

START-UP AND SHUTDOWN CONTROL OF A THREE-SHAFT BRAYTON CYCLE BASED POWER CONVERSION UNIT

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Stefan A. Laubscher

Supervisor: Prof. G. van Schoor

Assistant supervisor: Mr. C. R. van Niekerk

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SUMMARY

The Pebble Bed Modular Reactor (PBMR) is a graphite-moderated, helium-cooled reactor that uses the Brayton direct gas cycle to convert the heat, which is generated in the core by nuclear fission. The heat is transferred to the coolant gas (helium), and converted into electrical energy by means of a gas turbo-generator.

The Pebble Bed Micro Model (PBMM) is a model that was developed to demonstrate the operation of the closed, recuperative three-shaft Brayton cycle in order to gain a better understanding of its dynamic behaviour and to demonstrate the control strategies that will eventually be used in the PBMR. It is also used to demonstrate the ability of Flownex to simulate the integrated performance of the cycle.

Flownex is a general-purpose thermal-fluid network analysis code. It solves the flow, pressure and temperature distribution in large unstructured thermal-fluid networks and provides the engineer or designer with essential information about the interaction between network components. Flownex can handle a wide variety of network components such as pipes, pumps, orifices, heat exchangers, compressors, turbines, controllers and valves. A complete Flownex model of the PBMM exists and will be used throughout the entire project.

The start-up and shutdown sequences of the Pebble Bed Modular Reactor (PBMR) is characterised by numerous checks and control actions that occur in a very specific order. This order of events and continuous checking of important system parameters are intuitively based on rules that inherently describe the safe and preferred operating region of the plant.

Presently most of the sequences and actions are performed by an expert who knows the system very well. Some of the sequences and actions are controlled by simple controllers and are only activated by the operator.

A need therefore exists to capture the different control events of the start-up and shutdown sequences in a control model or method. A control model or method was developed to control the start-up and shutdown sequence of the PBMM model in Flownex. The control method was implemented in SIMULINK[®] as there is an existing interface between Flownex and SIMULINK[®].

The control method directly controls the procedures of start-up and shutdown through the Flownex/ SIMULINK[®] interface. The most important system parameters are monitored and adjustments are automatically made by the control method in response to system changes. A graphical user interface allows a user to manually activate start-up and shutdown.

The aim of the project is to develop a controller that can control the PBMM through start-up as well as shutdown. Special emphasis is placed on critical transitions and pressure considerations due to the control of the start-up blower system rotational speed. The project establishes expertise in the control of the start-up and shutdown sequence of the PBMM in Flownex.

Flownex was successfully used as a modelling platform to simulate the normal and dynamic operation of the PBMM. Identification of start-up and shutdown was a result of investigating the start-up and shutdown checklist documents as well as a detailed consideration of data captured by the PBMM. A control method was implemented in SIMULINK[®] and controls start-up and shutdown through the Flownex/ SIMULINK[®] interface. A graphical user interface allows in time system changes by a user. Data captured by the simulation model was evaluated against data captured from the real system.

OPSOMMING

Die korrel-bed modulêre reaktor (PBMR) is 'n grafiet gemodereerde, helium-verkoelde reaktor wat die Brayton direkte gassiklus gebruik om hitte wat in die kern deur fissie gegenereer word te omskep. Die hitte word oorgedra na die verkoelingsgas (helium) en omgeskakel na elektriese energie deur 'n gas turbogenerator.

Die korrel-bed mikromodel (PBMM) is 'n model wat ontwikkel is om die werking van die geslote drie-as Brayton siklus te demonstreer. Die model vergemaklik die verstaan van die dinamiese gedrag van die stelsel en demonstreer die beheerstrategieë wat uiteindelik by die PBMR gebruik sal word. Dit word ook gebruik om die vermoë van Flownex om die geïntegreerde gedrag van die siklus te demonstreer.

Flownex is 'n veeldoelige termovloei netwerkanalise pakket. Dit los die vloei, druk en temperatuurverspreiding in groot termiese vloei netwerke op en voorsien die ingenieur met belangrike informasie omtrent die interaksie tussen netwerkkomponente. Flownex kan 'n wye verskeidenheid van netwerkkomponente hanteer soos pype, pompe, pypvernouings, hitteruilers, kompressors, turbines, beheerders en kleppe. 'n Volledige Flownex model van die PBMM bestaan en word deurgaans in die projek gebruik.

Die aktivering en de-aktivering prosedures van die PBMR word gekarakteriseer deur baie kontroleer en beheer aksies wat in 'n spesifieke volgorde geskied. Hierdie sekwensie van gebeure word gebaseer op reëls wat die veilige werking van die mikromodel beskryf.

Huidiglik word die meeste van die aksies deur 'n kenner uitgevoer wat die stelsel goed ken. Van die beheeraksies word deur eenvoudige beheerders beheer en word slegs deur die gebruiker geaktiveer.

Daar bestaan dus 'n behoefte om die verskillende beheeraksies tydens aktivering en de-aktivering in 'n beheermodel of metode saam te vat. 'n Beheermodel of metode is ontwikkel om die aktivering en de-aktivering sekwensies van die mikromodel in Flownex te beheer. Die beheermetode is in SIMULINK[®] geïmplementeer weens die bestaande koppelvlak tussen Flownex en SIMULINK[®].

Die beheermetode beheer die sekvensie van aktivering en de-aktivering van die mikromodel direk deur die Flownex/ SIMULINK[®] koppelvlak. Die belangrikste stelselparameters word gemonitor en veranderings word outomaties deur die beheeralgoritme gemaak in ooreenstemming met stelselveranderings. 'n Grafiese koppelvlak stel 'n gebruiker in staat die stelsel te aktiveer of de-aktiveer.

Die doel van die projek is om 'n beheerder te ontwikkel wat die mikromodel in Flownex outomaties kan aktiveer en deaktiveer. Spesiale klem word gelê op kritiese oorgange en drukvariasie weens die beheer van die SBS se snelheid. Die projek vestig dan ook kundigheid in die beheer van die aktivering en de-aktivering prosedures van die mikromodel in Flownex.

Flownex is suksesvol gebruik as modelleringsplatform om die normale en dinamiese werking van die mikromodel te simuleer. Identifisering van aktivering en de-aktivering was die gevolg van 'n ondersoek na die aktivering en de-aktivering kontrole dokumente asook die data gegenereer deur die mikromodel. 'n Beheermetode is geïmplementeer in SIMULINK[®] en beheer aktivering en de-aktivering direk deur die Flownex/ SIMULINK[®] koppelvlak. 'n Grafiese koppelvlak stel 'n gebruiker in staat om intydse veranderings aan stelselveranderlikes te maak. Die simulasiemodel is geëvalueer teen data van die werklike mikromodel.

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LIST OF ABBREVIATIONS

PBMR	–	Pebble Bed Modular Reactor
PBMM	–	Pebble Bed Modular Reactor
HPC	–	High Pressure Compressor
LPC	–	Low Pressure Compressor
ELC	–	External Load Compressor
IC	–	Inter-cooler
RX	–	Recuperator
HS	–	Heat Source
HPT	–	High Pressure Turbine
LPT	–	Low Pressure Turbine
PT	–	Power Turbine
PC	–	Precooler
SBS	–	Start-up Blower System
CWT	–	Cooling Water Tower
NICS	–	Nitrogen Inventory Control System
GUI	–	Graphical User Interface

Chapter 1 - Introduction

This chapter aims to provide introductory information regarding the basic operation of the pebble bed modular reactor and pebble bed micro model in general. The problem statement that gave rise to the dissertation will then be discussed as well as the research methodology followed. A concise overview of the document is also presented.

1.1 The Pebble Bed Modular Reactor

1.1.1 Overview

The Pebble Bed Modular Reactor (PBMR) is a helium-cooled reactor that uses the Brayton thermodynamic gas cycle to convert nuclear energy into electrical energy. The PBMR core is based on the German high-temperature gas-cooled technology, and uses spherical fuel elements. The fuel elements are shown in figure 1. [1]

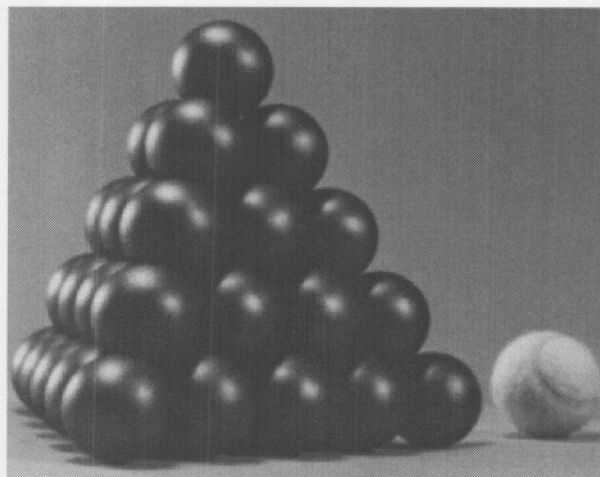


Figure 1: PBMR fuel elements

1.1.2 System Operation

Figure 2 describes the basic system layout of the three-shaft design of the PBMR. At nominal rated full power conditions, helium enters the reactor at a temperature of approximately 500 °C (932 °F) and 70 bar, and moves downward between the hot fuel spheres. It picks up the heat from the fuel spheres which have been heated by the nuclear reaction. The helium leaves the reactor at a temperature of approximately 900 °C (1 652 °F). [1]

The helium then moves through the High-pressure Turbine (HPT) and drives the High-pressure Compressor (HPC). Next, the helium moves through the Low-pressure Turbine (LPT), which drives the Low-pressure Compressor (LPC). The helium then moves through the Power Turbine (PT) which drives the generator.

The power control system is supplied by a series of helium storage tanks ranging from low to high pressure to maintain the required gas pressure in the circuit. Adjustable stator blades on the turbo machinery and bypass flow are used to achieve short-term control.

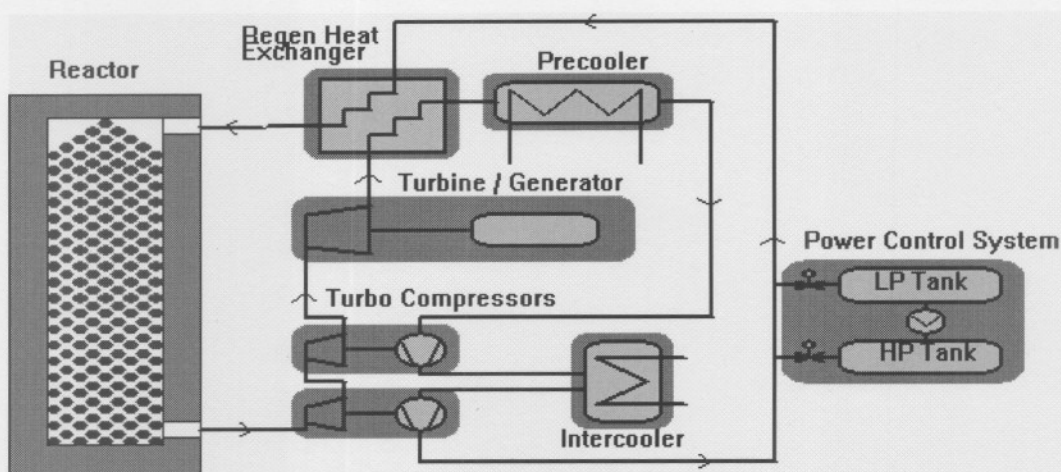


Figure 2: PBMR system layout

Power output control is achieved by adding or removing helium to the circuit. This increases or decreases the pressures and mass flow rate without changing the gas temperatures or the pressure ratios of the system. The increased pressure and subsequent increased mass flow rate increases the heat transfer rate, thus increasing the power. Power reduction is achieved by removing gas from the circuit.

1.1.3 The Brayton Cycle

The standard Brayton cycle is an ideal cycle for a simple gas turbine. It is a closed cycle using heat-transfer processes and gas turbines. [2] The PBMR uses the Brayton cycle to extract energy from the nuclear core by means of a circulating pressurized helium gas stream. This thermal energy is

then converted into electrical energy. For the PBMR, the Brayton cycle consists of a two-stage intercooled compression and recuperated process. [1]

1.2 The Pebble Bed Micro Model

The PBMM is a model that was developed to demonstrate the operation of the closed, recuperative Brayton cycle in order to gain a better understanding of its dynamic behavior and to demonstrate the control strategies that will eventually be used in the PBMR. It is also used to demonstrate the ability of Flownex to simulate the integrated performance of the cycle. Flownex is a general-purpose thermal-fluid network analysis code which solves flow, pressure and temperature distributions in large networks. The development and successful operation of the PBMM is an important milestone in the development of the PBMR as it is the first closed-cycle, multi shaft gas turbine in the world. The model was designed and built by the Faculty of Engineering at the Potchefstroom Campus of the North-West University near Johannesburg, with technical input from the PBMR project team. [3] Shown in figure 3 is a photo of the PBMM that was developed and tested at the University.

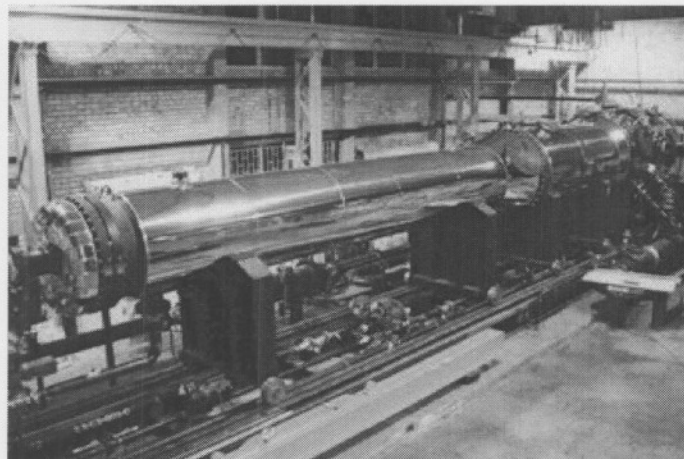


Figure 3: The PBMM test rig

1.3 Start-up and Shutdown

The start-up and shutdown procedures are control actions that were developed to safely operate the PBMM. Both the start-up and shutdown procedures are characterised by numerous checks and control actions that occur in a very specific order. These control actions are performed by an expert that knows the system well. The control actions describe the safest and preferred operation of the PBMM. [3]

1.4 Problem Statement

The purpose of this project is the development of an automatic control method for start-up and shutdown of the PBMM. In order to model such a control method which will include normal as well as dynamic system behaviour, system parameters such as the important system pressures, temperatures, heat transfer and mass flows need to be considered. The control method must respond to changes in the system parameters and must make adjustments accordingly to sustain normal or dynamic operation. The aim of this study is to design a comprehensive control method for control of the PBMM which could be used to test and design new control strategies.

1.5 Issues to be Addressed and Methodology

The control method is addressed in a system dividable into three main components. The system comprises a primary simulator which simulates the normal and dynamic behaviour of the PBMM, an interface which incorporates all the various control techniques and a graphical user interface which allows for change in system parameters by a user. Figure 4 depicts the system layout, with all the different components and their interconnection.

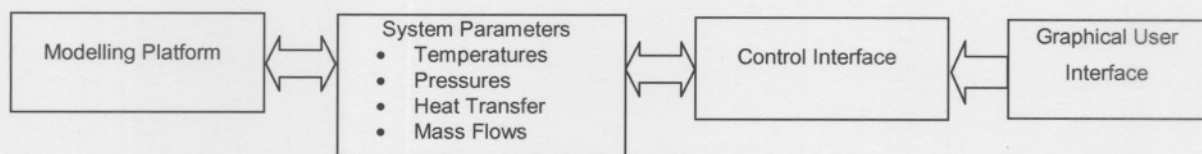


Figure 4: Basic system layout and interconnection

The modelling platform in the system of figure 4 existed prior to when the project was commenced. The modelling platform is used to generate values of important system parameters. Subsequently a process for design and implementation of the control interface and the graphical user interface was developed and follows below.

1.5.1 The use of a Modelling Platform - Flownex

The actual start-up and shutdown sequences of the PBMM are costly and tedious to perform. Flownex is a general-purpose thermal-fluid network analysis code. It solves the flow, pressure and temperature distribution in large unstructured thermal-fluid networks and provides the engineer or designer with essential information about the interaction between network components. Flownex can handle a wide variety of network components such as pipes, pumps, orifices, heat exchangers, compressors, turbines, controllers and valves. User interaction with Flownex is performed through a

user-friendly interface, the Graphical User Interface (GUI), where networks can be created and edited and where input data for networks are provided. [4]

The PBMM is a network of pipes, heat exchangers, compressors and turbines combined together in a network that follows the Brayton cycle to generate power. Therefore a simulation model for the PBMM was developed in Flownex to simulate the operation of the PBMM. This model in Flownex was used as a modelling platform for simulating or modelling the normal and dynamic operation of the PBMM.

1.5.2 Identify Start-up and Shutdown Sequences

Identifying the start-up and shutdown sequences of the PBMM involves investigating the various control actions that are performed by an expert during the actual start-up and shutdown of the PBMM. This is done by attending an actual start-up and shutdown of the PBMM and investigating the control actions during start-up and shutdown. Data generated when actual start-up and shutdown of the PBMM is performed was also used in investigating the start-up and shutdown procedures.

1.5.3 Model Start-up and Shutdown

A model of the PBMM exists in Flownex that is used to simulate the dynamic operation of the PBMM. The developed control model or technique controls the start-up and shutdown sequence of the model in Flownex. The controller is implemented in SIMULINK[®]. SIMULINK[®] interfaces directly with Flownex and provides a means of control for the model in Flownex. Figure 5 illustrates how the controller links to the model of the PBMM in Flownex. The system layout of figure 5 can be compared to the system layout of figure 4 and its interconnections via system parameters to Flownex, the modelling platform.

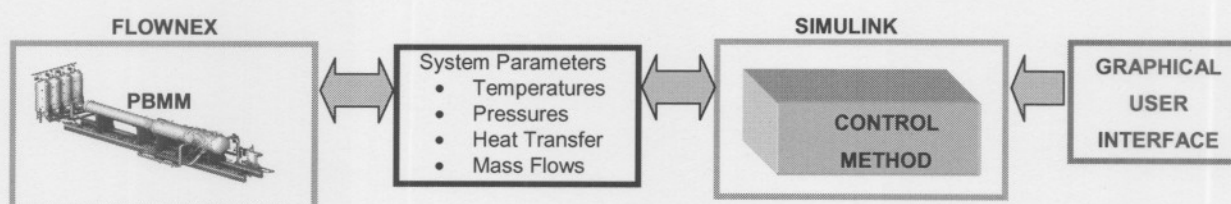


Figure 5: Basic system layout

1.5.4 System Evaluation

The only means of evaluation of the proposed system is to compare the dynamic behaviour of certain system parameters against the dynamic behaviour of corresponding physical system parameters.

1.6 Overview of the Dissertation

Chapter 2 provides an introduction to the simulation of plants in general. It also contains a detailed background study on the PBMR and PBMM. The history of the PBMR and the reason behind development is described. The basic operation of the PBMR is also considered. The main differences between the PBMR and PBMM are described as well as a preliminary description of the operation of the PBMM.

Chapter 3 contains a detailed investigation of data generated by the physical PBMM during start-up, shutdown and normal operation. This data proved immensely important in describing the operation of the physical PBMM as well as identifying the exact procedure followed during start-up and shutdown.

The simulation model of the PBMM in Flownex is described in chapter 4. The implementation of the model in Flownex is considered with a detailed description of all important subsystems like the cooling water cycle and the nitrogen supply system. Preliminary simulation results generated by the Flownex model are also considered. This illustrates the operation and general behaviour of the simulation model under normal operating conditions.

Chapter 5 describes the design and implementation of the control interface which interconnects with the Flownex simulation model.

The results of the final implementation consisting of the Flownex simulation model, the Flownex/SIMULINK[®] control interface and the graphical user interface is considered in chapter 6. These generated results are then compared to actual PBMM data.

Conclusions are drawn and recommendations discussed in chapter 7. Possibilities concerning Flownex simulation model improvements are discussed, which may be implemented to improve future system operation simulation capabilities.

