carry out helium mass transfer aims to reduce the reliance on auxiliary power sources outside the PCU.

The objective of this exercise is to develop a thermo-hydraulic model of the ICS with a view to use this model as a design and simulation tool. The following section of this

literature survey is aimed at exploring a few concepts, similar in role to the ICS, before selecting a suitable concept that will form the basis of the model. The emphasis of the survey will be on methods to minimise the volume of this gas storage facility, as this will ultimately have a cost advantage.

2.2 ICS Concept Survey for load following

Figure 2 shows a simplified schematic layout of a closed loop recuperative Brayton cycle on which the PBMR [1] is based. The flow-path is numbered to correspond with Figure 1. The two-stage compression and inter-cooling is simplified by a compressor which lies between 9 and 14. The reservoir is representative of the ICS and is connected to 14 for extracting helium, and to 7 for injecting helium.

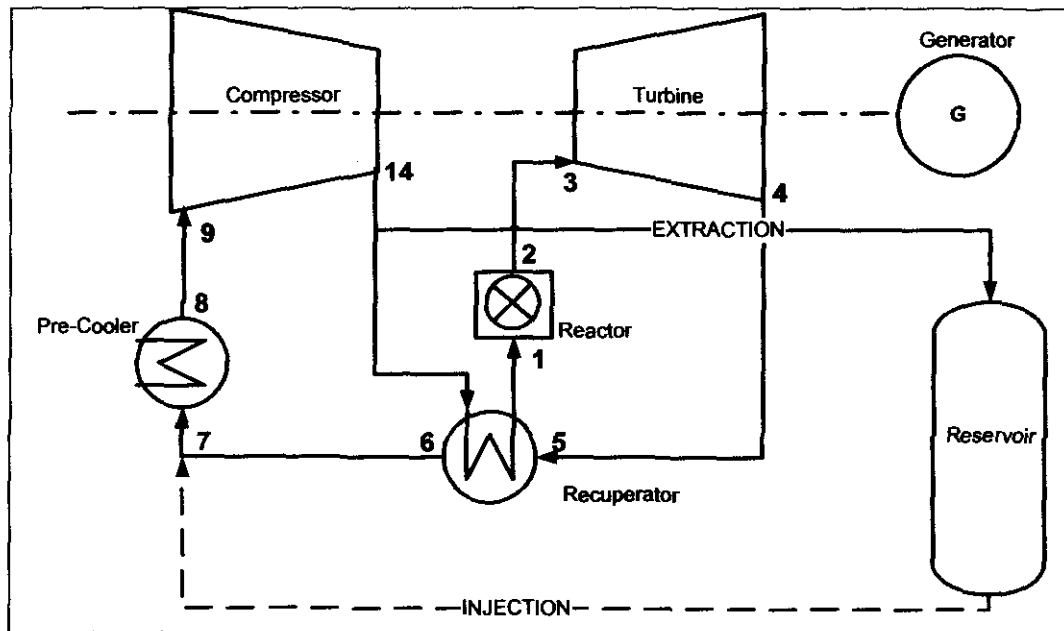


Figure 2: Closed Loop Power Plant

Figure 3 shows how the pressures at the extraction and injection points vary, as well as the reservoir pressure, during mass transfer. If the only means of extracting helium is by way of pressure differential, then it is clear that the reservoir or ICS pressure must always be lower than the pressure at point 14, P_{14} , until equalisation occurs. Conversely to inject under pressure differential, P_{ICS} must always be higher than P_7 . The minimum power at which the Brayton Cycle is self-sustaining is typically 40% [4] of the maximum.

This means the ICS must be able to store all the helium required to bring the power down to the prescribed minimum. Attempting to operate the Brayton Cycle at less than 40% power, may lead to the undesirable increase in Xenon concentration, a poison to the nuclear reaction [8]

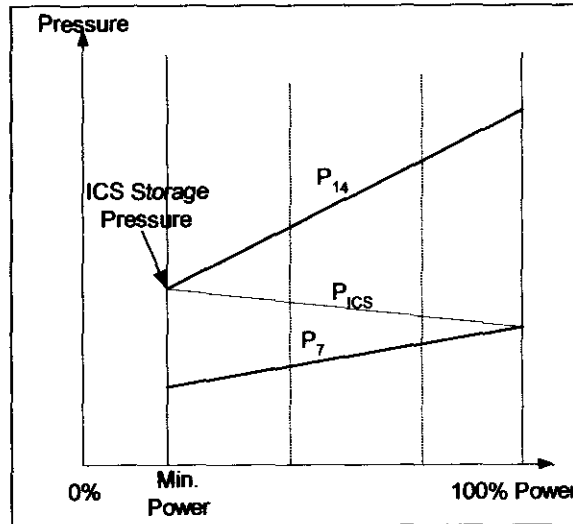


Figure 3: Pressure Characteristics

Equalisation during extraction is achieved when P_{14} and P_{ICS} meet, and further mass transfer by pressure differential cannot take place. Likewise during injection, equalisation is achieved when P_7 and P_{ICS} meet.

The point at which P_{14} and P_{ICS} meet determines the volume of the ICS tank, since the ICS must store a large amount of mass at a relatively low pressure. Assuming ideal gas behaviour, the volume is given by the equation of state $V=mRT/P$ [9].

With this in mind, a design objective would be to minimise the volume of the reservoir whilst storing all the helium required to bring the power down to approximately 40% or whatever the specified minimum is.

The following subsections include an investigation into techniques of mass transfer with an outlook to minimise the storage volume of the reservoir, which represents the ICS.

2.2.1 Using a pressure exchanger to aid mass transfer

According to Berchtold [2], a means of reducing the storage volume of the ICS entails

the use of a pressure exchanger for mass transfer, in addition to taking advantage of the pressure differential that may exist between the MPS power cycle and the ICS. For a similar power range to the one described earlier, Figure 4 shows the pressure variation of the ICS as power is varied with the aid of a pressure exchanger. It can be seen that at the given minimum power, the ICS stores the helium at a higher pressure than before, hence allowing a smaller volume to be used.

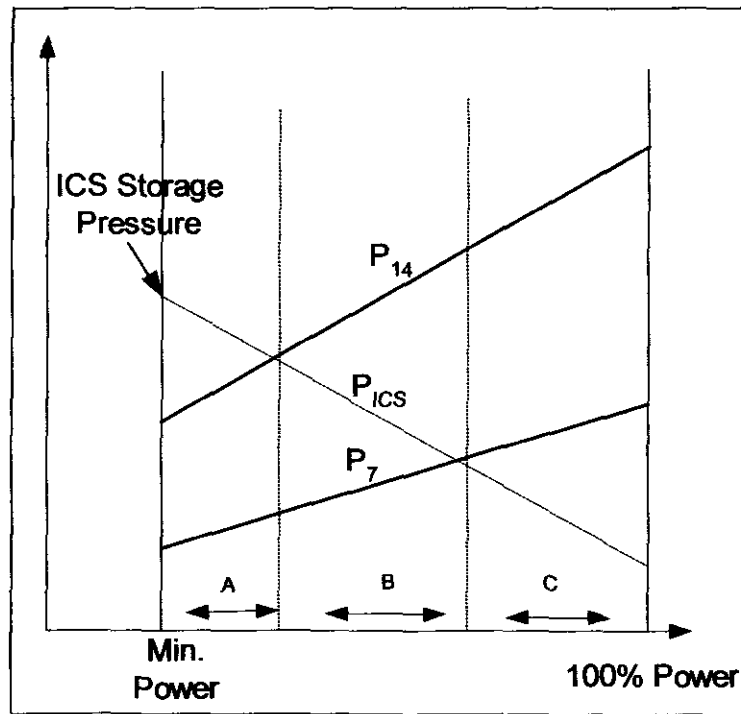


Figure 4: Pressures using pressure exchanger

The pressure exchanger in question consists of three ports as shown in Figure 5. Between these ports is a rotor with channels parallel to the rotor axis. The ports remain stationary relative to the rotor movement. Ports S and T are positioned on one side of the rotor, each one subtending almost half the circumference of the rotor. On the opposite side of the rotor, the port R, which also subtends half the circumference, is positioned in a perpendicular manner relative to ports S and T. In order to transfer mass, the rotor is spun, whilst the ports R, S and T are appropriately configured to be in communication with the pressures at P_{14} , P_7 and P_{ICS} . As the rotor channels traverse the ports at a particular speed, sound waves are generated. These waves form a pattern of high and low pressure regions, so that mass flow is forced from one end of the rotor to

the other, despite the delivery side of the rotor being connected to a higher pressure than the supply side!

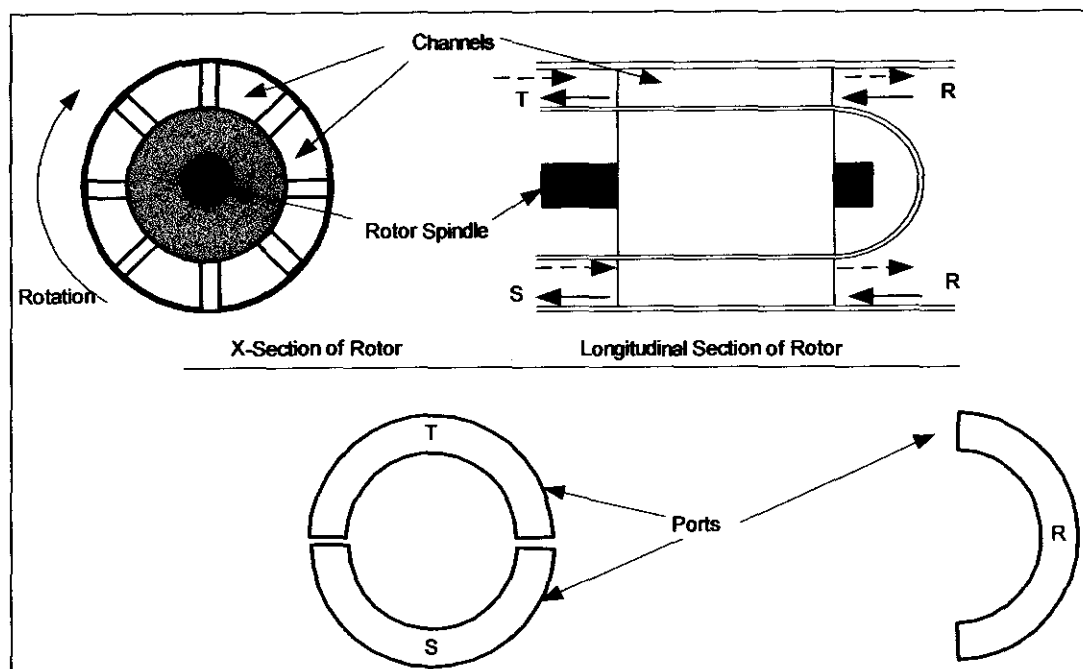


Figure 5: Pressure Exchanger

Region A in Figure 4 shows that the ICS is at a higher pressure than point 14. Therefore extraction from the MPS to the ICS by straightforward pressure differential is impossible. To achieve power reduction in region A, ports R, S and T are put into communication with P_{14} , P_7 and P_{ICS} respectively (See Figure 6). As the rotor is spun, a pattern of sound waves is generated as shown on the right hand side of Figure 6. The compression region $c'-c''$, which subtends port R, forces flow towards ports S and T, either of which is partially subtended by expansion regions $e'-e''$. Whilst the flow through port S is directed towards the ICS, flow through port T, serves to "short circuit" the flow by bypassing the reactor, turbine and recuperator, thus aiding in the power reduction.

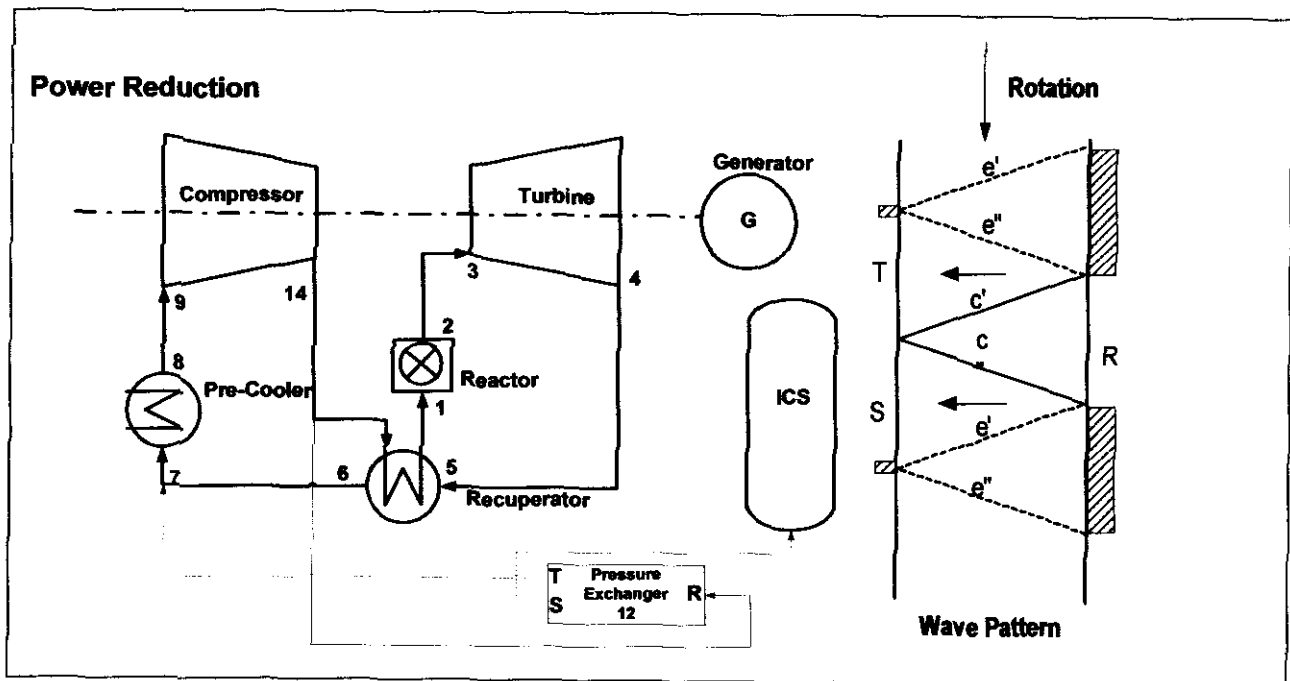


Figure 6: Power Reduction

Region C in Figure 4 shows that the ICS pressure is lower than the pressure at point 7. Therefore injection from the ICS to the MPS is impossible by simple pressure differential. To increase power in Region C, ports R, S and T are put into communication with P_{14} , P_7 and P_{ICS} respectively. As the rotor is spun in the direction shown, a pattern of sound waves is generated as shown on the right hand side of Figure 7. The expansion region e'-e'', which subtends port R allows flow from the compression regions, c'-c'' which partially subtend ports S and T.

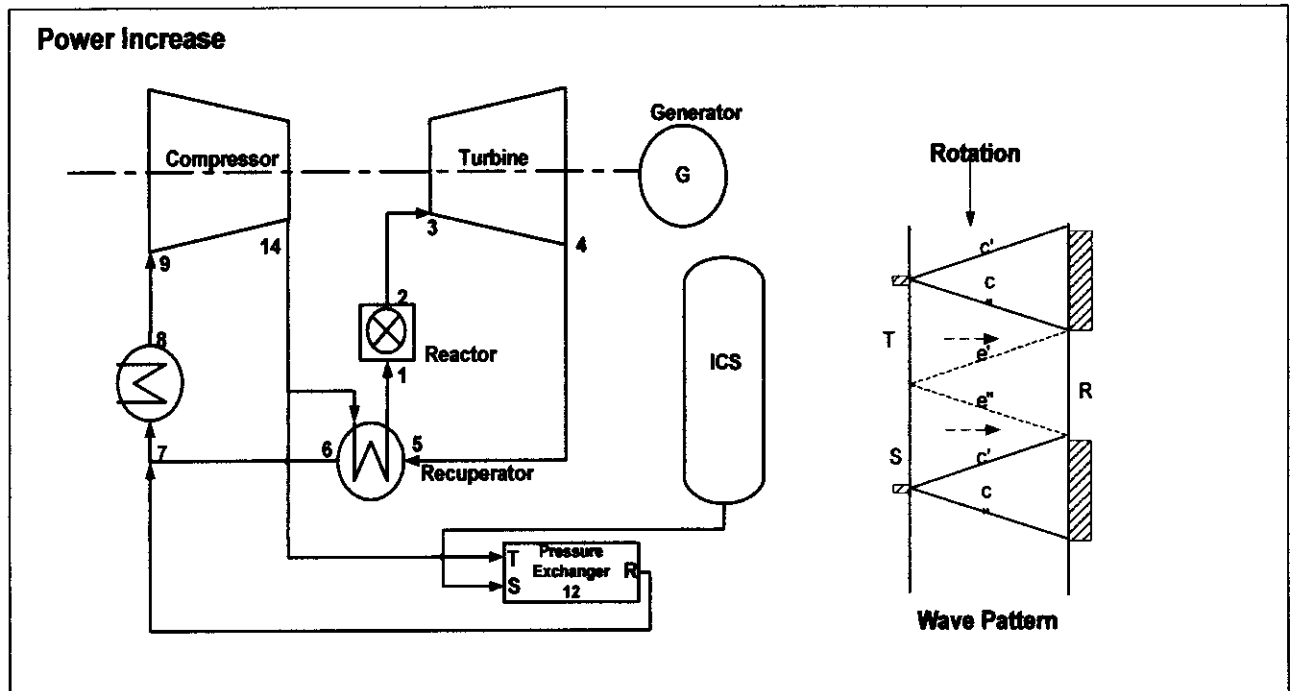


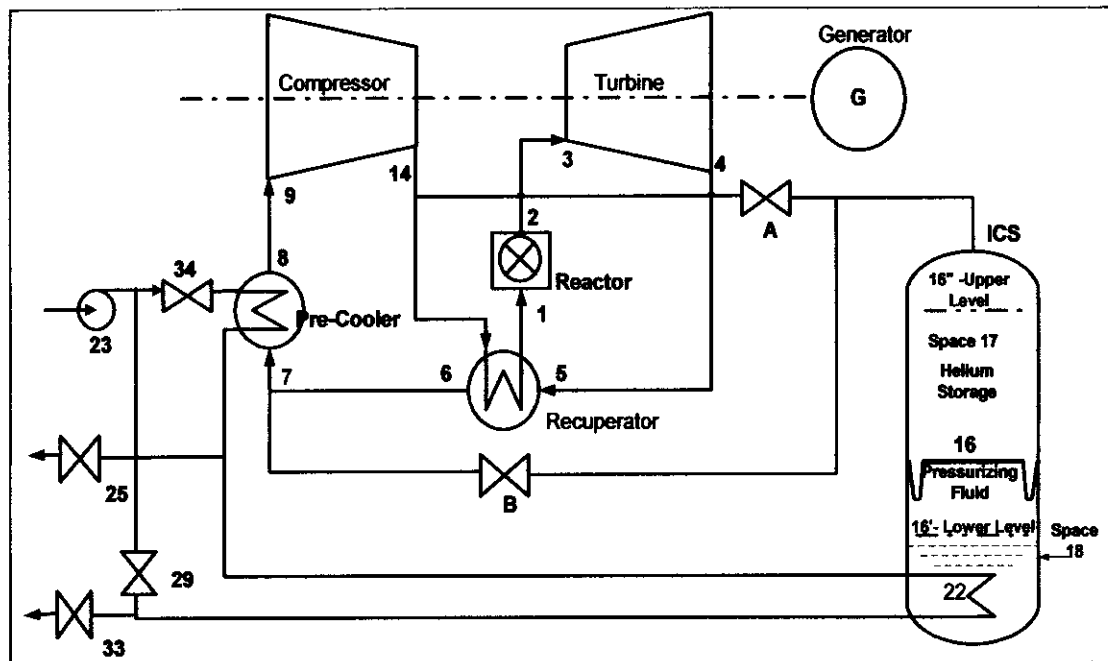
Figure 7: Power Increase

Region B in Figure 4 shows that the ICS pressure lies between point 14 and point 7, making it possible to use pressure differential for whichever direction of mass flow.

In regions A and C, despite the delivery pressure being higher, the pressure exchanger, does not 'pump' the working fluid, but merely serves to bring the channels in correct timing for communication with the stationary ports R, S and T. The value of this technique is supported by the fact that in region A the ICS pressure is higher than it would be in the absence of a pressure exchanger mechanism (see Figure 3), hence a smaller ICS volume can be used.

2.2.2 Using a flexible partition to aid mass transfer

In this method, Berchtold [3] presents an ICS with a movable partition 16, which subdivides the storage space in two, sealing them from each other. The upper part, space 17, is for storage of the helium working medium. The lower part (space 18) is filled with a medium partly in the liquid and partly in the gaseous phase. By varying the enthalpy in this liquid (using the heater 22), the position of the partition can be varied between the positions 16" and 16'. The partition 16 together with the heater 22 and the fluid in 18, constitute a pressurising mechanism.



With reference to Figure 8, power reduction is obtained by opening the valve A, which allows the pressure differential that exists between point 14 and the upper part of the reservoir, to drive the mass flow towards the latter. The incoming gas possesses energy, which causes the temperature in 17 to rise, leading to a pressure increase and hence towards equalisation between P_{ICS} and P_{14} . In order to curb the rate towards equalisation, so that more mass can be transferred, cooling flow is provided by the heater 22, which in turn is supplied by pump 23, when valve 29 is opened. Valve 33 is opened to discharge the cooling flow. This cooling flow causes the vapour part of the pressurising fluid to condense, which in turn deforms the flexible partition towards position 16', so that the upper volume 17 expands resulting in reduced pressure therein for more gas to be added. With reference to Figure 9:, the absence of the pressurising mechanism could mean a rapid increase in the ICS pressure as shown by the trace, P'_{ICS} , making it impossible to use pressure differential for further mass transfer, unless a larger ICS volume were used. On the other hand the presence of the pressurising mechanism, at the sacrifice of part the ICS reservoir volume, moves the equalisation point further down, so that the ICS pressure follows the trace P_{ICS}

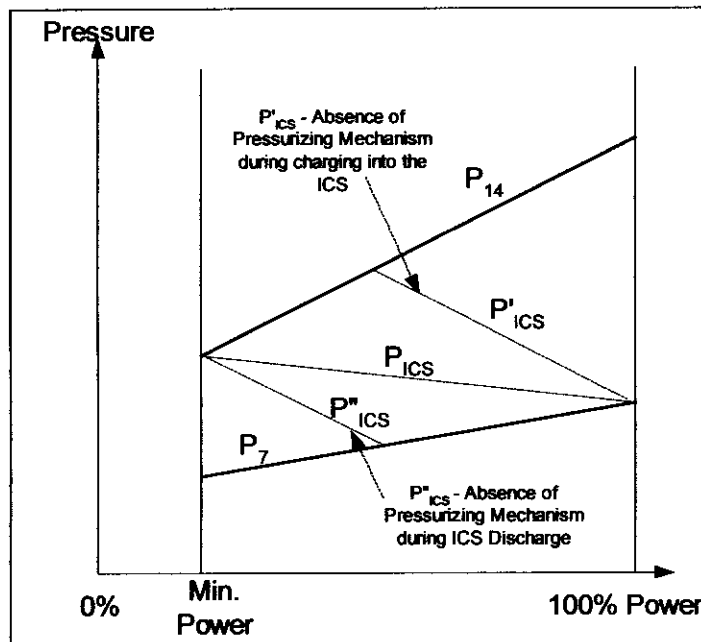


Figure 9: Comparison with and without Pressurizing Mechanism

To increase power, valve B is opened (and valve A is closed) so that the pressure difference that exists between the ICS and point 7 drives the mass flow. The absence of the pressurising mechanism could imply rapid equalisation of the ICS pressure, as represented by the trace P''_{ICS} . On the other hand more helium can be transferred to the power cycle by employing the pressurising mechanism. In this case, the ICS pressure is kept high by providing heating flow from the heater 22. The heating flow is obtained by opening the valve 34, whilst closing valve 29, to allow fluid from pump 23 via the pre-cooler (where it picks up heat). Valve 33 is also opened in place of 25 to discharge the heating flow. The resulting increase in enthalpy of the pressurising fluid causes increased evaporation in space 18 which deforms the partition 16 upwards towards position 16".

A suitable pressurising fluid must be in the saturation phase for the given operating pressures of the ICS. For example, if the regulation range is 10atm absolute and 22.5atm with respective reservoir temperatures of 26°C and 62°C, then propane would be the suitable fluid. Berchtold claims for a 10MW helium plant and a variation in power of 20% to 100%, a volume of 52m³ is required to cover the variation between the partition limits at 16' and 16".

A notable advantage of this method is that what could have been waste heat from the

power cycle, through the pre-cooler, is used to provide a means of moving the partition, which means not much auxiliary power is needed to drive the mechanism. It is expected that pump 23 consumes an insignificant amount of power for this application.

2.2.3 Using a tubular heat exchanger to aid mass transfer

Frutschi [5] offers a method in which mass transfer can be improved by implementing a tubular heat exchanger within the ICS reservoir. The tube has its ends appropriately connected to points in the power cycle to effect this application. Figure 10 illustrates.

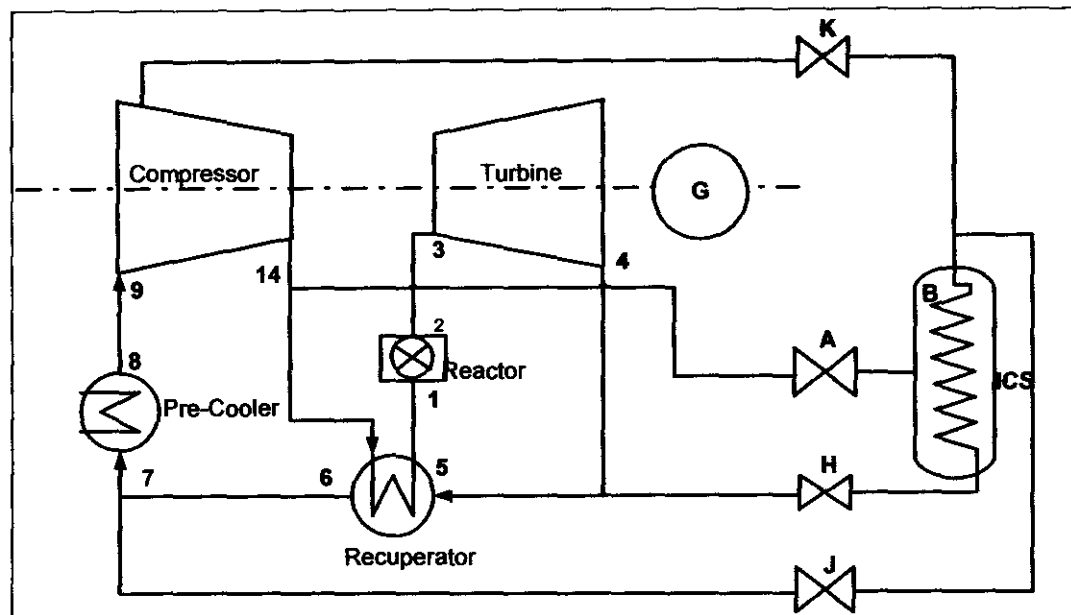


Figure 10: ICS with Tubular Heat Exchanger

Power reduction is achieved by opening the valve A, which allows the pressure difference between point 14 and the ICS to drive mass transfer towards the latter. To increase the effectiveness of mass transfer without enlarging the physical volume of the ICS, cooling flow is introduced through the tube B by opening valves K and H. This flow of helium through B, is cooled by the pre-cooler, after which it is partially compressed, before entering the tube via K and then back to the pre-cooler via H and the recuperator. The presence of the cooling flow through B, serves to lower the tank temperature, which curbs the rate of pressure build-up, allowing more gas to be transferred to the tank by pressure differential.

To increase power, the valve J is opened in place of K so that relatively hot fluid leaving the recuperator is drawn through to tube B. This aids the mass transfer back to the power cycle by providing heated fluid through tube B, which keeps the ICS internal temperature high and effectively a high pressure. Helium injection to the power cycle is in this case, carried out through point 14, since the heating of the ICS generates a sufficiently high pressure.

2.2.4 Using a multi-tank arrangement with cascaded initial pressures

This method by Forster [4] aims at improving mass transfer by breaking up the ICS into smaller volumes. Each volume is assigned a certain power range as shown in Figure 11. The initial pressure for each volume is the same as the pressure at P_7 , at the instant mass transfer to that volume is initiated (Figure 11).

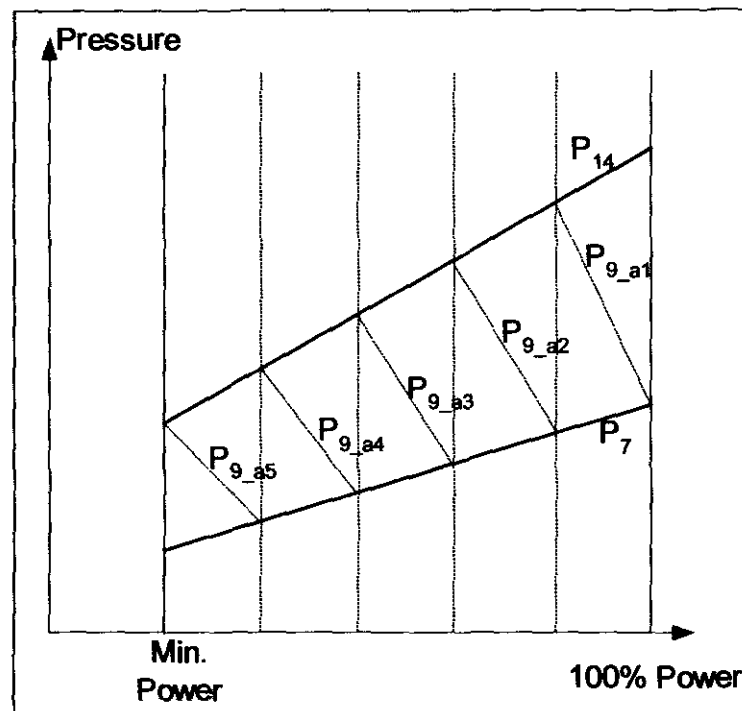


Figure 11: Multi Tank ICS

The multiple number of tanks which represent the ICS are labelled a1 to a5 (See Figure 12) The point g is connected to Point 14, the high pressure point as described in Figure 2, and point i is connected to point 7, the low pressure point.

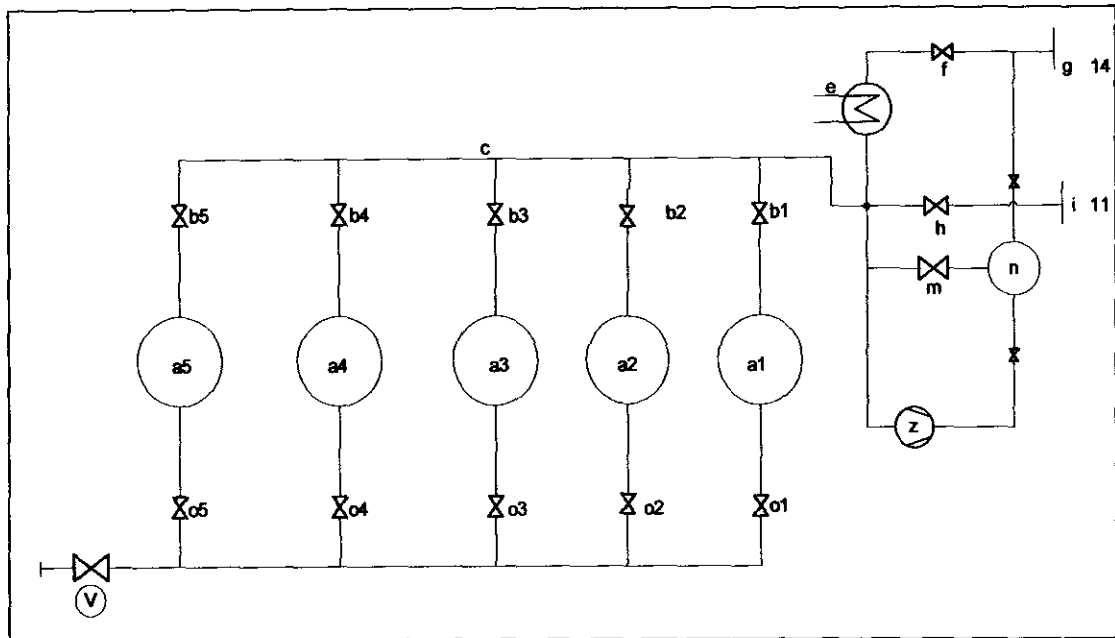


Figure 12: Multi Tank ICS

Power reduction is obtained by opening valve *f*. The ICS volumes *a1* to *a5* are selected sequentially by opening *b1* to *b5* respectively. The pressure differential that exists between the point *g* (connected to point 14) and each reservoir is responsible for mass transfer. The final storage pressure for each reservoir is determined by the conditions when P_{14} equalises with pressure of the reservoir in question. Bearing in mind that pressure differential through point *i* (connected to point 7) is used to return the helium to the power cycle, the initial pressure in each tank is calculated so that the power cycle returns to its initial condition prior to the power reduction that corresponds to the tank in question. The presence of the heat exchanger *e* in the flow-path ensures that the gas leaving the power cycle cools down, which curbs the temperature build-up, and consequently the pressure build-up, allowing more helium transfer under pressure differential.

Power is increased by opening flow from the lowest pressure ICS volume. In the event that all volumes have been fully charged, and the need is to return to full power, then reservoir *a5* would discharge through point *i* first, followed by reservoir *a4* and so on until *a1* has fully discharged. Each reservoir has a membrane *S* (see Figure 13), much like the partition described in section 2.2.2, which deforms appropriately to aid mass transfer under pressure differential for both directions of flow.

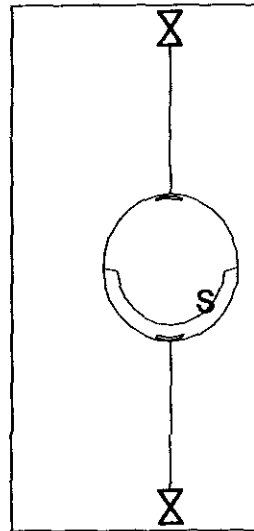


Figure 13: Membrane in tank

2.2.5 Using a multi-tank arrangement with heat capacitance

Nieuwoudt [6] suggests a similar approach to Frutschi, but instead of using the heat exchanger, *e* to cool the fluid leaving the power cycle, and the flexible membrane to increase pressure of the fluid leaving the tanks, he uses the idea of a passive heat capacitance which is placed within the tanks. This capacitance, which is in the form of perforated steel, much like a dish scourer, absorbs heat from the incoming gas which curbs the pressure build-up for more helium transfer. When gas leaves the tanks, the same capacitance dissipates heat that was absorbed as gas came in, so that the pressure in the tanks remains relatively high, assisting in the mass transfer.

2.3 Conclusion on Literature Survey

Based on the literature survey that highlights some load following techniques, the following conclusions are drawn;

- Berchtold's method which uses the pressure exchanger makes it possible to transfer mass from lower pressures to higher pressures, without really compressing. However this pressure exchanger requires an auxiliary power source which the inventor does not quantify, making it difficult to appreciate the effectiveness of such a method.
- Berchtold's other method, which was highlighted in this survey, offers a means for which no external power source is required, save for the pump 23, whose power consumption is expected to be minimal. However the use of such a flexible partition calls for an in depth investigation into suitable material properties that can undergo the required stress and flexibility. Furthermore, the manufacture of a reservoir which sees the integration of this partition may be costly.
- Frutschi offers a method which requires no auxiliary power to effect mass transfer. As opposed to Berchtold's method, better heat transfer within the tank can be expected since the tube B runs right through the ICS providing a large surface area for heat transfer. This idea of a heat transfer surface within the ICS is similar to Nieuwoudt's heat capacitance, but Frutschi's method still requires an element of power from the compressor within the gas cycle, to drive the fluid through the tube. This could compromise the efficiency of the gas cycle.
- Both Forster and Nieuwoudt's methods of breaking up the ICS into multiple volumes make it easier to manufacture the ICS since each tank is lighter in mass than a single large tank. Furthermore as can be demonstrated using thermodynamics (see 3.1.1), a multiple number of vessels also improves the storage efficiency in addition to using heat exchanger e or capacitance. The use of flexible membranes to aid mass flowing out of the reservoirs may be a drawback of Forster's method, but this can be addressed by the heat capacitance as Nieuwoudt suggests.

2.4 Recommendation of a suitable concept for the ICS

Based on the foregoing literature survey and conclusions, it is recommended that a combination of Frutschi's and Nieuwoudt's methods be implemented in formulating a concept for the Inventory Control System of the Pebble Bed Modular Reactor. Hence the ICS concept is characterised by a multi-tank arrangement for helium storage with a heat capacitance within each tank. Chapter 3 continues with a description of the chosen ICS concept, with the aid of thermo-dynamics.

3 DEVELOPMENT OF A THERMO-HYDRAULIC MODEL FOR THE ICS

As mentioned before, the purpose of the ICS thermo-hydraulic model is to use it as a design and simulation tool. As a design tool, the intention is to determine the optimum storage capacity of the ICS that will meet a required performance within a set of given constraints. Sensitivity studies can be carried out using this thermo-hydraulic model, as a way of optimising the design solution. Following a description of the ICS model concept, the performance requirements and the constraints, this chapter will elaborate on the thermo-hydraulic model for the ICS.

3.1 ICS model concept

The ICS concept consists of a multi-tank arrangement, which for the purposes of load following through mass transfer, has two interfaces with the Main Power System (MPS) of the PBMR (see 2.1), one at the High Pressure Compressor (HPC) outlet, through which extraction is carried out, and another at the Pre-Cooler (PC) inlet, through which injection is carried out (See Figure 14). **Extraction** implies the removal of the working fluid, helium, from the MPS to the ICS, the result of which is a reduction in power output. **Injection** implies the addition of stored helium from the ICS into the MPS, the result of which is an increase in power output. As mentioned in the literature survey (see 2.2.4), a multi tank arrangement improves the storage effectiveness of the ICS, in that it reduces the total capacity of the system. It will be shown later using thermodynamics how this is possible (see 3.1.1).

The driving force of the helium mass transfer is provided by the pressure differential that exists between the MPS and ICS during Brayton cycle operation [9].

In order to achieve continuous load following during extraction, the tanks are preset at cascaded pressure levels, as shown in Figure 14, with *Tank 1* having the highest initial pressure, P_1 , and *Tank n* the lowest initial pressure, P_n . To extract helium under pressure differential from the MPS, flow to tank 1 is opened first and controlled mass transfer at a specified rate (see section 3.2) is carried out. As soon as the pressure difference between the MPS and *Tank 1* is no longer sufficient to sustain the required flow-rate, switching occurs to *Tank 2*. **Error! Reference source not found.**

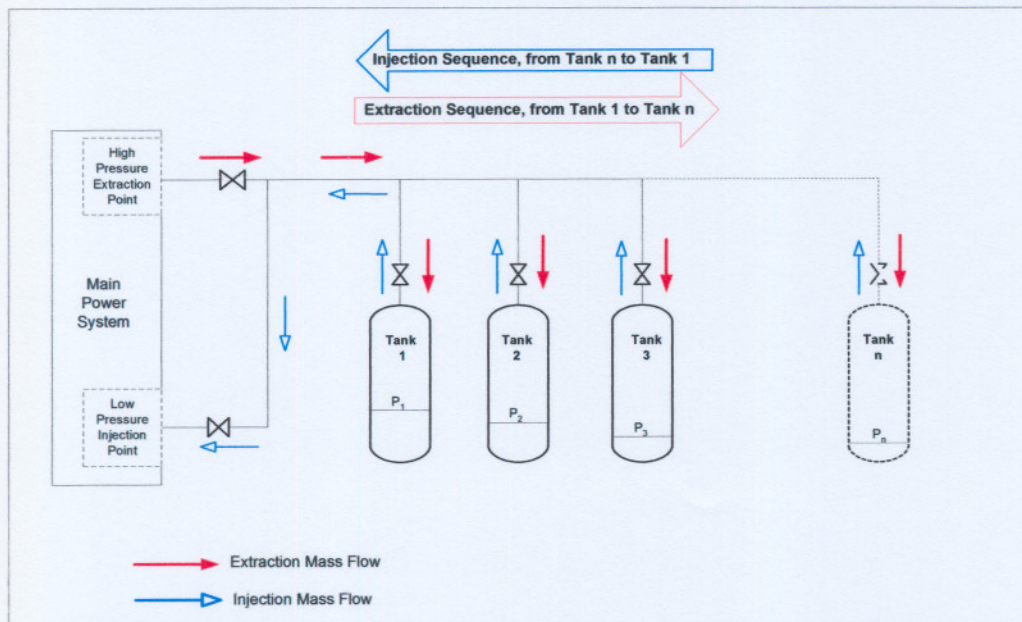


Figure 14: ICS Model Concept

Figure 14 shows the extraction sequence. The extraction process continues until mass transfer has been carried out to *Tank n*, at which point the MPS pressure at the HPC outlet is too low to drive mass flow to any of the tanks. At this point the MPS will be at its lower limit of a self sustaining Brayton operation. Further extraction will have to be done using compressor power. The High Pressure Compressor (HPC) outlet of the PBMR (see 2.1), from which extraction is carried out, is the highest pressure point within the MPS on the PCU side (see 2.1).

To carry out injection immediately after extraction as described above, *Tank n* blows down first to the MPS via the Pre-Cooler (PC) inlet (see 2.1). The PC inlet is one of the lowest pressure points within the PCU. When the pressure difference between *Tank n* and the MPS pre-cooler inlet is no longer sufficient to sustain the required mass flow-rate, switching occurs to *Tank n-1*. Switching from *Tank n-1* to *Tank n-2* occurs in the same manner and so on, until *Tank 1* has blown down to the MPS. At this point the MPS should be back at full power. Figure 14 shows the injection sequence.

Extracting from the high pressure point followed by injection at the low pressure point ensures maximum advantage of the pressure differential that exists between the systems. For example if the MPS blows down to *Tank 1* which initially is at a low pressure, P_1 , then the MPS and *Tank 1* will equalize at some pressure level which lies between the initial pressures of either system. If the intention is to replenish all

the helium that was extracted, by pressure differential, then the only means to do so is to inject to the MPS through a low pressure point, i.e. the PC inlet.

The cascaded initial pressures of the tanks, where *Tank 1* is the highest and *Tank n* is the lowest, are calculated so that when injecting, (immediately after extraction) exactly the same amount of mass is sent back to the MPS. That way the MPS and the tank in question return to their original state before extraction began. Therefore for an extraction-injection cycle, the state (i.e. pressure and temperature) of the MPS at the end of injection is exactly the same as at the beginning of extraction. It will be shown using thermodynamics, (see section 3.1.2) how the initial pressures in each tank are determined.

Apart from having a multi-tank arrangement, storage effectiveness is further improved by placing a heat capacitance in each tank (see 2.2.4). This capacitance is in the form of perforated steel. Its presence within the tanks ensures thermal inertia, so that as helium mass is extracted from the MPS into the tanks, the capacitance absorbs the heat from the incoming gas, thus lowering the temperature, and consequently retarding the pressure build-up. In this way more helium can be added to each ICS tank per unit volume than if no heat capacitance were present. The capacitance is also useful when injecting to the MPS from the ICS tanks, in that, it dissipates heat to the outgoing gas (which is expanding, hence cooling), so that the temperature in the tank remains relatively high, which maintains a high pressure. In this way more helium can be injected back to the MPS by pressure differential, than if the capacitance were not present.

3.1.1 Justification of a multi –tank arrangement

Although it is possible to have a single volume or tank to carry out extraction and injection, practical considerations such as tank size and cost, come into play. To explain the advantage of having a multiple number of storage tanks, consider a two-tank system where one tank represents the MPS as an equivalent volume (see Appendix A.1), and the other represents an ICS storage tank (See Figure 15). These two systems are coupled via a simple pipe so that mass transfer is performed by pressure differential only. A control valve serves to regulate the mass flow against a required rate. To reduce power, mass is transferred from the MPS to the ICS.

In this justification, mass transfer will stop once the system pressures equalise¹

In the variables stated below, the subscript *s* generally represents the MPS, and *t* represents an ICS tank, unless otherwise stated. *D* (Down in mass) represents extraction of helium from the MPS to the ICS and *U* (Up in mass), injection from the ICS to the MPS. The subscript, *i*, represents the *i*th ICS tank in a multi-tank arrangement. Subscripts **1** and **2** denote conditions before and after a mass transfer process respectively.

An example;

$P_{tD,i,1}$ This variable represents the Pressure (*P*), of the *i*th (*i*) tank, (*t*) before (**1**) extraction (*D*).

$m_{tU,i,2}$ This variable represents the mass (*m*) in the *i*th (*i*) tank (*t*) after (**2**) injection (*U*).

The subscript *i* is written for *i*=1 to *n*, where *n* is the number tanks

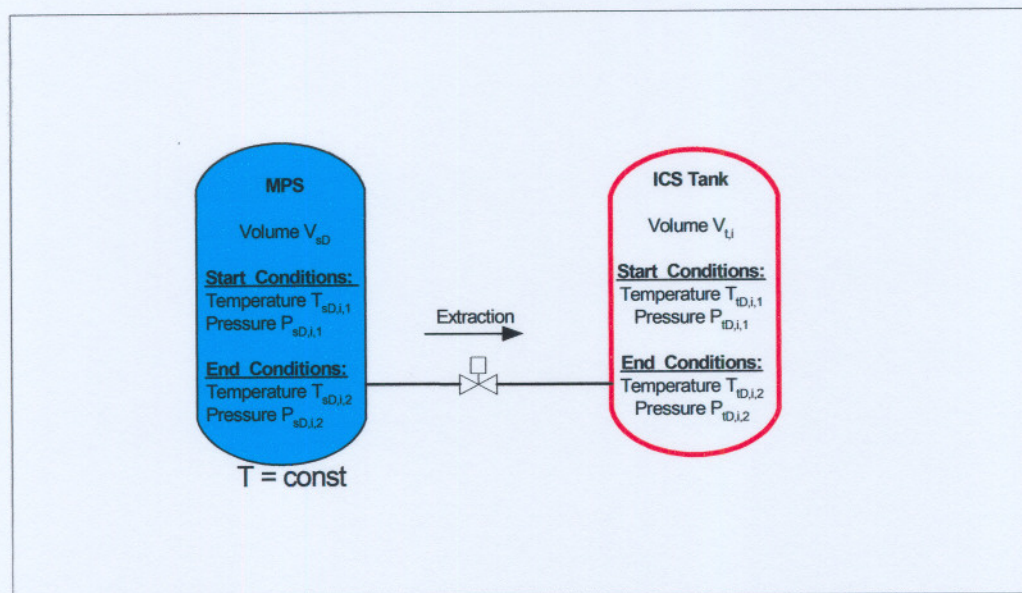


Figure 15: Extraction from MPS to Tank *i*

If to all practical intents and purposes the system temperatures remain constant during this mass transfer, the extraction process can be described by the following set of equations;

¹ To illustrate the need for a multi tank arrangement, the tank pressures will be allowed to equalise although this will not be the case in practice (see 3.1.4)

$$\Delta m_{sD,i} = \frac{\Delta P_{sD,i} V_{sD}}{RT_{sD}} \quad (3.1)$$

where

- $\Delta m_{sD,i}$ = Amount of helium extracted to the i^{th} tank.
- $\Delta P_{sD,i}$ = Change in MPS pressure due to extraction to the i^{th} tank
- V_{sD} = Equivalent Volume (A.1) of the MPS during extraction
- T_{sD} = Equivalent Temperature of MPS during extraction.
- R = Universal gas constant for helium

The ICS storage vessel is described using the equations;

$$\Delta m_{tD,i} = \frac{\Delta P_{tD,i} V_{t,i}}{RT_{tD}} \quad (3.2)$$

where

- $\Delta m_{tD,i}$ = Amount of helium received by the i^{th} tank
- $\Delta P_{tD,i}$ = Change in pressure within the i^{th} tank
- $V_{t,i}$ = Storage volume of the i^{th} tank
- T_{tD} = Temperature of the tank -this is assumed constant

Using Figure 16 as a reference;

- Extraction to the i^{th} tank or *Tank i* begins when the pressure of *Tank i-1* has equalised with the MPS at a time $T_{D,i-1}$.
- At a time, $T_{D,i}$ *Tank i* equalises with the MPS.
- At the end of extraction to *Tank i*, $P_{sD,i,2} = P_{tD,i,2}$. At this point, extraction to the next tank, *Tank i+1* begins. This manner of extraction is carried out until *Tank n*.
- At $T_{D,n}$ *Tank n* equalises with the MPS. This coincides with $P_{s,min}$ below which Brayton operation is not self sustaining.

$P_{s,max}$ and $P_{s,min}$ define the upper and lower limits of Brayton Cycle operation respectively. For now, all tanks have the same initial pressure $P_{tD,i,1}$

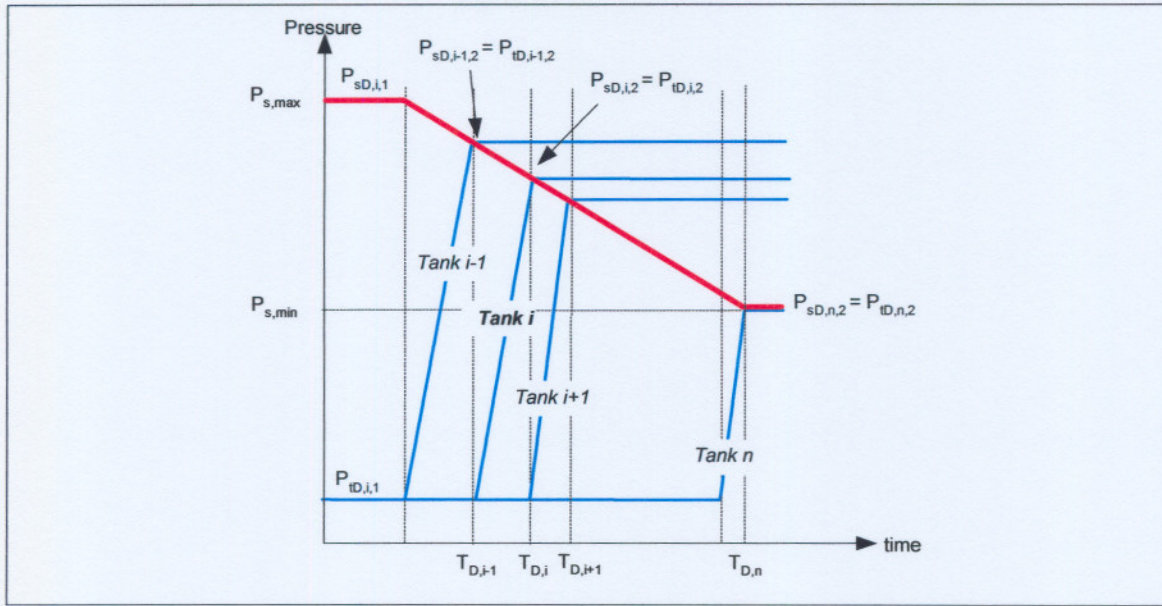


Figure 16: Concept of Pressure Change during Extraction

Applying the conservation of mass, so that all the mass leaving the MPS enters the ICS;

$$\Delta m_{tD,i} = \Delta m_{sD,i}$$

Using Equation (3.2) and substituting for $\Delta m_{tD,i}$, the volume of the i^{th} tank is given by;

$$V_{t,i} = \frac{\Delta m_{sD,i} R T_{tD}}{\Delta P_{tD,i}} \quad (3.3)$$

Equation (3.1) is used to substitute for $\Delta m_{sD,i}$ to give;

$$V_{t,i} = \frac{\Delta P_{sD,i} V_{sD} T_{tD}}{\Delta P_{tD,i} T_{sD}} \quad (3.4)$$

With the aid of Figure 16, $\Delta P_{sD,i} = P_{sD,i-1,2} - P_{sD,i,2}$ and $\Delta P_{tD,i} = P_{tD,i,2} - P_{tD,i,1}$

$$\therefore V_{t,i} = \frac{(P_{sD,i-1,2} - P_{sD,i,2}) V_{sD} T_{tD}}{(P_{tD,i,2} - P_{tD,i,1}) T_{sD}} \quad (3.5)$$

But $P_{sD,i,2} = P_{tD,i,2}$ since mass transfer by pressure differential is carried out until pressure equalisation between the two systems. Hence

$$V_{t,total} = \sum V_{t,i} = \frac{V_{sD} T_{tD}}{T_{sD}} \sum_{i=1}^{i=n} \frac{(P_{sD,i-1,2} - P_{sD,i,2})}{(P_{sD,i,2} - P_{tD,i,1})} \quad (3.6)$$

Equation (3.6) is valid for system pressures lying between $P_{s,max}$ and $P_{s,min}$

From Figure 16 it can be seen that *Tank i* reduces the MPS pressure from $P_{sD,i-1,2}$ to $P_{sD,i,2}$ and stores the helium at the latter². Increasing the number of tanks that operate between $P_{s,max}$ and $P_{s,min}$ implies a smaller $\Delta P_{sD,i}$ for each ICS tank, since $P_{sD,i,2}$ will tend to $P_{sD,i-1,2}$. If $P_{sD,i,2}$ tends to $P_{sD,i-1,2}$, then the numerator of the summation in Equation 3.6 becomes smaller as the denominator increases. As a result, the summation decreases as n increases for the same pressure limits. Thus the total volume of the ICS decreases as the number of tanks is increased. **This justifies a multi-tank design for the ICS.**

A more intuitive way of understanding how a multiple number of tanks is more effective as n increases, is to picture a situation where if only one large ICS tank were used, all the helium leaving the MPS by pressure differential would have to be stored, at a low pressure ($P_{s,min}$). On the other hand, a multiple number of tanks means some tanks can store portions of the mass at higher pressures, hence, can be made smaller, the total volume of which will be less than the single tank.

3.1.2 Initial ICS tank pressures

The previous section which justifies the need for a multi-tank arrangement, used the same initial pressure for all ICS tanks. But the concept shows a cascaded arrangement for the initial pressures. To explain the need for this, consider injection from one of the ICS tanks to the MPS through the PC inlet. As in the case for extraction, an equivalent volume during injection is used to describe the MPS. Figure 17 summarises the idea. As in the extraction case, injection will stop when the pressures equalise.