The documents which describe the start-up and shutdown procedures of the physical PBMM are given in *Appendix A*. These documents have to be completed by an operator when start-up and shutdown is performed. The steps followed in these documents describe the safe and preferred operation of the PBMM.

Appendix B is dedicated to illustrate the detailed layout of the main power system of the physical PBMM. The layout of the physical PBMM can therefore be compared to the Flownex PBMM model provided on the data CD accompanying this dissertation.

Appendix C is dedicated to describing important responses of the actual PBMM. Captured data of all the important system parameters are described.

1.7 Conclusion

The aim of the project is to develop an automatic control method for start-up and shutdown of the Pebble Bed Micro Model. Such a control method will make use of the most appropriate control strategy and will directly control the start-up and shutdown sequence of the PBMM simulation model in Flownex through a SIMULINK[®] interface. Special emphasis is placed on critical transitions and the pressure considerations introduced by speed control of the start-up blower system.

Chapter 1 gave some background on the PBMR and PBMM which was followed by the problem statement. The issues that need to be addressed are highlighted as well as the methodology that will be followed. A short overview of the dissertation is also presented. Chapter two contains a detailed literature study on some of the aspects needed to successfully complete the project.

Chapter 2 – The PBMR and PBMM

2.1 Plant Simulation

A simulator is a powerful tool used to train employees to operate power plants. A simulation is the most effective and efficient way of gaining instrumentation and control experience. A simulation has the ability to run "what if" scenarios without harming any of the equipment. Today a wide variety of simulators exist varying from classroom training simulators to full scale simulators that can simulate the dynamic response of plants as complex as nuclear power plants. One of the key elements that determine the operational safety of a nuclear power plant is the training and technical knowledge of the operators about the behaviour of the plant. The importance of simulators is therefore evident in establishing viable training programs for any plants; nuclear, commercial, production or power generation.

Commercial simulators have grown considerably during the last few years as a direct result of advances made in computational strength and speed of computers. Many companies today provide simulators that are fully emulated with the capability to simulate plant operation in a dynamic and a continuous manner. However the main purpose of commercial simulators is as training tools for operators and provides little or no simulation potential for new plants in development. Modelling software such as ASPEN and SIMULINK[®] has made the development of simulators easy. These modelling software packages have been used successfully in simulating newly developed plants. [7,8] More importantly is the validation of the simulators that often require the development of a smaller demonstration plant [7,8,9] to compare results obtained by a simulation to results of a functional replica demonstration plant. Most simulators are implemented in a manner to allow easy upgrade of simulation model parameters to that of full scale system parameters.

In this chapter a detailed background study is given. The history of the PBMR and the reason behind development is described. The basic operation of the PBMR is considered. The main differences between the PBMR and PBMM are described as well as a preliminary description of the operation of the PBMM. Although only a background study, the importance of this study should not be underestimated. The knowledge of plant operation forms the backbone of this dissertation.

2.2 The PBMR - History

Investigation of the Pebble Bed Modular Reactor (PBMR) was started by ESCOM, South Africa's largest supplier of electrical energy, in 1993 as part of its Integrated Electricity Planning process. The purpose of these investigations was to determine if the PBMR could form a part of their electrical supply expansion plans and what advantages it would have. To supply in an ever growing demand in electrical energy the PBMR proved to be an excellent concept as it has short construction lead time, low operating costs, fast load-following characteristics and a plant would be small enough to be placed close to places of high demand. [5]

The PBMR company was thus formed in 2000 by ESCOM, the Industrial Development Corporation of South Africa (IDC), British Nuclear Fuel (BNFL) and the US utility EXELON, to build and market PBMR-based power plants. The primary objective was to build and operate a single plant that will serve as a demonstration plant. Thereafter the plant will be commercialized with ESCOM most likely being the first customer. [5]

Originally High-temperature Reactor (HTR) Technology was developed in Germany in the mid-1980s. A 40 MW thermal, delivering 15 MW electrical power HTR was built to test fuel design, fuel loading and safety considerations of the pebble bed fuel concept. The Chernobyl disaster in 1986 led to the shutdown of this reactor and others that was also built for the purpose of testing. In 1996 ESCOM bought the HTR technology licence from HTR to develop it into a usable and safe resource. [1]

The PBMR project is to develop a pilot fuel plant at Pelindaba and also to develop a demonstration plant at Koeberg near Cape Town. The plant is scheduled to be completed by 2010 and construction will begin in 2007. The first commercial plant is due to be completed by 2013. [5]

2.3 The PBMR Recuperative Brayton Cycle

Shown in figure 6 is a basic layout of the most important components of the PBMR's original design. Starting at 1, helium at a relatively low pressure and temperature (1) is compressed by a low pressure compressor (LPC) to an intermediate pressure (2), after which it is cooled in an intercooler (IC) to state 3. A high pressure compressor (HPC) then compresses the helium to state 4. From 4 to 5, the helium is preheated in the recuperator (RX) before entering the reactor, which heats the

helium to state 6. After the reactor, the hot high-pressure helium is expanded in a high pressure (HP) turbine to state 7, after which it is further expanded in a low pressure (LP) turbine to state 8. The HP turbine drives the HPC while the LP turbine drives the LPC. After the LP turbine, the helium is further expanded in the power turbine (PT) to pressure 9, which is approximately the same as the pressure at 10 and 1. From 9 to 10, the still hot helium is cooled in the recuperator, after which it is further cooled in the pre-cooler to state 1. This completes the cycle. The heat rejected from 9 to 10 is equal to the heat transferred to the helium from 4 to 5. [1]

The cycle illustrated by figure 6 is commonly referred to as the three-shaft Brayton cycle based power conversion unit because of the three different shafts of the HP, LP and PT. The original design concept of the PBMR was to use three shafts. Recently it was changed to the use of only a single shaft. This change was made after the development and design of the PBMM and therefore the PBMM still contains the original design using a three-shaft Brayton cycle.

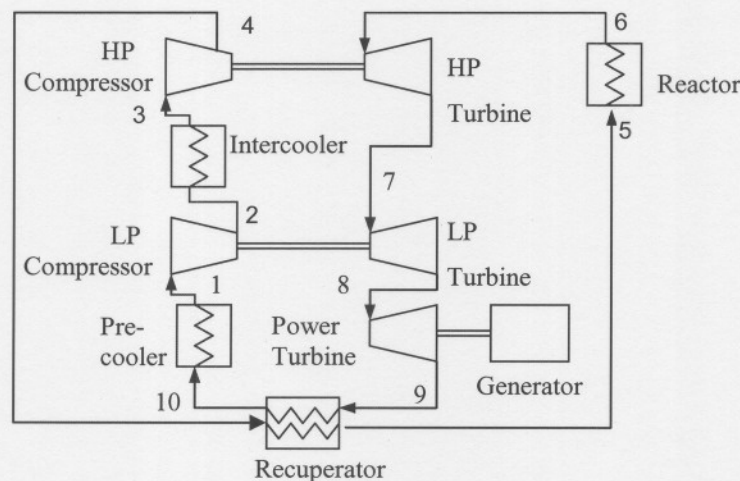


Figure 6: Basic PBMR system layout

Figure 6 depicts the typical pressure and temperature values of gas passing through an entire cycle. Figure 7 depicts the Brayton cycle with various gas temperatures in the cycle against the entropy of the gas in the cycle. Entropy is a measure of the internal energy of a gas.

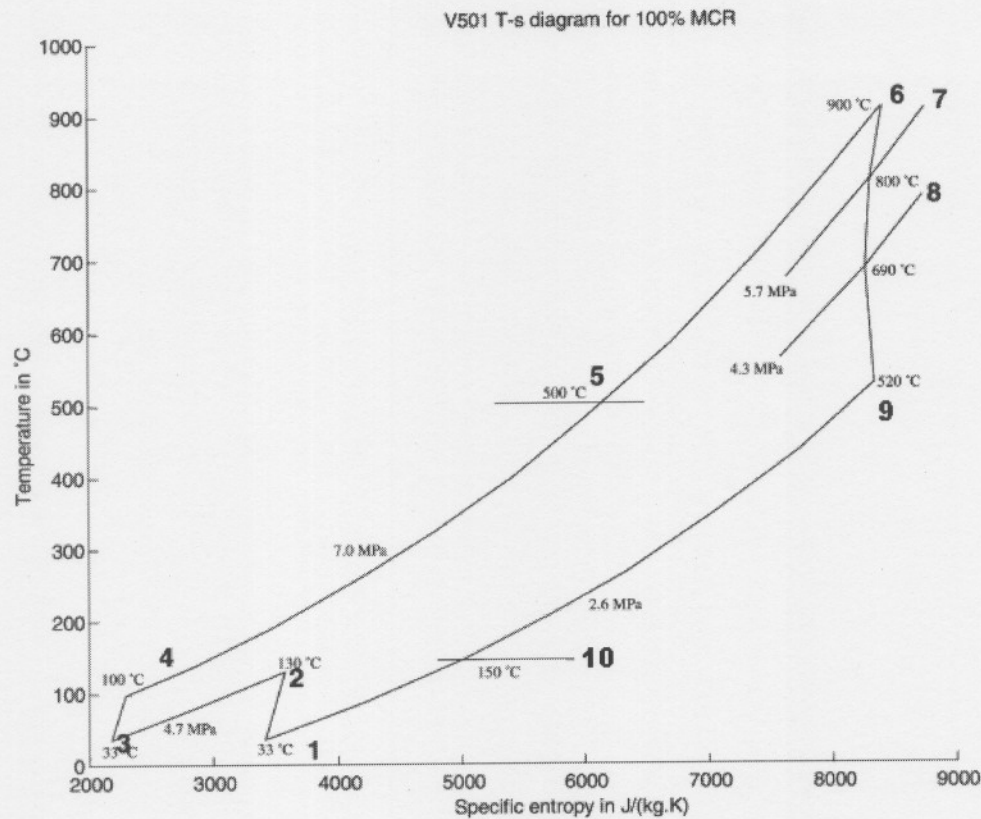


Figure 7: Temperature-Entropy diagram of the PBMR recuperative Brayton cycle [1]

2.4 General Description of PBMR Components

2.4.1 Fuel

The PBMR fuel cell is designed around the Low Enriched Uranium (LEU) Triple Coated Particle (TRISO) technology that was developed for the HTR in Germany. The properties of these LEU-TRISO fuel cells are the most important factor of determining the levels of safe radiation for any operational pebble bed reactor. The spherical fuel cell consists of stoichiometric uranium dioxide. Each cell has four layers that surround a centre kernel that is uranium enriched to approximately 8% U-235. These layers are designed to limit inner pressure build up of the fuel cell. U-235 is the isotope of uranium that undergoes the fission reaction in the reactor core. [1]

The loading of fuel cells into the reactor core has a bottom-to-top structure. Used fuel is removed from the bottom of the reactor and tested for the amount of fissionable material left in the cell. If the amount of fissionable material in the pebble is still sufficient, the pebble is returned to the reactor at the top for another cycle. When a fuel cell is depleted it is removed and sent to a spent fuel storage

facility. A cycle lasts approximately 3 months and a fuel cell passes through the reactor core 10 times. The reactor will use 10 to 15 fuel loads in its lifetime. [1] Figure 8 depicts a cross section diagram of a fuel sphere.

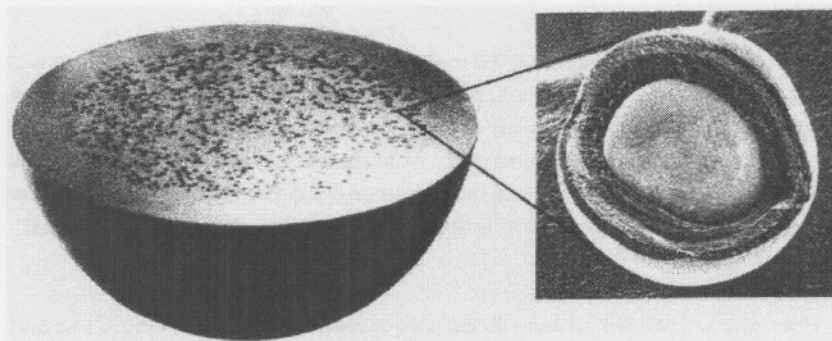


Figure 8: Cut away of fuel sphere [1]

2.4.2 The Reactor Unit

The reactor of the PBMR is a high-temperature reactor with ceramic fuel cells and structurally consists of graphite. These materials can be submitted to very high temperatures and therefore the reactor is thermally very efficient. The reactor core consists of an inner zone containing 110 000 inert graphite spheres and an outer zone that contains 330 000 fuel cells. The reactor also has a few core structures of which the ceramic core reflector structure provides neutron reflection by top, bottom and side reflectors as well as neutron and gamma shielding and thermal insulation. Control rods that control the nuclear reaction are housed in the side reflector. [1]

2.4.3 The Coolant – Helium

Helium is used as coolant gas to extract the heat generated in the reactor core. Helium is used as coolant gas because it is chemically inert and has a high thermal conductivity. The Helium Inventory Control System (HICS) consists of various subsystems which controls the supply of helium as well as the purity of the coolant. These sub-systems include the Inventory Control System (ICS), the Helium Purification System (HPS) and the Helium make-up System (HMS). The primary function of the ICS is to control the pressure in the main power system. Helium is extracted from lower pressure points within the system to lower-pressure storage tanks and injected from primary high-pressure storage tanks into the system. The main function of the HPS is to purify the helium

and to extract contaminants such as water, dust and carbon monoxide. The HMS is used to replenish helium lost through everyday leakage. [1]

2.4.4 Main Power System

All the systems and sub-systems combine to ultimately form the Main Power System (MPS). The primary function of the MPS is to convert nuclear energy into electrical energy. This is done in two processes. Firstly nuclear energy or heat is transferred to the coolant gas and the thermal energy is then turned into electrical energy. [1] The MPS consists of the following systems that all function together to form the power production unit.

- Reactor Unit
- Core Structures
- Reactivity Control and Shutdown Systems
- HP Turbo-units
- LP Turbo-units
- Power Turbine
- Generator
- Recuperator
- Coolers
- Hot Pipe and Valve System
- Primary Pressure Boundary
- Core Conditioning System
- Reactor Pressure Vessel Conditioning System
- Helium Inventory and Control System
- Start-up Blower System. [3]

Shown in figure 9 is the basic structural layout of the MPS as well as the most important flows of helium through the system.

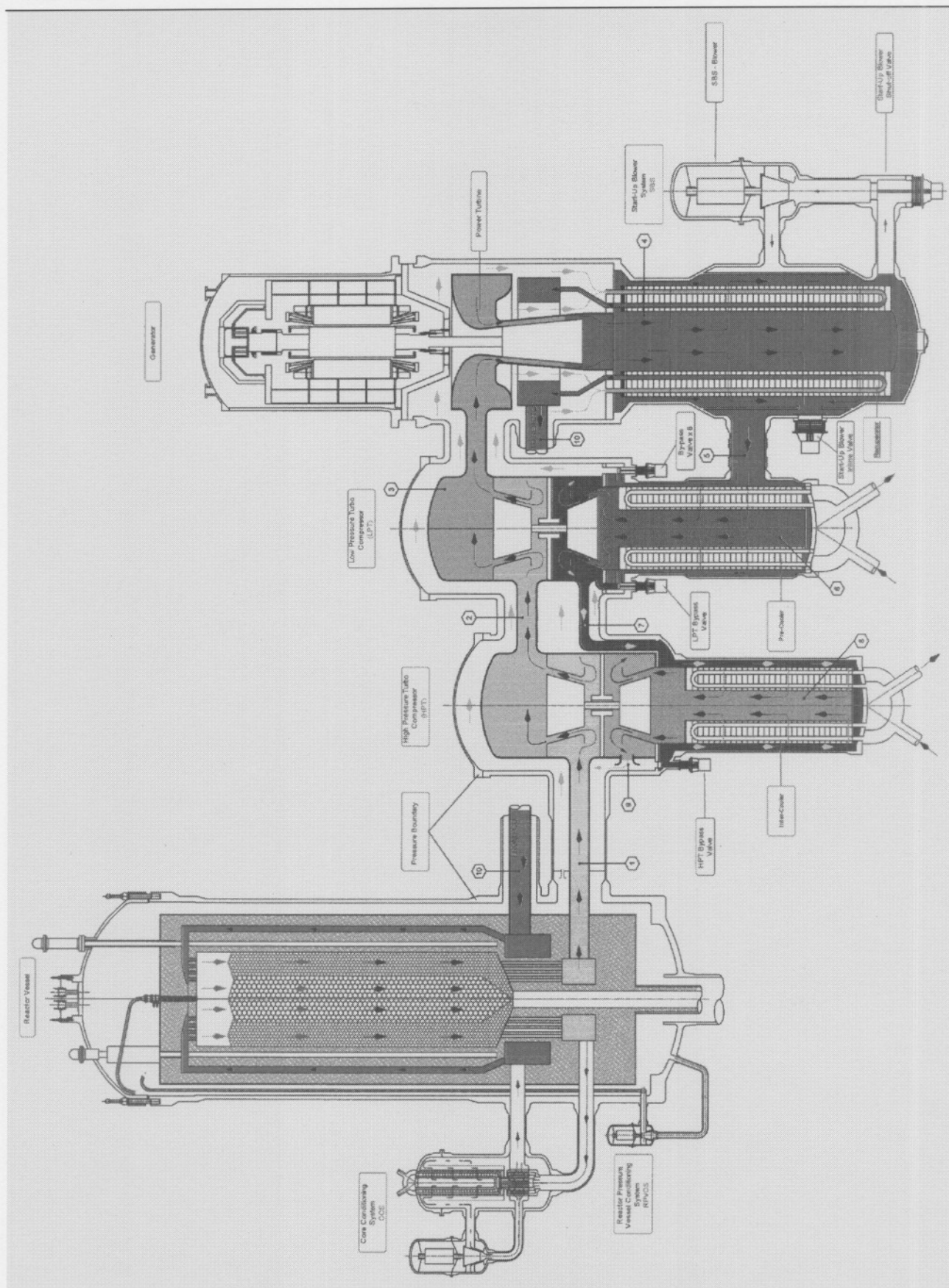


Figure 9: Schematic representation of helium gas flows through the MPS [1]

2.5 The PBMM

The PBMM is a model that was developed to demonstrate the operation of the closed, recuperative Brayton cycle in order to gain a better understanding of its dynamic behaviour and to demonstrate the control strategies that was to be used in the original design of the PBMR. It is also used to demonstrate the ability of Flownet, a predecessor of Flownex, to simulate the integrated and dynamic performance of the cycle. Flownet originally was a simulation software package used to simulate the operation of thermal-fluid networks like the PBMM. Flownex is an improved successor of Flownet which also simulates the operation of thermal-fluid networks and has since replaced Flownet as primary simulator of the PBMM.

The PBMM was therefore developed with the following design constraints:

- The dynamic behaviour of the PBMM must display the same trends as that of the three-shaft PBMR, but not necessarily with comparable time constants.
- The PBMM plant layout must have the same topology and representative major components as that of the three-shaft PBMR.
- The control system of the PBMM must have the same topology and degrees of freedom as that of the three-shaft PBMR.
- The PBMM must use off-the-shelf turbo chargers as opposed to purpose designed machines
- The PBMM must use a conventional heat source.

These design constraints resulted in the following major differences between the three-shaft PBMR and PBMM:

- The micro model uses nitrogen instead of helium as the working fluid. The objective of the model is not to address specific issues related to the use of helium as a working fluid but to develop a system that has the same overall characteristics as the prototype plant.
- The helium inventory control system (HICS) is therefore be replaced by a nitrogen inventory control system (NICS) and mimics the operation of the HICS.
- The micro model uses cheaper off-the-shelf single stage centrifugal turbo-chargers instead of purpose designed multistage axial flow turbo machines. The performance characteristics of centrifugal turbo machinery closely resemble that of axial flow.
- The heat source is an electrical resistance heater instead of a nuclear reactor.