² It is assumed that after extraction to the i^{th} tank the cooling effect is negligible so that the storage pressure remains constant

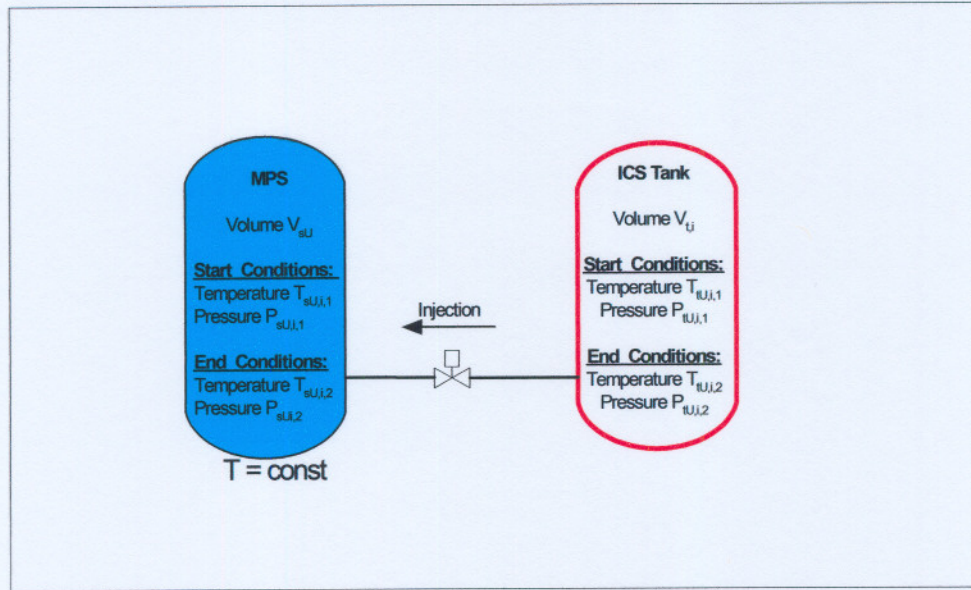


Figure 17: Injection from Tank i to MPS

Using thermo-dynamics;

$$\Delta m_{sU,i} = \frac{\Delta P_{sU,i} V_{sU}}{RT_{sU}} \quad (3.7)$$

where

$\Delta m_{sU,i}$ = Amount of helium injected to the MPS

$\Delta P_{sU,i}$ = Change in MPS pressure

V_{sU} = Equivalent Volume (A.1) of MPS during injection

T_{sU} = Equivalent Temperature of MPS during injection

The ICS storage vessel is described using the equations;

$$\Delta m_{tU,i} = \frac{\Delta P_{tU,i} V_{t,i}}{RT_{tU}} \quad (3.8)$$

$\Delta m_{tU,i}$ = Amount of helium leaving the i^{th} tank

$P_{tU,i}$ = Change in pressure within the i^{th} tank

$V_{t,i}$ = Storage volume of i^{th} tank

T_{tU} = Temperature of i^{th} tank during injection

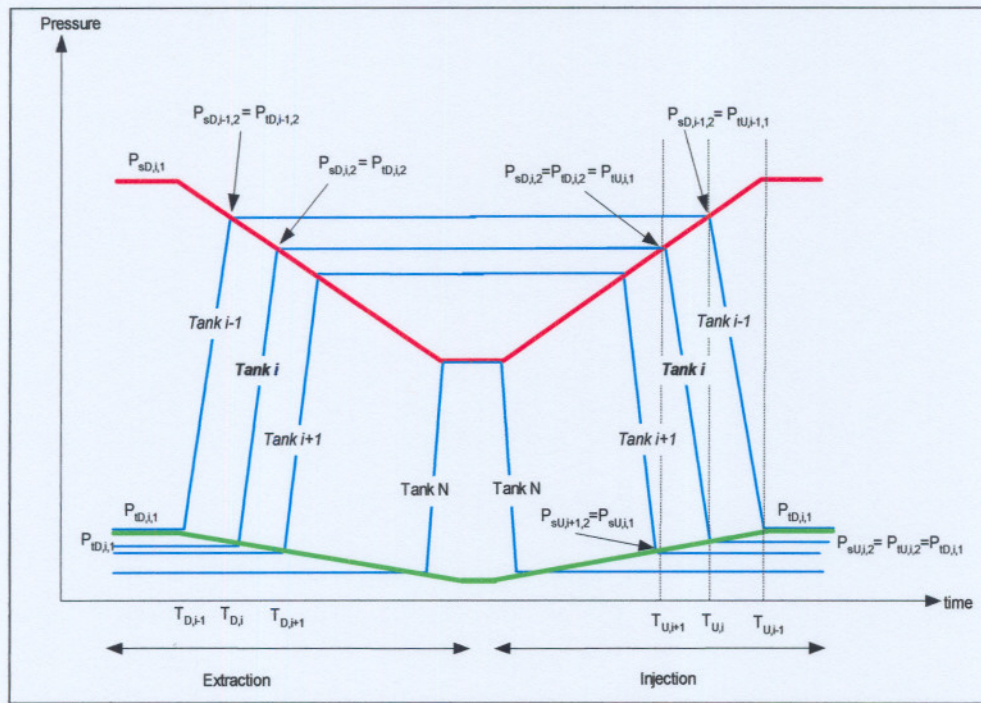


Figure 18: ICS Initial Pressures

Applying the conservation of mass $\Delta m_{tU,i} = \Delta m_{sU,i}$

$$V_{t,i} = \frac{\Delta m_{sU,i} RT_{tU}}{\Delta P_{tU,i}} \quad (3.9)$$

Using 3.7 to substitute for $\Delta m_{sU,i}$ leads to;

$$V_{t,i} = \frac{\Delta P_{sU,i} V_{sU} T_{tU}}{\Delta P_{tU,i} T_{sU}} \quad (3.10)$$

Re-arranging;

$$V_{t,i} = \frac{(P_{sU,i,2} - P_{sU,i+1,2}) V_{sU} T_{tU}}{(P_{tU,i,1} - P_{tU,i,2}) T_{sU}} \quad (3.11)$$

And re-writing with $P_{tU,i,2}$ as the subject of the formula;

$$P_{tU,i,2} = P_{tU,i,1} - \frac{(P_{sU,i,2} - P_{sU,i+1,2}) V_{sU} T_{tU}}{T_{sU} V_t} \quad (3.12)$$

From Figure 18,

$$P_{tU,i,2} = P_{tD,i,1} \text{ and } P_{tU,i,1} = P_{sD,i,2}$$

A pressure ratio PR is defined as the relation between of the MPS pressure to the

ICS pressure at any given point in time. Therefore;

$$P_{sU,i+1,2} = \frac{P_{sD,i,2}}{PR} \text{ and } P_{sU,i,2} = \frac{P_{sD,i-1,2}}{PR}$$

And maintaining the tank temperature constant, $T_{tU} = T_{tD}$

$$P_{tD,i,1} = P_{sD,i,2} - \frac{\left(\frac{P_{sD,i-1,2}}{PR} - \frac{P_{sD,i,2}}{PR} \right) V_{sU} T_{tD}}{T_{sU} V_{t,i}} \quad (3.13)$$

$$P_{tD,i,1} = P_{sD,i,2} - \frac{(P_{sD,i-1,2} - P_{sD,i,2}) V_{sU} T_{tD}}{PR \times V_{t,i} T_{sU}} \quad (3.14)$$

$$P_{tD,i,1} = \frac{P_{sD,i,2} \times PR \times V_{t,sU} - (P_{sD,i-1,2} - P_{sD,i,2}) V_{sU} T_{tD}}{PR \times V_{t,i} T_{sU}} \quad (3.15)$$

$$P_{tD,i,1} = \frac{P_{sD,i,2} (PR \times V_{t,sU} + V_{sU} T_{tD}) - P_{sD,i-1,2} V_{sU} T_{tD}}{PR \times V_{t,i} T_{sU}} \quad (3.16)$$

Examining equation 3.16 shows that the initial pressure for each tank must be high if the storage pressure $P_{sD,i,2}$ is high. This explains why tanks that store helium at high pressures require higher initial pressures than those which store helium at lower pressures. **This justifies the need for cascaded initial pressures.**

In a design case where the intention is to typically to determine $P_{tD,i,1}$ and $V_{t,i}$, equations 3.5 and 3.16 must be applied simultaneously.

3.1.3 The need for heat capacitance

The concept also highlights the need for heat capacitance to improve storage efficiency. To illustrate this using thermo-dynamics, consider a tank with a volume $V_{t,i}$. This volume can be defined by the equation of state, so that

$$P_{tD,i,1} = \frac{m_{tD,i,1} R T_{tD,i,1}}{V_{t,i}}$$

If a certain mass is transferred to the tank so that the final mass in the tank is $m_{tD,i,2}$, then

$$P_{tD,i,2} = \frac{m_{tD,i,2} R T_{tD,i,2}}{V_{t,i}}$$

The change in pressure as a result of mass addition is given by

$$P_{w,i,2} - P_{w,i,1} = \frac{m_{w,i,2}RT_{w,i,2} - m_{w,i,1}RT_{w,i,1}}{V_{t,i}}$$

And re-arranging ;

$$V_{t,i} = \frac{m_{w,i,2}RT_{w,i,2} - m_{w,i,1}RT_{w,i,1}}{P_{w,i,2} - P_{w,i,1}}$$

Consider, firstly an operational requirement which dictates what amount of helium is added, so that $m_{w,i,2}$ and $m_{w,i,1}$ are known. Secondly the final tank pressure, $P_{w,i,2}$, is limited by pressure vessel design. And finally, if the initial conditions $T_{w,i,1}$ and $P_{w,i,1}$ are known, then the final temperature $T_{w,i,2}$ will influence the design volume of the tank $V_{t,i}$.

In an adiabatic case, $T_{w,i,2}$ will be greater than $T_{w,i,1}$ since no heat escapes the walls of the tank. This will lead to a larger volume for the tank. Conversely, in an isothermal case $T_{w,i,2} = T_{w,i,1}$ where the temperature does not rise will mean a relatively smaller tank. But considering the relatively high flow-rates that are required to transfer mass to the ICS, it may not be practical to have isothermal mass transfer as the tank will not have sufficient time to cool. Rather, an adiabatic process will result. To minimise the impact of adiabatic expansion the heat capacitance is introduced which retards the temperature rise and consequently the pressure build-up allowing more helium to be stored.

3.1.4 ICS pipe connection

When carrying out mass transfer, the pressure loss in the pipe is a function of pipe friction, bends and velocity [15]. These effects are combined in the equation below.

$$\Delta p_o = \left[\frac{fL}{D} + K_{loss} + \frac{\Delta T_o}{T_o} \right] \cdot \frac{p_o \cdot \gamma \cdot M^2}{2}$$

where

f = Friction co-efficient of pipe

L = Length of Pipe

- D = Inner diameter of pipe
- K_{loss} = Loss co-efficient of pipe including the valve
- ΔT_o = Total temperature difference
- T_o = Mean total temperature in element
- p_o = Mean total pressure in element

In a thermodynamic context, the role of the pipe is to account for the pressure difference between the MPS and the ICS. As the system pressures draw towards equalisation, the pressure difference decreases, until the pipe losses impede the flow so much that the required flow cannot be sustained. It is at this point that switching is carried out from one tank to another, as described earlier.

3.2 Performance requirements

Since power output to the grid depends on the amount of helium mass in the MPS, power control can be achieved by carrying out mass transfer between the MPS and the ICS. The power output to the grid is defined in terms of a *percentage of the Maximum Continuous Rating (%MCR)* [19]. The helium mass within the MPS which gives a particular %MCR is defined in terms of a *percentage of Maximum Continuous Rating Inventory (%MCRI)* and has the same value as the former. Hence to produce 100%MCR, 4716 kg of helium is required. This mass of helium is assigned 100%MCRI. To produce 80%MCR, a certain mass of helium is required, and this mass is 80%MCRI. But 80%MCRI is not 80% of 4716 kg. However, the relationship between the actual helium value in kg and the %MCRI is assumed linear for this exercise, and is given by $\%MCRI = 0.0221\text{Mass} - 4.3331$. The equation is obtained by drawing a straight line between the mass at 100%MCRI and 40%MCRI.

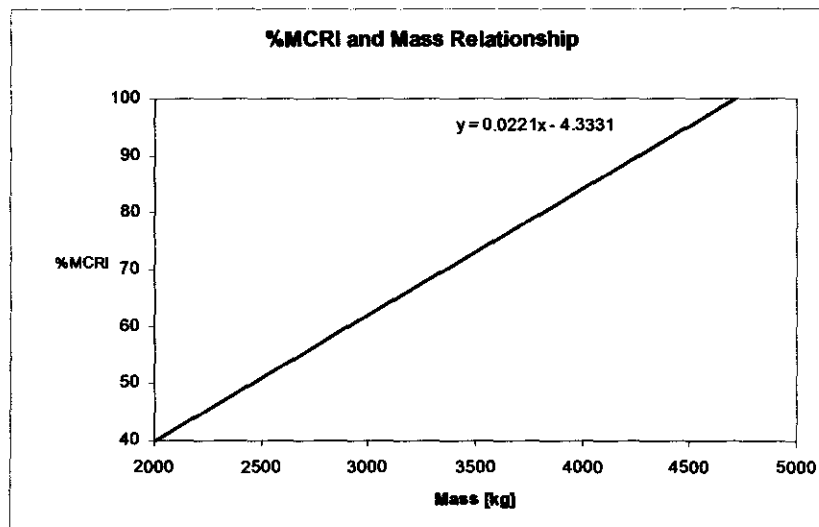


Figure 19: %MCRI and Mass Relationship

Extracting helium to levels below 40%MCRI may lead to a build-up in Xenon concentration which acts as a poison [8] to the nuclear reaction, hence to a collapse of the Brayton cycle. Table 1 summarizes this discussion.

Table 1: Helium Mass to Power Relation

	Maximum Brayton Operation		Minimum Brayton Operation	
Power	166 [MW]	100%MCR	66 [MW]	40%MCR
Helium Inventory	4716 kg	100%MCRI	2006 [kg]	40%MCRI

The performance requirements for the ICS are defined in terms of two aspects;

- i. The **range** of load following which is set between 100%MCR to 45%MCR (or 100%MCRI to 45%MCRI)
- ii. The **rate** of load following, which is set at a maximum of 10%MCR/minute (or 10%MCRI/minute)

The specified range shows that the ICS will operate well above the Brayton cycle's lower limit. Although it is practical to use the ICS to take the power as far down as 40%MCR, economic concerns make it more sensible to use alternative methods for power control between 45%MCR and 40%MCR. Such methods typically include the use of a gas cycle bypass valve (see 2.1) whose extent of opening renders the Brayton cycle less efficient, resulting in reduced power output.

Whereas the range of load following is ultimately governed by the sustainability of the Brayton cycle, the specified rate of load following has no real basis, other than that it is possibly higher than known rates for existing power plants. Thus such a 'high' load following rate (of 10%MCR/min) could constitute a selling point when the PBMR plant reaches a commercial phase.

Since the ICS is concerned with the transfer of helium as a means of power control, it is prudent to also express the performance requirements in terms of kg and kg/s for range and rate respectively. From simulations on the MPS thermo-hydraulic model [39] in Flownex, 100%MCRI corresponds to 4716 [kg] of helium and 45%MCRI corresponds to 2232 kg. (Note that the kg value at 45%MCRI is not 45% of 4716.)

10%MCRI/min is achieved by reducing power from 100% MCRI to 45%MCRI in 330s. This implies removal of 2484 [kg] in the same time. So the flowrate is $2484/330 = 7.5$ kg/s Table 2 summarizes.

Table 2: Performance Requirements

Range of ICS operation	4716 [kg] -2232 [kg]
Rate of ICS operation	7.5 [kg/s]

3.3 Detailed ICS thermo-hydraulic model

The ICS thermo-hydraulic model brings together all the aspects of the ICS concept (see 3.1) and performance requirements (see 3.2) in mathematical form. The crux of the model lies in the principles of *mass continuity*, *energy conservation* and *momentum conservation* [16]. In addition to this, the model includes the helium gas properties, the MPS boundary inputs, the ICS boundary inputs and a cost structure for the ICS. A complete set of equations, which describes the model, is given in section A.2 of the Appendix. This thermo-hydraulic model was developed in the Engineering Equation Solver (EES) software environment. Table 3 summarizes the manner in which the model description has been broken down according to the corresponding chapter.

Table 3: Model Summary

3.3.1	Helium gas properties
3.3.2	Main Power System boundary inputs
3.3.3	ICS heat capacitance boundary inputs
3.3.4	ICS tank boundary inputs
3.3.5	Mathematical model to describe ICS mass transfer
3.3.6	ICS model for storing helium during maintenance
3.3.7	ICS tank design

The outputs of this model will define a solution for the ICS. To adequately describe the solution, the following outputs are necessary;

- The number of tanks,
- The internal volume of each tank,
- The height of each tank and

- The estimated cost of the ICS system

The model is structured to give a solution in which all tanks have a uniform height and equal volumes.

3.3.1 Helium gas properties

Helium gas is the working medium in the PBMR Brayton Cycle. It is regarded as a suitable fluid for this purpose primarily because it is chemically and radioactively inert [2]. For the purposes of the ICS thermo- hydraulic model, the properties shown in Table 4 were used.

Table 4: Helium Gas Properties

Parameter	Description
R	Gas constant for helium
c_p	Constant pressure specific heat capacitance for helium
μ_{comp}	Compressibility coefficient for helium
μ	Viscosity for helium

3.3.2 Main Power System boundary inputs

The Main Power System of the PBMR consists primarily of the nuclear reactor, turbo-machinery and heat exchangers, all of which are configured to function using helium as the working fluid to produce the Brayton cycle. For simplicity the MPS is modelled as an equivalent volume (see Appendix-A.1) when extracting and when injecting.

Table 5: Main Power System Boundary Inputs

Parameter	Description
V_{sysD}	Equivalent extraction volume for the MPS
V_{sysU}	Equivalent injection volume for the MPS
$p_{sys,ext}$	Starting pressure at the HPC outlet
$p_{sys,inf}$	Starting pressure at the Pre-Cooler inlet

Parameter	Description
$mass_{sys}$	Total helium mass in the MPS at 100% MCRI

3.3.3 ICS Heat Capacitance Boundary Inputs

The heat capacitance serves to reduce the size of the ICS tanks by providing thermal inertia. Table 6 shows the inputs

Table 6: ICS Tank Capacitance Boundary Inputs

Parameter	Description
c_{capa}	Specific heat capacitance of steel
$density_{cap}$	Density of steel capacitance
ΔT_{lag}	Temperature lag between incoming or outgoing gas, and the steel capacitance.
HC_{Ratio}	Capacitance packing ratio in the each tank

3.3.4 ICS tank boundary inputs

It was shown earlier in the document why a multi-tank arrangement is necessary. For reasons associated with manufacturability, the ICS tanks are cylindrically shaped. Furthermore hoop stresses [22] put a limit on the diameter of the tanks. For design convenience an outer diameter is fixed for each ICS tank. Therefore for a given tank diameter, a tank thickness must be calculated.

Table 7: Tank Boundary Inputs

Parameter	Description
$outer_r$	Tank outer radius
S_{allow}	Maximum allowable stress
$cost_{ratio}$	Cost ratio of capacitance to tank material
$cost_{kilo_t}$	Cost of tank material per kg

Parameter	Description
$valve_{cost}$	Cost of a set of valves per tank
T_{amb}	Ambient temperature

3.3.5 Mathematical model for ICS mass transfer using conservation principles

3.3.5.1 Extraction

During extraction from the MPS to the ICS tank, energy flows from the MPS to the ICS tank. During this process, the MPS temperature is assumed constant whilst the ICS temperature increases. The assumption of a constant MPS temperature is valid because the MPS is large relative to one ICS tank, and thus constitutes a temperature reservoir. Within the ICS tank, energy is transferred from the incoming gas to the heat capacitance. Figure 20 shows a two-tank system where one tank represents the MPS and the other represents one of the ICS tanks (This method is an elaboration of the approach taken by Nieuwoudt [6]).

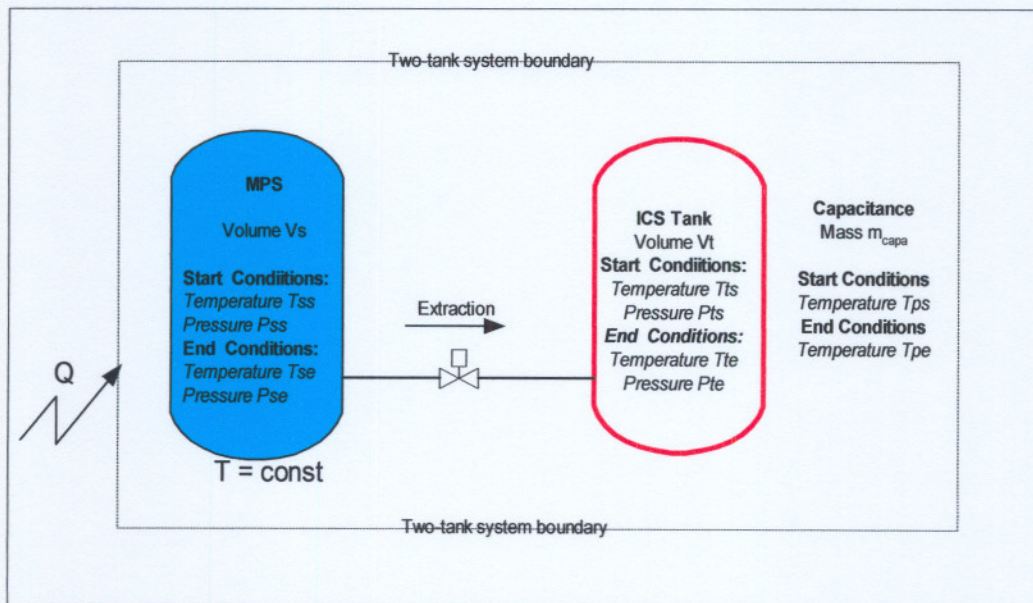


Figure 20: MPS-ICS System for Extraction

Consider heat addition to this two-tank system via the MPS tank. (The dashed boundary represents a control volume (CV)) For the combined system, the first law of

thermodynamics can be stated;

$$\delta Q - \delta W = \delta K.E. + \delta P.E + \delta U$$

This is a stationary closed system, hence

$$\delta K.E. = \delta P.E = 0.$$

And since no boundary work is done,

$$\delta W = 0$$

$$\therefore \delta Q = \delta U$$

which simply states that the heat added to the two-tank system results in a change of internal energy within the system

The above equation can be rewritten as;

$$\delta Q = \delta U_s + \delta U_t \quad (3.17)$$

where the subscripts *s* represents the MPS and *t* represents the ICS tank. Therefore all the heat that is added to the two-tank system goes into changing the internal energies of the MPS and ICS tank. Hence equation 3.17 describes the energy balance of the two-tank system.

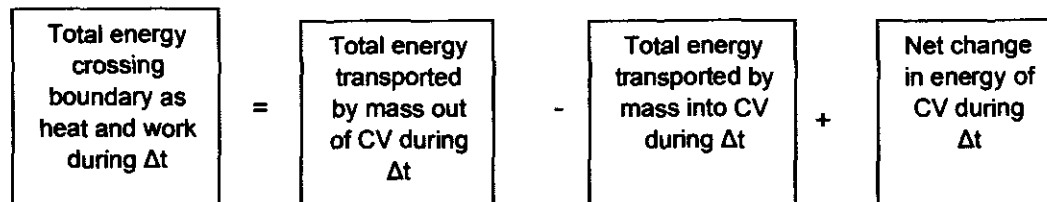
Energy balance on the MPS tank only

Carrying out an energy balance for the MPS tank only, would lead to the following equation for a control volume [9]

$$\delta Q - \delta W = \delta m_e \left(h_e + \frac{v_e^2}{2} + gZ_e \right) - \delta m_i \left(h_i + \frac{v_i^2}{2} + gZ_i \right) + (m_{t+\Delta t} e_{t+\Delta t} - m_t e_t)_{CV} \quad (3.18)$$

where the subscript *e* represents exit quantities, *i* represents inlet quantities and *t* represents time

This energy balance equation states;



If the changes in kinetic and potential energy associated with the control volume (CV) and fluid streams are negligible, then

$$\delta Q - \delta W = \delta m_e h_e - \delta m_i h_i + (m_{i+\delta} u_{i+\delta} - m_i u_i)_{CV}$$

In the case of the MPS volume:

$\delta m_i = 0$ since no mass is entering the control volume.

$\delta W = 0$ since no work is being done on the boundary of the control volume.

$$\therefore \delta Q = \delta m_e h_e + (m_{i+\delta} u_{i+\delta} - m_i u_i)_{CV}$$

which for convenience can be rewritten as;

$$\delta Q = \delta U_s + \delta m_s h_s \quad (3.19)$$

In equation 3.19, the subscript e is replaced by s, since that quantity is relevant to the MPS, and the control volume quantity is rewritten in delta form.

Energy transfer from MPS to ICS

Comparing equations 3.17 and 3.19, it can be shown that;

$$\delta U_i = \delta m_s h_s \quad (3.20)$$

which states that the change in internal energy of the ICS tank is equal to the enthalpy due to the mass transported from the MPS to the ICS tank

Integrating Equation 3.20 to find the total change in internal energy within the ICS tank;

$$U_{ie} - U_{is} = - \int_{m_{is}}^{m_{ie}} \delta m_s c_{ps} T_{ss}$$

Assuming that T_{ss} and c_{ps} are constant and swapping the limits to change the sign on the RHS;

$$U_{ie} - U_{is} = c_{ps} T_{ss} \int_{m_{ie}}^{m_{is}} dm_s$$

This equation can be rewritten using the notation described in 3.1.1:

$$c_v m_{iD,j,2} T_{iDa,j,2} - c_v m_{iD,j,1} T_{iD,j,1} = c_p (m_{sD,j,1} - m_{sD,j,2}) T_{sD} \quad (3.21)$$

The change in internal energy within the ICS tank occurs as heat is transferred from the incoming gas to the capacitance. The temperature $T_{iDa,j,2}$ is the value that the temperature would have been if no heat capacitance were available. However the heat capacitance absorbs this energy and rises in temperature from $T_{capD,j,1}$ to $T_{capD,j,2}$.

Therefore the energy balance in the tank is ;

$$c_v m_{iD,i,2} T_{iD,i,2} - c_v m_{iD,i,1} T_{iD,i,1} = m_{cap} c_{cap} (T_{capD,i,2} - T_{capD,i,1}) \quad (3.22)$$

If we assume that the heat is conducted from the gas to the capacitance with a temperature lag of ΔT_{lag} , then the final tank temperature is given by;

$$T_{iD,i,2} = T_{capD,i,2} + \Delta T_{lag} \quad (3.23)$$

Equations 3.21 to 3.23 form the energy balance for extraction.

The mass conservation is addressed by equating the helium mass leaving the MPS to that entering the ICS tank. This is described by equation 3.24 below.

$$m_{sDi,1} - m_{sDi,2} = m_{iD,i,2} - m_{iD,i,1} \quad (3.24)$$

The conservation of momentum is accounted for by the pipe losses;

$$P_{sDi,2} - P_{iD,i,2} = \Delta P_{Di,2} \text{ (Defined in 3.1.4)}$$

Combining the above conservation equations with the equations of state below;

$$m_{sDi,2} = \frac{P_{sDi,2} V_{sD}}{RT_{sD}}, m_{ie} = \frac{P_{iD,i,2} V_t}{RT_{iD,i,2}}, m_{sDi,1} = \frac{P_{sDi,1} V_{sD}}{RT_{sD}}, m_{iD,i,1} = \frac{P_{iD,i,1} V_{t,i}}{RT_{iD,i,1}}$$

The problem can be solved.

3.3.5.2 Injection

The injection model is also described using a two-tank model (Nieuwoudt [6]) as below.

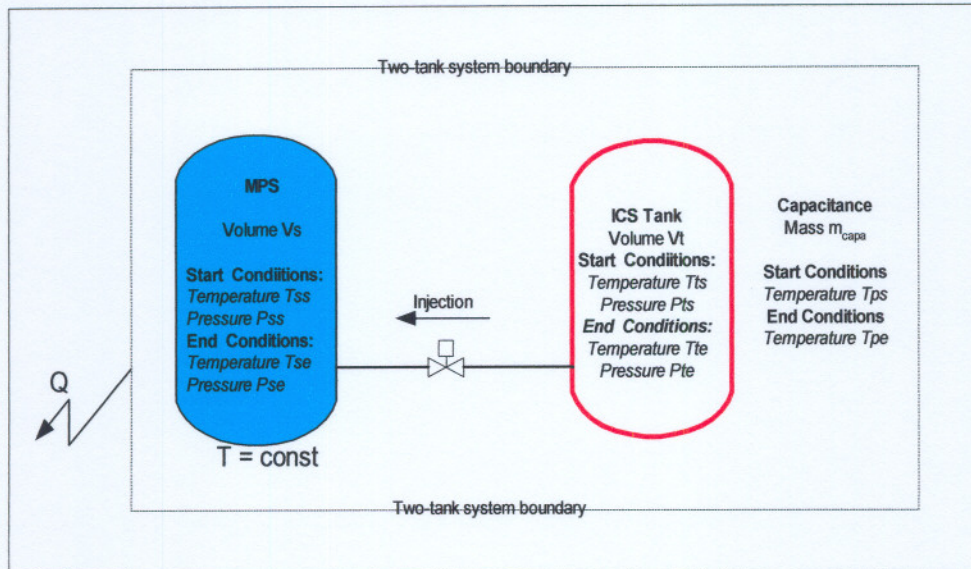


Figure 21: MPS-ICS Model for Injection

Using a similar approach as for extraction, a two-tank system representing the MPS and ICS is modelled, but this time with heat flowing out of the system.

Applying the first law of thermo-dynamics yields

$$-\delta Q = \delta U_s + \delta U_t$$

Following an energy balance on the MPS control volume,

$$\delta Q = \delta U_s + \delta m_s h_s$$

Comparing the above equations leads to;

$$U_{te} - U_{ts} = - \int_{m_{ss}}^{m_{se}} \delta m_s c_{ps} T_{ss}$$

Which is the re-written as;

$$-(U_{te} - U_{ts}) = \int_{m_{ss}}^{m_{se}} \delta m_s c_{ps} T_{ss}$$

And re-arranged to give;

$$U_{ts} - U_{te} = c_{ps} T_{ss} \int_{m_{ss}}^{m_{se}} dm_s$$

The above equation is rewritten in the notation described in 3.1.1:

$$c_v m_{tU,i,1} T_{tU,i,1} - c_v m_{tU,i,2} T_{tU,i,2} = c_p (m_{sU,i,2} - m_{sU,i,1}) T_{sU} \quad (3.25)$$

The change in internal energy within the ICS tank occurs as heat is transferred from

the capacitance to the outgoing gas. The temperature $T_{iUa,i,2}$ is the value that the temperature would have been if no heat capacitance were available. However the heat capacitance dissipates heat to the outgoing gas, and drops in temperature from $T_{capU,i,1}$ to $T_{capU,i,2}$

$$c_v m_{iUi,1} T_{iU,i,1} - c_v m_{iUi,2} T_{iUa,i,2} = m_{cap} c_{cap} (T_{capU,i,1} - T_{capU,i,2}) \quad (3.26)$$

Assuming that the heat is conducted from the gas to the capacitance with a temperature lag of ΔT_{log} , then the final tank temperature is given by;

$$T_{iUi,2} = T_{capDUi,2} + \Delta T_{log} \quad (3.27)$$

Equations 3.25 to 3.27 form the energy balance for injection

The mass conservation is addressed by equating the helium mass leaving the ICS tank to that entering the MPS. This is described by equation 3.28 below.

$$m_{sUi,2} - m_{sUi,1} = m_{iUi,1} - m_{iUi,2} \quad (3.28)$$

Since the same amount of helium extracted from the MPS must be injected back, equation 3.29 below completes the mass balance and links it to the extraction process.

$$m_{sUi,2} - m_{sUi,1} = m_{sDi,1} - m_{sDi,2} \quad (3.29)$$

The conservation of momentum is accounted for by the pipe losses;

$$P_{iUi,2} - P_{sUi,2} = \Delta P_{Ui,2} \text{ (Defined in 3.1.4)}$$

Combining the above equations with the equations of state below;

$$m_{sUi,2} = \frac{P_{sUi,2} V_{sU}}{RT_{sU}}; m_{iUi,2} = \frac{P_{iUi,2} V_{iU}}{RT_{iUi,2}}; m_{sUi,1} = \frac{P_{sUi,1} V_{sU}}{RT_{sU}}; m_{iUi,1} = \frac{P_{iUi,1} V_{iU}}{RT_{iUi,1}}$$

the injection problem can be solved.

The energy balance described for injection is suitable for small amounts of helium gas. However, since the energy leaving the capacitance must go to the helium gas, it is not possible to accurately apply an energy balance for a large mass leaving the tank, therefore the energy balance is corrected by replacing equations 3.25 and 3.26 with the combination of 3.30 and 3.31

$$\frac{T_{tUi,2}}{T_{tUi,1}} = \frac{C_{cap} m_{cap} + C_v m_{eq} \left[\frac{m_{tUi,2}}{m_{tUi,1}} \right]^{k-1}}{C_{cap} m_{cap} + C_v m_{eq}} \quad (3.30)$$

$$m_{eq} = \alpha m_{tUi,1} + (1 - \alpha) m_{tUi,2} \quad (3.31)$$

A variable m_{eq} , defines the mass in the tank which is made up of portions before and after injection. The value $\alpha=0.22$, apportions the mass in the tanks so that the contribution of each of the mass portions, i.e. before and after injection, is accounted for. This value was a result of extensive numerical formulation based on the conservation principles described earlier.

Equations 3.30 and 3.31 are a result of a numerical solution (see Appendix A.3) which begins with the energy balance as described before but caters for small amounts of mass transfer so that the approximation, that all energy stored by the capacitance is transferred to the outgoing gas, is made valid.

3.3.6 ICS design for helium storage

An additional role of the ICS is to store all the helium from the MPS when the latter is taken down for maintenance. A possible means of going down to maintenance involves using pressure differential to transfer mass as described before. At 45%MCR, a PCU trip [19] is initiated causing the Brayton cycle to collapse. At this point helium is transferred to the ICS using compressor power. The tanks are designed to hold equal amounts of mass when the entire MPS has been evacuated. As will be shown by the design results (see 4.2.3), the tanks store different amounts of helium when the plant has been reduced to 45%MCR. However for design convenience the tanks are topped up to the same level when the MPS is in a maintenance condition. Figure 22 illustrates.

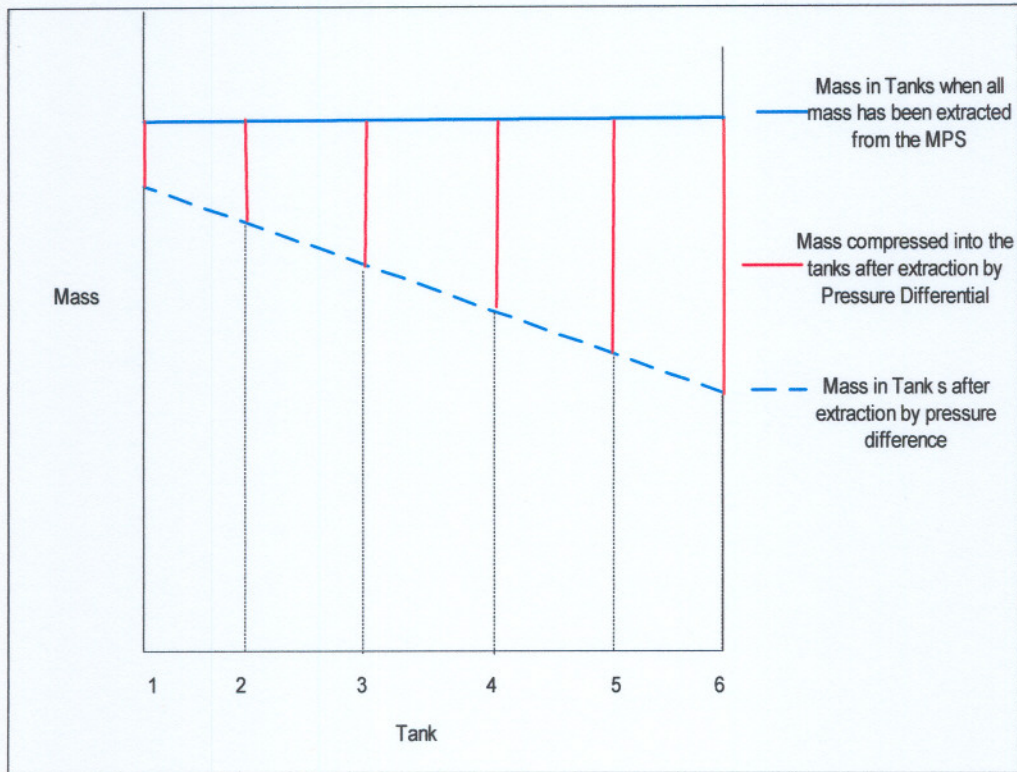


Figure 22: Mass Storage of the ICS when MPS is in Maintenance

The total is made up of the mass in the tanks at the end of mass transfer by pressure differential, plus what is remaining in the MPS at 45%MCR.

$$m_{tot} = \sum_{i=1}^n m_{iDi,2} + MPS_{Remain}$$

The mass in each tank is;

$$m_{full,i} = \frac{m_{tot}}{n}$$

This is the same for all tanks so;

$$m_{full,i} = m_{full}$$

The pressure for a full tank is calculated using the equation of state below;

$$m_{full,i} = p_{full,i} \cdot \frac{V_{t,i}}{\left[1 + \mu_{comp} \frac{p_{full,i}}{T_{tD}^{1.2}} \right] \cdot R \cdot T_{tD}}$$

Having obtained the tank pressures when fully compressed, the design pressure is calculated as shown below;

$$P_{iDesign,i} = P_{ifull,i} \times 1.1 \times 1.03 \quad [17]$$

The thickness of the tank wall is a function of the design pressure and based on ASME standards, can be calculated from the design pressure by the following equation.

$$thick_{t,i} = \frac{P_{iDesign,i} \times radius_{t,i}}{S_{allow} - 0.6 P_{iDesign,i}} \quad [6]$$

S_{allow} is the maximum allowable hoop stress that the tank can handle. [17]

The inner radius of the tank is simply;

$$radius_{t,i} = outer_r - thick_{t,i}$$

Each ICS tank is made up of a cylindrical shell with an ellipsoidal volume on either end as shown in Figure 23 below.

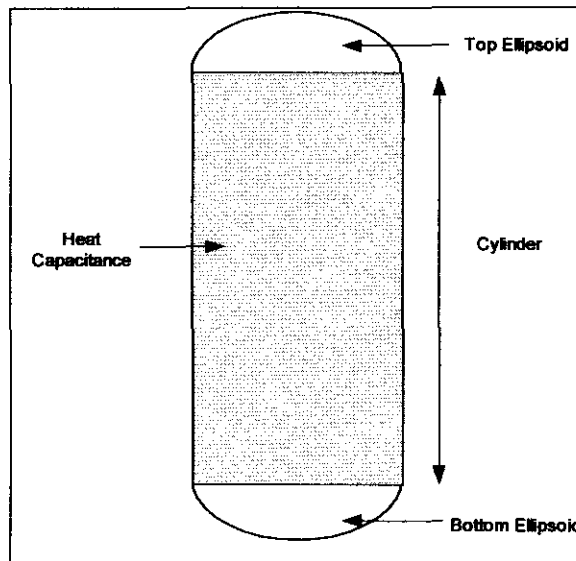


Figure 23: Component Break-down of an ICS tank

The height of the ellipsoid is half of the outer tank radius;

$$h_{ellip,i} = \frac{outer_r}{2}$$

which implies the cylindrical part has a height given by;

$$h_{cyl,i} = h_{tank} - 2 \cdot h_{ellip,i}$$

The internal volume of the cylindrical shell is;

$$V_{cyl,i} = h_{cyl,i} \cdot \pi \cdot radius_{i,i}^2$$

and the ellipsoid holds a volume given by

$$V_{ellip,i} = \frac{2 \cdot \pi \cdot radius_{i,i}^3}{3}$$

Therefore the internal volume of each tank is

$$V_{tan k,i} = V_{ellip,i} + V_{cyl,i}$$

Since some of the internal volume is occupied by the heat capacitance, the gas volume is given by;

$$V_i = V_{tan k,i} - \frac{m_{cap,i}}{density_{cap}}$$

Given the capacitance packing ratio and a density of steel (7850kg/m³), it is possible to calculate the capacitance mass in each tank as shown below

$$m_{cap,i} = 7850 \cdot V_{tan k,i} \cdot HC_{Ratio}$$

The mass of the cylindrical shell is given by;

$$m_{cyl,i} = 7850 \cdot h_{cyl,i} \cdot \pi \cdot (outer_r^2 - radius_{i,i}^2)$$

And the mass of the ellipsoidal shell;

$$m_{ellip,i} = \frac{7850 \cdot 2 \cdot \pi \cdot (outer_r^3 - radius_{i,i}^3)}{3}$$

The total cost of the ICS system is calculated as shown below

$$Total_{cost} = n \times [(m_{cyl,i} + m_{ellip,i}) \times cost_{kilo} + (m_{cap,i}) \times cost_{kilo_capa} + cost_{valve}]$$

The total cost, $cost_{valve}$, includes the cost of a set of valves for each tank.

4 ICS THERMO-HYDRAULIC SOLUTION AND EVALUATION

It was shown in section 3.1.1 that a multi tank design with heat capacitance improves storage effectiveness, which could make the ICS cheaper.

This chapter aims at presenting an optimised solution for the ICS, followed by a validation of the model which is used to generate the solution. Finally the solution of the ICS is evaluated by performing transient analyses which are representative of the actual operation of the ICS.

4.1 Obtaining the optimum design solution for the ICS

In order to obtain an optimum solution for the ICS, the following constraints were imposed.

Table 8: ICS Boundary Inputs

Parameter	Description	Value
$outer_r$	Tank outer radius	1.925 [m]
$cost_{kilo_t}$	Cost of tank material per kg	R50/kg
$cost_{ratio}$	Ratio of Capacitance cost to tank material	0.9
$valve_{cost}$	Cost of a set of valves per tank	R1 million
T_{amb}	Ambient temperature	298.15 [K]
L	Pipe length	50 [m]
D	Pipe diameter	0.223 [m]
K_{Loss}	Pipe losses: K	25
HC_{Ratio}	Capacitance packing ratio by volume	0.025

These constraints were obtained from the ICS development specification [17]

Table 9: Target Performance

Description	Value
Range	³ 100%-45%MCR at least
Flow-rate	10%MCR/min=7.5kg/s

³ See section 3.2 on Performance Requirements

Table 10: Design Target

Cost Constraint	Minimum Possible Cost
Height Constraint	Below 12 [m]
Lateral Space Constraint	Not more than 8 tanks, each with a diameter of 3.85 [m]

Table 11: Varied Inputs

Number of tanks	2 to 10
Capacitance Packing Ratio	0 to 0.1

Initially the number of tanks was varied whilst keeping the capacitance constant at 2.5%⁴ between 2 and 10 tanks. When the optimum number of tanks was obtained, the capacitance was varied. These results are described in the following section.

4.1.1 Varying the number of ICS tanks

With reference to Figure 24: As the number of tanks is increased, the volume required for storage decreases sharply between two and six tanks. Thereafter, the impact of more tanks on total storage volume is progressively less, tending towards a constant value.

⁴ This value was known to be close enough to the optimal

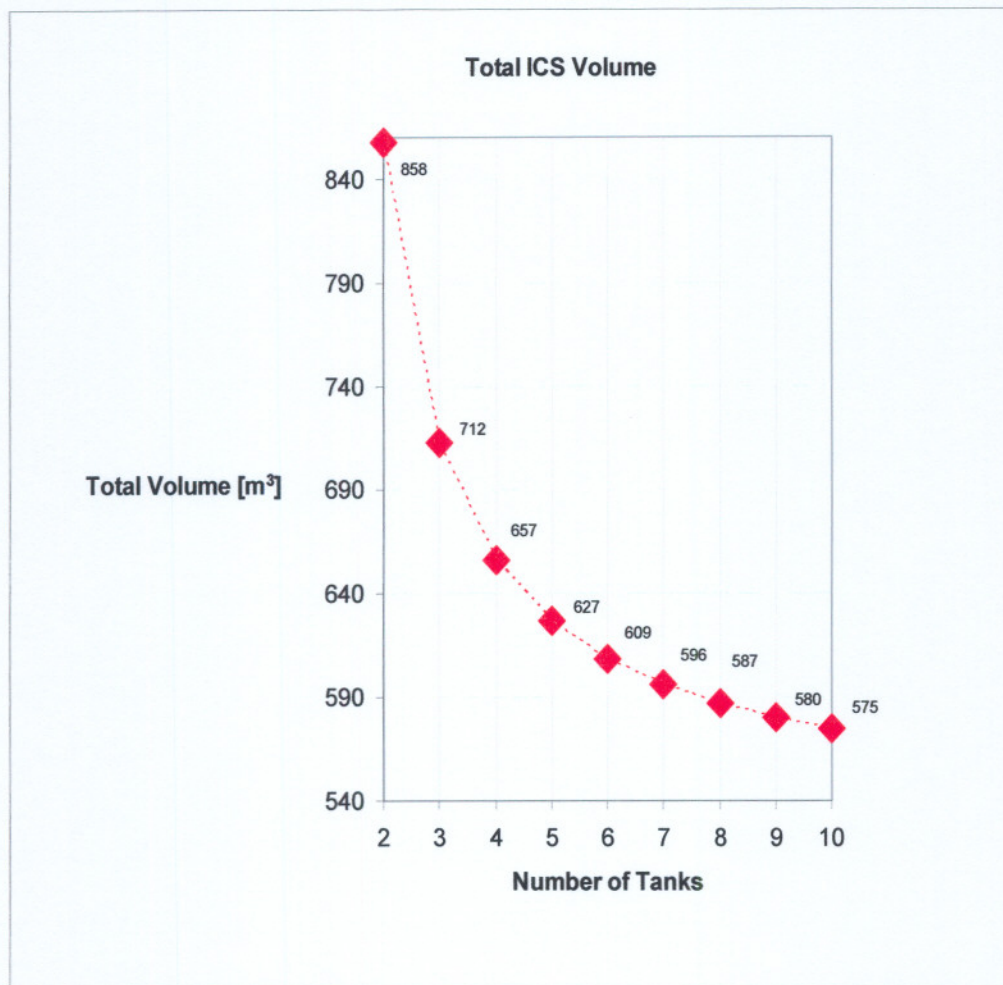


Figure 24: Total Volume of ICS

Since the outer diameter of the tanks is fixed, a change in volume translates to a change in height. Figure 25 shows how the height of the ICS varies with the number of tanks, which would give the corresponding volumes in Figure 24. Also shown is the relative lateral space usage of the ICS as the tanks increase.

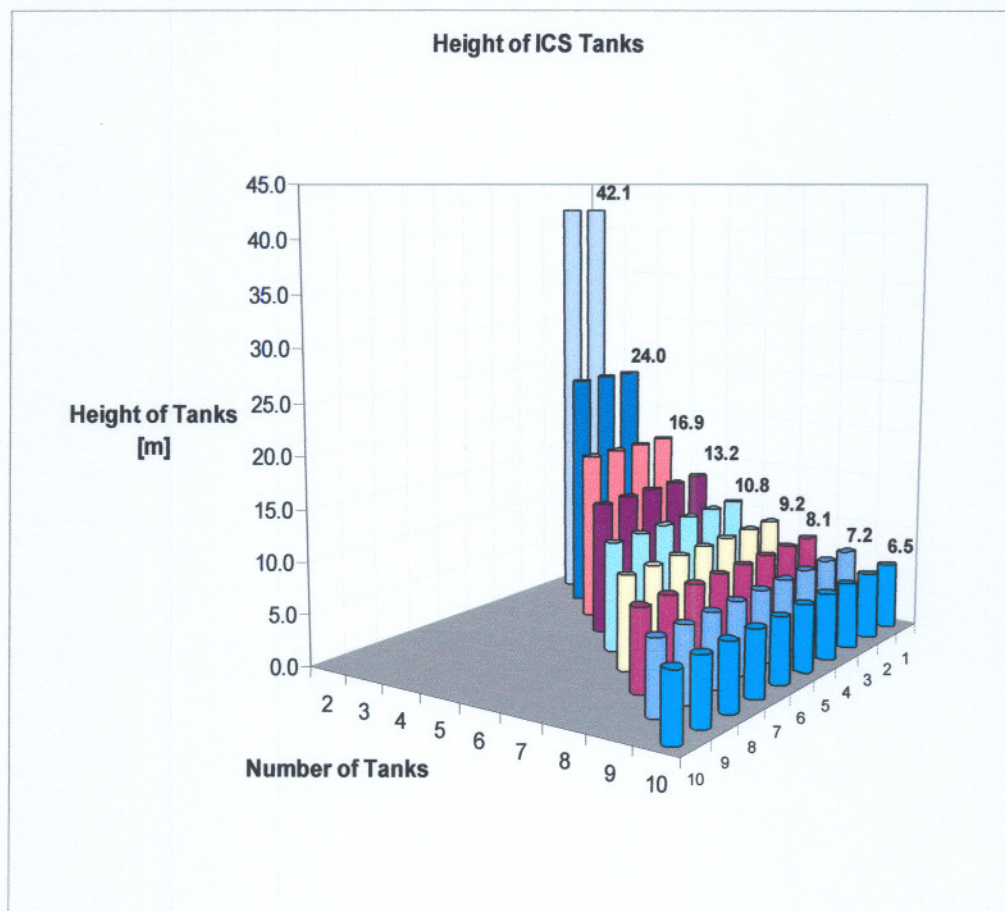


Figure 25: Height of ICS

The tank height progressively decreases as the number of tanks increase, owing to the fact that the volume is also decreasing. However the decrease in height becomes less significant with more tanks. The cost associated with the number of tanks is shown below in Figure 26. A 3-tank system for the ICS would yield the cheapest possible solution with a cost estimate of 49.3 million Rand.

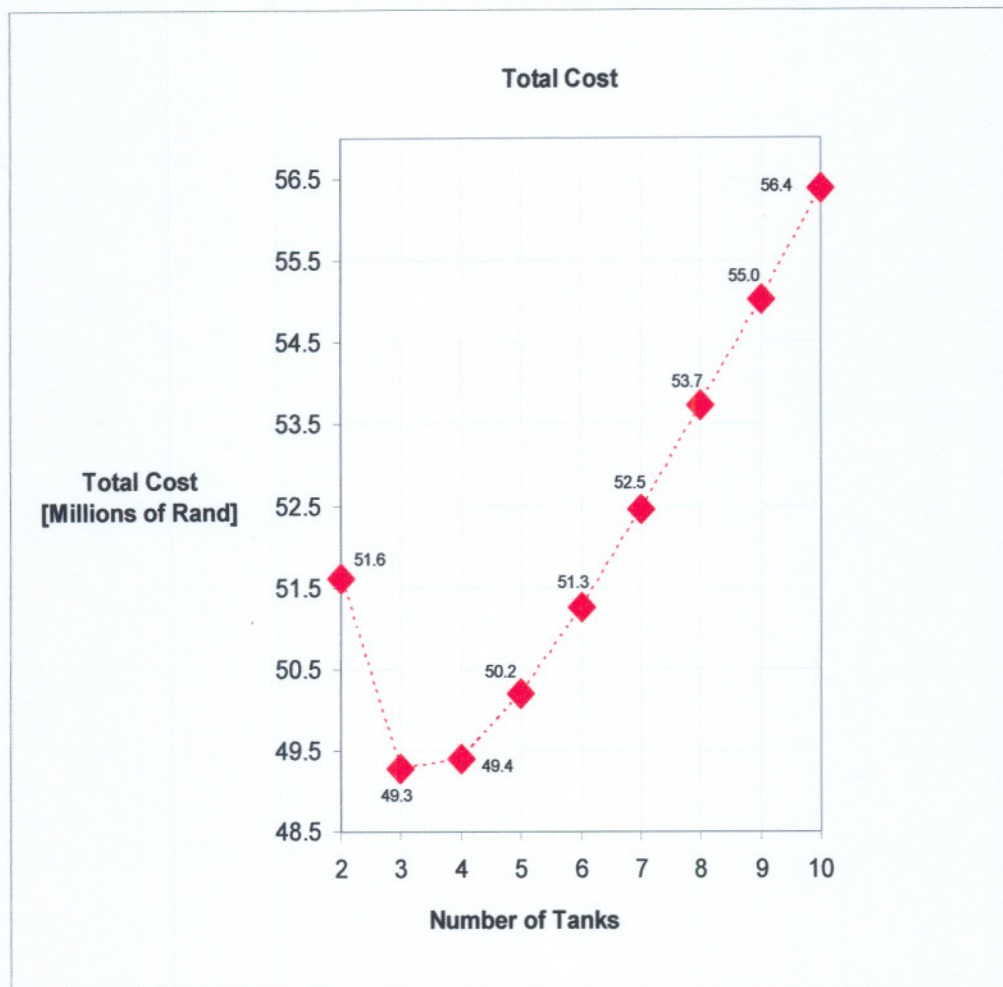


Figure 26: Total Cost of ICS

The cost of the ICS can be broken down according to the components that make up the tanks. From Figure 23, these are mainly the top and bottom ellipsoids of the tank, the cylindrical part of the tank, and the heat capacitance within the tank. Additional components include the valves and piping system for each tank.

Figure 27 shows that the total cost of the ICS is dominated by the cylindrical component. However since the cylindrical component becomes shorter with more tanks, its contribution to the total cost is progressively less.

The cost of the capacitance tends to decrease with more tanks. This is because the capacitance packing ratio is fixed at 2.5% of the internal volume of the ICS tanks, so as the volume decreases, the amount of capacitance decreases leading to a decrease in its cost.

The cost of valves (which includes piping), increases with the number of tanks simply

because each tank requires a set of valves.

The ellipsoids also increase in cost because more of them are required as the number of tanks increase. Unlike the cylindrical part which decreases in height, the ellipsoid has fixed outer dimensions since the tank outer diameter is fixed.

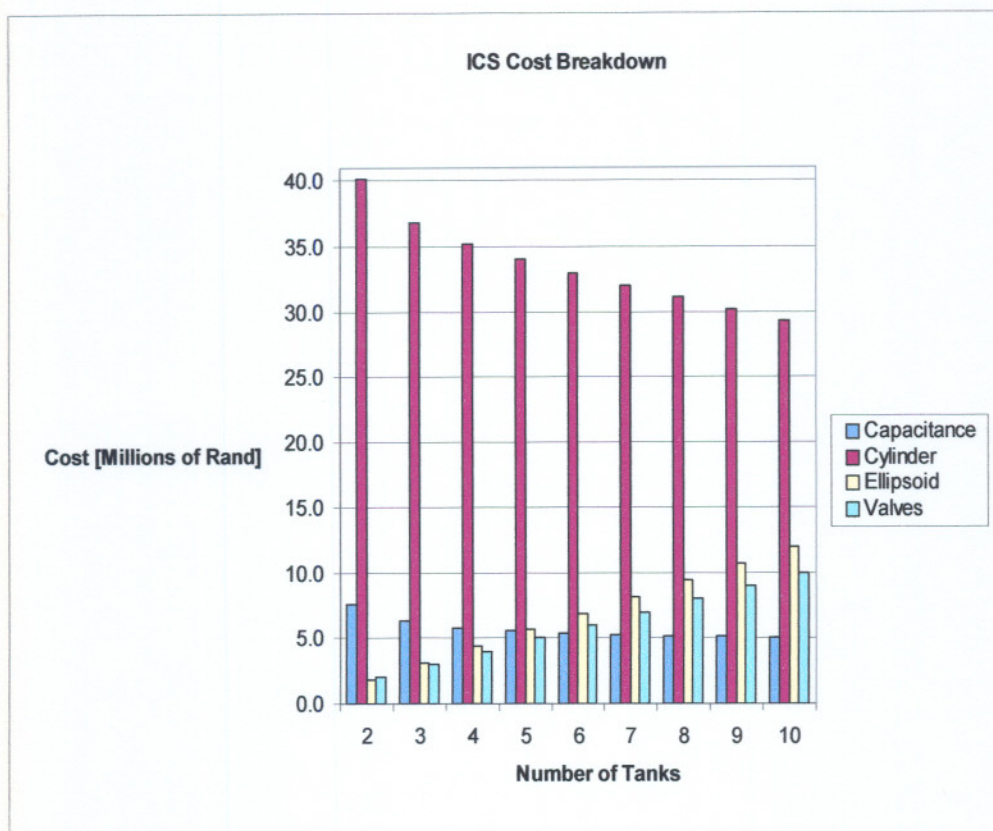


Figure 27: Cost Breakdown of ICS

Figure 28 takes a closer look at the cost breakdown. The right hand axis of the graph is scaled for the cost of the ellipsoids, capacitance and valves. For the range of tanks chosen this scale is much less than that of the cost of the cylinder which is scaled on the left hand axis of the graph.