- The load on the power turbine is a compressor with an external load cooler. This compressor dissipates power through a control valve and a heat exchanger. The main reason is that suitable generators running at such high speeds without a gearbox is not readily available.
- Heat rejection is done via a cooling tower which supplies cooling water to the pre- and intercoolers instead of an intermediate heat exchanger.
- The Start-up Blower System (SBS) is positioned differently to the position in the PBMR.

2.6 PBMM Operation

The PBMM operates, apart from the differences mentioned in previous section, in much the same manner as the three-shaft PBMR. Shown in figure 10 is a basic system layout of the PBMM. Gas at relative low pressure and temperature enters the low pressure compressor (LPC) and is compressed to an intermediate pressure. This gas is then cooled by means of an intercooler before it is further compressed by a high pressure compressor (HPC). The nitrogen is preheated by the recuperator before entering the heater. The gas that exits the heater is hot and under high pressure. The gas is now allowed to expand through a series of three turbines, the high pressure turbine (HPT), the low pressure turbine (LPT) and the power turbine (PT). The HPT and LPT are connected to the HPC and LPC and drive the HPC and LPC. Before gas enters the precoolers, it is compressed by the LPC which finishes the cycle. Heat is dissipated in the recuperator (RX) to the cooler stream coming from the HPC prior to entering the heater.

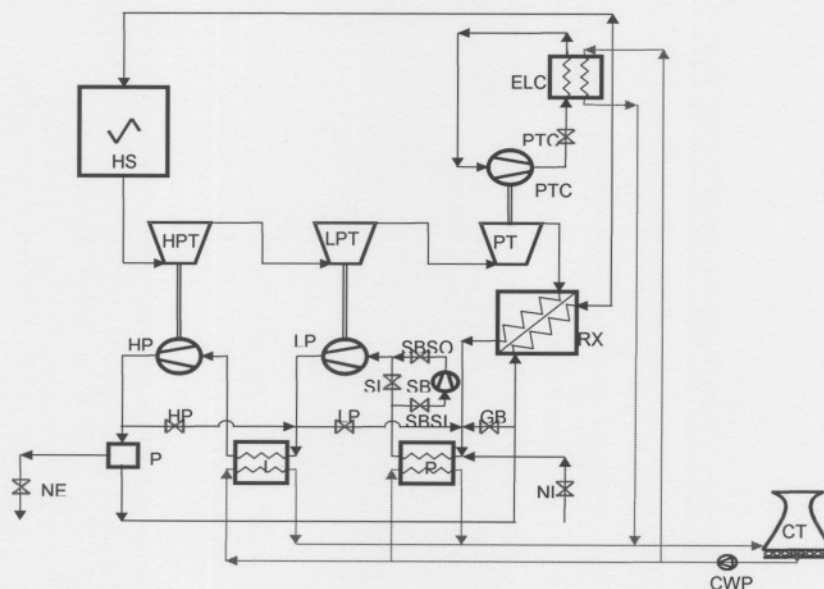


Figure 10: The PBMM system layout

Heat dissipation by the pre-cooler (PC) and inter-cooler (IC) is achieved by a supply of cold water from a cooling tower (CT). Nitrogen gas is injected into the system at the point with the lowest

pressure in the cycle. This point is just before the pre-cooler. Nitrogen can be extracted from the point with the highest pressure. This point is just after the HPC. The Start-up Blower System (SBS) is used to circulate the gas through the system when the cycle is not in a Brayton cycle state.

2.7 PBMM Layout

Shown in figure 11 is the actual layout of the physical PBMM. The system is supplied with nitrogen by a series of four nitrogen containers at a high pressure. These are called the Nitrogen Inventory Control System (NICS). The pressure differential between the system and NICS tanks are used to inject or extract gas from the system. The Pressure Vessel (PV) houses the recuperator, the electrical heaters and the complex combination of turbomachinery. The Pre- and Intercooler is supplied with cold water by a cooling tower which dissipates the heat which is extracted when the water passes through the Pre- and Intercooler. The PBMM is controlled from a single control room from where every system parameter can be monitored and necessary changes be made.

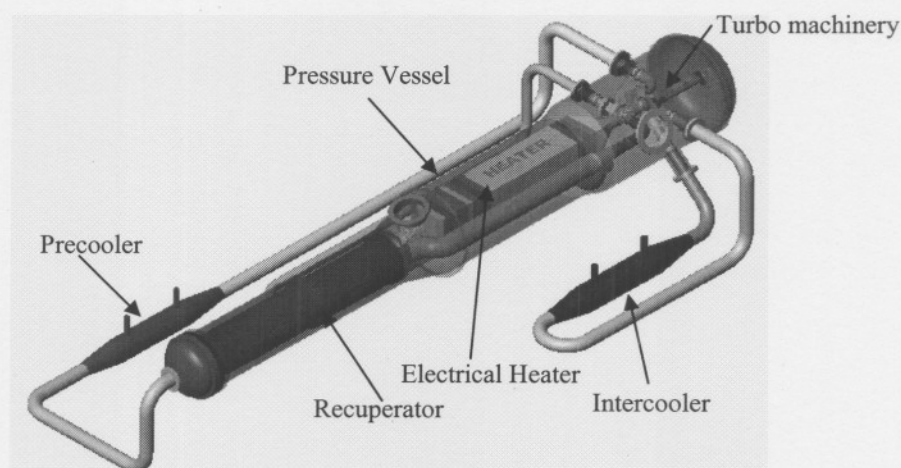


Figure 11: The pressure vessel layout

2.8 Conclusion

The PBMR project's purpose is to build a demonstration plant at Koeberg and a pilot fuel processing plant at Pelindaba. The demonstration plant is scheduled to be finished by 2010 with the first commercial plants to be available by 2013. The original design concept or topology of the PBMR was used in developing the PBMM – a demonstration plant to illustrate the dynamic behaviour of the three-shaft PBMR. The PBMM was built at the North-West University in

Potchefstroom. The PBMM is the only plant in the world using three-shaft Brayton cycle based technology.

Chapter 2 gave introductory information of power plant simulation in general. This was followed by a background study on the PBMR and PBMM. Knowledge of plant operation is essential in the course of development of this dissertation.

Chapter 3 – Start-up and Shutdown

3.1 Overview

The PBMM start-up and shutdown procedures are performed by a user who has to adhere to a checklist containing the steps of the start-up and shutdown procedure. This checklist describes every step or action the user must perform in sequence in order to complete both procedures. In this chapter the start-up and shutdown procedure of the PBMM will be described. Both the start-up and shutdown procedures comprise a combination of actions in which various sub-systems are manipulated through the entire process. The process of start-up and shutdown will become apparent as the actual start-up and shutdown checklist is investigated. Along with the checklist (given in *Appendix A*), data generated during an actual start-up and shutdown proved immensely important in identifying the operation of the PBMM, which is also presented in this chapter.

3.2 The PBMM Start-up and Shutdown Checklist

Start-up and shutdown of the PBMM are characterised by numerous checks and control actions. These actions are performed in a specific sequence by an operator by following a predetermined checklist which describes the safest and preferred operation of the PBMM. Refer to *Appendix A* for an actual detailed start-up and shutdown checklist.

3.3 Start-up of the PBMM

The start-up procedure consists of 7 basic actions. Firstly the cooling water system is started. This supplies cold water to keep the turbomachinery from overheating. The cold water is also used to cool down the coolant gas in the pre-cooler and intercooler. The nitrogen supply system is then used to attain a pressure of 130 kPa within the entire system. Nitrogen injection is done at a point in the system where the pressure is the lowest when the system is operational. It is extracted at the point with the highest pressure. The lubrication system is then started and can only be started when the pressure of the gas within the entire system is higher than 90 kPa. The lubrication system supplies the turbomachinery of lubricating oil. There is a possibility that the oil might contaminate the coolant gas if the pressure of the gas drops below 90 kPa.

The start-up blower system (SBS) is then started. The SBS is a system that is used to circulate the coolant gas through the system when the Brayton cycle is not self sustaining during the start-up and

shutdown sequences. The heater service is then activated to simulate the use of a nuclear reactor core. When the SBS system is operational, gas has to be injected to compensate for a loss in pressure at the SBS inlet. The SBS is in essence a pump used to pump gas through the system but when it is started, it causes an undesirable sudden drop in pressure at the SBS inlet. Gas from the NICS is injected at the SBS inlet side to compensate for this loss in pressure. When there is a zero pressure ratio across the SBS, the SBS is deactivated and a point of operation is reached that is termed “bootstrap” or otherwise referred to as a self-sustaining Brayton cycle state.

3.4 Shutdown of the PBMM

The shutdown procedure consists of 5 basic actions. Firstly the heater service is shut down. This results in the loss of core temperature of the electrical heaters that simulate the use of a nuclear reactor core. As a result of this temperature loss, the gas in the system slowly loses momentum as it passes through the system causing the turbomachinery to slowly lose speed until it eventually comes to a halt. This is the second action that has to be performed by the user. He has to wait for the turbomachinery to come to a halt after the heat has been turned off. The third step is to bleed off some of the gas within the system until it reaches a pressure of 130 kPa. The gas is bled off as the SBS casing cannot handle very high pressures. Therefore gas is bled off to reach a safe pressure prior to SBS activation.

The cooling cycle then commences. This is the fourth step. Gas is re-circulated through the system by the Start-up Blower System to extract the excess heat from the heaters and turbomachinery. When the heater outlet temperature is below 200 °C the SBS is shut down along with the lubrication and cooling system. This is the fifth and final stage of the shutdown procedure.

3.5 Actual Start-up and Shutdown Data

3.5.1 Overview

The following section describes the start-up and shutdown procedures of the PBMM by using data that was attained during an actual start-up and shutdown of the physical PBMM. The data is presented in a manner to directly illustrate the procedures followed in start-up and shutdown. The data was obtained by temperature, pressure and other sensors that are used to monitor and control the operation of the physical PBMM. Shown in figure 12 is a small extract of the PBMM system layout illustrating temperature and pressure sensors that monitor the electrical heater system.

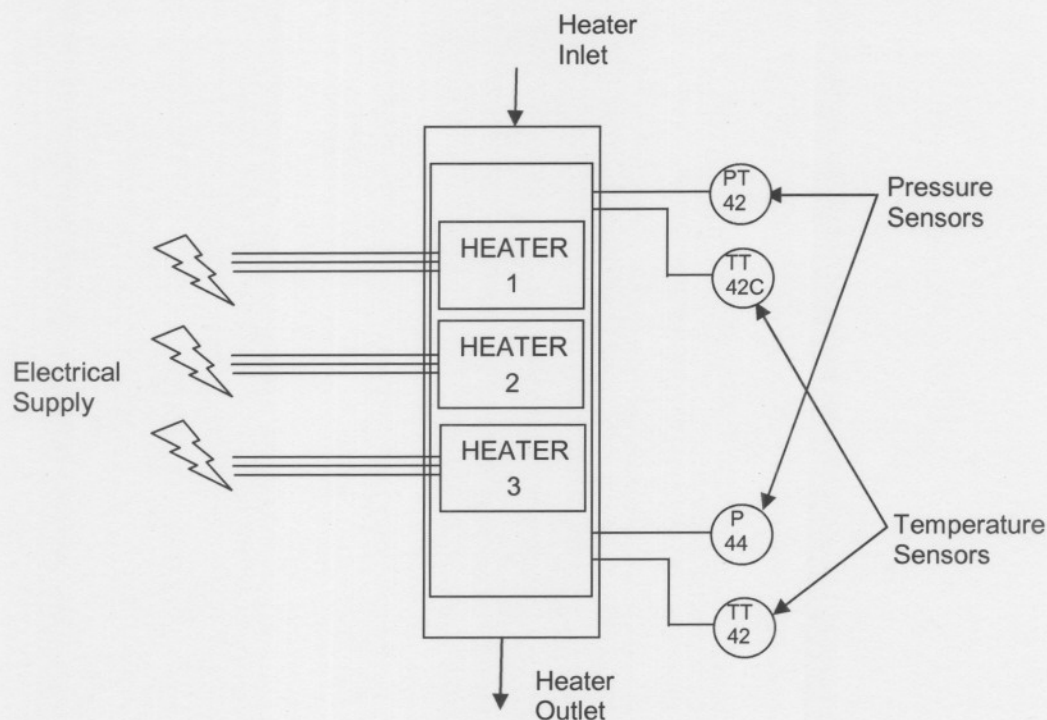


Figure 12: Heater element of PBMM showing pressure and temperature sensors

3.5.2 Start-up

1. Injection of gas

The first important step after the cooling water cycle has been started is to ensure that the gas pressure within the entire system is maintained at 130 kPa. The nitrogen supply system (NICS – Nitrogen Inventory Control System) consists of four gas tanks containing the nitrogen gas at a high pressure. These tanks are connected to a manifold by means of pipes and valves. At the manifold gas can be injected or extracted by means of a valve – the NICS injection/extraction main valve CV501A. This valve regulates the amount of gas being injected or extracted. Figure 13 depicts the basic layout of the four NICS gas tanks and how they connect with the injection and extraction valves.

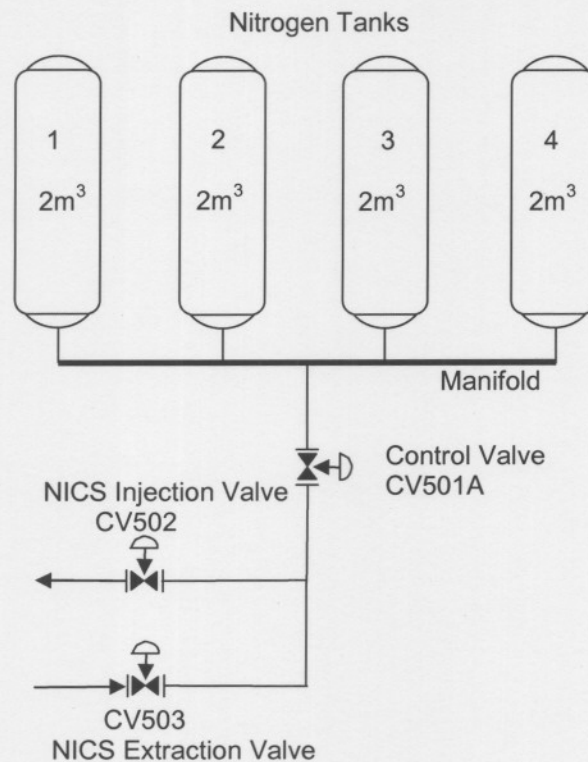


Figure 13: Basic layout of nitrogen injection system

Figure 14 depicts the gas pressure of the manifold as well as the percentage that valve CV501A was opened. Notice how the pressure in the manifold drops as gas is injected into the system. The valve stays open for the first 75 minutes of time as shown by the figure. This is because of the SBS that was started with the resultant drop in pressure at the inlet. Therefore injection to compensate is clearly depicted. The valve is again opened at a time of 220 minutes. This is at the SBS reactivation point during the shutdown cycle.

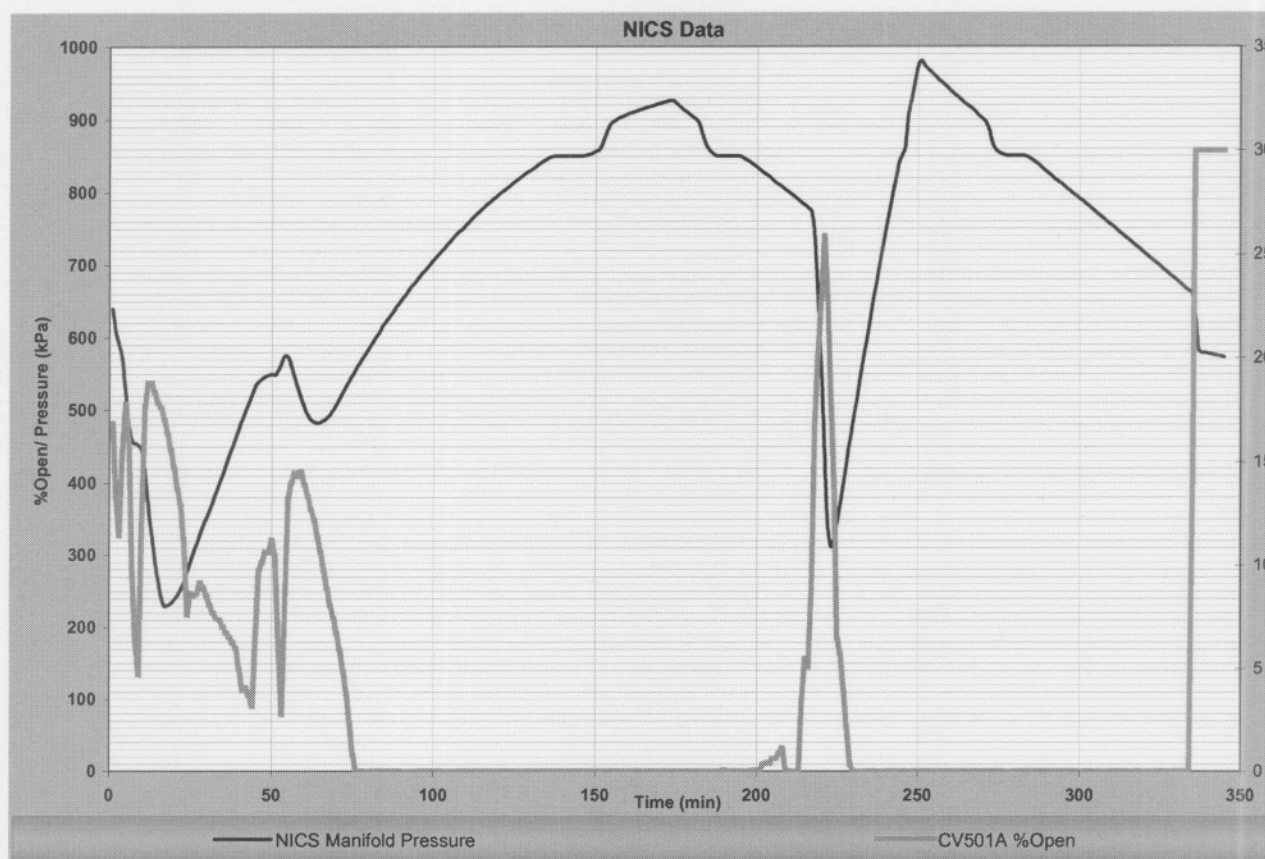


Figure 14: NICS manifold pressure and valve % open

2. SBS Activation

As previously mentioned the SBS activation is preceded by the activation of the lubrication system when a certain pressure is reached within the system. In figure 15 the basic layout of the SBS is depicted. The SBS consists of a pump that is driven by an electrical motor and a combination of valves to relay the gas through the SBS or to bypass it when bootstrap occurs. When the SBS is operational the system inline valve is closed and the SBS inlet and outlet isolation valves are opened so that the gas passes through the SBS. When the SBS is not operational the system inline valve is open and the SBS inlet and outlet isolation valves are closed to prevent gas from passing through the SBS.

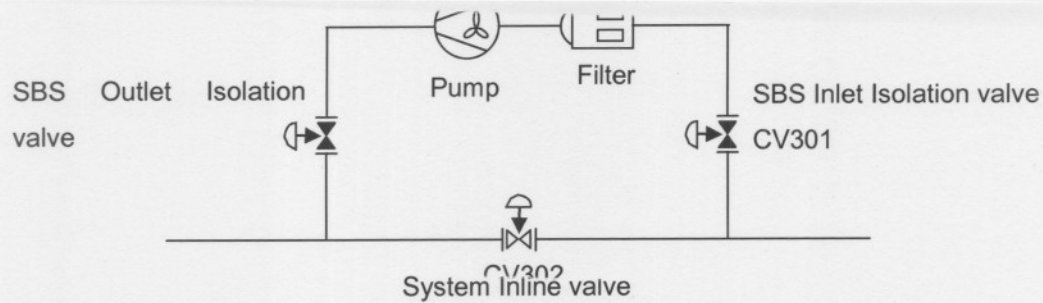


Figure 15: SBS layout

Figure 16 depicts the power in kilowatt drawn by the SBS when it is operational. The pressure differential across the SBS is also illustrated along with the power drawn. The pressure differential is the difference between the outlet pressure and the inlet pressure of the SBS. Notice that when the SBS is initially activated the pressure differential is very high. This shows that the inlet pressure is low in comparison to the outlet pressure when the SBS is activated. The gradual drop in the pressure differential occur as a result of the coolant gas slowly gaining momentum and pressure as the heaters are activated while the SBS is still running.