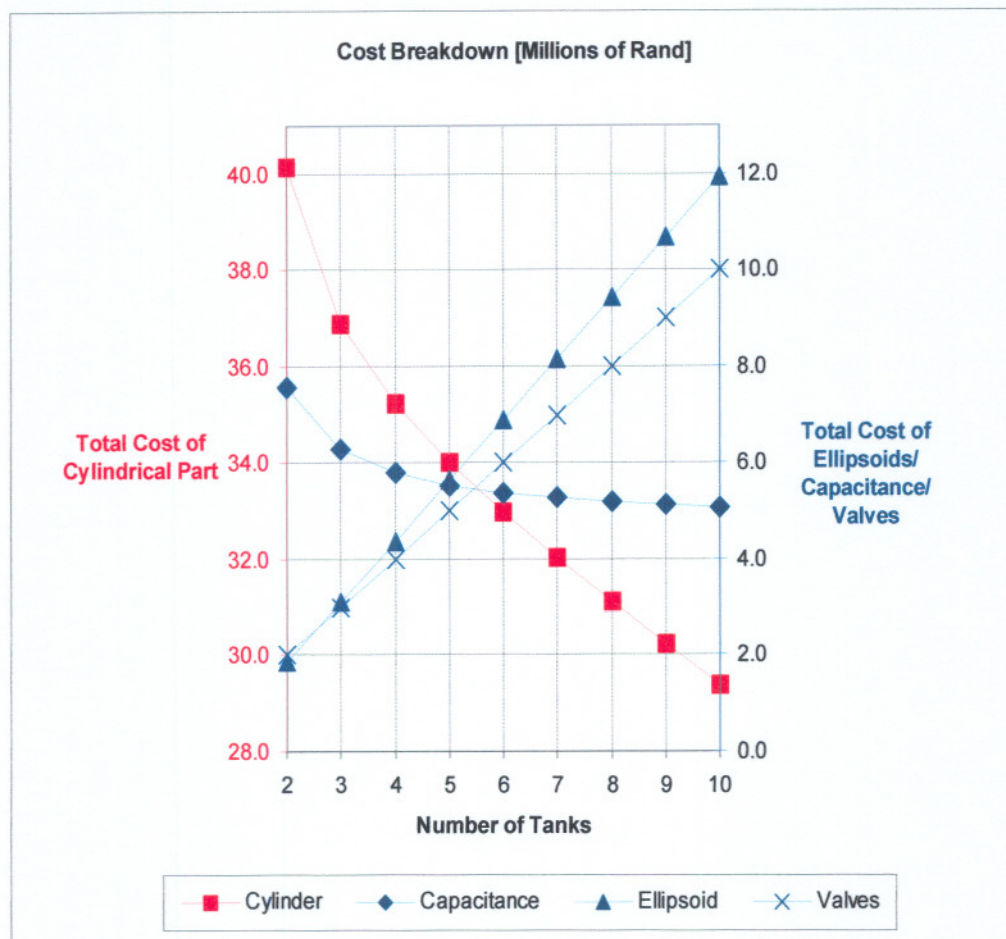


Figure 28: Cost Breakdown of ICS

From the above results it can be seen that a 3-tank design is the cheapest, but its tanks will not fit into the vertical allocation of the building. The best design which will fit into the vertical and lateral allocation of the building for the lowest cost is a **6 six tank design**. Compared to the 3 tank, the six tank costs 2 million Rand more.

4.1.2 Varying the heat capacitance

Having decided on a six tank ICS design, the amount of heat capacitance is now varied to obtain an optimum value. The same boundary and target values as described in Table 8 to Table 10 are used.

Since the outer diameter is fixed at 3.85m for all tanks, a change in volume translates to a change in tank height. Figure 29 shows how the tank height varies with capacitance. Initially, increasing the capacitance packing ratio makes it possible to use progressively smaller tanks, since the former provides thermal inertia which

slows down the pressure build-up when helium is transferred to the tank under pressure differential. This allows more helium to be stored per unit volume. However, beyond 6.5% of capacitance packing ratio, progressively larger tanks have to be used to meet the performance, since the increasing capacitance starts to “eat away” the gas storage volume. Hence a value of 6.5% packing ratio gives the most effective storage volume.

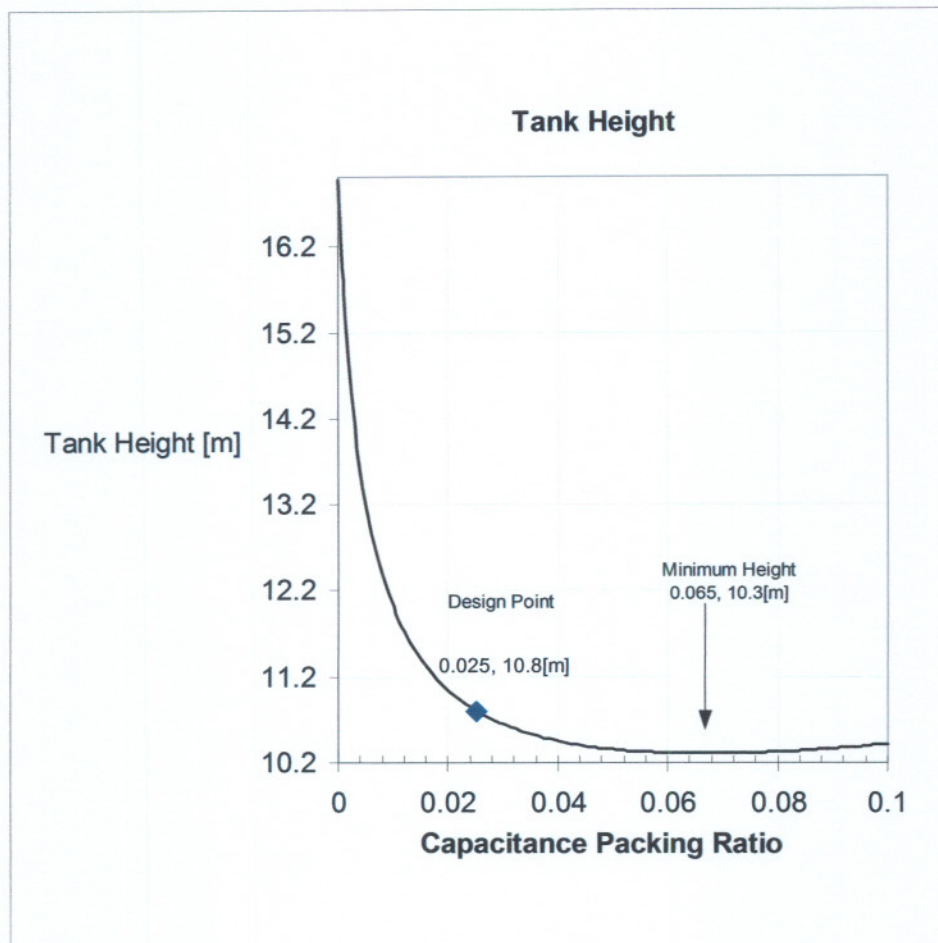


Figure 29: Varying the heat capacitance

As can be expected the total ICS cost will change with a variation in capacitance as shown in Figure 30. The minimum system cost occurs at a packing ratio of 2%. From the graph it can be seen that increasing the packing ratio to 6.5% (which gives the minimum storage volume) results in relatively huge increase in cost - approximately 6 million Rand. Such a large increase is not justified. As a result, a packing ratio of 2.5% is chosen as this gives a cost which is fairly close to the minimum and not too

far from the minimum height (or storage volume).

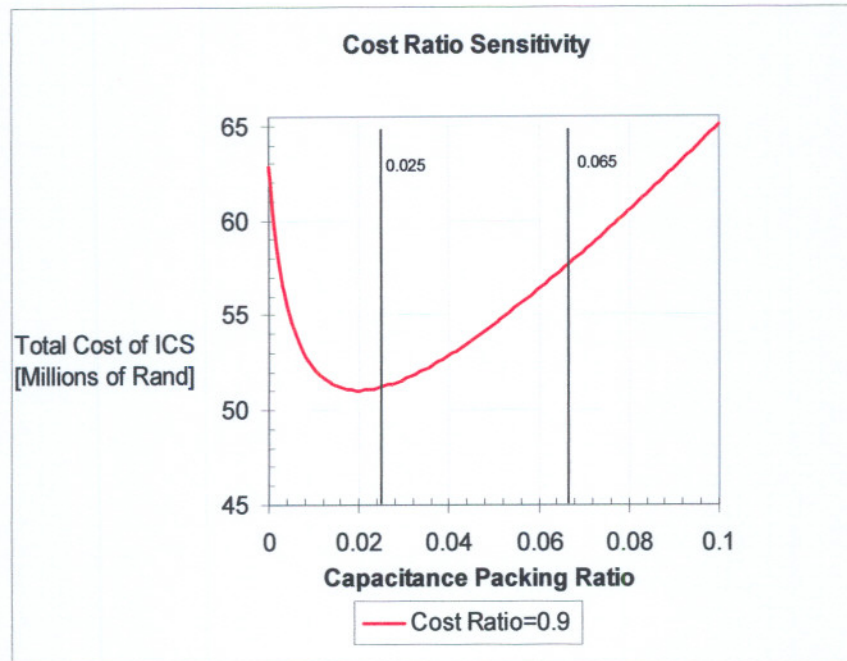


Figure 30: Varying the heat capacitance – Cost

To get more value out of the capacitance, a lower cost ratio (cheaper capacitance) can be used, so that the cost of the capacitance has less influence on the total cost. Figure 31 shows the impact of varying the cost ratio.

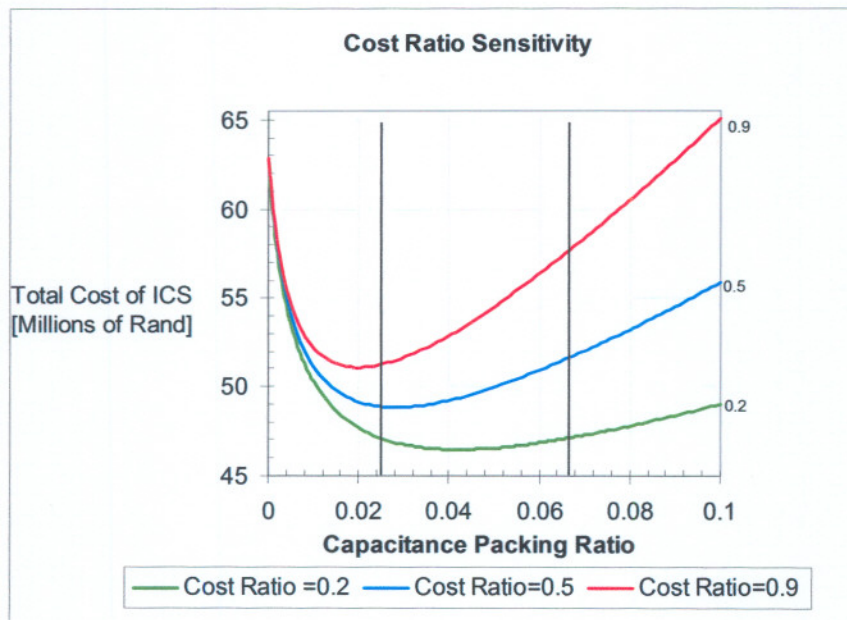


Figure 31: Capacitance Cost Sensitivity

Compared to a cost ratio of 0.9, a low cost ratio of 0.2 gives a minimum system cost at a packing ratio of 4%, which is closer to the packing ratio (6.5%) that would give the minimum volume. Since the influence of the heat capacitance on cost is low for a cost ratio of 0.2 it may be possible to implement a packing ratio of 6.5% as the total system cost will then be very close to the minimum value. However current estimates show that the cheapest available capacitance gives a cost ratio of 0.9.

4.1.3 Design solution

Based on the optimisation described above, the design solution is characterised by six tanks, measuring 10.8m high, 3.85m outer diameter and containing a heat capacitance packed at 2.5% of the internal volume of each tank. Table 12 summarises a breakdown of the ICS design.

Table 12: ICS Summary of Design Solution

Volume per tank [m³]	101.4
Height Per tank [m]	10.8
Outer Diameter [m]	3.85
Wall Thickness [mm]	131
Cost Ratio	0.9
Total ICS Cost [Millions of Rand]	51.3

Figure 32 shows a layout of the six-tank ICS design in the PBMR power plant

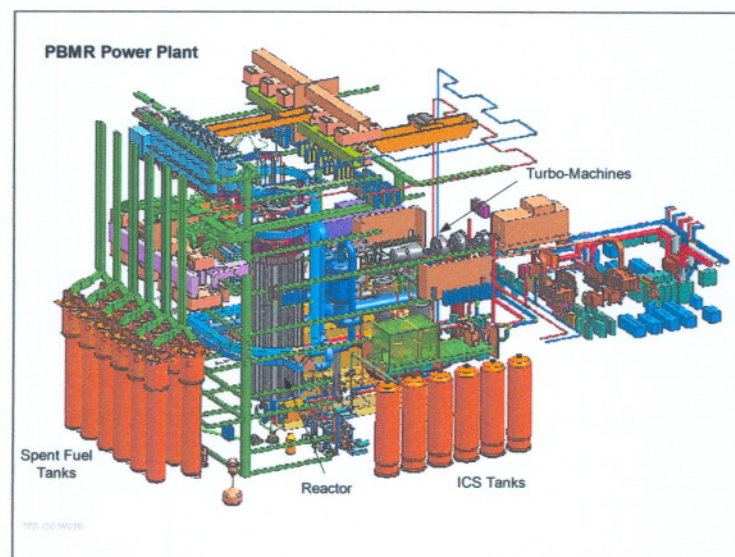


Figure 32: ICS Tanks in the power plant

4.1.4 Sensitivity analysis and model evaluation

Having decided on a six tank design with a 2.5% capacitance packing ratio, sensitivity analyses were carried out as a way of ranking the design parameters in order of to determine which ones have the greatest impact on the solution. These analyses are important particularly in the event that the MPS design is modified, resulting in a larger amount of helium in circulation.

The ICS will then have to accommodate more helium for the same range in performance. This implies the tanks will have to be made larger, or pipe losses reduced so that more mass can be transferred under pressure differential without losing the required flow rate, or the capacitance packing ratio will have to be increased. Table 13 and Table 14 show the sensitivity results for a $\pm 10\%$ variation about the design value of selected boundary parameters.

Table 13: ICS Sensitivity Summary

Variable	% Variation in Total Cost	% Variation in Performance Range (100%MCR-45%MCR)
Tank Outer Radius	10.8	29.7
Tank Height	4.4	16.6
Pipe Diameter	2.1	6.8
Capacitance Packing Ratio	1.0	1.5

Sensitivity analyses show that the tank outer radius is the most sensitive to cost for a $\pm 10\%$ variation about the optimum solution. However, the impact on performance when varying the outer radius is also the greatest compared to the other parameters.

The capacitance packing ratio may have a slightly insignificant impact for a $\pm 10\%$ variation about the optimum solution, but its impact is more significant at lower values as shown in Figure 29.

An alternative ranking scheme entails determining the ratio between the **variation in total cost** to **variation in performance**, i.e. a "cost to benefit" ratio, as shown below.

Table 14: ICS Cost Benefit Classification

Variable	Cost to Benefit Ratio
Tank Height	0.26
Pipe Diameter	0.31
Tank Outer Radius	0.37
Capacitance Packing Ratio	0.67

Table 14 is interpreted in the sense that, given a certain amount of money the tank height will yield the best improvement in performance, when considering a near optimum solution, whereas the capacitance packing ratio will give the lowest improvement.

The cost to benefit ratio of the capacitance can be improved by using cheaper capacitance material (Figure 30) compared to the steel that is used to manufacture the tanks. If the current cost ratio of 0.9 is lowered to 0.2, then the cost to benefit ratio of the capacitance would drop to 0.43.

4.2 ICS EES thermo-Hydraulic model evaluation using Flownex

The thermo-hydraulic model described in Chapter 3 was developed in the Engineering Equation Solver software environment (see Appendix A.2). The solution of this model includes values for the thermo-dynamic properties in the MPS, as well as in each ICS tank. (See Appendix A.8) The solution is structured to reflect the properties in the systems before and after each of the extraction and injection processes. This model does not give solutions as a function of time.

To evaluate the accuracy of these results, another model of the ICS is developed in the Flownex Nuclear [15] software environment. The Flownex code has been validated and verified extensively, notably in the Pebble Bed Micro Model project at the Northwest University [40] in which the code accurately predicted the performance of a three shaft recuperative Brayton cycle. Botha [21] also demonstrated the validity of the code by comparing Flownex solutions for transient flow through junctions, against Lax-Wendroff, a well known analytical scheme for time dependant compressible flow problems.

The results of the ICS Flownex model are then compared with those of the ICS EES

model. Flownex can perform transient simulations making it possible to obtain solutions as a function of time. This is useful in evaluating the ICS performance.

4.2.1 ICS Flownex system model test set up

Figure 33 shows a schematic layout of the ICS Flownex model test set up that is used to validate the ICS thermo-hydraulic model as described in section 3.1.

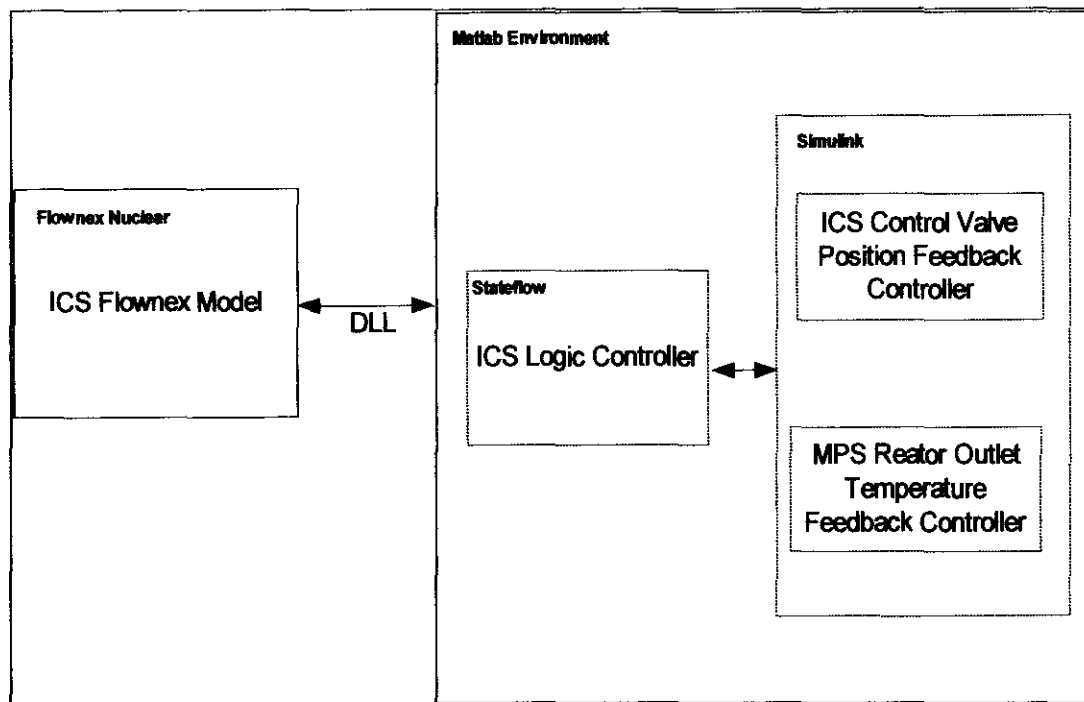


Figure 33: ICS Model Test Set up

The ICS Flownex model (see Appendix A.4) is constructed through a Graphical User Interface to form a network of nodes and elements which represent components of the ICS. The Flownex GUI allows input data to be populated to each of the components. This data will typically include physical boundary conditions such as tank volumes, pipe lengths, pipe roughness, pipe losses etc, and thermo-hydraulic properties such as pressures, temperatures, heat transfer coefficients, etc. The transient mode of Flownex makes it possible to calculate a thermodynamic solution of the ICS operation as a function of time.

To aid the generation of a transient solution, a controller is built in the Matlab software environment. This controller interfaces with the ICS Flownex model through a Dynamic Link Library (DLL) file. The purpose of the controller is to provide tank-

switching logic based on criteria as described in section (3.1). The logic is implemented using the Stateflow component of Matlab that allows logic signals to be generated from a finite state machine.

Additionally, the controller has two feedback mechanisms, one to regulate the mass flow-rate against a given set-point by controlling the opening of a control valve. The second feedback mechanism regulates the Reactor Outlet Temperature (ROT) by controlling the external reactivity, or the position of the control rods [8]. Both feedback mechanisms are constructed in the Simulink component of Matlab. It is worth noting that, to carry out a transient analysis of the ICS operation, the model must be coupled to the MPS Flownex model (A.4). This makes it possible to capture all the dynamics of the MPS during the ICS operation.

4.2.2 Test procedure

Having set up the Flownex model as described in the previous section, and populated data appropriately into the components, a transient test can be performed. For the purposes of comparison with the ICS EES model, the best transient test entails extraction of helium from the MPS when it is initially operating at full power, and using pressure differential to transfer mass to all 6 tanks in a sequential manner. In so doing the MPS power is reduced in a manner that is more or less proportional to the helium mass circulating within the Brayton cycle.

The feedback controller will open the valve to maintain a mass flow-rate of 7.5 kg/s, which is equivalent to 10%MCR/min (3.2). At a time when the pressure differential cannot sustain 10%MCR/min, the logic controller will switch to the next tank. When the last vessel, Tank 6, has more or less equalised with the MPS, injection begins a short while later.

The sequence of injection starts with Tank 6 releasing helium under pressure differential to the MPS. Upon the switching criteria being met, the next tank is selected until Tank 1 has released its stored helium to the MPS. In so doing, the MPS power increase with helium mass.

The initial conditions for the transient test described above are summarized in Table 15 and Table 16. These initial conditions are generated from the ICS thermo-hydraulic model in EES. The tank volumes are also calculated from the model. Section A.4 in the Appendix gives a full description of the Flownex simulation set-up.

Table 15: MPS Initial Conditions

Description	Value
Pressure at the HPC outlet	9000[kPa]

Table 16: ICS Tanks Initial Conditions

Tank Number	Pressure [kPa]	Temperature [°C]
1	3040	25
2	2733	25
3	2462	25
4	2228	25
5	2026	25
6	1855	25

4.2.3 Validation of the ICS Thermo -hydraulic Model

Since the boundary and initial conditions are the same between the EES and Flownex models of the ICS, a comparison was carried out on the “end” conditions. In this context end conditions imply the end of extraction and the end of injection. The results presented in this chapter include a comparison on mass transfer, system pressures and system temperatures.

Comparison of Mass Transferred

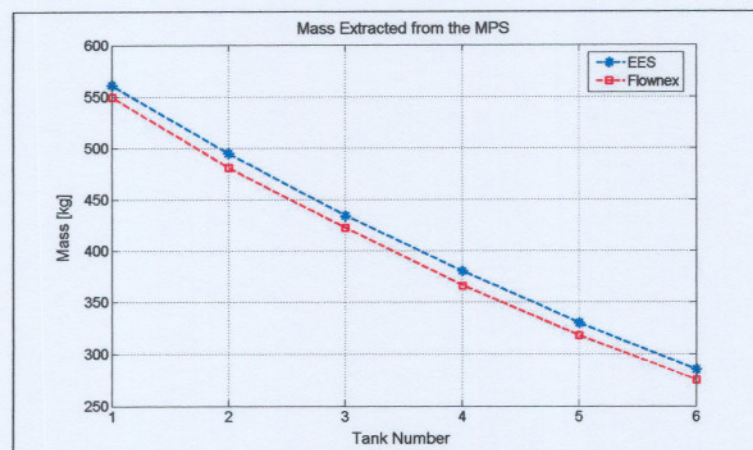


Figure 34: Mass Extracted from the MPS to the ICS

Figure 34 shows a comparison of the mass extracted to each ICS tank. The difference varies between 1.9% for the first tank, and 3.7% for the last tank as shown in Table 17. The average difference is 3.1%.

Table 17: Mass transfer comparison at the end of extraction

Tank No.	1	2	3	4	5	6
% Difference	1.9	2.7	3.0	3.6	3.8	3.7

Figure 35 below shows a comparison of the mass injected to the MPS from the tanks.

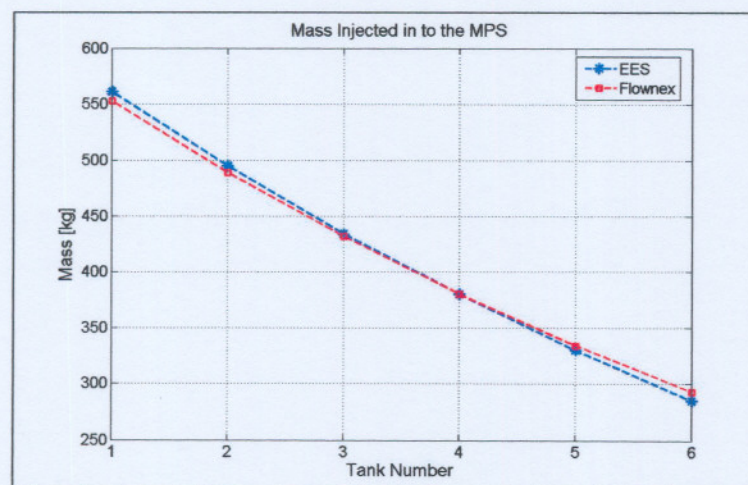


Figure 35: Mass Injected into the MPS from the ICS

The difference varies between 1.4% for the first tank, and -2.7% for the last tank as shown in Table 17. The average difference is 0.1%.

Table 18: Mass transfer comparison at the end of Injection

Tank No.	1	2	3	4	5	6
% Difference	1.4	1.2	0.5	-0.1	-1.2	-2.7

Comparison of ICS Pressures

As stated in the test procedure, the pressure condition at the end of an extraction sequence is the same as at the start of injection. Figure 36 shows the EES/Flownex comparison for ICS pressures at the start of injection.

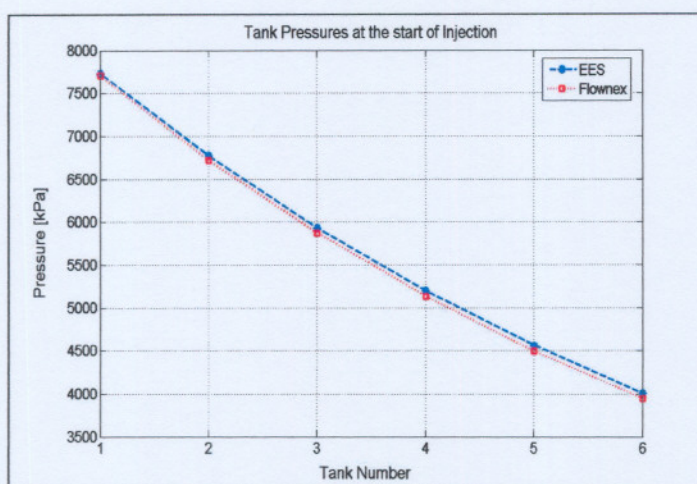


Figure 36: ICS Tank Pressures at the start of Injection

The difference in tank pressures varies between 0.4% for the first tank and 1.5% for the last tank. The average difference is 1.1%.

Table 19: Pressure comparison at the start of injection

Tank No.	1	2	3	4	5	6
% Difference	0.4	0.8	1.0	1.3	1.5	1.5

The comparison for tank pressures at the end of injection is shown in Figure 37 below.

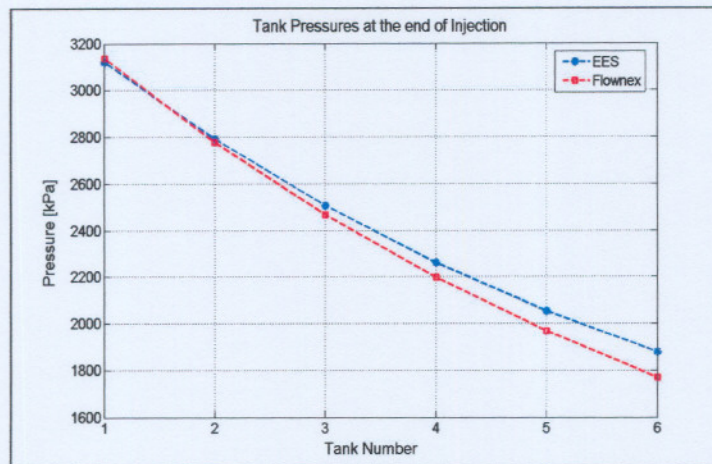


Figure 37: ICS Tank Pressures at the end of Injection

The difference in pressure varies between 0.5% for the first tank and -5.8% for the last tank. The average difference is 2.4%.