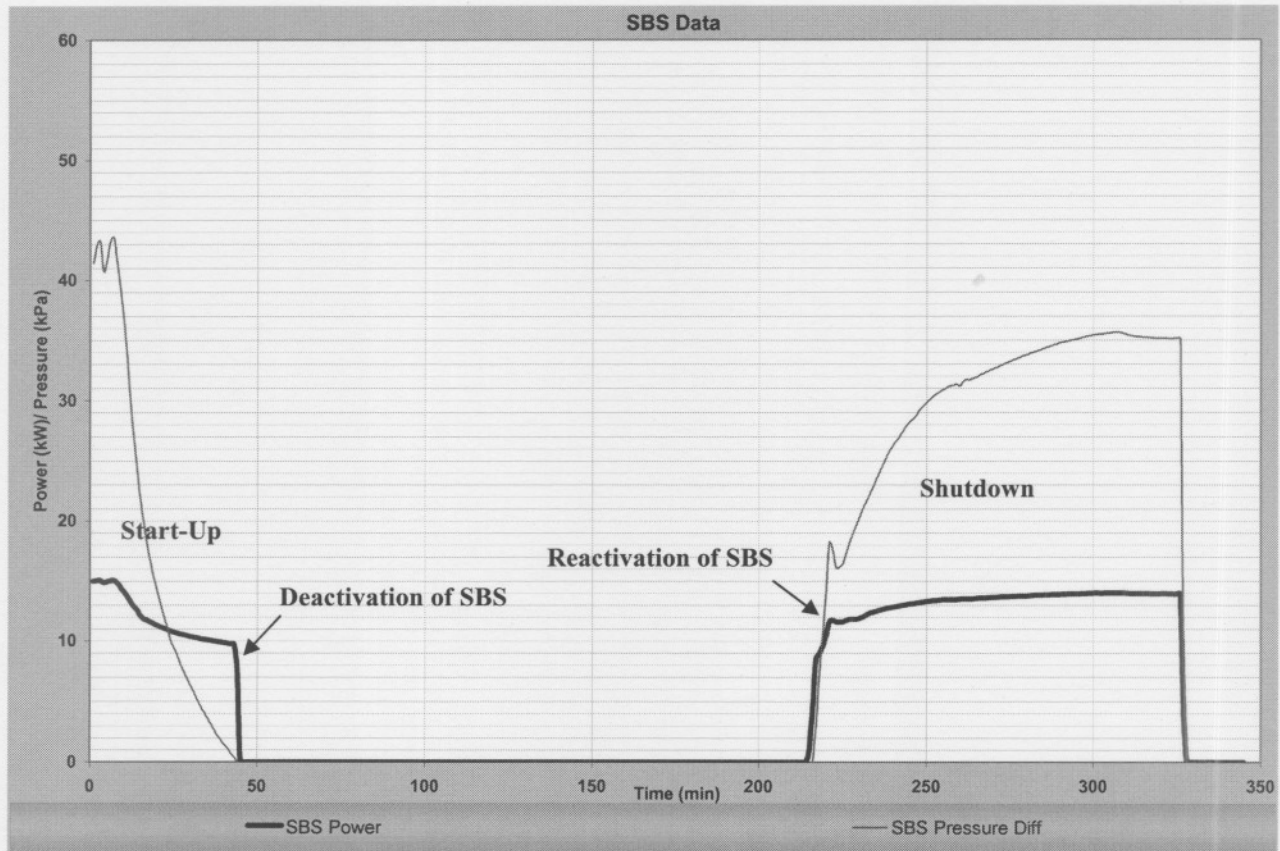


Figure 16: SBS power and pressure differential

Notice that when the pressure differential across the SBS becomes zero or less than zero the SBS is automatically deactivated. Figure 17 depicts the operation of the SBS isolation valve and system inline valve corresponding to the activation and deactivation of the SBS.

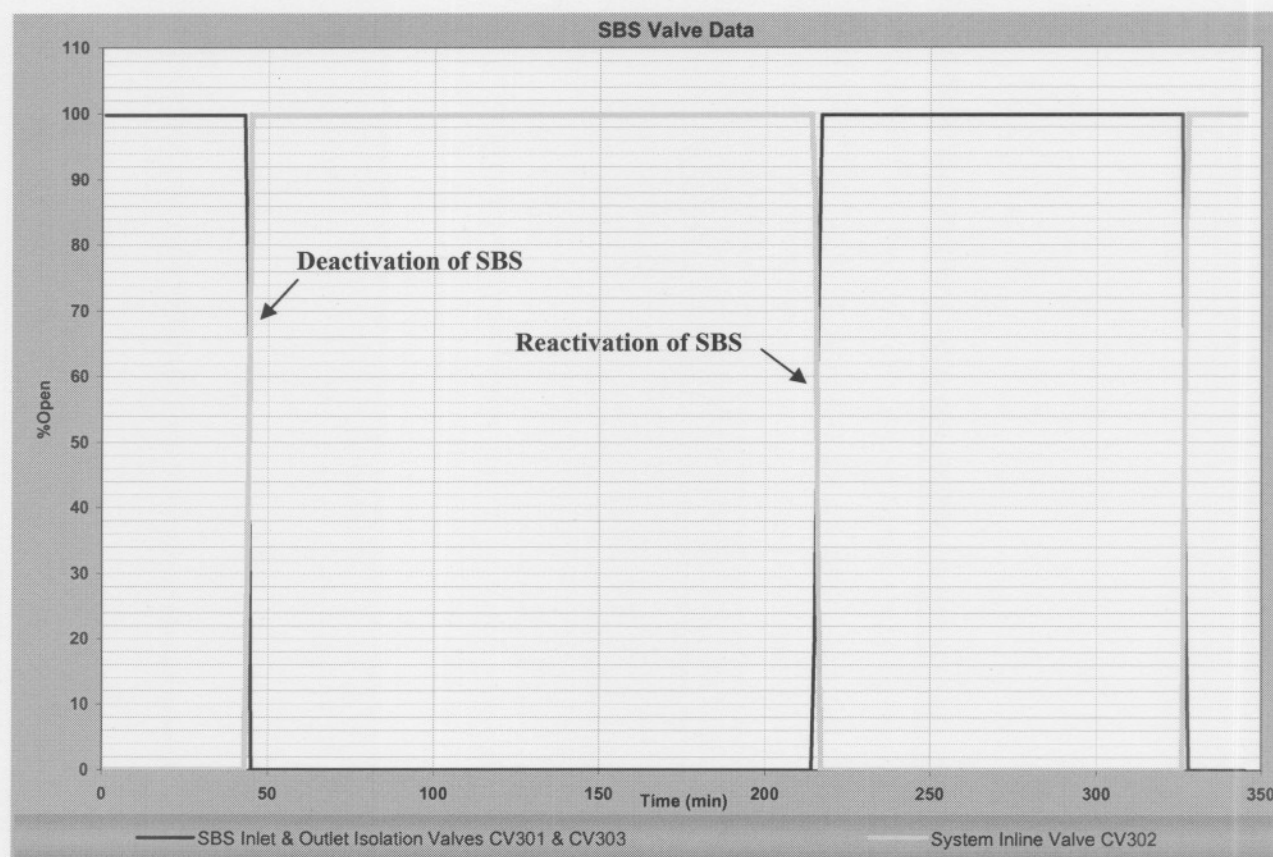


Figure 17: SBS Valve Operation

3. Activation of Heater System

The basic layout of the heater system was shown in figure 12. The heater system is started while the SBS is still operational. This ensures that gas is passing through the heaters at a certain speed when the heaters are activated. The heater power and inlet and outlet temperature are shown in figure 18. Comparing the heater power with the SBS power of figure 16 it can clearly be seen that heaters are only activated a short time after the SBS has been activated.



Figure 18: Heater data

These three steps comprehensively describe the start-up procedure. Start-up finishes after the heaters are activated and the pressure differential across the SBS reaches zero. At this stage the heaters effectively power the entire system. Gas at high pressure and temperature exiting the heaters power the high pressure turbine (HPT), the low pressure turbine (LPT) and the power turbine (PT). These turbines in turn drive the high pressure compressor (HPC) and the low pressure compressor (LPC). The compressors increase the pressure of the cold gas before it is heated by the recuperator and heaters.

3.5.3 Shutdown

1. Heater Service Deactivation

The first step in the shutdown procedure is the deactivation or shutdown of the heater system. This results in a sudden drop of temperature at the heater outlet as depicted by figure 19. Shutdown commenced at around 208 minutes after the system was initially started.

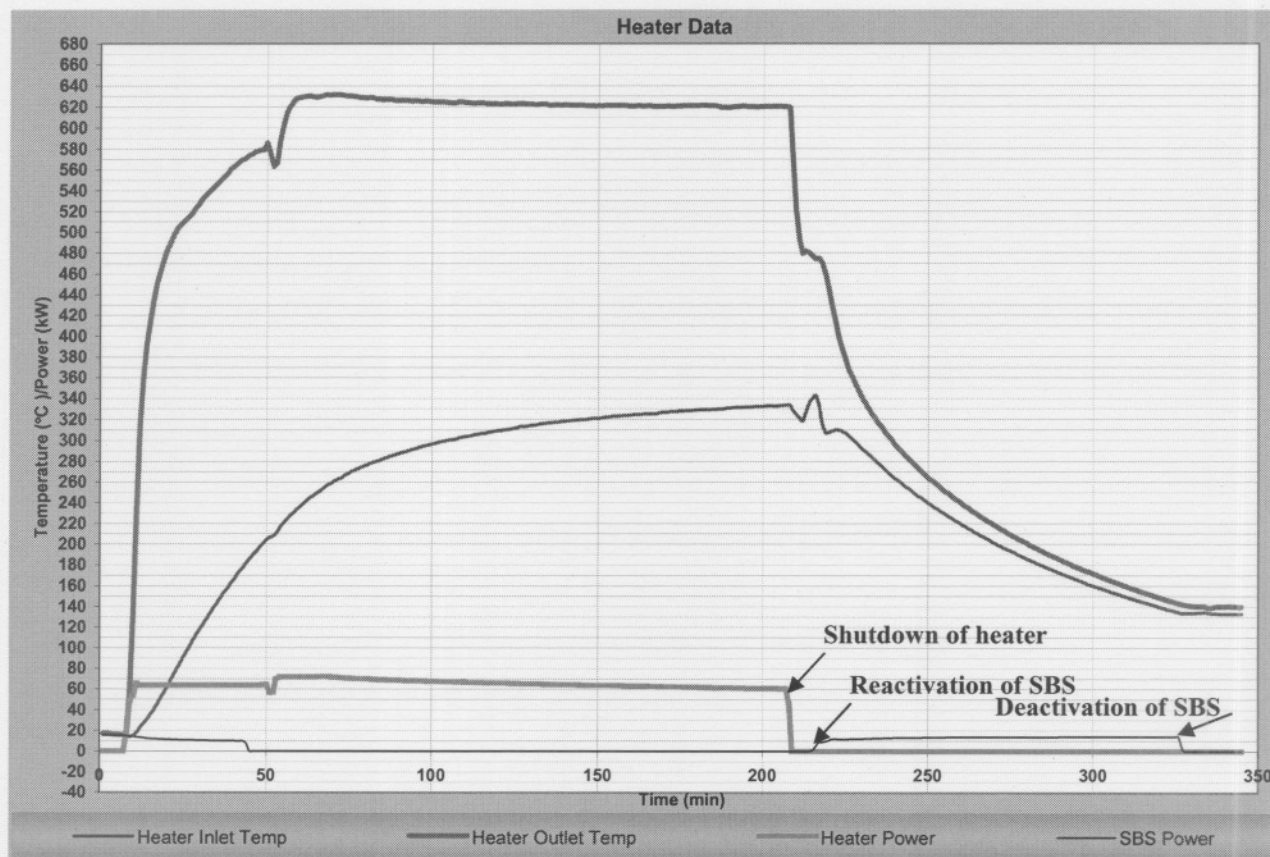


Figure 19: Heater and SBS data

2. Turbomachinery comes to a halt

Once the heaters are deactivated the user has to wait for the turbomachinery to come to a halt. At this stage there is still a lot of energy or heat within the gas but as soon as the heaters are deactivated the gas starts to lose the energy resulting in the turbomachinery slowly coming to a halt. This is clearly depicted in figure 20 illustrating the gradual decrease in rotational speed of the turbomachinery.

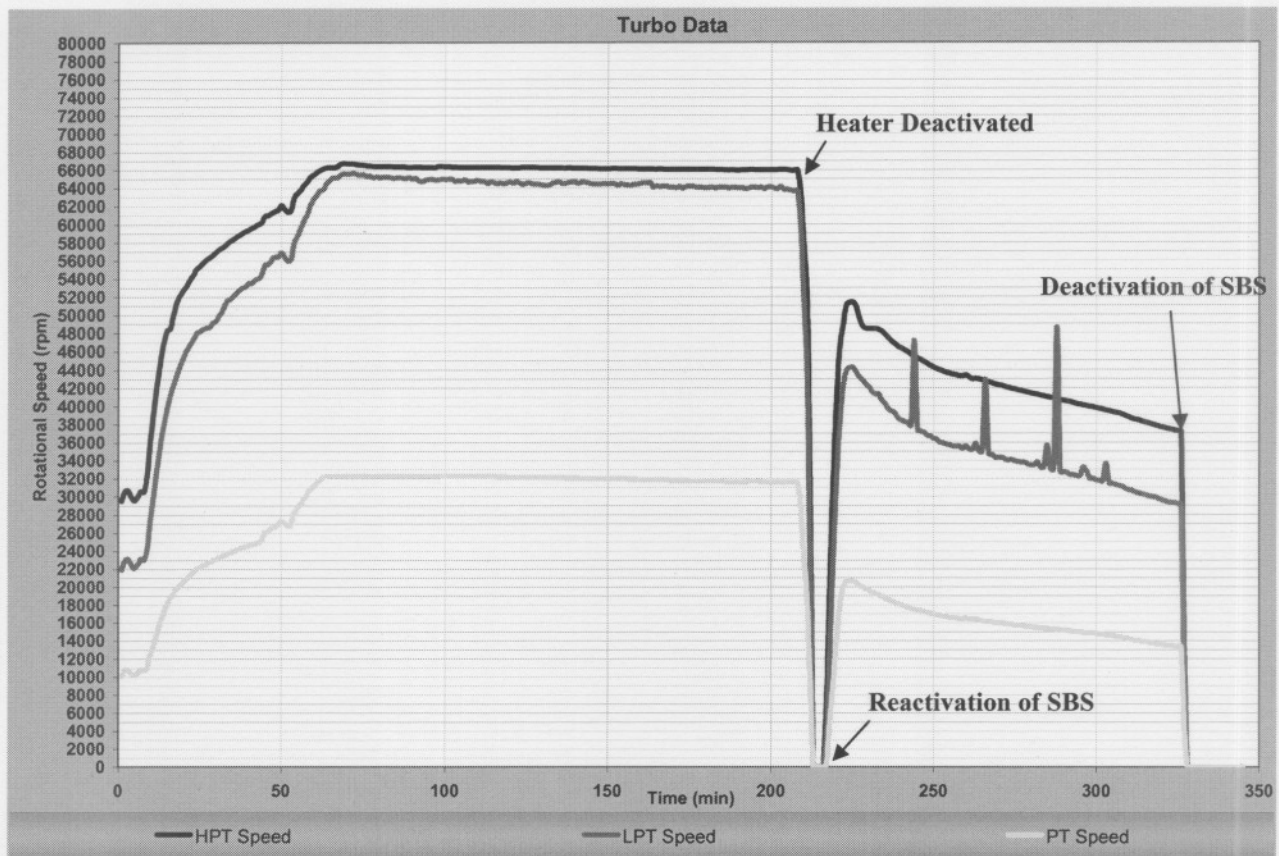


Figure 20: Turbomachinery rotational speed

3. Bleed off gas to a pressure of 130 kPa

The gas is released into the atmosphere by opening a valve connected to the high pressure side. This means that the valve is connected at the HPC outlet. The turbomachinery has to come to a halt which allows the entire system to have the same pressure. By opening this valve the pressure in the system drops as excess gas is released into the atmosphere. This can clearly be seen in Figure 21 which depicts the time that the control valve was opened to a certain percentage to bleed off some of the gas. Gas is blown off to protect the SBS casing which can handle only lower pressures.

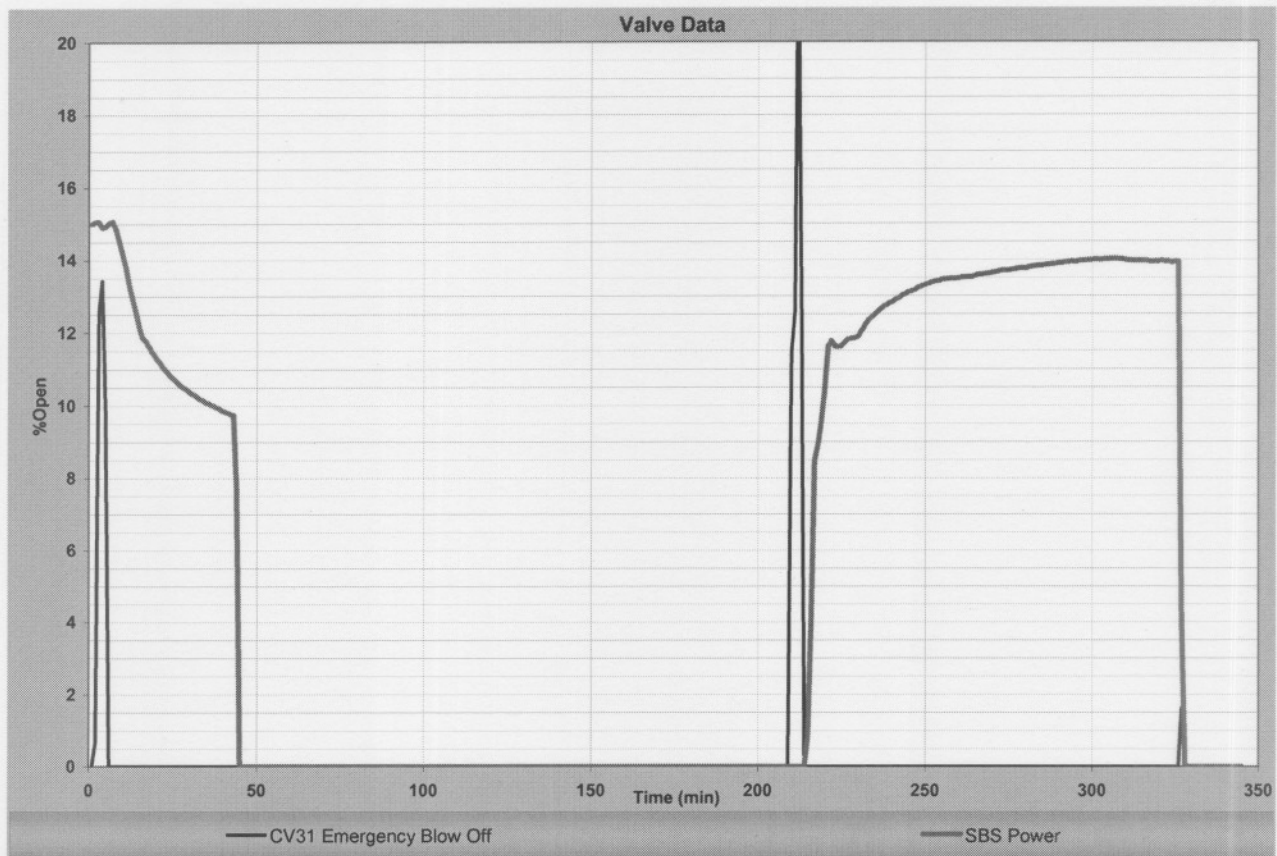


Figure 21: Emergency gas blow off valve

4. Activation of cooling cycle

The cooling cycle commences with the activation of the SBS to extract the excess heat from the heaters as well as the turbomachinery by circulating the gas through the system. This is clearly seen in figures 19 and 20 where it is shown that once the turbomachinery has come to a complete standstill, the turbomachinery gradually gain speed because of the gas that is now again circulating the system as a result of the SBS being operational.