Table 20: Pressure comparison at the end of injection

Tank No.	1	2	3	4	5	6
% Difference	0.5	-0.5	-1.6	-2.8	-4.2	-5.8

Comparison of ICS Temperatures

The temperature conditions at the start of injection are similar to those at the end of extraction. Figure 38 shows a comparison of the tank temperatures at the start of injection.

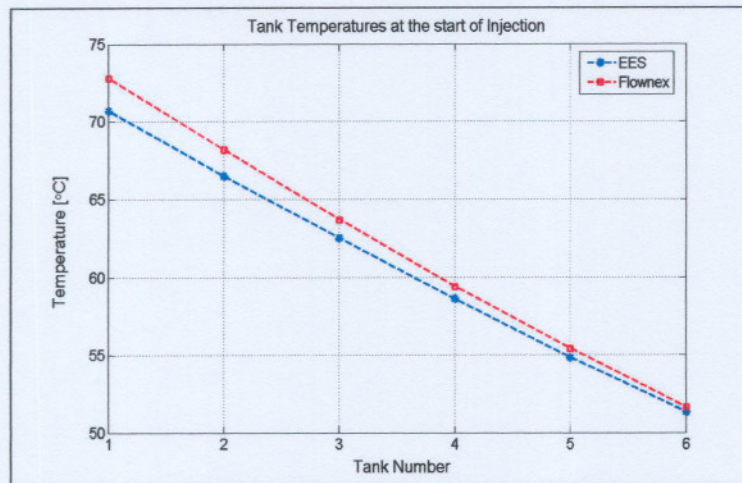


Figure 38: ICS Tank Temperatures at the start of Injection

The difference in tank temperature varies between 3.0% for the first tank and 0.7% for the last tank. The average difference is 1.8%.

Table 21: Temperature comparison at the start of injection

Tank No.	1	2	3	4	5	6
% Difference	3.0	2.6	2.0	1.5	1.2	0.7

Figure 39 below shows a comparison of the tank temperatures at the end of injection.

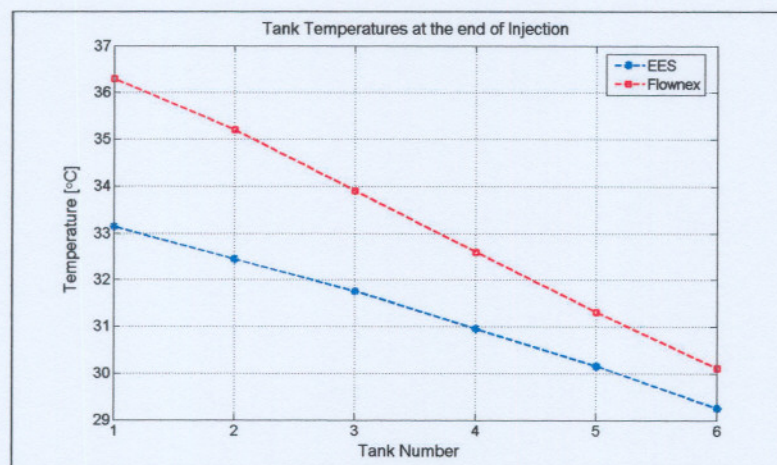


Figure 39: ICS Tank Temperatures the end of Injection

The difference in tank temperature varies between 9.5% for the first tank and 2.9% for the last tank. The average difference is 6.1%.

Table 22: Temperature comparison at the end of injection

Tank No.	1	2	3	4	5	6
% Difference	9.5	8.5	6.8	5.3	3.8	2.9

Overall Performance Comparison

The overall performance comparison is shown in Table 22

Table 23: ICS Flownex/EES Comparison

	Power Range	Mass Extracted [kg]	Mass Injected [kg]
EES	100%MCR-45%MCR	2484	2484
Flownex	100%MCR-45%MCR	2419	2481

4.2.4 Conclusion on model validation

Based on the above validation the following conclusions can be made;

- **Mass extracted in Flownex is slightly less but performance is still achieved**

The assumption of linearity between the %MCRI and the kg value; $\%MCRI = 0.0221Mass - 4.3331$, leads us to design the ICS to remove of 2484 kg of helium from the MPS in order to bring down the power to 45%MCR. Using the tank sizes and initial pressures obtained in the design, Flownex shows that only 2419 kg of helium has to be removed to reduce the power to 45%. This implies the tanks are slightly over-designed in EES, and as such, the linearity assumption is slightly incorrect. However, the error in total mass transferred is acceptable. To improve the correlation, more points could be fitted on the graph which relates %MCRI and helium mass in the system (3.2.)

- **Good correlation between EES and Flownex is shown for injection, but**

the total injected mass slightly exceeds the required amount.

Although a better correlation of mass transfer is shown for injection, more mass is injected than extracted with 2481 kg for the former and 2419 kg for the latter. (The extra mass comes from the initial mass in the tanks i.e. before extraction (A.8). As will be shown in the simulation results, this means the MPS will produce slightly more power at the end of injection. But this extra power is within the range of the PBMR's Operational Control System (OCS) [24] which is capable of adjusting several system parameters to correct the error in the power output.

- **Good correlation is shown in the pressures at the end of extraction**

The tank pressures at the end of extraction correlate very well between EES and Flownex. This implies the tank switching mechanism in EES correlates well with that in Flownex. In EES switching occurs when the pressure drop across the valve is 30% of the total pressure drop in the pipe-work [38], whereas in Flownex switching occurs when the mass flow-rate has dropped to 75% of the set-point.

- **Greater deviation is shown between EES and Flownex for pressures at the end of injection**

At the end of injection from the last tanks Tank 4 to Tank 6, the pressure correlation between EES and Flownex shows greater deviation. This could possibly be a result that the switching mechanism between the two models does not correlate close enough. However this deviation does not have a huge impact on the performance, and is deemed acceptable.

- **Temperatures differences between EES and Flownex are acceptable**

The differences in tank temperatures between EES and Flownex could be attributed to the equivalent volume assumption made in the former. The equivalent volume assumption lumps the entire MPS into a single volume with an equivalent pressure and temperature [A.1]. This means the temperature of the fluid exiting or entering this volume will not necessarily be the same as that leaving the HPC outlet or entering the PC inlet. As a result the tank temperatures at the end of each mass transfer process will differ. However the difference between the EES and Flownex models is acceptable as it does not seem to influence the overall performance.

From an overall perspective the ICS model is accurate enough as a design tool to determine the tank volumes, and carry out sensitivity analyses.

4.3 ICS Model as a simulation tool

Having validated the model, it is possible to use it to evaluate the ICS performance

The suitability of the ICS design is assessed in terms of its ability to meet the requirements as mentioned before, that is:

- i. Mass transfer between the MPS and the ICS is carried out using pressure differential only and that the mass transferred to any one of the ICS tanks during extraction is exactly equal to that leaving that tank during injection.
- ii. An operational range of 100%MCR to 45%MCR is targeted by the design. The transient analyses will show if this can be achieved.

Using the above assessment criteria, the transient results are presented and interpreted below.

4.3.1 Fluidic power output

Figure 40 shows the output of the power turbine when helium is extracted from the MPS to all six tanks before injecting immediately from all six tanks, back to the MPS.

The power trace is described by the following points;

- **A : Beginning of Extraction to Tank 1**
- **A to B:** Between points A and B the power output drops sharply before stabilising to a constant rate at B. This is due to the fact that, for an instant the power turbine, which is downstream of the HPC outlet (Figure 1), sees less flow in circulation compared to the LPC which still has to drive a relatively higher mass flow rate. Hence all of a sudden the turbine must work against a relatively higher load which results in sharp decrease in power. Eventually the reduced circulation finds its way to the LPC allowing the turbine to "catch up" to the prescribed ramp rate at B.

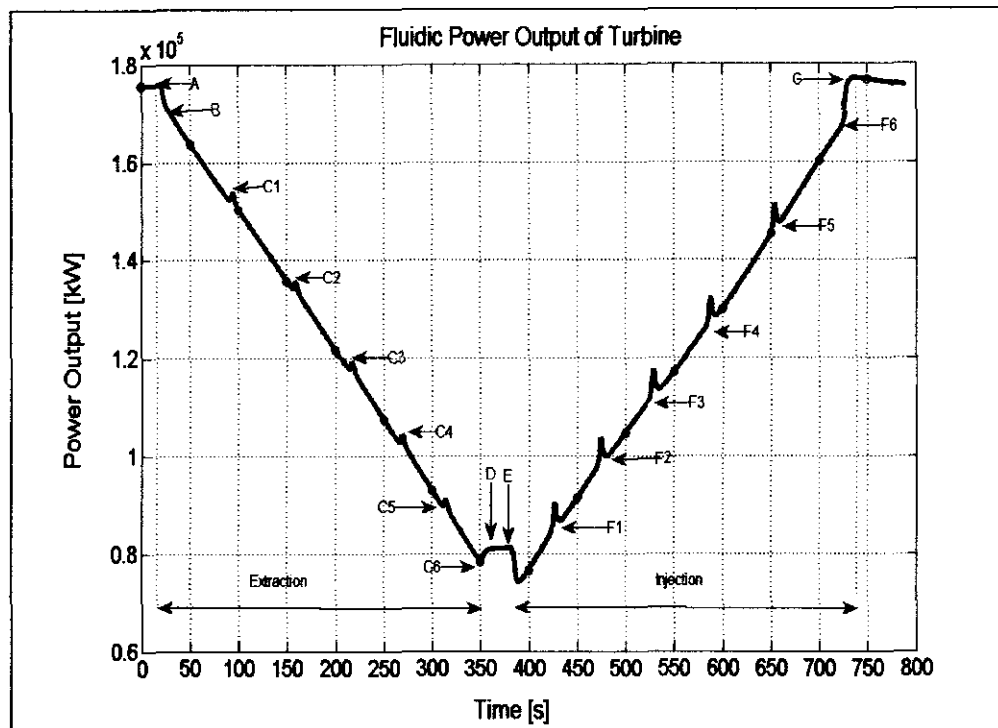


Figure 40: Fluidic Power Output of Turbine

- C1 to C6:** Represent the points of switching flow from one tank to the next. At C6, flow to the last tank is closed and extraction is stopped because there is no more pressure differential between the MPS and any of the ICS tanks. Power spikes at these points are brought about by the fact that, as the control valve closes flow to the current tank, the mass flow-rate in the power cycle increases. Since the turbine is ahead (taking the HPC outlet as the reference) of the compressors along the helium flow-path, it receives the extra flow first before the compressors, leading to a power boost. Before the power has stabilised flow is opened to the next tank. The system then undergoes a similar dynamic as described for A to B. Hence, the sudden closure and opening of the control and isolations valves during switching results in power spikes.
- C6 to D:** After flow to Tank 6 has been closed, the MPS power turbine receives a power boost owing to the increased flow-rate that reaches it before the compressors. At D the power stabilises as the flow in the cycle becomes homogenous.
- E:** Injection begins at point E. Flow is selected from the tanks beginning with Tank 6 back to Tank 1 [3.1]

- **E to F:** Between E and F the MPS undergoes a similar dynamic as that explained before for A to B, when flow in circulation is disturbed. But in this case, sudden helium injection to the inlet of the LPC increases the relative load that the PT must drive. From the point of injection, the turbine is further downstream in the flow-path than the compressors. Hence the compression load increases before the increased flow reaches the PT. Eventually the PT catches up as the cycle flow becomes homogenous. This non-minimal phase effect, where the power dips before increasing again, can be controlled out by using the bypass valves within the MPS.
- **G6 to G1:** Switching occurs, causing power spikes as described for C1-C6.
- **G1 to H:** After flow from Tank 1 has been closed, the compression load decreases relative to the PT resulting in a power boost. An intuitive explanation is that, the energy which was 'sprung' into the MPS between E and F is now released to the power cycle.
- Beyond H the power output eventually stabilises back to more or less the value at A.
- The power range for an extraction-injection cycle as described above is 100%MCR-45%MCR for extraction, and 45%MCR to 100.4%MCR for injection.

4.3.2 ICS and MPS pressures

Figure 41 below shows the MPS and ICS Pressures during an extraction-injection cycle. The points A, D, E and H shown on this graph correspond to the same points described in Figure 40

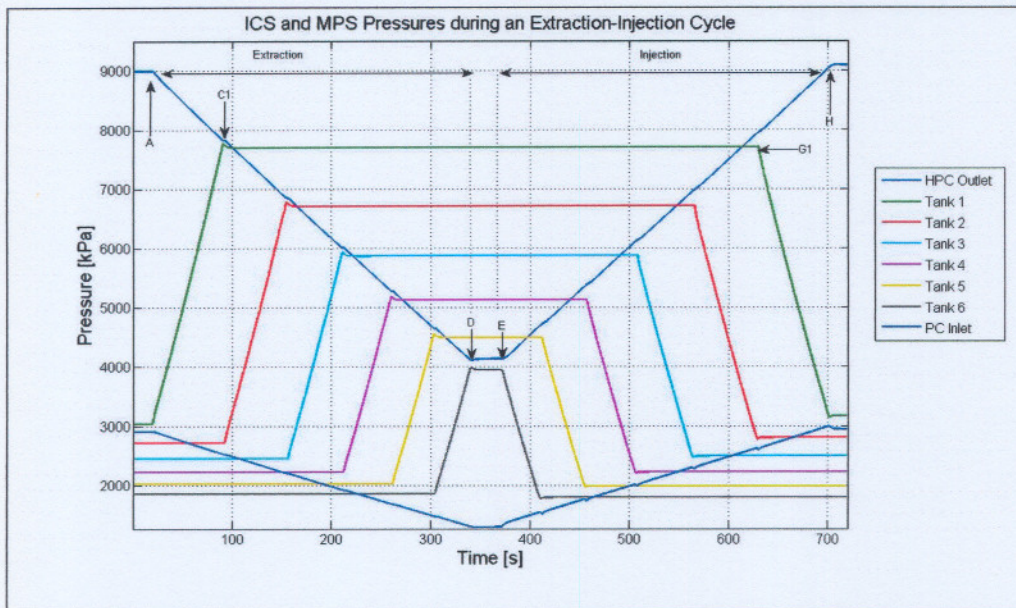


Figure 41: MPS and ICS Pressures

It can be seen that the pressures at the end of injection for Tank 6, Tank 5 and Tank 4 are lower than were they started before extraction. This implies that these tanks are injecting more mass than they should.

Tanks 1, 2 and 3 end up at slightly higher pressures than were they started, but as shown in Table 24, also contribute extra mass to the MPS during injection. This extra helium comes from the tanks which, prior to extraction, are pre-compressed for load following purposes (see 3.1).

Table 24: Extra Mass during Injection.

Tank	1	2	3	4	5	6
Extra Mass During Injection [kg]	2	6	9	12	15	28

This means the MPS carries an extra 61 kg at the end of injection than it did before the extraction-injection cycle. As a result the MPS power output is slightly higher than the 100%MCR. The corresponding pressure at the HPC outlet is 9096 kPa. These values are well within the capability of the Operational Control System (OCS) which can regulate the power to a more exact value, according to the requirement.

4.3.3 Conclusion on the ICS model as a simulation tool

Based on the result above it can be concluded that the ICS model can be used as a simulation tool, since fairly accurate results were obtained that meet the design criteria. However, the non-minimal phase effect is undesirable and can affect the accuracy of load following particularly when low flowrates are required. This can be addressed by the use of the Gas Cycle Bypass valve which changes the pressure ratio of the system so that there is no load mismatch between the turbine and compressors at the start of a mass transfer process.

Based on this conclusion, a load following test was done with bypass control as explained in the next section. (The detail of bypass control does not fall within the scope of this exercise)

4.3.4 Load Following against a Reference

As mentioned in the first chapter the primary purpose of the ICS is to achieve load following by adjusting the power output to the grid against a power demand which varies during the course of the day. Figure 42 shows a typical demand curve [42] that was used as a load reference to carry out load following simulations using the ICS model. This load reference is for a 24 hour period i.e. 86400 seconds.

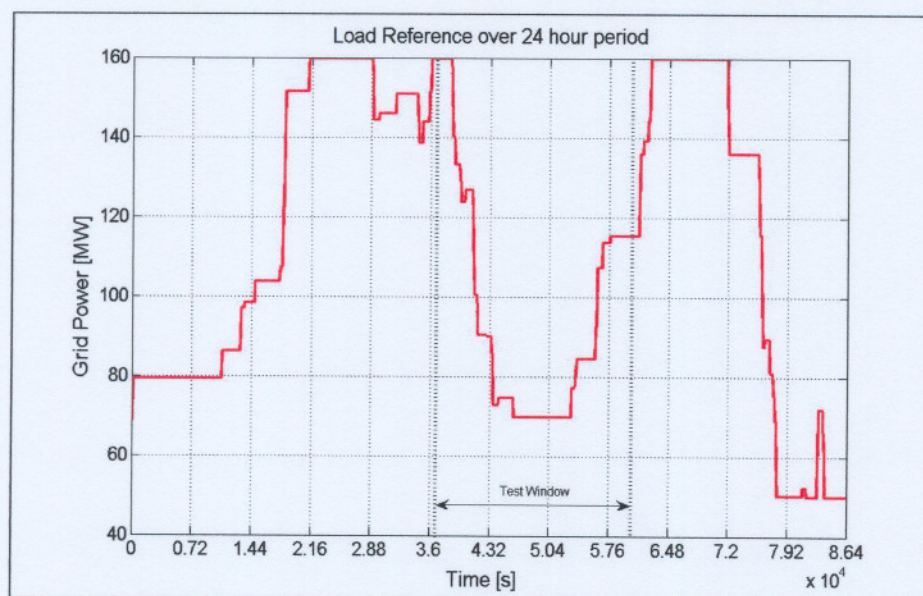


Figure 42: Load Reference

A test window was chosen on the load reference in which the power demand drifts to a low value and stays for some time before increasing again to full power.

With the aid of a power controller (A.7) and bypass control, the simulation showed that the ICS can achieve load following fairly closely as shown in Figure 43. The MPS responded by tracking the load reference as appropriate amounts of helium were transferred to and from the ICS.

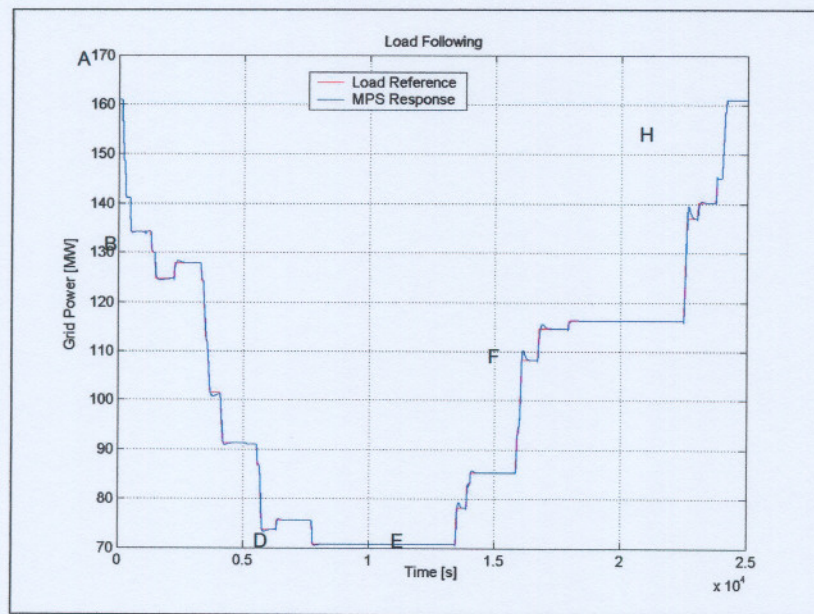


Figure 43: Load Following

Figure 44 below shows the MPS and ICS pressures during this load following simulation. The points A,B,D,E,H in Figure 44 correspond to the same points in Figure 43.

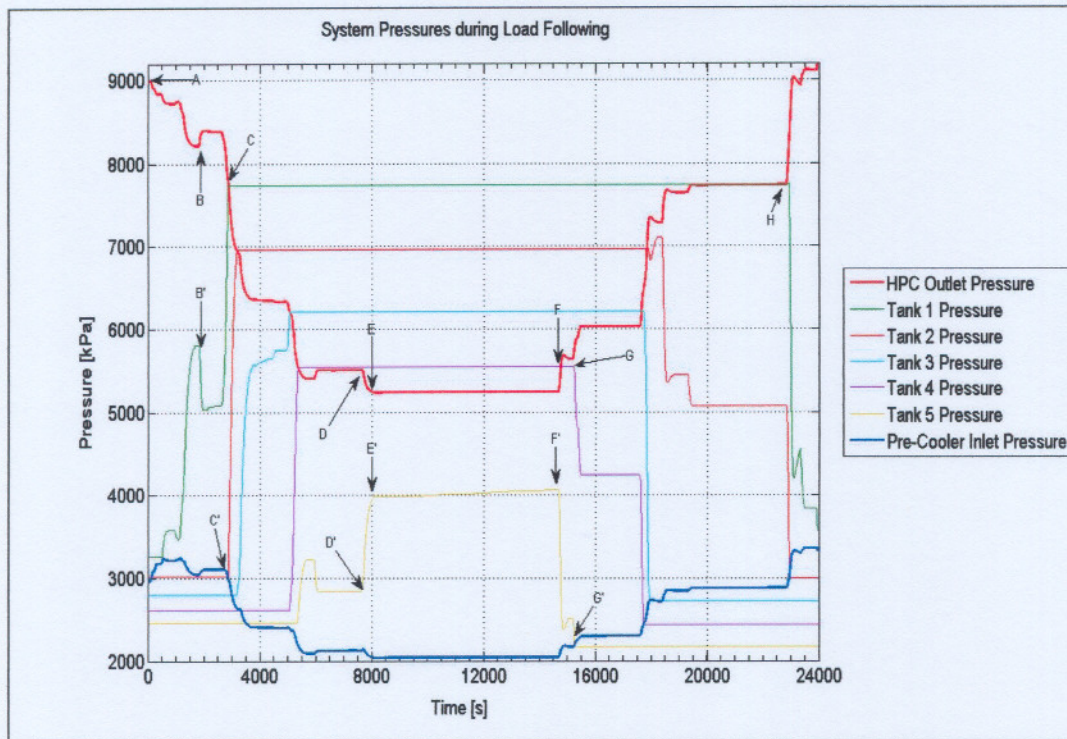


Figure 44: MPS and ICS Pressures during Load Following

On the graph, a few points were selected and are described as follows;

A: Power demand starts to reduce so the HPC Outlet pressure drops as helium is removed from the MPS. Tank 1 pressure starts to increase as helium flows therein.

B: Power demand increases slightly so helium flow is opened from Tank 1 to the MPS. The MPS pressure increases while Tank 1 pressure decreases.

C: MPS and Tank 1 pressures equalise and at C'. Tank 2 is selected so that helium flows from the MPS to reduce power.

D: Power demand drops. Tank 5, which at this stage is the selected tank, receives helium while reducing power output from the MPS.

E: The MPS pressure stays constant since the demand is constant.

F: Demand starts to increase gain. Tank 5 depressurises into the MPS and equalises with the PC inlet of the MPS at G, at which point Tank 4 is selected.

H: Tank 1 depressurises as power demand continues to increase.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the model development and results the following conclusions can be drawn;

5.1.1 The ICS model can be used as a design tool, but multivariable optimisation may be required

The ICS thermo-hydraulic model can be used as a design tool by varying certain input parameters to obtain an optimum design point. In this exercise, there were only two variables used to reach the optimum design solution, namely the number of tanks and the capacitance packing ratio. Each of the two parameters was varied individually whilst the other was kept constant. Finding the optimum point was made easier by the fact that the near optimum value of the capacitance was known. However, in the event of more variables whose near-optimal values are not well known, obtaining the optimum solution by varying one variable at a time is more challenging. It would then be necessary to expand the model to accommodate multivariable optimisation or sensitivity studies. Since the EES software environment in which the model was developed cannot support multi-variable optimisation, it may be necessary to develop an interface with a software program like Matlab which does support a variety of optimisation techniques.

5.1.2 The most cost effective improvement may not be practical

The results show that the most cost effective way to improve the performance is by increasing the height, whereas increasing the heat capacitance is the least effective. However space limitations in the PBMR building (owing to the presence of other plant equipment) dictate the outer dimensions such as tank height and diameter.

The pipe diameter may be limited by valve costs, or by the maximum allowable penetration into the pressure boundary of the MPS. Hence the cost benefit of changing these parameters to improve the performance of the ICS may be far outweighed by the cost of changing the overall plant layout or equipment. So as the overall PBMR plant design matures, it becomes less practical to change the abovementioned parameters for performance improvement purposes.

This leaves the capacitance packing ratio as the only means by which performance can be improved. However, as shown in the results, increasing the capacitance is not cost effective, nor does it yield that much better performance. So the most practical means to anticipate the need for improvement is to include a margin on the performance target. As a result the ICS tanks will have to be slightly larger (taller) than necessary.

5.1.3 The ICS model can be used as a simulation tool to characterize the MPS response

Since the ICS simulation results in Flownex correlate well with those predicted by the thermodynamic model in EES, the latter can be translated to Flownex which supports a capability for transient simulations to a high degree of accuracy. It is important to characterize the MPS response as this helps in the development of plant control schemes. As was shown in the results the non-minimal phase is undesirable and a means of controlling it out is required.

5.1.4 Load following can be achieved fairly closely with bypass control

Although the ICS is capable of extracting and injecting helium over a wide power range with reasonable accuracy in the desired power output, the non-minimal phase effect would be undesirable particularly where close tracking is required. In a load following case, this problem was addressed by using the ICS in conjunction with the Gas Cycle Bypass Valve which gave good tracking results.

5.2 Recommendations

Based on the conclusions the following recommendations can be made;

5.2.1 Implement a multi-variable optimisation scheme

Implement a multivariable optimisation scheme, possibly by developing an interface with Matlab to communicate with the EES program. Alternatively develop and optimise a similar thermo-hydraulic model in Matlab.

5.2.2 Include a design margin

Include a design margin to cater for a possible increase in the amount of helium that

has to be stored in the ICS.

5.2.3 Use bypass for injection

In all simulations involving injection include the use of the Gas Cycle Bypass valve to counter against the non-minimal phase effect.

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APPENDICES

A.1 Determining the Equivalent Volume for Extraction and Injection

The Equivalent Volume Concept applies to the manner in which the MPS is modelled thermo-hydraulically during a mass transfer transient to and from the MPS. It is a simplification which entails the reduction of the MPS helium pressure boundary (HPB) [35] into a single volume consisting of a uniform pressure and temperature. Hence if extraction is carried out from the MPS to the ICS via the HPC outlet, the equivalent volume will be a representation of the volume that the ICS 'sees' through the HPC outlet. In other words the net effect of the MPS during extraction through the HPC can be modelled as a node with a certain pressure and temperature. An equivalent volume is therefore defined for extraction through the HPC and denoted by V_{sysD} .

Similarly, during injection from the ICS to the MPS via the PC inlet, the ICS 'sees' a certain volume which will be termed the equivalent volume at injection and denoted by V_{sysU} .

To calculate the equivalent volume at extraction V_{sysD} , it is necessary to perform a transient simulation on the MPS thermo-hydraulic model in Flownex, in which mass is removed continuously from the MPS at a rate equivalent to the required performance of 10%MCR/min and for a duration which would reduce the power to 45%MCR. Whilst doing this, the pressure and temperature at the HPC outlet (point of extraction) are noted, and assuming that all the helium is concentrated at the point of extraction, one can then use the equation of state to determine V_{sysD} at each time step. Figure 45 shows how the equivalent volume at extraction varies with time. The average of this is also shown. The ICS model in EES uses this average equivalent volume.

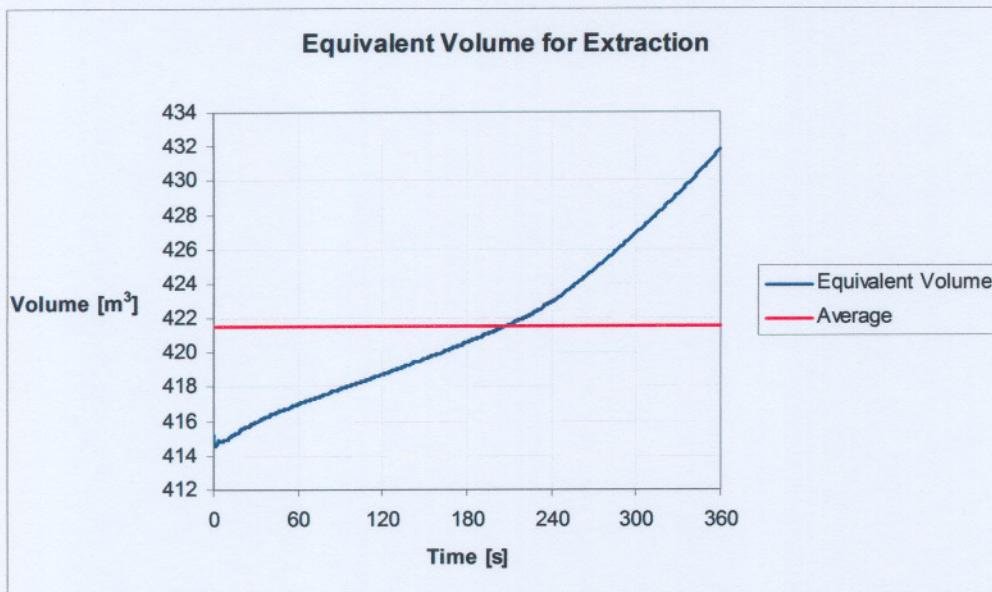


Figure 45: Equivalent Volume at Extraction

The equivalent volume at injection is calculated in a similar manner except the injection is carried out to the MPS via the PC inlet until a similar amount of helium that was removed during extraction is replenished to the MPS. The equation of state is used to determine V_{sysU} at each time step. The result is shown in Figure 46 and the average volume of this is used to model the injection volume in EES

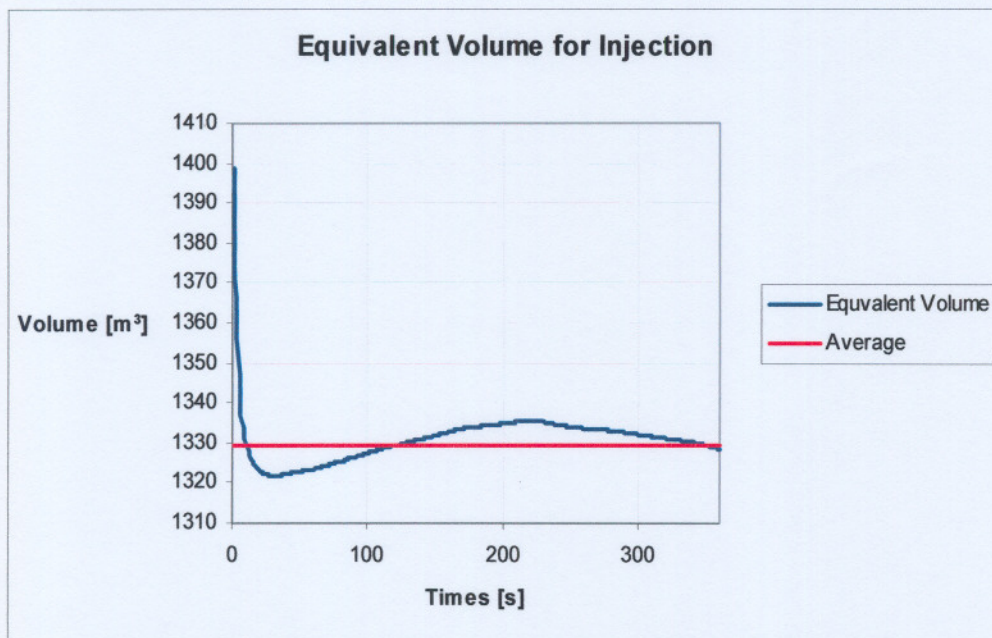


Figure 46: Equivalent Volume at Injection

A.2 ICS EES model

"-----HELIUM GAS MODEL-----"

Kel	= 273.15	" Celsius to Kelvin difference"
R	= 2077.27	"[J/kg-K] Gas constant for Helium"
cp	= 5195	"[J/kg-K] Constant pressure heat capacitance for Helium"
cv	= cp-R	"[J/kg-K] Constant volume heat capacitance for Helium"
k	= cp/cv	"Capacitance ratios for Helium"
mu_comp	= 0.4446e-5	" Compressibility coefficient for Helium"
mu	=2.2181E-05	"kinematic viscosity of Helium"
gamma	=1.6667	"ratio of cp to cv"

"-----MPS BOUNDARY CONDITIONS-----"

V_sysD	= 421	"[m^3] Equivalent extraction volume for the system"
V_sysU	=1329	"[m^3] Equivalent injection volume for the system"
p_sys_ext	= 9000e3	"[Pa] Pressure at HPC Outlet"
p_sys_inj	= 2941e3	"[Pa] Pressure at PC Inlet"
mass_sys	= 4716	"[kg] Total helium mass in MPS"

"This section determines the equivalent temperature for the system"

V_sysD	= mass_sys*(1+mu_comp*p_sys_ext/T_sys_ext^1.2)*R*T_sys_ext/p_sys_ext
V_sysU	= mass_sys*(1+mu_comp*p_sys_inj/T_sys_inj^1.2)*R*T_sys_inj/p_sys_inj

"-----ICS TANK BOUNDARY CONDITIONS-----"

n = 6 "Number of tanks in ICS"
 outer_r = 1.925 "[m] Outer radius is fixed for all tanks"
 {h_tank = 10.81 " Height of tanks"}
 S_allow = 20000*6.8948e3 "Maximum allowable stress for tank material ASTM A516 Gr 70"
 HC_Ratio = 0.025 "Capacitance Packing Ratio"
 a_temp = 0 "Cooling down ratio 0 - no cooling 1 - full cooling"
 alpMeq = 0.22 "Mass Ratio between mass in tank after injection to mass in tank before injection"

Duplicate i=1,n

m_cap[i] = HC_Ratio*V_tank[i]*density_cap "Mass of Capacitance in each tank"
 Vt[i] = V_tank[i] - m_cap[i]/density_cap "Volume occupied by Helium gas"
 A_cap[i] = (m_cap[i]/2*(5)) "[m^2] Heat absorption surface are of capacitance"
 t_cap[i] = m_cap[i]/(density_cap*A_cap[i]) "thickness along the path of conduction in capacitance"

end

density_cap = 7850 "[kg/m^3] density of capacitance material"
 c_cap = 450 "[J/kg-K] Heat capacity for steel"
 delta_T = 4 "[T] Temperature lag between gas and material"

"-----INITIAL CONDITIONS-----"

T_amb = 25+ Kel "[K] Ambient temperature"
 psD[1,1] = p_sys_ext "Initial MPS pressure"
 msU[n,1] = msD[n,2] "Helium before injection = helium after extraction to all tanks"

Duplicate i = 2,n


```

psD[i,1]      = psD[i-1,2]    "The pressure of the MPS before extraction to the current tank = the pressure of the MPS after extraction to the previous
tank"
end

```

Duplicate i = 1,n-1

```

      psU[i,1]= psU[i+1,2]    "The pressure of the MPS before injection from the current tank = the pressure of the MPS after injection from the previous
tank"
end

```

Duplicate i = 1,n

TsD[i,1]	= T_sys_ext	"MPS Temperature during Extraction"
TsU[i,1]	= T_sys_inj	"MPS Temperature during Injection"
TtD[i,1]	= T_amb	"Initial Tank Temperatures before Extraction"
TtU[i,1]	= a_temp*T_amb + (1-a_temp)*TpD[i,2]	"Initial Tank Temperatures before Injection"
TpD[i,1]	= TtD[i,1]	"Initial Capacitance Temperature before Extraction"
TpU[i,1]	= TtU[i,1]	"Initial Capacitance Temperature before Injection"

"-----CONSERVATION EQUATIONS-----"

"Momentum Conservation during Extraction"

$$psD[i,2] - ptD[i,2] = D_presD[i]*(mtD[i,2] - mtD[i,1])/sqrt(1+(mtD[i,2] - mtD[i,1])^2)$$

"Energy Conservation during Extraction"

TsD[i,2]	= TsD[i,1]
cp*(msD[i,1]-msD[i,2])*TsD[i,1]	= mtD[i,2]*cv*TtaD[i] - mtD[i,1]*cv*TtD[i,1]
mtD[i,2]*cv*TtaD[i] - mtD[i,2]*cv*TtD[i,2]	= m_cap[i]*c_cap*(TpD[i,2]-TpD[i,1])

$$TtD[i,2] = TpD[i,2] + \delta T$$

"Momentum Conservation during Injection"

$$ptU[i,1] = TtU[i,1]/TtD[i,2]*ptD[i,2]$$

$$psU[i,2] - ptU[i,2] = D_presU[i]*(mtU[i,2] - mtU[i,1])/sqrt(1+(mtU[i,2] - mtU[i,1])^2)$$

"Energy Conservation during Injection"

$$TsU[i,2] = TsU[i,1]$$

$$meq[i] = (1 - \alpha p_{Meq}) * mtU[i,1] + \alpha p_{Meq} * mtU[i,2]$$

$$TpU[i,2]/TtU[i,1] = (m_cap[i]*c_cap*TpU[i,1]/TtU[i,1] + cv*meq[i] * (mtU[i,2]/mtU[i,1])^{(k-1)})/(m_cap[i]*c_cap + cv*meq[i])$$

$$TtU[i,2] = TpU[i,2] + \delta T * (mtU[i,2] - mtU[i,1])/sqrt(1+(mtU[i,2] - mtU[i,1])^2)$$

"Conservation of Mass"

$$msD[i,1] - msD[i,2] = mtD[i,2] - mtD[i,1] \quad \text{"Continuity equations"}$$

$$msU[i,1] - msU[i,2] = mtU[i,2] - mtU[i,1] \quad \text{"Continuity equations"}$$

$$msU[i,1] - msU[i,2] = msD[i,2] - msD[i,1] \quad \text{"Mass inj ext equality"}$$

"These are the equations of state"

Duplicate j=1,2

$$msD[i,j] = psD[i,j]*V_sysD/((1+\mu_comp*psD[i,j]/TsD[i,j])^{1.2}*R*TsD[i,j]) \quad \text{"Equations of state"}$$

$$msU[i,j] = psU[i,j]*V_sysU/((1+\mu_comp*psU[i,j]/TsU[i,j])^{1.2}*R*TsU[i,j]) \quad \text{"Equations of state"}$$

$$mtD[i,j] = ptD[i,j]*Vt[i] / ((1+\mu_comp*ptD[i,j]/TtD[i,j])^{1.2}*R*TtD[i,j]) \quad \text{"Equations of state"}$$

$$mtU[i,j] = ptU[i,j]*Vt[i] / ((1+\mu_comp*ptU[i,j]/TtU[i,j])^{1.2}*R*TtU[i,j]) \quad \text{"Equations of state"}$$

end

end

"-----PERFORMANCE-----"

m_t_steelrans_D	= sum(msD[i,1] - msD[i,2] ,i=1,n)	"Total Mass Transferred during Extraction"
m_t_steelrans_U	= sum(msU[i,1] - msU[i,2] ,i=1,n)	"Total Mass Transferred during Injection"
MCR	= 0.0221*MPS_remain -4.3331	"Relationship between MCR and Mass in the MPS"
MPS_remain	= mass_sys -m_t_steelrans_D	
MCR	=45	
percentage_moved	= m_t_steelrans_D*100/mass_sys	"Percentage of Helium mass transferred to the total inventory."

"-----PIPE MODEL-----"

D	=0.223	"Pipe Diameter [m]"
L	=50	"Average Length of Pipe [m]"
K_bend	=25	"Total Losses due to Bends"
epsilon	=40e-6	"Pipe Roughness"
A	=(pi*D^2)/4	"Pipe flow x-sectional area [m^2]"
Re	=(Actual_Mass_Flow*D)/(mu*A)	"Reynolds number - Assuming turbulent flow"
f	= 0.25/(log10(0.27*(epsilon/D)+(5.74/Re^0.9)))^2	"Friction Factor"
K_loss	=(f*L)/D+ K_bend	"Total K-Loss"
Average_Mass_Flow	=7.5	"Average Mass Flowrate to give 10%MCR/min"
Actual_Mass_Flow	= m_t_steelrans_D/(Eff_blowtime)	"Actual Mass Flow - without taking valve closure into account."
valve_time	= n*1.6	"Time for valve closure and opening"
Eff_blowtime	= blow_time-valve_time	"Effective time during which helium is transferred - excluding valve closure and opening"
blow_time	=m_t_steelrans_D/Average_Mass_Flow	"Total time taken to transfer helium including valve closure and opening"

"-----Switching Pressure-----"

Duplicate i=1,n

"Extraction"

$D_presD[i] = 1.3 * (K_loss + (DELTA T_{o_D_ave}[i] / T_{o_D_ave}[i])) * p_{o_D_ave}[i] * \gamma * (M_D[i]^2)^{0.5}$ "This represents the pipe model in extraction mode"

$T_{o_D_ave}[i] = (TsD[i,2] + TtD[i,2]) / 2$ "Average Pipe Temperature"
 $DELTA T_{o_D_ave}[i] = (TsD[i,2] - TtD[i,2])$ "Temperature Difference between Inlet and Outlet"
 $p_{o_D_ave}[i] = (psD[i,2] + ptD[i,2]) / 2$ "Average Pipe Pressure"
 $DELTA p_{o_D_ave}[i] = D_presD[i]$ "Pressure Difference between Inlet and Outlet"

$M_D[i] = v_hel_D[i] / (\gamma * R * (T_{o_D_ave}[i]))^{0.5}$ "Mach Number in pipe"
 $V_D[i] = \text{Average_Mass_Flow} / \rho_{hel_D}[i]$ "Volume Flowrate of Helium through pipe"
 $v_hel_D[i] = V_D[i] / A$ "Velocity of Helium through pipe"
 $\rho_{hel_D}[i] = p_{o_D_ave}[i] / (z_D[i] * R * T_{o_D_ave}[i])$ "Average Density of Helium in pipe"
 $z_D[i] = 1 + \mu_{comp} * (p_{o_D_ave}[i] / T_{o_D_ave}[i])^{1.2}$ "Compressibility of helium in pipe"

"Injection"

$D_presU[i] = 1.3 * (K_loss + (DELTA T_{o_U_ave}[i] / T_{o_U_ave}[i])) * p_{o_U_ave}[i] * \gamma * (M_U[i]^2)^{0.5}$ "This represents the pipe model in injection mode"

$T_{o_U_ave}[i] = (TsU[i,2] + TtU[i,2]) / 2$ "Average Pipe Temperature"
 $DELTA T_{o_U_ave}[i] = (TsU[i,2] - TtU[i,2])$ "Temperature Difference between Inlet and Outlet"
 $p_{o_U_ave}[i] = (psU[i,2] + ptU[i,2]) / 2$ "Average Pipe Pressure"
 $DELTA p_{o_U_ave}[i] = D_presU[i]$ "Pressure Difference between Inlet and Outlet"

M_U[i]	= v_hel_U[i]/(gamma*R*(T_o_U_ave[i]))^0.5	"Mach Number in pipe"
V_U[i]	= Average_Mass_Flow/rho_hel_U[i]	"Volume Flowrate of Helium through pipe"
v_hel_U[i]	= V_U[i]/A	"Velocity of Helium through pipe"
rho_hel_U[i]	=p_o_U_ave[i]/(z_U[i]*R*T_o_U_ave[i])	"Average Density of Helium in pipe"
z_U[i]	=1+mu_comp*(p_o_U_ave[i]/T_o_U_ave[i]^1.2)	"Compressibility of helium in pipe"

end

"-----TANK DESIGN-----"

Duplicate i=1,n

m_full[i]	= pt_full[i]*Vt[i] /((1+mu_comp*pt_full[i]/TtD[1,2]^1.2)*R*TtD[1,2])	"Equation of state to calculate full mass in each ICS tank"
ptDesign[i]	= pt_full[i]*1.1*1.03	"Equation to calculate Design Pressure"
thick_t[i]	=ptDesign[i]*radius_t[i]/(S_allow-0.6*ptDesign[i])	"thickness of tank wall"
radius_t[i]	= outer_r - thick_t[i]	"Internal Radius of Tank"
h_cyl[i]	=h_tank - 2*h_ellip[i]	"height of Cylindrical Part of Tank"
h_ellip[i]	= outer_r/2	"Height of Ellipsoidal part of tank"
V_cyl[i]	= h_cyl[i]*pi*radius_t[i]^2	"Volume of Cylindrical Part of Tank"
V_ellip[i]	=2/3*pi*radius_t[i]^3	"Volume of Ellipsoidal Part of Tank"
V_tank[i]	= V_cyl[i]+V_ellip[i]	"[m^3] Volume of inside of tank with no capacitance and 2:1 ellipsoid"
m_t_steel_cyl[i]	=7850*pi*(outer_r^2-radius_t[i]^2)*h_cyl[i]	"Mass of cylinder for each tank"
m_t_steel_ellip[i]	= 7850*2/3*pi*(outer_r^3-radius_t[i]^3)	"Mass of ellipsoid for each tank"
m_t_steel[i]	=m_t_steel_cyl[i]+m_t_steel_ellip[i]	"Mass of cylinder and ellipsoid for each tank"
cost_t[i]	= cost_kilo_t * m_t_steel[i] + cost_kilo_capa * m_cap[i]	"Cost of ellipsoid, cylinder and capacitance for each tank"


```

cost_mass[i]      = cost_kilo_t * m_t_steel[i]           "Cost of ellipsoid and cylinder for each tank"
cost_cap[i]       = cost_kilo_capa * m_cap[i]           "Cost of capacitance in each tank"
cost_mass_cyl[i]  = cost_kilo_t * m_t_steel_cyl[i]      "Cost of cylinder for each tank"
cost_mass_ellip[i] = cost_kilo_t * m_t_steel_ellip[i]   "Cost of ellipsoid for each tank"
end
m_tot =m_full*n           "Total Helium in ICS"
Duplicate i=1,n
    m_full[i]=m_full      "Helium in each tank is the same when ICS is fully pressurised"
end
m_tot=(sum(mtD[i,2],i=1,n))+MPS_remain    "Total Helium is made up what is remaining in the MPS after extraction by p.d. + what is already in the tanks"

"Cost Structure"
cost_kilo_t      = 50           " R/kg for steel pressure vessel "
cost_ratio       =0.9           "Cost Ratio - Capacitance material to Tank material"
cost_ratio       =cost_kilo_capa /cost_kilo_t

"Total Costs"
Total_cost       =(cost_cyl+cost_cap+cost_ellip+n*cost_valve)/1000000
cost_valve       =1000000
cost_valves      =n*cost_valve/1000000           "Total Cost of Valves"
cost_mass        =sum(cost_mass[i],i=1,n)         "Total Cost of tank Material ; cylinder and ellipsoid"
cost_cap         =sum(cost_cap[i],i=1,n)          "Total Cost of Capacitance"
cost_cyl         =sum(cost_mass_cyl[i],i=1,n)      "Total Cost of Cylinders"
cost_ellip       =sum(cost_mass_ellip[i],i=1,n)    "Total Cost of Ellipsoids"

h_cyl_total      =sum(h_cyl[i],i=1,n)             "Total Height of tanks - if they are stacked on top of each other"

```


V_tank_avg	= sum(V_tank[i] ,i=1,n)/n	"Average Volume of the Tanks"
Total_Volume	=sum(V_tank[i] ,i=1,n)	"Total Voluem of the Tanks"
V_cyl_total	=sum(V_cyl[i],i=1,n)	"Total Volume of the Cylinders"
V_ellip_total	=sum(V_ellip[i],i=1,n)	"Total Volume of the ellipsoids"
total_m_t_steel	= sum(m_t_steel[i] ,i=1,n)	" Total Mass of Steel for Tank Material"
"-----END-----"		

A.3 Determining injection equations for small amounts of helium transfer [6]

Assuming that the amount of helium injected is small. The following four equations hold (Nieuwoudt [6]);

Assume adiabatic expansion to a temperature and pressure of T'_{te}, P'_{te}

$$\frac{P'_{te}}{P_{ts}} = \left[\frac{T'_{te}}{T_{ts}} \right]^{\frac{k}{k-1}}$$

The equation of state for T'_{te}, P'_{te} is given by:

$$P'_{te} V_t = m_{te} R T'_{te}$$

If all the possible heat is transferred from the capacitance to the gas, then

$$c_p m_p (T_{te} - T_{ts}) = c_v m_{te} (T'_{te} - T_{te})$$

and finally the equation of state for T_{te}, P_{te}

$$P_{te} V_t = m_{te} R T_{te}$$

Solving the four equations reduces the equation to the following:

$$\frac{T_{te}}{T_{ts}} = \frac{c_p m_p + c_v m_{te} \left[\frac{m_{te}}{m_{ts}} \right]^{k-1}}{c_p m_p + c_v m_{te}}$$

Note that this equation is satisfied where $\delta m = m_{te} - m_{ts} \rightarrow 0$

The problem for large Δm with the product of the ratios for each δm , where $\Delta m = n \delta m$

$$\frac{T_{te}}{T_{ts}} = \prod_{i=1}^n \frac{c_p m_p + c_v (m_{ts} - i \delta m) \left[\frac{m_{ts} - i \delta m}{m_{ts} - (i-1) \delta m} \right]^{k-1}}{c_p m_p + c_v (m_{ts} - i \delta m)}$$

where $n \rightarrow \infty, \delta m \rightarrow 0$

This equation is not simple to solve and by using a Taylor expansion a formula was

derived that gave good results only when the ratio $\frac{c_p \cdot m_p}{c_v \cdot m_{te}}$ is greater than 1.

Thus, intuitively the following formula was postulated:

$$\frac{T_{pe}}{T_{is}} = \frac{c_p \cdot m_p + c_v \cdot m_{eq} \left[\frac{m_{te}}{m_{is}} \right]^{k-1}}{c_p \cdot m_p + c_v \cdot m_{eq}}$$

with

$$m_{eq} = \alpha \cdot m_{is} + (1 - \alpha) m_{te}$$

This was compared to numerical solutions of the above product and a value of $\alpha=0.22$ was determined.

A.4 ICS Flownex model description

The ICS Flownex model is created by entering data into interconnected nodes and elements laid out in a GUI. These nodes and elements represent the ICS components. Figure 47 shows a picture of the ICS model in Flownex. This is followed by a description of the input data

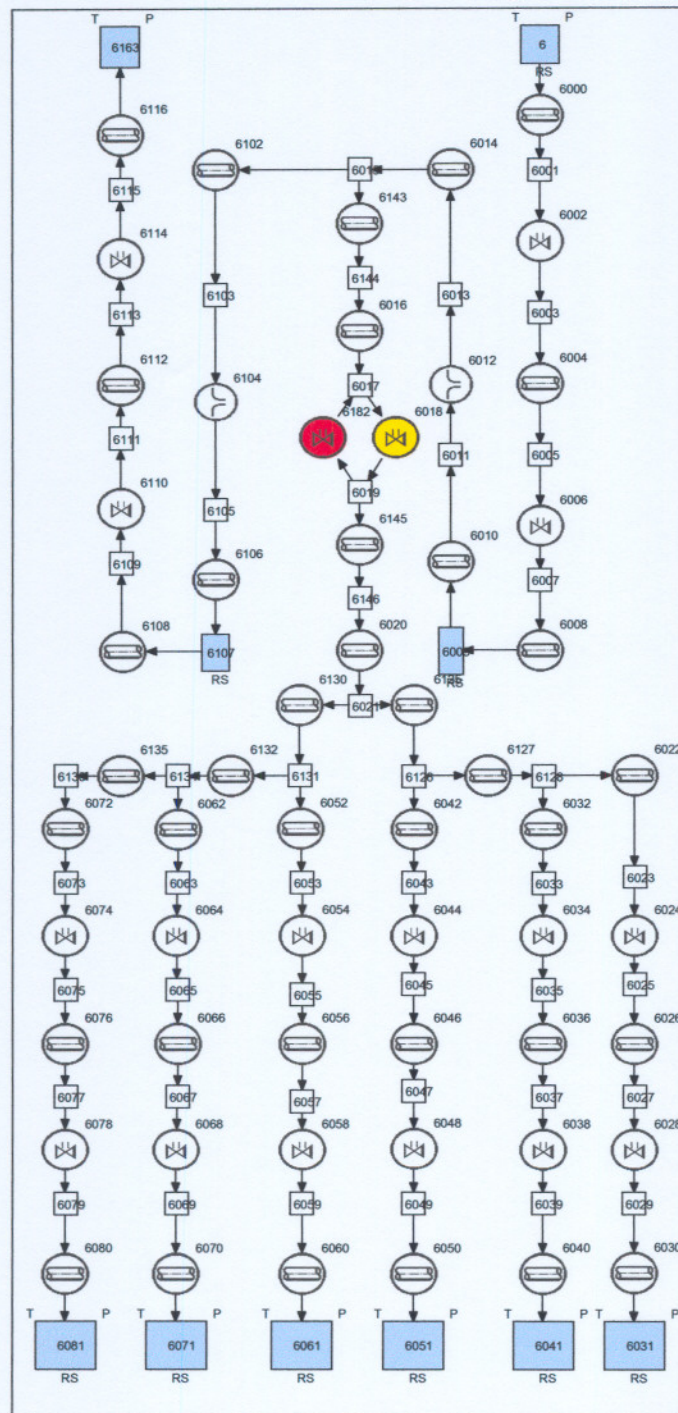


Figure 47: ICS Flownex Model

All pipes have a roughness of 40 microns and it is assumed no heat loss occurs across the thickness of the pipe walls.

The detail of the ICS Flownex input data is described in the following tables

No.	Element Type	Description	Parameter	Value
6030 6040	Pipe	ICS Pipe	Length [m]	13
6050 6060			Diameter [m]	0.223
6070 6080			Kf	3
			Kb	3

Kf and Kb represent pipe losses in the forward and backward flow direction respectively.

No.	Element Type	Description	Parameter	Value
6028	CLC	ICS Isolation Valve	Valve Diameter [m]	0.223
6038			Pipe Diameter Inlet [m]	0.223
6048			Pipe Diameter Outlet [m]	0.223
6058			xT Forward	0.6
6068			xT Backward	0.65
6078			Valve Chart	Isolation.cv1

xT is defined as the pressure drop ratio factor, beyond which choking is likely to occur [38].

The **Isolation.cv1** valve chart describes flow characteristics in relation to the valve opening. These characteristics are shown in section A.6 of the Appendix.