5. Deactivation of SBS

When the heater outlet temperature is below 200 °C the SBS is shut down along with the lubrication and cooling system. This is the fifth and final stage of the shutdown procedure.

3.5.4 Summary

Start-up is initiated with the injection of gas. Then the lubrication system is activated along with the cooling system. Start-up continues with the activation of the SBS. When activated the SBS immediately runs at maximum speed as seen by the power drawn by the SBS. This causes a drop in

SBS inlet pressure and has to be compensated for by injecting gas. Along with the SBS the heaters are also activated. The pressure differential over the SBS then slowly decreases as the coolant gas gains momentum and energy in the heaters. The system is said to have bootstrapped when the pressure differential across the SBS becomes zero. At this point the system is in a self-sustaining Brayton cycle state and the SBS is deactivated. However the turbomachinery will still increase in speed until a speed is reached referred to as a nominal point of operation.

Shutdown commences with the deactivation of the heaters. When the turbomachinery comes to a halt, the SBS is reactivated to recirculate the gas to cool down the heaters. Prior to reactivation gas is blown off to protect the SBS casing from high pressure. When the heater outlet temperature drops below 200 °C the SBS is deactivated and the system is said to be permanently shutdown until the next operation is required.

3.6 Conclusion

The data taken of actual start-up and shutdown was used in directly identifying these two processes. The data also provided a better understanding of the operation of the PBMM. Provided in Appendix B is a complete illustration of system parameters of each important component of the PBMM. These parameters include the most important inlet and outlet pressures and temperatures, rotational speeds and power.

The data considered in this chapter was generated when the SBS was still operated by activation at maximum speed. However, during the duration of this project the activation implementation of the SBS of the physical PBMM system was changed which allowed the SBS to be gradually accelerated to maximum speed. The effect of this manner of operation will be considered later in this document. This older data was purposefully used in identifying and illustrating the start-up and shutdown procedures. The data has a simple but clear representation of actual events and allows a reader to easily grasp the fundamental concept behind the two processes considered in this chapter.

Chapter 3 gave a detailed investigation of data that was generated during actual start-up and shutdown of the PBMM. This data was used in directly identifying the discrete steps of start-up and shutdown. Chapter 4 investigates simulation results as performed by the Flownex PBMM model.

Chapter 4 - Flownex Simulation

4.1 Overview

Flownex is a general-purpose thermal-fluid network analysis code. An existing Flownex model of the PBMM was used to simulate the operation of the PBMM. This chapter describes the complete Flownex model. The various components are considered individually to describe the most important differences to the actual physical system. A strategy to implement start-up and shutdown in Flownex is also considered. The strategy for start-up and shutdown was implemented in the Flownex simulation model and data was generated that can be compared to actual start-up and shutdown of the physical system.

4.2 Simulation Model of the PBMM in Flownex

The Flownex model essentially follows the Brayton cycle in the same manner as that of the actual PBMM. Most of the important systems of the physical PBMM are included in the simulation model. The systems that do not influence the process of activating, sustaining and terminating the Brayton cycle, like the lubrication system, are not included in the simulation model as well as systems such as the heater electrical supply system and the compressed air supply system. Systems like the cooling water system are implemented in the physical PBMM by circulating the water through the system and cooling it by means of a cooling water tower. In the simulation model this is achieved by supplying the system with a constant stream of cold water. In this section the individual components of all important systems will be considered separately to clarify operation and major differences with the actual PBMM.

4.2.1 The Heater Element

The electrical heaters of the physical PBMM are implemented in the Flownex model by the use of a component termed the conductive heat transfer element (CHT). The CHT element uses conduction, convection and radiation to transfer heat from one element or body to another. Shown in figure 21 is a schematic representation of the CHT element where only conduction and convection are considered. [4]

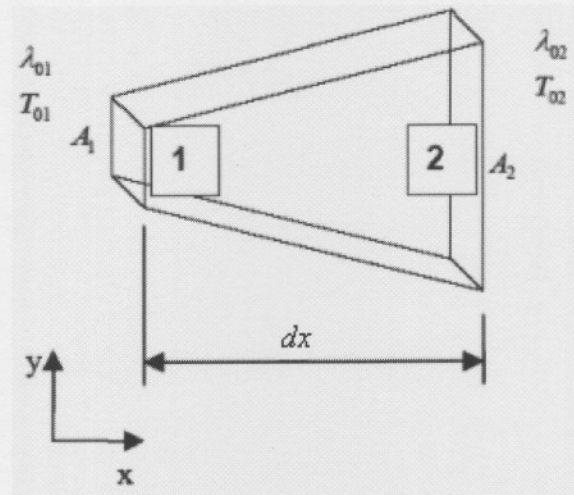


Figure 22: Schematic representation of the CHT element with conduction and convection [4]

In figure 22:

- 1 and 2 - the up- and downstream sides of the CHT element respectively,
- λ_0 - the surface heat transfer convection coefficient ($\text{W/m}^2 \cdot \text{K}$),
- T_0 - the ambient temperature (K),
- dx - the thickness in the x-direction (m),

Figure 23 describes the path of the heat transfer flow through the CHT element by means of conduction and convection.

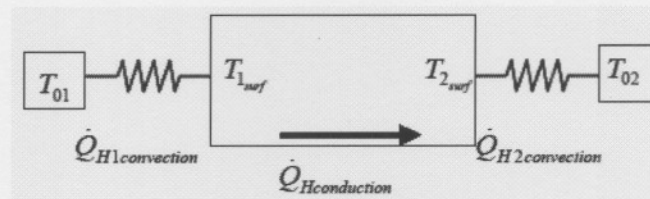


Figure 23: Heat transfer paths of the CHT element

Consider the CHT element as it is implemented in a simple gas flow system as in figure 24. Air is passed through each pipe individually. Pipe element 1 is then heated to illustrate the heat transfer from one stream of heated air flow to a cooler stream of air flow by means of the CHT element. Initial conditions of flow in both pipes are the same. In figure 24 both the nodes numbered 1 and 4 are at a pressure of 100 kPa and 25 °C. Notice in figure 24 the direction of the arrows between nodes 4 and 6 and nodes 1 and 3 describe the direction of the flow of gas. The arrows which pass

through the CHT from node 2 to 5 have no purpose in illustrating the direction of heat transfer. Heat transfer always occurs from the warmer flow to the colder flow through the CHT irrespective of what these arrows might suggest.

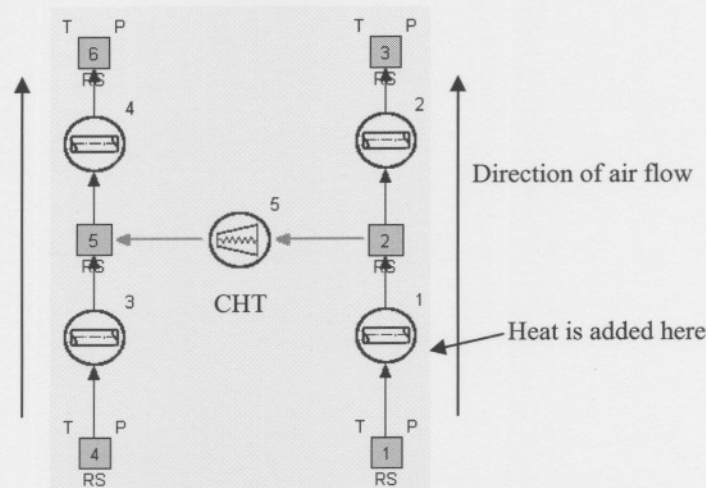


Figure 24: CHT-air gas flow heat transfer system

Shown in figure 25 is the response of the system of figure 24 when 100 kW of heat is added to pipe element 1 and then removed exactly 145 seconds after the heat was added initially. The temperature rise in pipe 4 is a result of the heat transferred from the heated flow through pipe 1 and 2 by the conductive heat transfer element.

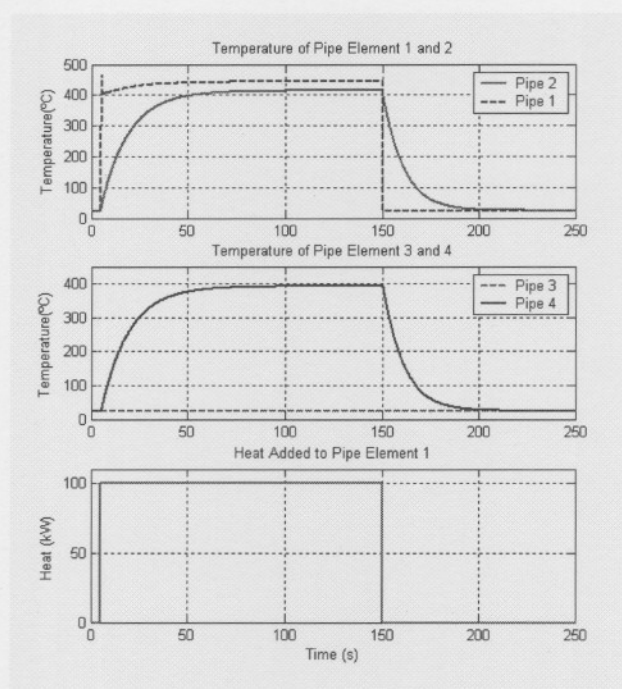


Figure 25: System Response

The basic concept of using a heated flow in one stream and to transfer the heat to another stream by means of a conductive heat transfer element establishes the fundamental concept of how the heater

element is implemented in the simulation model of the PBMM. A heated flow of air is used to transfer heat to the nitrogen gas (the coolant gas of the PBMM). Shown in figure 25 is a basic layout of how the heater was implemented in the simulation model.

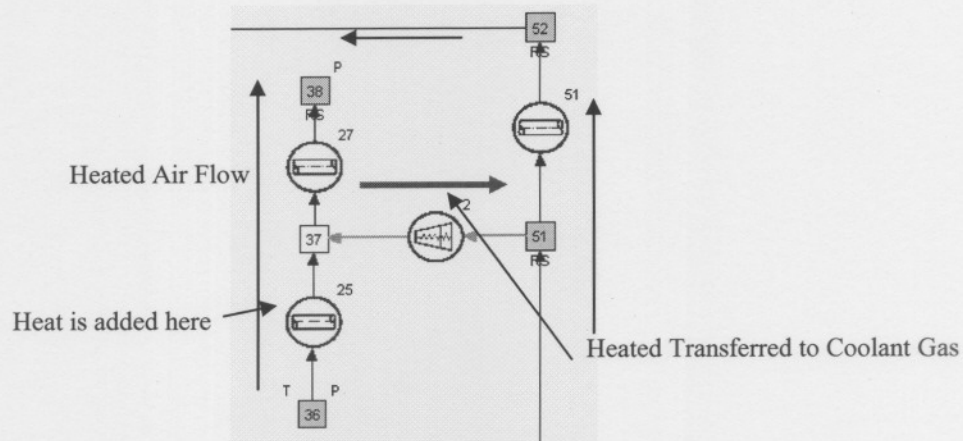


Figure 26: Heater implementation of simulation model in Flownex

Node 36 is kept at a temperature of 25 °C and a pressure of 100 kPa. Node 38 is kept at a pressure of 10 kPa. The difference in pressure ensures a mentionable mass flow between these two nodes. The heat is added at pipe 25. A heat transfer power of about 620 kW is necessary to obtain a 700 °C outlet temperature at pipe 51. This describes the implementation of the heater model in Flownex. Activation and Deactivation of this heater model has been implemented in a way to directly simulate the use of the real PBMM electrical heater counterparts.

During normal operation, heat is passed from the heated stream through node 37 and the CHT to the primary flow of the coolant gas through node 51. When deactivated, the heat transfer to pipe 25 is removed and the pressure of node 38 is made 99.99 kPa. This causes a nearly zero mass flow between nodes 36 and 38. This means that no heat can pass through the CHT from node 51 to 37. The primary flow of the coolant gas will then remove all the excess heat from the CHT which has a heat capacitance similar to that of the electrical heaters of the PBMM. When the heater model is activated, the pressure of node 38 is again set at 10 kPa establishing a mass flow between nodes 36 and 38. Heat is added to pipe element 25 and heat transfer to the primary coolant gas flow is regained.

4.2.2 The Start-up Blower System (SBS)

The Start-up Blower System (SBS) is a system that is used to circulate the coolant gas through the system when the Brayton cycle is not self sustaining during the start-up and shutdown procedures.

During start-up the SBS is used to supply the necessary energy needed to start and to gradually increase the speed of the turbomachinery. This results in an increasing flow of coolant gas through the heater. The gas gradually gains energy or heat until a nominal point of operation is reached. At this point the system has reached a self sustaining Brayton cycle state and the SBS is deactivated. During shutdown the system is forced out of a self sustaining Brayton cycle state by deactivating the heaters. The energy or heat of the coolant gas gradually decreases as heat is lost to the atmosphere by radiation and conduction and by dissipation in the coolers. Therefore the energy in the turbomachinery is lost resulting in a gradual decrease in shaft speed. Eventually the turbomachinery will come to a halt after which the SBS is reactivated to remove excess heat from the heaters.

The physical SBS consists of a pump that is driven by an electrical motor and a combination of valves to relay the gas through the SBS or to bypass it when nominal operation is reached. In the Flownex simulation model the SBS is implemented in much the same manner as in the physical PBMM System. However, the SBS cannot be activated or deactivated in Flownex as in the physical PBMM. The SBS is deactivated in the simulation model by specifying the mass flow as zero. Flownex employs a segregated solution algorithm which solves the governing equations of mass, energy and momentum sequentially. Only when convergence criteria are met within a small error margin the following time step is considered. Therefore when the mass flow of the SBS is specified as zero the solution algorithm will not converge along the path of the SBS but will compute along the path as shown by figure 27(a). In this case mass flow bypasses the SBS. This relates to a deactivated state of the SBS as there is no mass flow through it and therefore no energy is added by the SBS. If the SBS is required to supply energy, it is activated by allowing Flownex to solve the governing equations along the path shown by figure 27(b). Mass flow now passes through the SBS and gains energy as a result of an operational SBS.

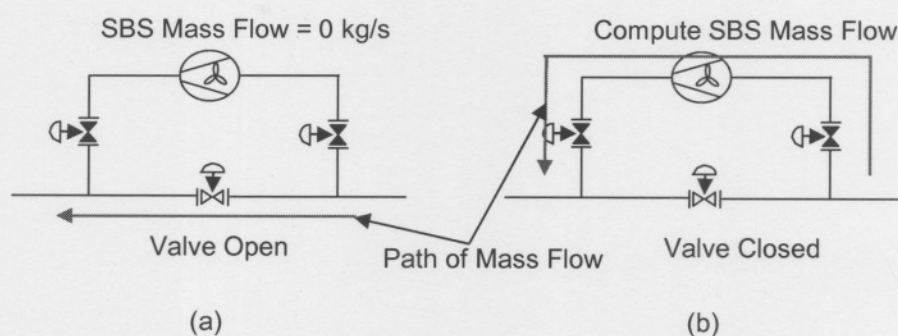


Figure 27: SBS activation and deactivation

4.2.3 The Cooling Water System

In the physical PBMM water is used as primary coolant by the intercooler (IC), the pre-cooler (PC) and the electrical load cycle heat exchanger (ELCHX). Cool water is passed through the three components extracting heat from the primary coolant (nitrogen gas) within the PBMM system. The excess heat or energy gained by heat exchange is then dissipated to the atmosphere by means of a cooling tower (CT). The water is then reintroduced into the system by a cooling water pump (CWP). The CWP and CT ensure a constant supply of cool water for heat dissipation in the three components.

In Flownex the need for a cooling tower was not necessary. Figure 28 depicts the implementation of the cooling water cycle in the simulation model. The elements numbered 800 and 811 are nodes that are set to have certain fixed conditions. Node 800 has a fixed node temperature (T - see figure 28) of 20 °C and a fixed node pressure (P - see figure 27) of 88.9 kPa. Node 811 has a fixed node pressure 150 kPa and there is a difference in height (H – see figure 28) of 2.2 m between these two nodes. The element numbered 801 is a pump and is used to pump the water through the IC, PC and ELCHX. At the outlet of pipe element number 803, the water splits up to each of the heat exchangers. The water that reaches these three heat exchangers has a temperature of 20 °C. It then passes through the heat exchangers where heat is added. It then combines and returns as a single flow of water through pipe number 810. The temperature of this water is about 23 °C. The total supply of water is 12 kg/s. Both the IC and PC receives a flow of 5 kg/s each and the ELCHX a flow of 2 kg/s.

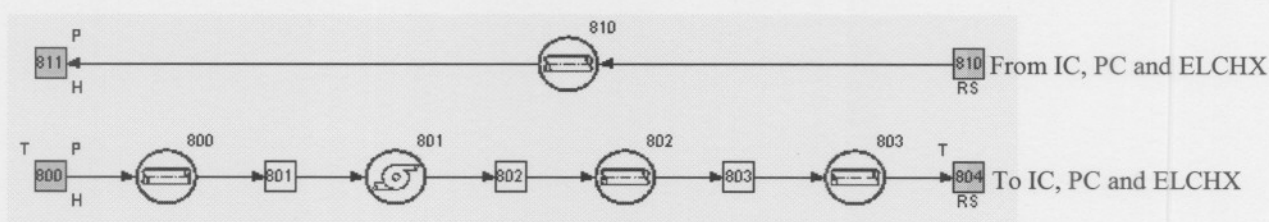


Figure 28: Cooling water cycle of simulation model

4.2.4 The Nitrogen Inventory Control System (NICS)

The NICS of the physical PBMM is fully described in section 3.5.2. The NICS is implemented in the simulation model in the same manner as in the physical system. Gas is injected into the system at the point with the lowest pressure and extracted at the point with the highest pressure.

4.3 Shutdown Strategy

4.3.1 Strategy Overview

In this section a strategy for shutdown of the Flownex simulation model is considered. The shutdown procedure of the physical PBMM consists of 5 basic actions: 1) the heater service is shut down. 2) As a result of the temperature loss in the heaters the turbomachinery comes to a halt after a short while. 3) Gas within the system is then bled off until the system reaches a pressure of 130 kPa. 4) Gas is then re-circulated through the system by the start-up blower system to extract the excess heat from the heaters and turbomachinery. 5) When the heater outlet temperature is below 200 °C the SBS is shut down along with the lubrication and cooling system completing the shutdown procedure.

When simulated, the PBMM simulation model starts off with certain initial conditions. These initial conditions describe a specific operation point of the model. The simulation starts as if the system is operating at normal operating conditions in a fully self-sustaining Brayton cycle state. Figures 29 and 30 depict the initial operation characteristics of the heater element and the turbomachinery illustrating the state the Flownex simulation model is in. During this simulation the SBS is off, the cooling water cycle is operational and there is no injection or extraction of gas.



Figure 29: Simulation results of heater element in Flownex

As a result of the initial self-sustaining Brayton cycle state of the simulation model, a strategy for performing the start-up and shutdown procedure was developed. The strategy is therefore to perform the shutdown prior to start-up. Normally the physical PBMM is firstly started and then operated until shutdown is performed some time later. The simulation model starts as if the system has been operational for a long time, hence the reason for shutdown prior to start-up.

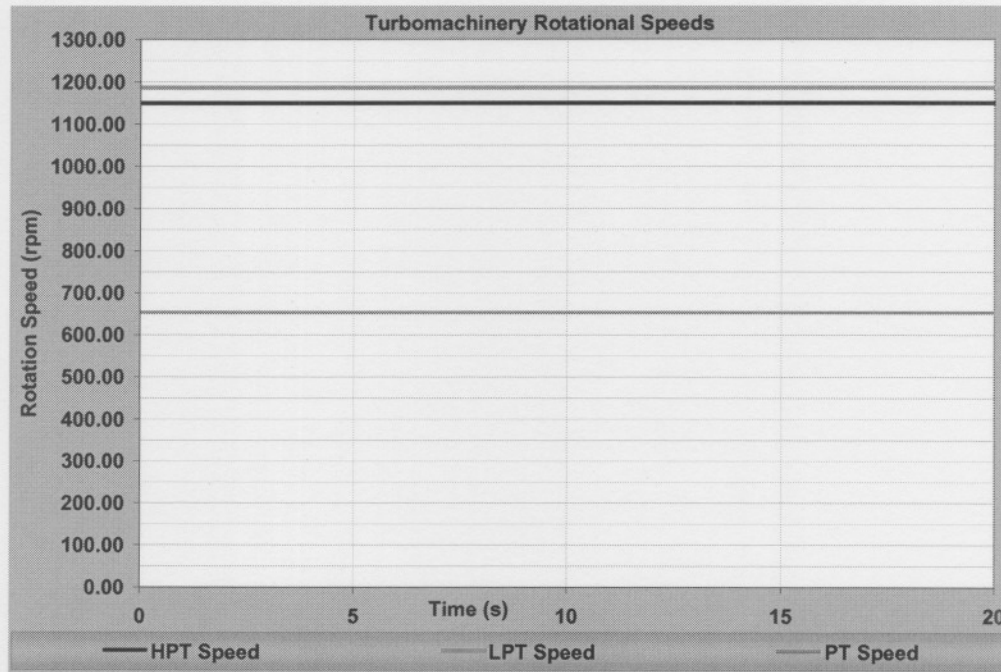


Figure 30: Simulation results of turbomachinery in Flownex model

4.3.2 Implementation of Shutdown in Flownex Model

As in the shutdown procedure of the physical PBMM, the first step is to deactivate the heaters. This is done in the Flownex model by removing the heat added to the heater implementation of figure 26. Flownex has dynamic modelling capabilities that allow the user to insert and activate certain transient events at a specific time. The deactivation of the heater element is inserted as a user-defined transient which occurs at exactly 20 seconds after the simulation has been started. The deactivation of the heater results in a loss of temperature in the heater and a gradual decrease in speed of the turbomachinery. This transient is clearly described by figures figure 32 and 33.

Notice in figure 31 the heat transfer is deactivated after 20 seconds by decreasing the heat added to the system of figure 26 and by decreasing the mass flow from node 36 to 38. The result is temperature loss in both the heater inlet and outlet temperature.

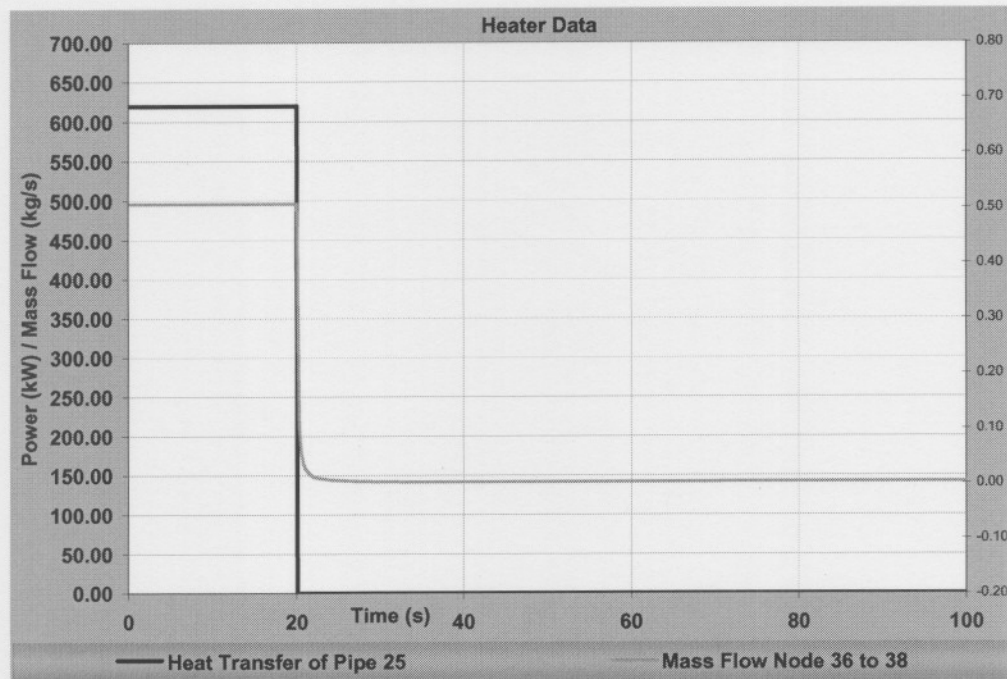


Figure 31: Heater element heat transfer



Figure 32: Heater Inlet and Outlet Temperature

In figure 33 the turbomachinery are running at a constant speed until the heater service is deactivated. This initial speed corresponds to the initial self-sustaining Brayton cycle state the simulation model is in prior deactivation of the heater. Normally the turbomachinery will then gradually lose speed until they eventually come to a halt.

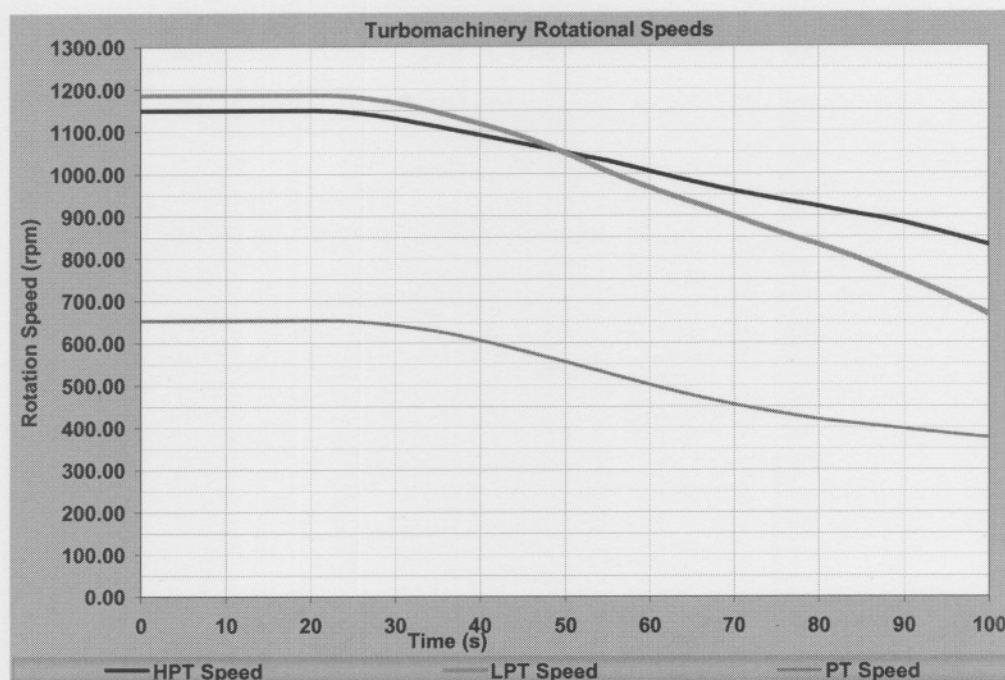


Figure 33: Rotational speed of HPT, LPT and PT

In Flownex complete standstill of a compressor or a turbine is, however, not possible to simulate. Flownex solves the partial differential equations for mass, momentum and energy conservation to obtain the mass flow and temperature distributions throughout a network. Flownex follows a segregated solution algorithm that solves these equations sequentially. This process is repeated until they converge within a small error margin before the next time step is considered. [4] For a detailed description of each of these equations refer [4].

The performance characteristics of both turbines and compressors, being the pressure ratio and efficiency, are specified in Flownex by means of a component database. The component database uses charts to describe the pressure ratio against non-dimensional mass flow as well as isentropic efficiency against non-dimensional flow using the non-dimensional speed in both cases as parameter for both a compressor and turbine. During a simulation Flownex determines these performance characteristics by interpolating the values specified in the component database.

To keep the simulation running at normal operating and simulation conditions, the SBS is activated prior to when a critical error might be reached. The SBS is then responsible for driving the turbomachinery and therefore keeps the system at a stage of operation which will not generate errors. This procedure is shown in figures 33 through 35. Notice in figure 34 that the heater has been off for a long time and as a result the turbomachinery has lost considerable speed. In figure 35

the mass flow through the SBS is zero for some time before it changes to a value larger than zero at a time of 110 seconds. This is the point where the SBS became operational to prevent the Flownex model to go into an error condition. Prior to this point the SBS was not operational as the mass flow through it was zero. Also notice how the turbomachinery gain some rotational speed as the SBS slowly accelerates as shown by figure 36. In the physical PBMM the SBS consists of a compressor driven by an electrical motor. The acceleration of figure 36 is therefore a pre-programmed transient that would occur under normal operating conditions of the physical system. Also notice that in figure 36, the initial speed of the SBS is 30 rad/s.

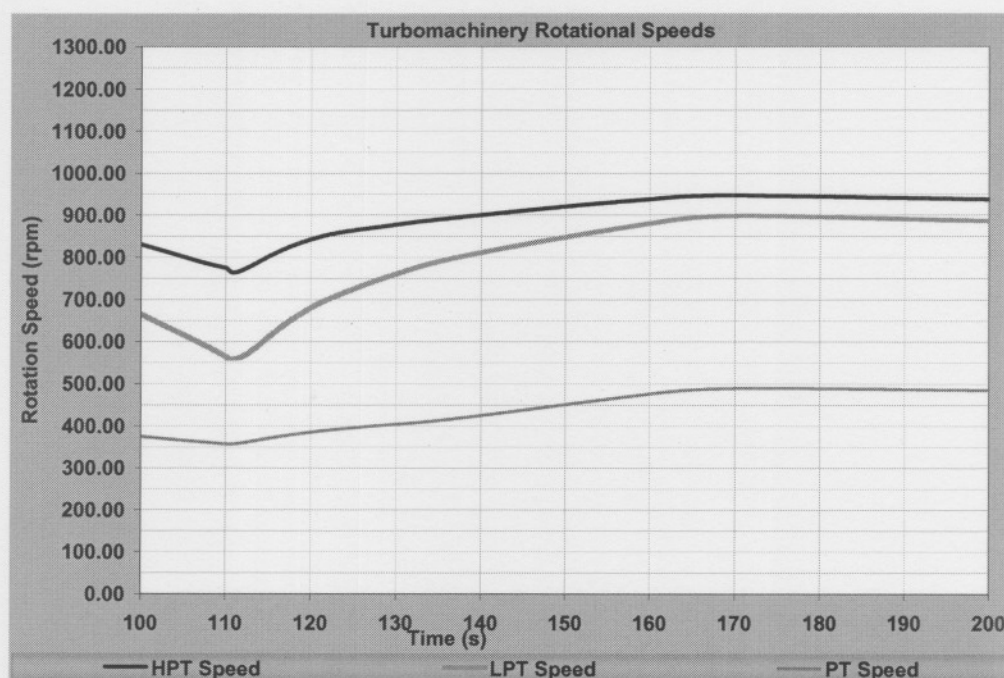


Figure 34: Turbomachinery rotational speed

A step which is not performed during this procedure in comparison to actual shutdown of the physical PBMM, is step 3 – the bleeding off of gas to a system pressure of 130 kPa. This step is only applicable when the turbomachinery are at a complete standstill and the pressure throughout the entire system is the same. The shutdown strategy of the simulation model implies that the turbomachinery never comes to a standstill and therefore the pressure throughout the system varies from one point in the system to another. Depressurising the system will only cause a further destabilisation.

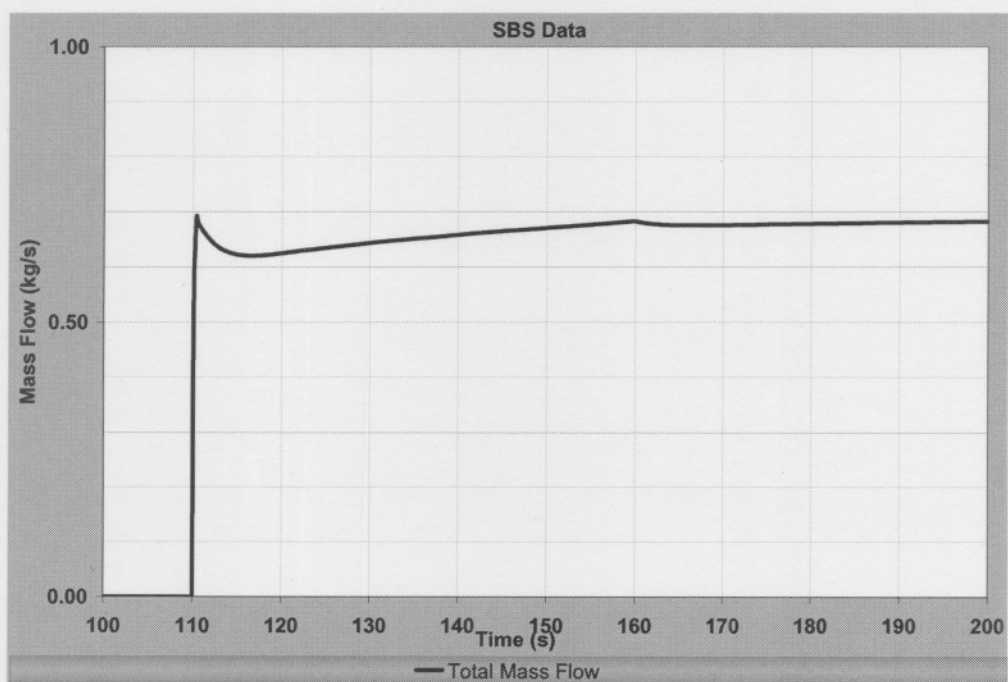


Figure 35: SBS mass flow

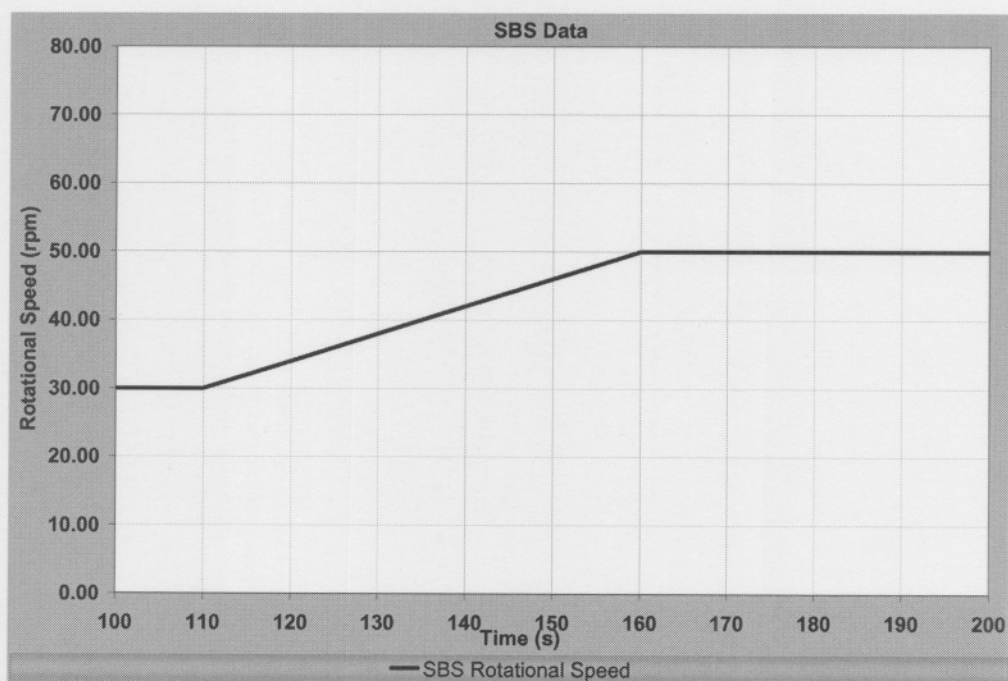


Figure 36: SBS rotational speed

4.4 Start-up Strategy

4.4.1 Strategy Overview

The start-up procedure's main purpose is to get the system into a self-sustaining Brayton cycle state. This is done by using the SBS to circulate gas through the system before the heaters are activated. The gas will then slowly acquire heat and momentum as it passes through the heater. The energy needed from the SBS then slowly decreases as the gas gains energy until eventually there is enough energy in the system to sustain itself. The SBS can then be deactivated.

4.4.2 Implementation of Start-up in the Flownex Model

As seen in the previous section, shutdown was performed prior to start-up as a result of the initial operating conditions of the simulation model. The shutdown procedure resulted in a non-self sustaining Brayton cycle state of operation. The purpose of the start-up procedure is to regain a self-sustaining state. This is done in the physical system by firstly activating the SBS. In the simulation model the SBS is already operational prior to start-up. Therefore the next logical step is to activate the heaters. Shown below is the response of the simulation model illustrating a start-up sequence.

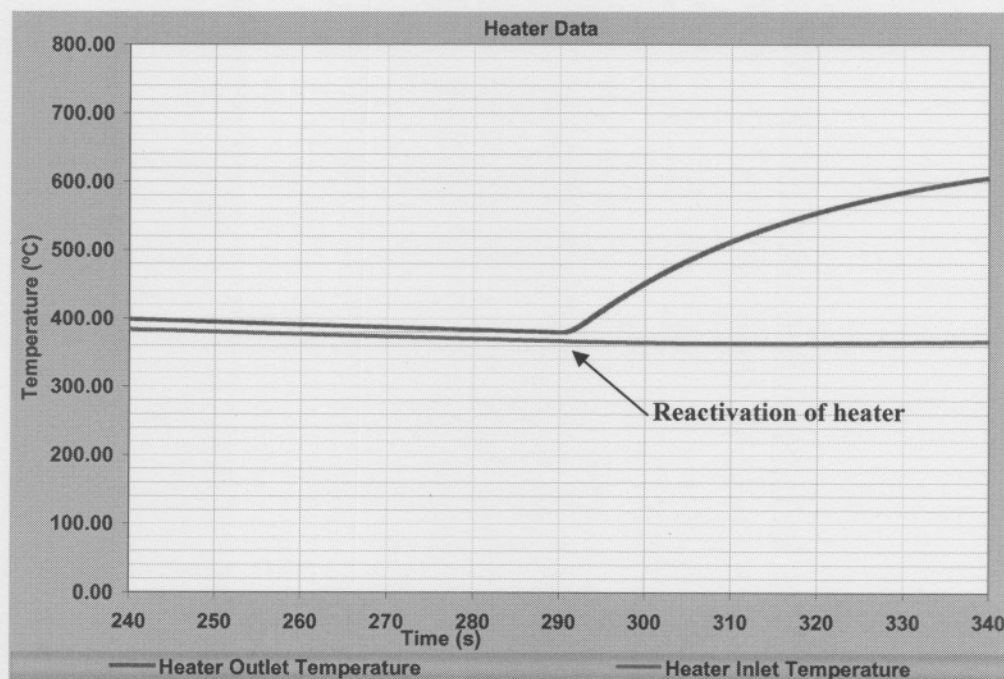


Figure 37: Heater Inlet and Outlet Temperature

Notice in figure 37 the heater is reactivated at 290 seconds of runtime after it was initially deactivated at 20 seconds. At this reactivation point the SBS is running at a constant rotational

speed and it is supplying the system with energy to keep the coolant gas circulating through the system. The rotational speed of the turbomachinery will gradually increase as the gas gains momentum and heat. This is illustrated in figure 38.