No.	Element Type	Description	Parameter	Value
6026 6036	Pipe	ICS Pipe	Length [m]	2.5
6046 6056			Diameter [m]	0.223
6066 6076			Kf	0
			Kb	0

No.	Element Type	Description	Parameter	Value
6024	CLC	ICS Isolation Valve	Valve Diameter [m]	0.223
6034			Pipe Diameter Inlet [m]	0.223
6044			Pipe Diameter Outlet [m]	0.223
6054			xT Forward	0.6
6064			xT Backward	0.65
6074			Valve Chart	Isolation.cv1

No.	Element Type	Description	Parameter	Value
6022 6032	Pipe	ICS Pipe	Length [m]	1.2
6042 6052			Diameter [m]	0.223
6062 6072			Kf	1.2
			Kb	1.2

No.	Element Type	Description	Parameter	Value
6127 6132 6135 6130 6131	Pipe	ICS Pipe	Length [m]	1.2
			Diameter [m]	0.223
			Kf	1.2
			Kb	1.2

No.	Element Type	Description	Parameter	Value
6000 6116	Pipe	ICS Pipe	Length [m]	10
			Diameter [m]	0.223
			Kf	3
			Kb	3

No.	Element Type	Description	Parameter	Value
6002 6114	CLC	ICS Isolation Valve	Valve Diameter [m]	0.223
			Pipe Diameter Inlet [m]	0.223
			Pipe Diameter Outlet [m]	0.223
			xT Forward	0.6
			xT Backward	0.65
			Valve Chart	Isolation.cv1

No.	Element Type	Description	Parameter	Value
6004 6112	Pipe	ICS Pipe	Length [m]	1.5
			Diameter [m]	0.223
			Kf	0
			Kb	0

No.	Element Type	Description	Parameter	Value
6006 6110	CLC	ICS Isolation Vale	Valve Diameter [m]	0.223
			Pipe Diameter Inlet [m]	0.223
			Pipe Diameter Outlet [m]	0.223
			xT Forward	0.6
			xT Backward	0.65
			Valve Chart	Isolation.cv1

No.	Element Type	Description	Parameter	Value
6008 6108	Pipe	ICS Pipe	Length [m]	2
			Diameter [m]	0.223
			Kf	1.5
			Kb	1.5

No.	Element Type	Description	Parameter	Value
6010 6106	Pipe	ICS Pipe	Length [m]	12
			Diameter [m]	0.223
			Kf	0.69
			Kb	1.19

No.	Element Type	Description	Parameter	Value
6012 6104	RD	Open Close Valve	Diameter [m]	0.223
			Cd	0.6

No.	Element Type	Description	Parameter	Value
6014 6102	Pipe	ICS Pipe	Length [m]	1
			Diameter [m]	0.223
			Kf	1
			Kb	1

No.	Element Type	Description	Parameter	Value
6143 6016 6145 6020	Pipe	ICS Pipe	Length [m]	0.35
			Diameter [m]	0.223
			Kf	0
			Kb	0

No.	Element Type	Description	Parameter	Value
6018	ANSI Control Valve	ICS Flow Control Valve	Valve Diameter [m]	0.1
6182			Pipe Inlet Diameter [m]	0.1
			Pipe Outlet Diameter [m]	0.1

No.	Node Type	Description	Parameter	Value
6031	Node with volume	ICS Tanks	Internal Volume [m ³]	101.4
			Gas Volume [m ³]	98.9
			⁵ Capacitance Surface Area [m ²]	49768
			⁶ Capacitance thickness [mm]	0.05

⁵ See Section A.5

⁶ See Section A.5

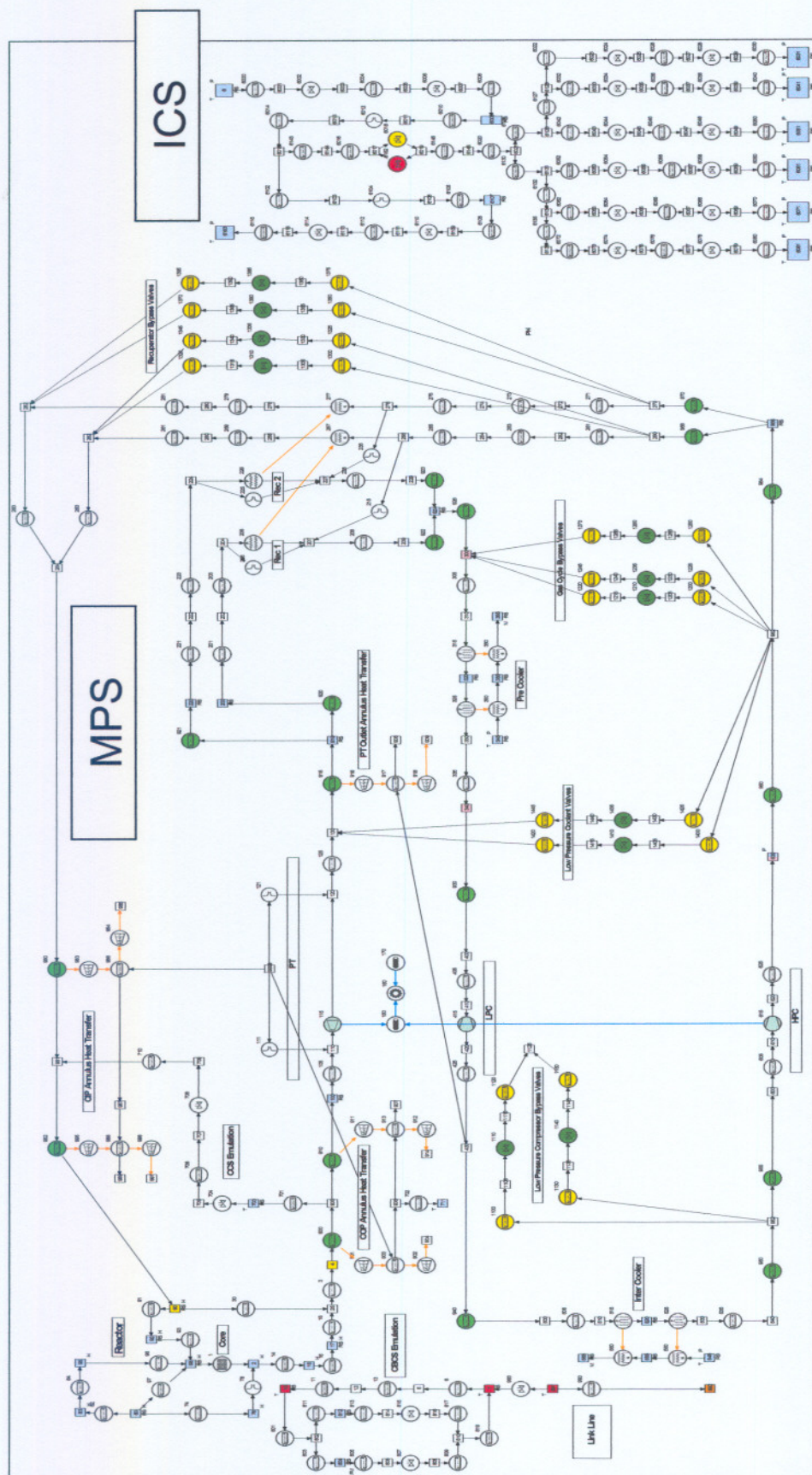


Figure 48: MPS-ICS Coupled Network

A.5 ICS heat capacitance modelling in Flownex

The purpose of the ICS capacitance is to provide thermal inertia during mass transfer under pressure differential. In the extraction mode, the capacitance absorbs heat from the incoming gas, thus lowering the internal pressure to allow more gas to be transferred to the tank. In the injection mode, the capacitance dissipates heat to the outgoing gas, raising the pressure, which allows for a greater mass transfer. Physically, the ICS capacitance is a mass of perforated steel.

The capacitance mass is modelled in Flownex as a heat transfer area with a certain thickness. Consider the mesh is unravelled into a flat strip of a certain thickness $2t$ and total heat absorption area A_0 . This strip absorbs heat from either side as shown in Figure 49.

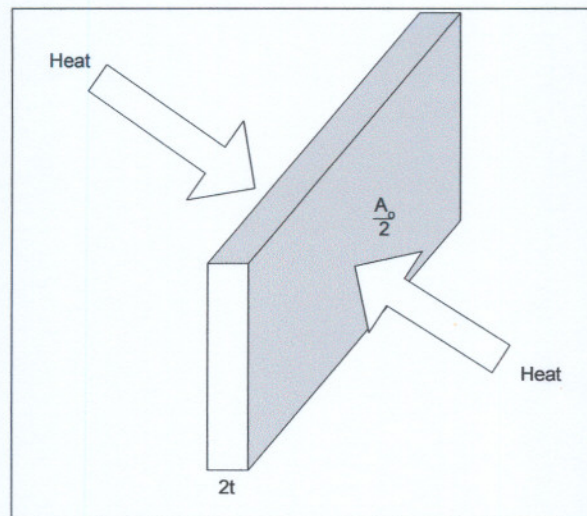


Figure 49: ICS Heat Capacitance Strip

If, for argument's sake, the strip is split along its centreline and opened up, then heat can be considered to flow from one side with a total area A_0 , across a thickness, t and towards a surface area A_i as shown in Figure 50. The area A_i serves to complete the heat transfer part and since no heat physically crosses this area, a very small value is given for A_i relative to A_0 . This is done to ensure Flownex gives a solution.

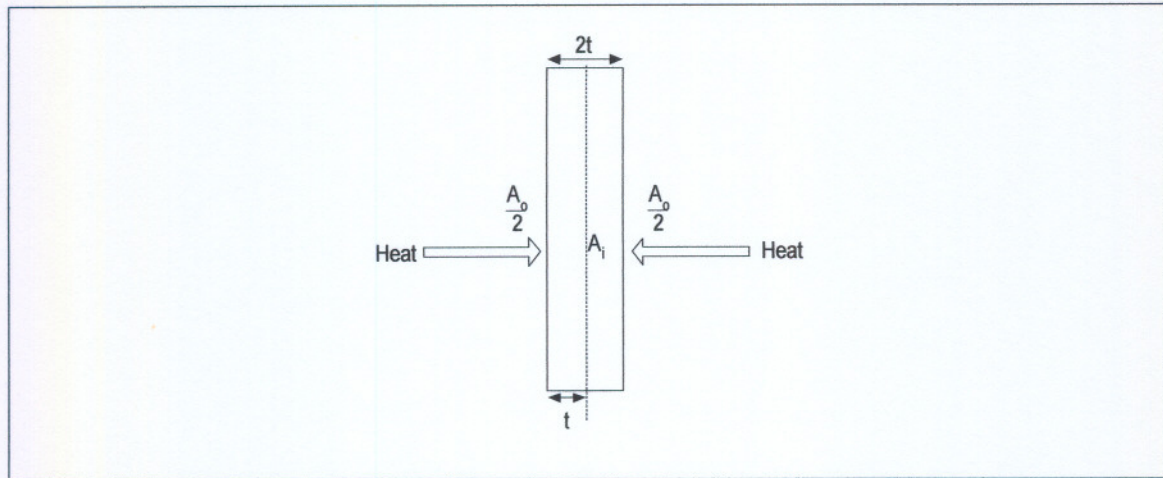


Figure 50: ICS Heat Capacitance

Given a relationship, that 50 000 m² of capacitance weigh 20 000kg [17] , the surface area, A_{cap} of capacitance for each tank is calculated;

$$A_{cap} = \frac{m_{cap}}{m_{known, cap}} A_{cap, known}$$

where m_{cap} is the capacitance mass in each tank, $m_{known, cap}$ is the mass of capacitance (20 000kg), that corresponds to the known surface area of $A_{cap, known}=50\,000\text{m}^2$.

$$t_{cap} = \frac{V_{cap}}{A_{cap}}$$

The thickness of the capacitance is equal to a calculated volume of capacitance in each tank, divided by the calculated surface area of the capacitance in each tank.

The parameters used to model the ICS capacitance are shown in Table 25 [17]

Table 25: Additional Capacitance Parameters

Parameter	Value
Conductivity	54 [W/m.K]
Capacitance (ρc_p) 7850 x 450	3532.5 kJ/m ³ .K
Coefficient of heat transfer, h_i	20 [W/m ² .K]
Ambient Temperature (T_o)	25 ⁰ C

Parameter	Value
Heat transfer Area exposed to ambient	1

A.6 ICS Valve Characteristics [38]

The ICS valve characteristics as modelled in Flownex are shown in Figure 51 to Figure 54.

FI=Pressure Recovery Factor according to ISA S75

xT=Pressure Drop Ratio Factor according to ISA S75

z=Valve specific characteristic pressure drop ratio VDMA 2442

Cv-Loss Coefficient of valve

d-Flow diameter of valve.

Control Valve

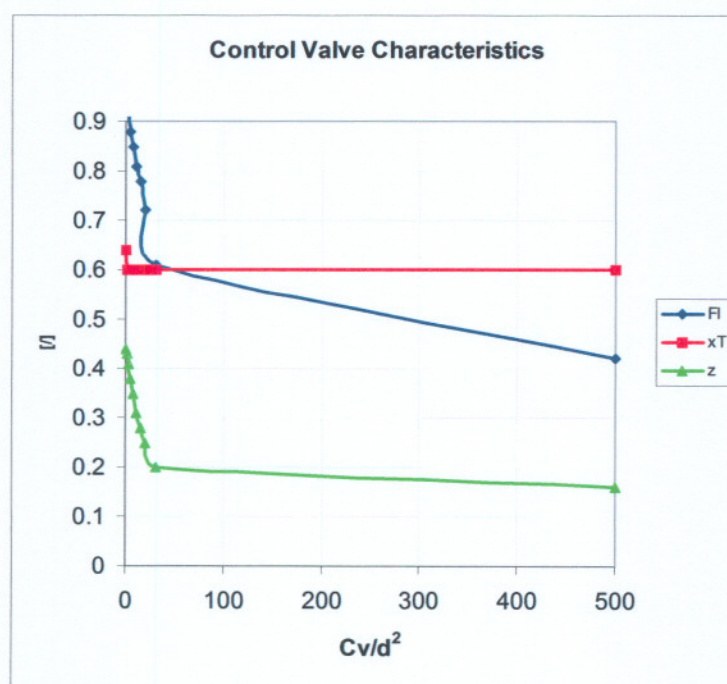


Figure 51: Control Valve Characteristics

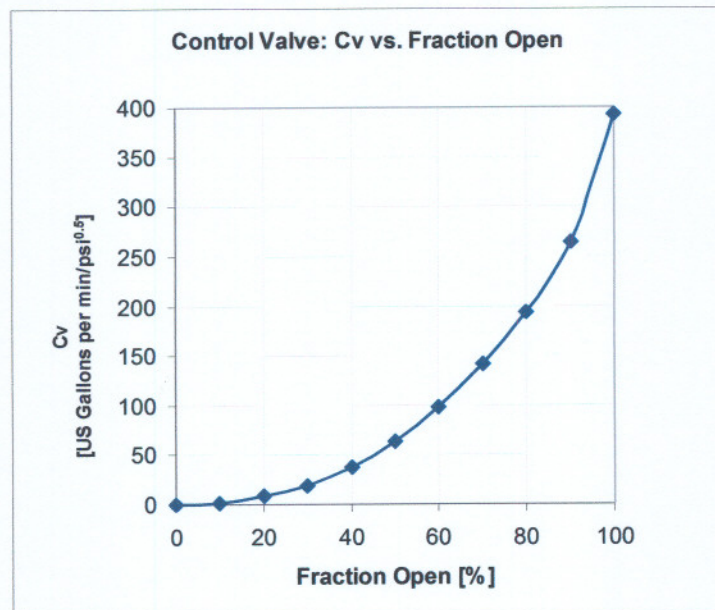


Figure 52: Control Valve: Cv vs. Fraction Open

Isolation Valve

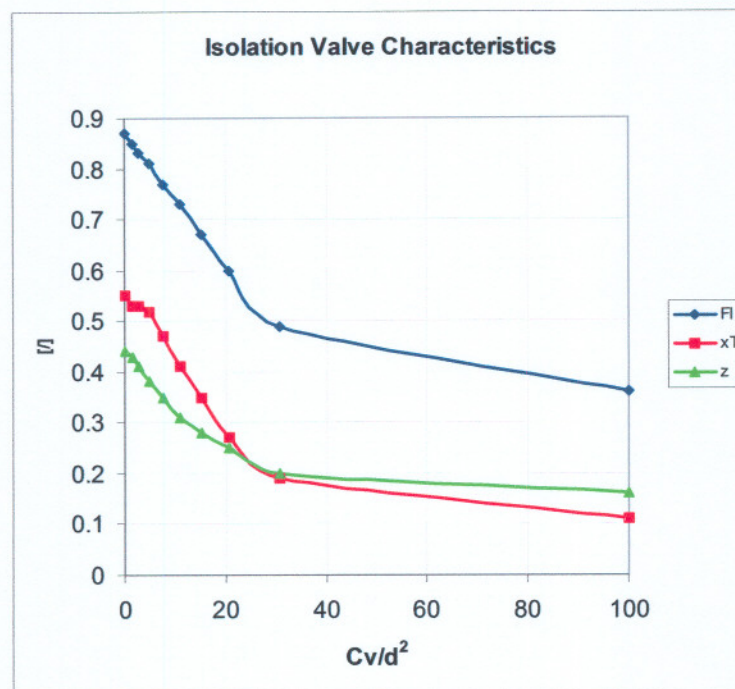


Figure 53: Isolation Valve Characteristics

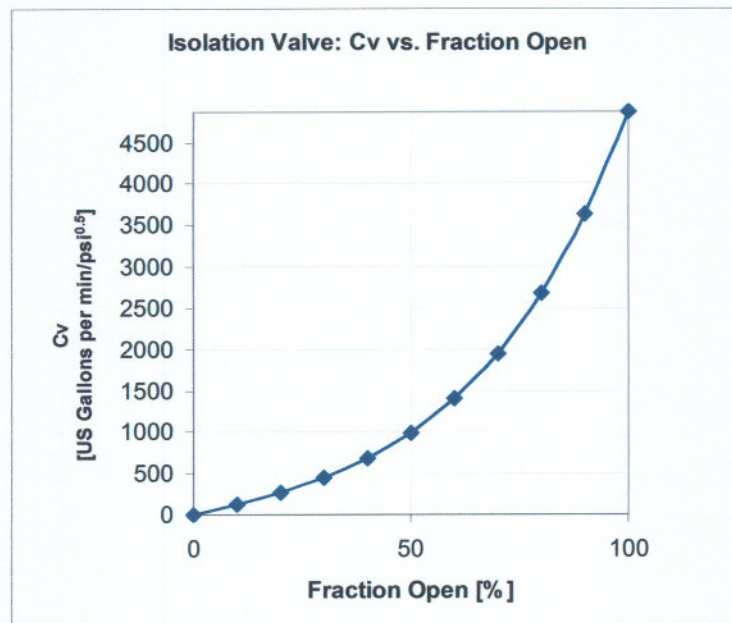


Figure 54: Isolation Valve: Cv vs. Fraction Open

A.7 ICS Controller

Logic Controller

The purpose of the logic controller is to select the correct tank during helium mass transfer between the MPS and the ICS. Generally switching occurs when the mass flowrate falls below 75% of the require setpoint of 7.5[kg/s]

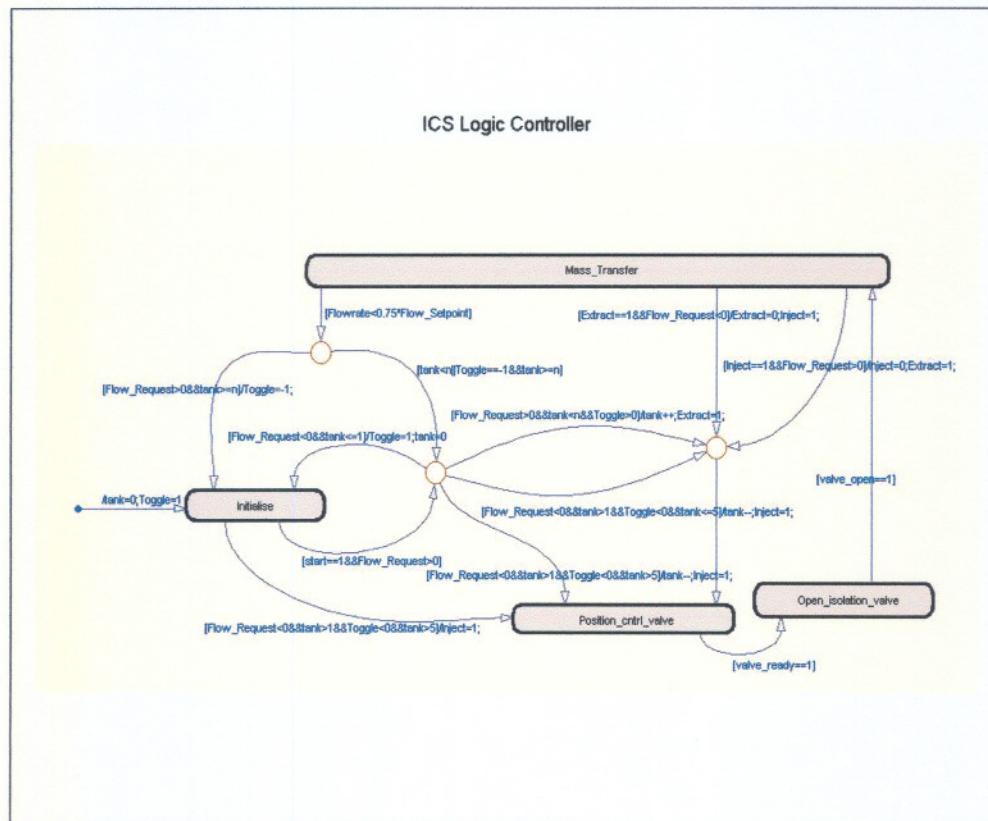


Figure 55: ICS Logic Controller

Valve Controller

The valve controller consists of a feedback mechanism [37] where the opening of the valve is corrected to give the required flowrate of 7.5[kg/s].

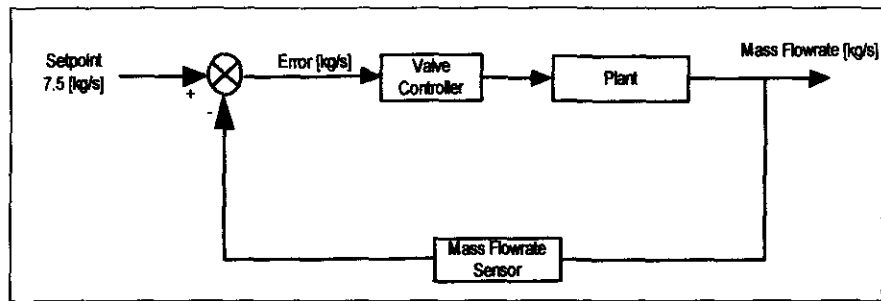


Figure 56: ICS Valve Controller

ROT Controller

The ROT controller consists of a feedback mechanism where the positioning of the control rods is adjusted to give the required Reactor Outlet Temperature of 900°C

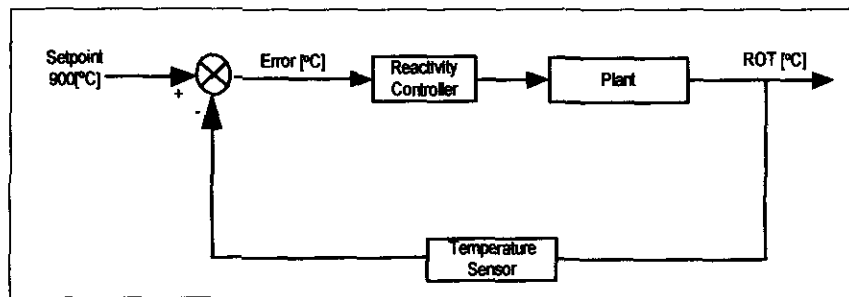


Figure 57: ROT Controller

Power Controller

The power controller consists of a cascaded feedback mechanism. The inner loop is the valve controller and the outer loop is used to correct the power output against a power demand curve.

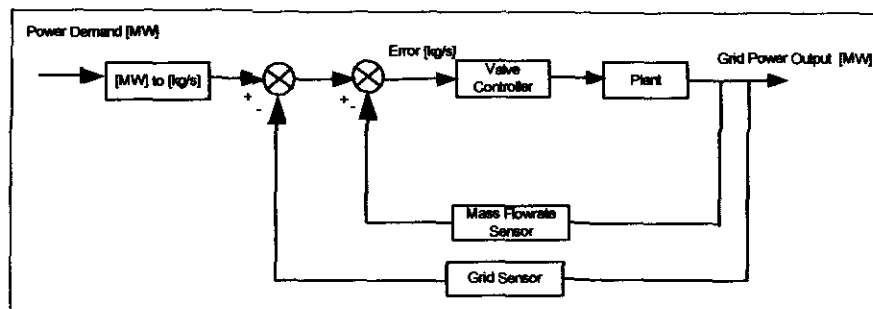


Figure 58: Power Controller

A.8 DETAILED RESULTS OF ICS DESIGN

Extraction from MPS													
Temperature [°C]					Mass [kg]					Pressure [Pa]			
System HP			Tank		System		Tank		Δm	System HP		Tank	
Tank	Start	End	Start	End	Start	End	Start	End		Start	End	Start	End
1	101.4	101.4	25.0	74.7	4716.0	4166.0	478.5	1039	561	9000	7900	3040	7826
2	101.4	101.4	25.0	70.5	4166.0	3679.0	429.4	924	495	7900	6936	2724	6852
3	101.4	101.4	25.0	66.5	3679.0	3251.0	386.9	821.2	434	6936	6095	2451	6001
4	101.4	101.4	25.0	62.6	3251.0	2875.0	350.3	729.9	380	6095	5364	2217	5258
5	101.4	101.4	25.0	58.8	2875.0	2548.0	319.1	649	330	5364	4732	2018	4612
6	101.4	101.4	25.0	55.3	2548.0	2264.0	292.9	577.8	285	4732	4188	1851	4054
						Total	2257	Total	2484				

Injection to the MPS													
Temperature [°C]					Mass [kg]					Pressure [kPa]			
System LP			Tank		System		Tank		Δm	System LP		Tank	
Tank	Start	End	Start	End	Start	End	Start	End		Start	End	Start	End
1	121.9	121.9	70.7	37.2	4155	4716	1039	478.5	561	2588	2941	7736	3122
2	121.9	121.9	66.5	36.5	3661	4155	923.9	429.4	495	2278	2588	6773	2792
3	121.9	121.9	62.5	35.8	3227	3661	821.2	386.8	434	2006	2278	5930	2506
4	121.9	121.9	58.6	35.0	2847	3227	729.8	350.2	380	1768	2006	5195	2261
5	121.9	121.9	54.8	34.2	2517	2847	649	319.1	330	1562	1768	4557	2052
6	121.9	121.9	51.3	33.3	2232	2517	577.8	292.9	285	1768	2006	5195	2261
						Total	4741	Total	2484				

Tank Design											
Temperature [°C]					Volume [m ³]						
	During extraction		During Injection		gas	tank	Helium Design Mass [kg]	Tank operating pressure	Wall Thickness [mm]	Mass [tonne]	
Tank	Start	End	Start	End						Capacitance	Tanks
1	25.0	70.7	74.7	41.1	98.9	101.4	1162	8785	0.1351	19.9	132.9
2	25.0	66.6	70.6	40.4	98.9	101.4	1162	8785	0.1351	19.9	132.9
3	25.0	62.6	66.6	39.7	98.9	101.4	1162	8785	0.1351	19.9	132.9
4	25.0	58.8	62.8	39.0	98.9	101.4	1162	8785	0.1351	19.9	132.9
5	25.0	55.1	59.1	38.2	98.9	101.4	1162	8785	0.1351	19.9	132.9
6	25.0	51.6	55.6	37.3	98.9	101.4	1162	8785	0.1351	19.9	132.9
									Total	119.4	797.5

ICS		MPS	
Number of tanks	6	System helium mass	4 716 kg
Cooling ratio	0	Total mass of helium	6 973 kg
Tank height	10.8 m	Mass of helium moved (extraction)	2 484 kg
Tank outer diameter	3.85 m	Mass of helium moved (injection)	2 484 kg
Total mass of tanks	799 tonne		
Total mass of capacitance	119.4 tonne		
Mass ratio factor	1		
ΔT (gas to capacitance)	4 °C	Percentage mass moved	52.7%
Cost of tank steel	R50/kg	Ambient temperature	25 °C
Cost of capacitance steel	R45/kg	Volume system (Extraction)	430 m ³
Allowable stress in steel	137.9 MPa	Volume system (Injection)	1 329 m ³
Estimated Cost of Valves per tank	1.00 Million Rand	System pressure ratio	3.06
Total System Cost	51.25 Million Rand		