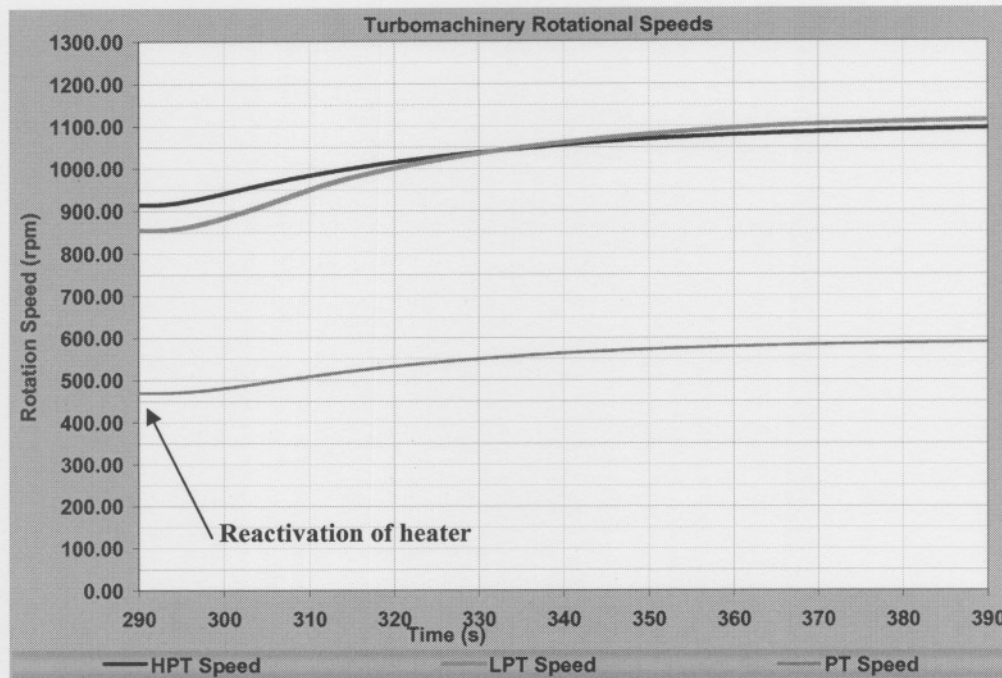


Figure 38: Rotational speed of turbomachinery

The activation of the heater results in a gradual decrease of the pressure ratio across the SBS. When the pressure ratio over the SBS reaches a value of 1 no more energy is added to the coolant gas by the SBS and it is therefore deactivated. At this point the system has reached a self sustaining Brayton cycle state. The heaters are now supplying the system with sufficient energy to stay within this self-sustaining state.

4.5 Conclusion

In this chapter both the start-up and shutdown procedures was performed on the PBMM simulation model in Flownex. When simulated, the simulation model describes a steady operation point of the system. This means that the system is initially in a self-sustaining Brayton cycle state. The heater supplies sufficient energy to keep the system within this state. The strategy therefore is to perform the shutdown procedure before the start-up procedure. Shutdown is performed by deactivating the heater. During actual shutdown the turbomachinery have to come to a halt before the SBS is activated. This however causes an error in the solution algorithm used by Flownex and to prevent the occurrence of an error during the simulation, the SBS is activated earlier in the simulation than during normal operation. The SBS then supplies sufficient energy to keep the system within an

operational state. Start-up is performed by reactivation of the heater. The pressure ratio across the SBS is a measure of the amount of energy supplied by the SBS. The pressure ratio gradually decreases as the heater supplies more and more energy and less energy is required by the SBS. Eventually no energy is needed by the SBS and the system has regained a self sustaining Brayton cycle state. This completes the start-up procedure.

Shown in figure 39 are the heater inlet and outlet temperatures as well as the heat transfer during both start-up and shutdown. The data was generated by the Flownex model and plotted with Excel. The point at which start-up and shutdown was initiated can be clearly seen.

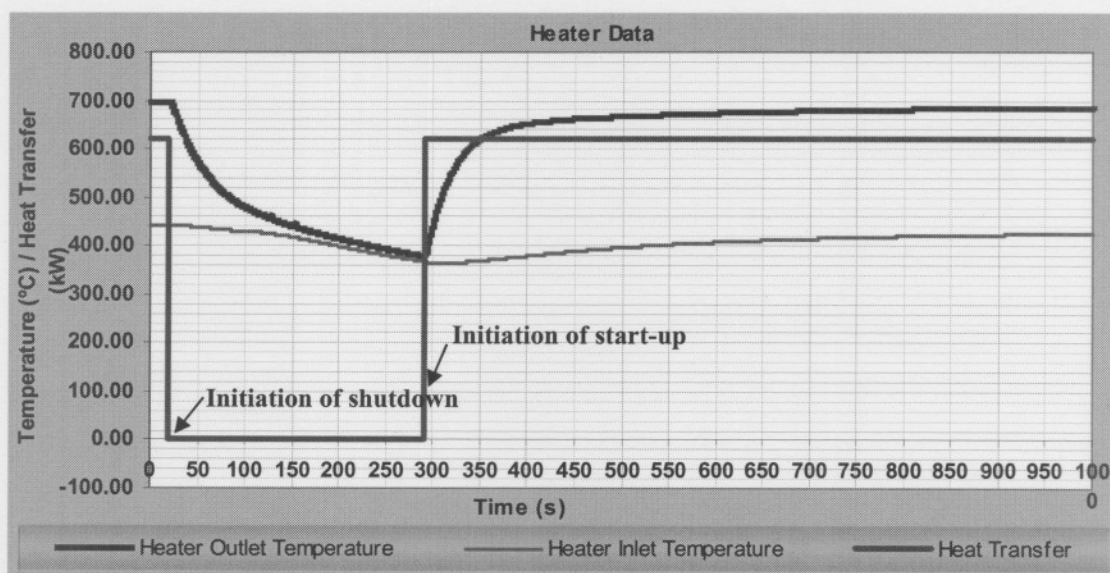


Figure 39: Heater inlet and outlet temperature

Shown in figure 40 are the SBS characteristics during shutdown and start-up of the Flownex model. Notice the points of SBS activation and deactivation as well as the point where the heater was deactivated.

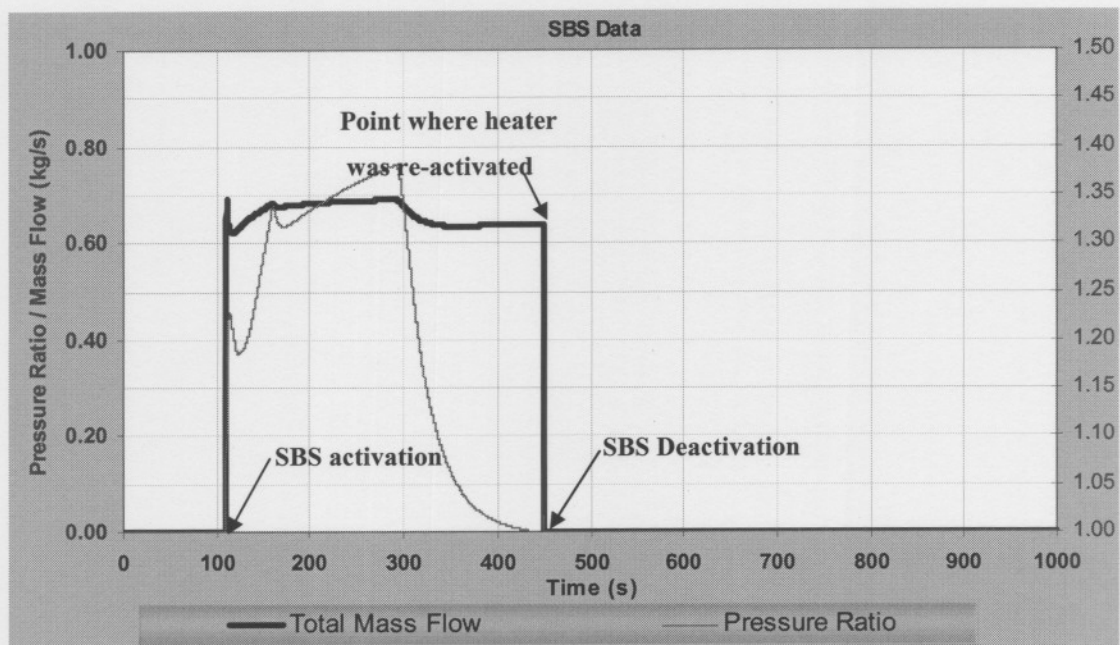


Figure 40: SBS Characteristics

Shown in figure 41 is the rotational speed of the turbomachinery. This figure is very important in illustrating both start-up and shutdown. Both the heaters and the SBS affect the rotational speed of the turbomachinery. Therefore the rotational speed of the turbomachinery is the best system characteristic used to describe both start-up and shutdown where shutdown was performed prior to start-up.

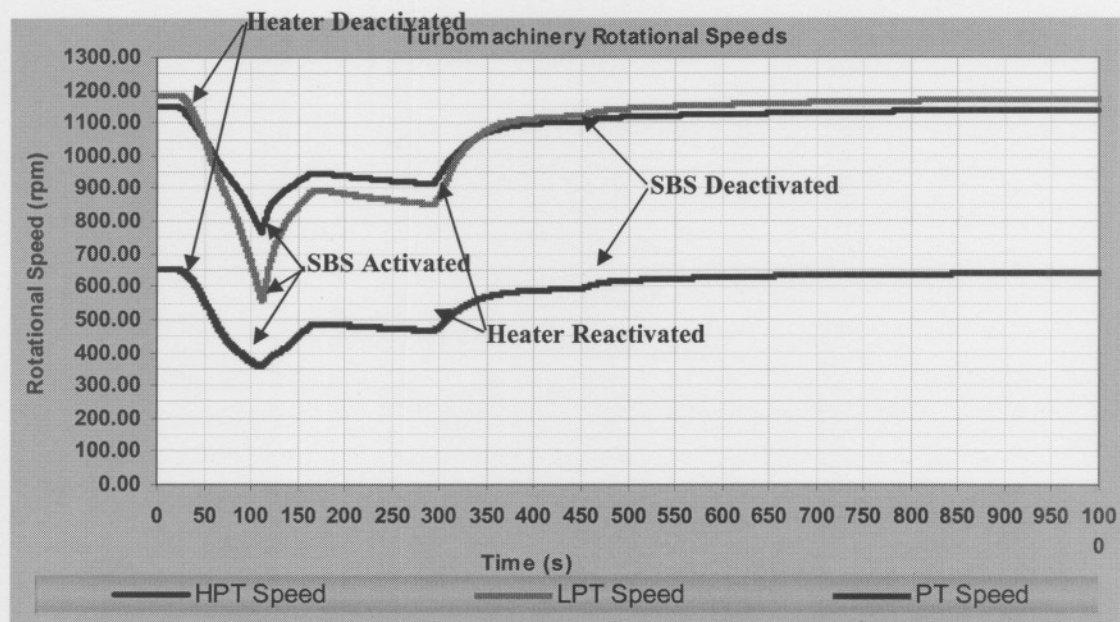


Figure 41: Rotational Speed of Turbomachinery

Chapter 5 gave a detailed description of the Flownex PBMM model. This model was then used to generate results of start-up and shutdown. Notice that this data does not necessarily reflect the actual start-up and shutdown procedures, but provide preliminary Flownex simulation considerations of start-up and shutdown. Chapter 5 and 6 follows with simulation data which reflect actual start-up and shutdown.

Chapter 5 Design and Implementation of an External Control Interface with Flownex

5.1 Overview

This chapter is concerned with the design and implementation of an external control interface with Flownex. The control interface allows a user to automatically control start-up and shutdown and to control important PBMM simulation model parameters during normal operation. Control strategies in Flownex are limited. Apart from a PID controller, Flownex provides control only through pre-programmed timed transient events. These pre-programmed timed transient events are specified prior to execution of a simulation and occur during simulation as a range of sequential events with a pre-specified change in value of system parameters. The need for external control that allows control over system parameters during a simulation is therefore apparent. Simulink was chosen as a basis for an external control interface.

5.2 Graphical User and External Control Interface Design

5.2.1 Overview

The first step in the design of the external control interface is to identify the system parameters of the PBMM simulation that has to be observed and controlled to perform the processes of start-up, shutdown and normal operation. Then a graphical user interface has to be designed that allows the user to control certain system parameters manually. An automatic control technique must also be designed that allows for automatic execution of start-up and shutdown without any user interference. This section describes the design procedure followed in designing the graphical user and external control interface.

5.2.2 System Parameters

In chapter 3 the physical PBMM was investigated in terms of data generated during actual start-up and shutdown. This data proved imminent in identifying and describing the actual processes of start-up and shutdown. It was shown in chapter 3 that the two most important systems in execution of start-up and shutdown are the heaters and the SBS. Control of the heaters and SBS are therefore important when considering the PBMM simulation model. Other processes that might be useful to

control include the nitrogen gas injection and extraction system and the load cycle system. The different rotational speeds of the turbomachinery must be observed to prevent Flownex from going into an error state. Shown below is a list of all system parameters which either has to be observed or controlled to perform start-up and shutdown in the Flownex simulation.

System parameters to be observed:

1. SBS pressure ratio
2. HPT, LPT and PT rotational speed

System parameters to be controlled:

1. SBS rotational speed
2. Heater power input
3. Nitrogen injection and extraction
4. Load cycle

5.2.3 Graphical User Interface Design

The system parameters mentioned above have to be controlled by a user through the use of a graphical user interface (GUI) which allows for in-time changes in system parameters. The user might for instance want to change the heater power input to observe resulting system changes. Therefore a GUI was developed that allows the in-time change in system parameters. The GUI is shown in Figure 42 as it is implemented in GUIDE in Matlab. GUIDE is a toolbox used to design graphical user interfaces in Matlab.

5.2.4 Control Design

SIMULINK[®] was used as the external program from which system parameters can be observed or controlled. The reason for the use of SIMULINK[®] is the existing interface between Flownex and SIMULINK[®]. In Flownex, system parameters can be defined as inputs or outputs. Through the interface, SIMULINK[®] can read these defined output parameters and return changes to Flownex via the defined input parameters. SIMULINK[®] therefore also provides a basis for implementing automatic control of start-up and shutdown.

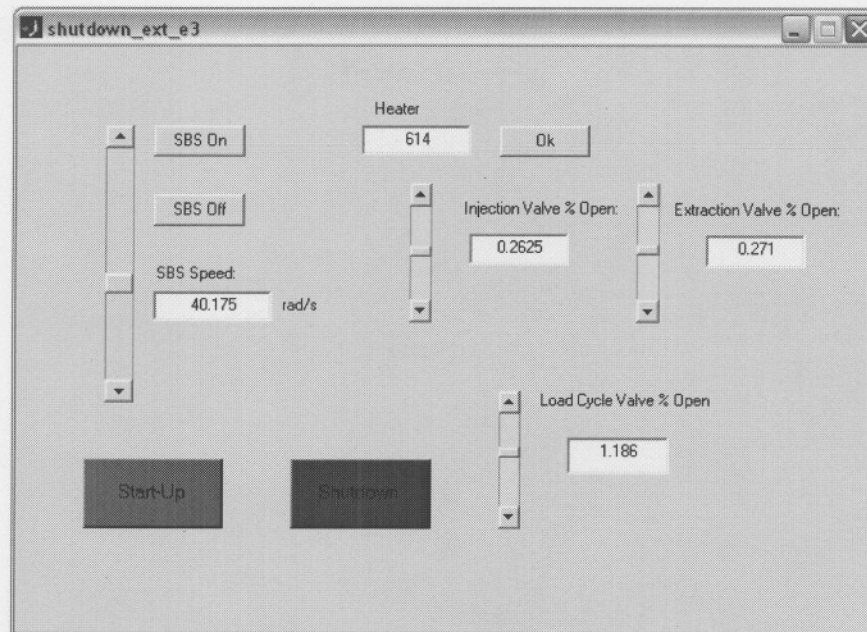


Figure 42: GUI for user control of system parameters

The GUI of figure 42 directly links to SIMULINK[®] and not to Flownex. SIMULINK[®] in turn applies the changes made by a user in the GUI. Shown in figure 43 is a conceptual design representation of how the GUI, SIMULINK[®] and Flownex interface to control the PBMM simulation model.

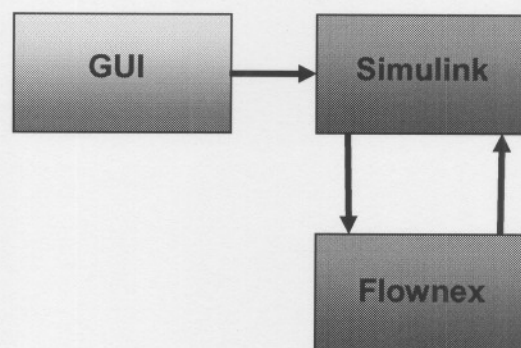


Figure 43: The conceptual design diagram of interface between Flownex, SIMULINK[®] and the GUI

Notice that the GUI only allows changes to system parameters through SIMULINK[®] and has no representation of the current values of system parameters.

5.3 Implementation of Control

5.3.1 Overview

Implementation of the external control strategy consisted of defining the necessary system parameters as inputs or outputs to be used in SIMULINK[®]. Flownex allows for easy definition of input and output system parameters through the use of an external control specification dialog. Once the necessary system parameters are defined as inputs or outputs, the interface with the GUI is established as well as a control strategy for automatic start-up and shutdown.

5.3.2 Automatic SBS Activation Control

Automatic SBS activation control is a control strategy implemented in SIMULINK[®] to prevent the Flownex simulation from obtaining simulation errors as a result of decelerating turbomachinery. The purpose of the control strategy is therefore to monitor the rotational speed of the turbomachinery and to react before errors occur. This is done by activating the SBS. The SBS then supplies the system with enough energy to keep the turbomachinery from decelerating any further. The control strategy is implemented by observing the value of the pressure ratio across the HPC, LPC and ELC and when this value reaches 1.05 across anyone of them, the SBS is automatically activated.

5.3.3 Automatic SBS Deactivation during Start-up

During start-up of the physical PBMM the energy supplied by the SBS to the system gradually decreases as the coolant gas slowly gains heat and momentum as a result of the heat added in the heaters. The SBS is then deactivated when no more addition of energy by the SBS is needed. This automatic deactivation control strategy was also implemented in the SIMULINK[®] control model. In SIMULINK[®] the pressure ratio across the SBS is observed during start-up and when the pressure ratio reaches a value of 1.00, the SBS is automatically deactivated.

5.3.4 Automatic Start-up and Shutdown Activation Control

The GUI of figure 42 is used to manually activate the start-up and shutdown procedures. When start-up is activated, the heaters are automatically started and the automatic SBS deactivation control strategy will deactivate the SBS at the correct instance. When the shutdown sequence is activated, the heaters are automatically deactivated and the automatic SBS activation control strategy will activate the SBS at the correct instance.

5.4 The Simulink External Control Interface Model

Shown in figure 44 is the SIMULINK[®] external control interface model. This model allows for changes in system parameters in the Flownex PBMM simulation model. It also observes changes in system parameters and reacts to these changes.

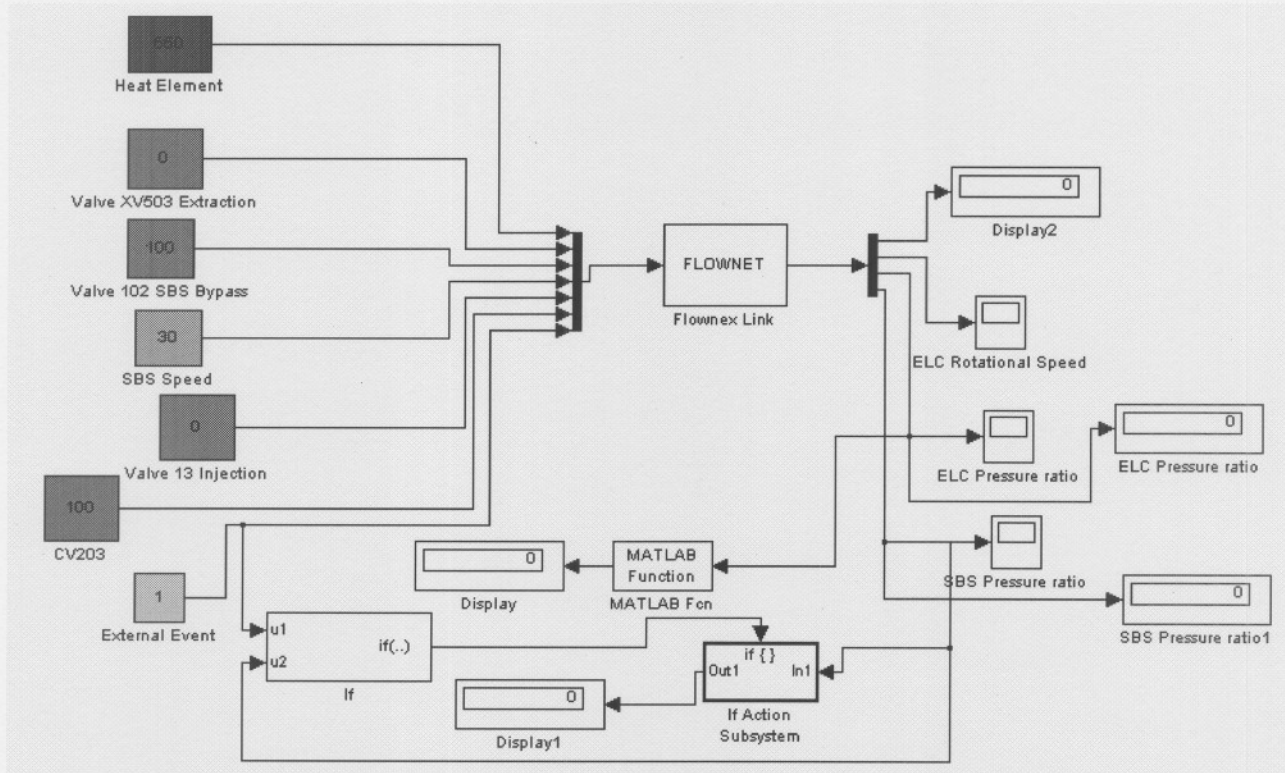


Figure 44: The SIMULINK[®] external control interface model

The most important block in figure 44 is the Flownex Link block. This block is responsible for the interface between SIMULINK[®] and Flownex. Shown in figure 45 is a simplified representation of the functioning of the control interface model of figure 44. Important system parameters are measured in SIMULINK[®] and are then passed to the control strategies. The control strategies respond by changing certain system parameters.

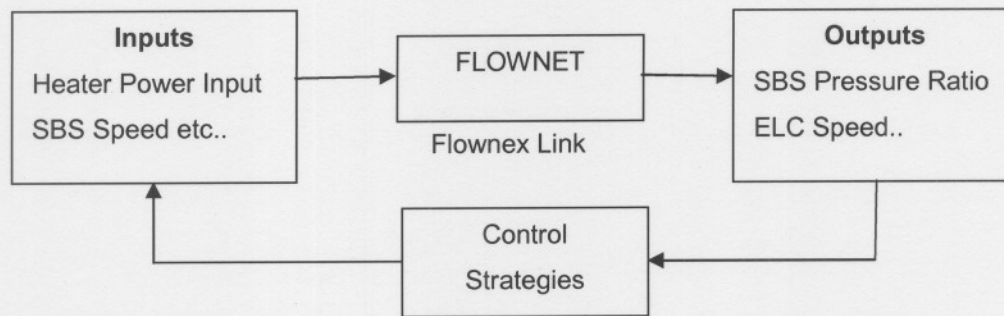


Figure 45: Simplified representation of SIMULINK[®] control interface

5.5 Conclusion

In this chapter an external control interface with Flownex was considered which allows the control of the PBMM simulation model in Flownex. A GUI allows a user to control various important system parameters like the heater power input and to activate automatic control of start-up and shutdown.

Chapter 5 gave a detailed design and implementation of the Flownex/SIMULINK[®] control interface as well as the interconnections with the GUI. Chapter 6 contains results generated by the Flownex/SIMULINK[®] model.

Chapter 6 – Results

6.1 Overview

This chapter is concerned with results generated by the Flownex PBMM simulation model as used with the SIMULINK[®] control interface. Various results of start-up and shutdown are generated and compared to actual start-up and shutdown data of the physical PBMM. The purpose of this chapter is to investigate and evaluate the start-up and shutdown procedures as performed by the simulation model against actual start-up and shutdown data. The effect of activation of the SBS on pressure variations during start-up and the variation of the rotational speed of the SBS will also be investigated.

6.2 Flownex Simulation Model – Shutdown

6.2.1 Heater Service Deactivation

As described in section 3.4 the procedure of shutdown is initiated by deactivation of the heaters. The implementation of the heaters in Flownex was considered in section 4.2.1 and will not be discussed here. In this section results of important heater characteristics as generated by the Flownex/SIMULINK[®] simulation model are shown. Figure 46 depicts the heater power and the corresponding heater inlet and outlet temperatures. Notice that the heaters were initially on. At about 45 seconds the heater service was deactivated until it was again activated at about 560 seconds.

6.2.2 Turbomachinery

During normal shutdown the turbomachinery will gradually lose rotational speed due to the deactivation of the heaters, until they eventually come to a halt. Flownex can however only simulate the operation of turbomachinery under working conditions while the turbos are running at a minimum speed. Therefore the control strategies as implemented in SIMULINK[®] will realise that deactivation of the heater service will cause the turbomachinery to decelerate beyond proper simulation conditions and will automatically activate the SBS service while the turbos are still running. The SBS then keeps the system and more specifically the turbomachinery running so that gas flow is accomplished until the system cools down.

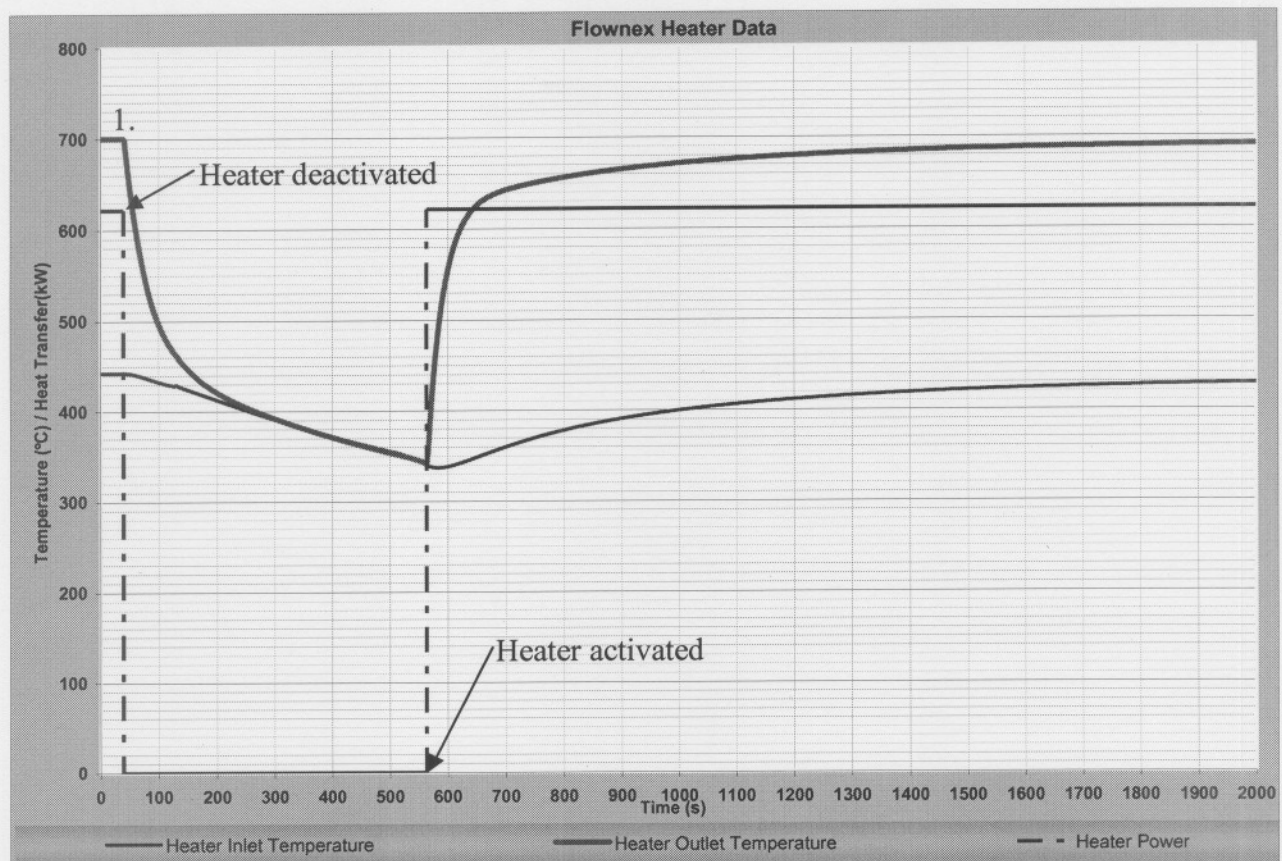


Figure 46: Important heater characteristics

Shown in figure 47 is the rotational speed of the three turbos; the HPT, the LPT and PT. They also describe the rotational speed of the HPC, the LPC and the ELC as the three turbos are respectively connected to the HPC, LPC and ELC and drive them by means of three separate shafts.

Notice the various stages of shutdown which can be clearly observed by investigating the rotational speed of the turbomachinery in figure 47. At 1. (refer to figure 47) the system is at normal operating conditions, hence the constant speed line for all three turbos. At 2. the heaters were deactivated resulting in the gradual loss in rotational speed. The deceleration continues up until a certain point is reached at 3. where control from SIMULINK[®] automatically activates the SBS. The SBS then ensures that gas is circulated through the system. At this point the rotational speed of the SBS is at the lowest speed necessary to sustain the system.

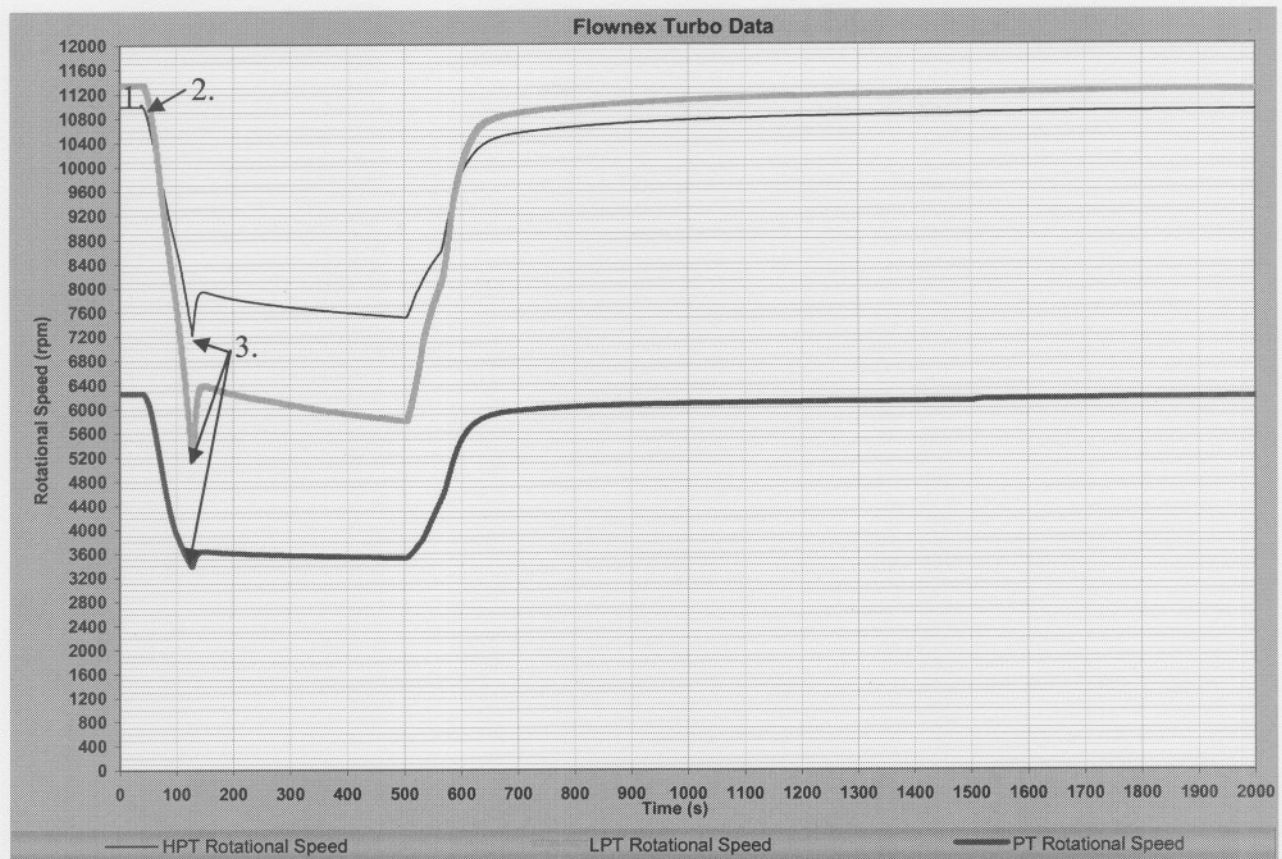


Figure 47: Rotational speed of the HPT, LPT and PT

Normally when the turbomachinery come to a complete halt, the cool down cycle commences with gas blown off to decrease system pressure. Then the SBS is activated for recirculation. In the simulation however, the SBS is activated prior to when the turbomachinery come to a standstill. No gas is blown off prior to this point as the system is still operational with different pressures at different points throughout the system, unlike normal shutdown where gas is blown off to protect the SBS casing from high pressure surges. The early activation of the SBS therefore suffices as the beginning of the cool down cycle. This concludes the shutdown procedure when investigating the simulation model. At this point the heaters are off, the SBS is activated and circulates gas through the system which drives the turbomachinery and removes excess heat from the heaters. The removal of excess heat can be clearly seen in figure 46. After the initial deactivation point at 1. the heater inlet and outlet temperature gradually decreases until room temperature is reached and will continue to decrease as long as the heaters are deactivated.

6.3 Flownex Simulation Model – Start-up

6.3.1 Injection of gas

The first step during normal start-up of the physical PBMM is to inject nitrogen gas into the system to attain a pressure of 130 kPa. This is done to ensure that the pressure is sufficient to prevent oil from the lubrication system of contaminating the coolant gas. The gas is supplied by a series of four containers containing the gas at a high pressure.

This procedure is not performed during start-up of the simulation model. The reason is that no gas was blown off during shutdown. It is therefore not necessary to inject gas as the amount of gas with which the simulation was initially started is still present.

6.3.2 SBS Activation

During normal start-up of the physical PBMM the SBS is activated after gas has been injected into the system. The SBS is activated by gradually accelerating it until it reaches its maximum allowable speed. The same is done with the simulation model. In the simulation, prior to the activation of the start-up procedure, the heaters are off and the SBS is the only component circulating the gas which drives the turbomachinery. At this point the SBS is running at the lowest possible speed necessary to sustain normal operating conditions in Flownex and therefore allows for acceleration during start-up. When the user activates the start-up procedure in the GUI, the command is passed to SIMULINK[®] which then passes it on to Flownex where the SBS is then accelerated to a maximum speed. This is shown in figure 48. Notice that the initial activation point of the SBS at 1. is the activation during shutdown. It can be seen that start-up was activated at 500 seconds with the resulting acceleration of the SBS.

6.3.3 Activation of Heaters

During normal start-up the heaters are activated directly after the SBS has reached its maximum speed. This procedure is automatically performed by the SIMULINK[®] control interface. The heaters are automatically activated when the SBS reaches its maximum speed. This procedure is apparent when comparing the point where the SBS reaches its maximum speed in figure 48 to the

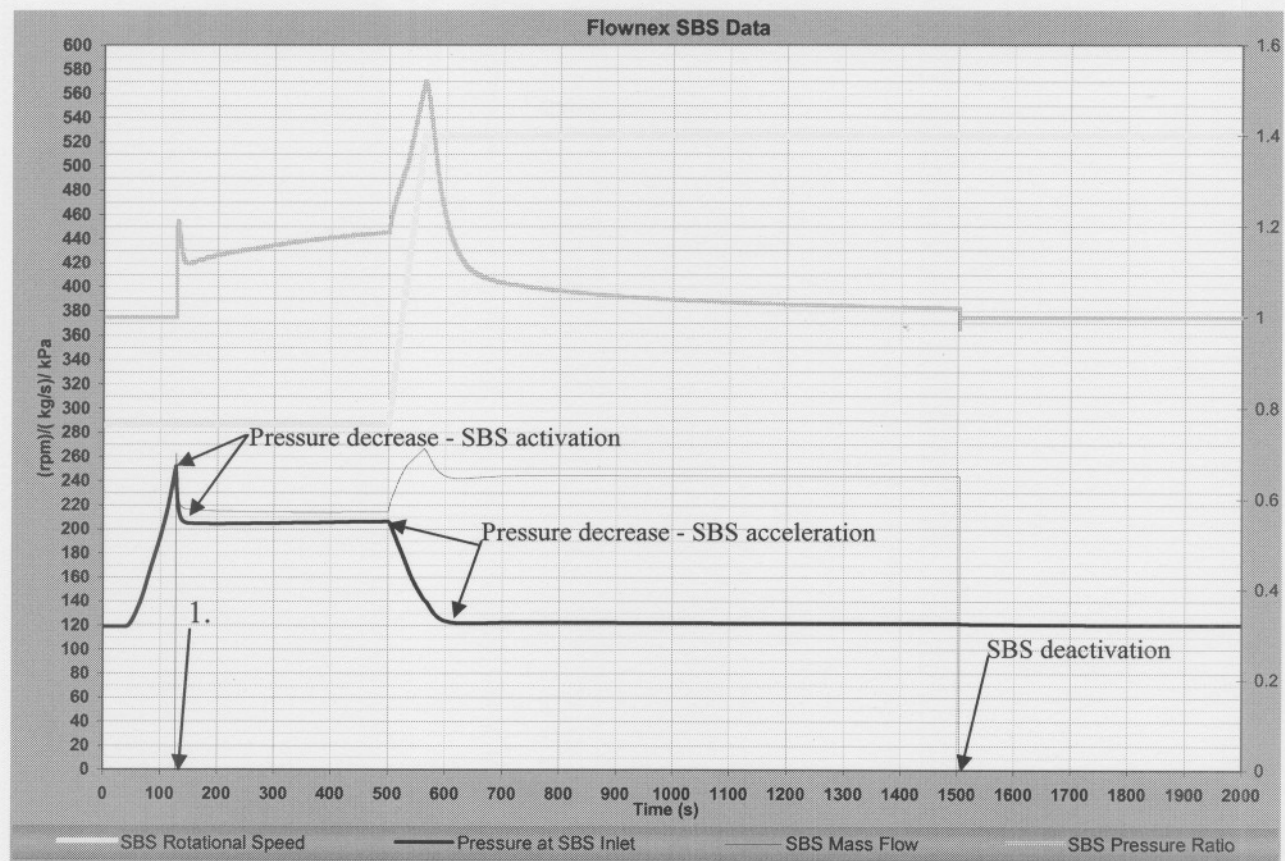


Figure 48: Flownex SBS characteristics

point of heater reactivation in figure 46. When the heaters are activated the pressure ratio across the SBS gradually decreases as more and more energy is added by the heaters and less energy is required by the SBS. Eventually no additional energy is required and the SBS is automatically deactivated. At this point the simulation model has bootstrapped and has regained a Brayton cycle state. This occurs at about 1500 seconds

6.4 Flownex Simulation Model Comparison

6.4.1 Actual PBMM Data

In this section the data generated by the simulation model will be compared to data captured from the actual system. More specifically the SBS data will be considered to illustrate the effect of the SBS rotational speed on the pressure at the inlet of the SBS. The effect of SBS activation on the SBS inlet was described in chapter 4. Originally the SBS was installed to immediately run at maximum speed when activated during start-up and shutdown. This posed pressure variation problems at the inlet of the SBS. To resolve this problem gas was injected at the SBS inlet side to compensate for this loss in pressure. Refer to figure 49 to observe the injection of gas at the SBS

inlet side when the SBS is activated. Notice the SBS power. The power during start-up is initially high and then gradually decreases as more energy is added by the heaters. This also illustrates that the SBS is at maximum power when activated and therefore at maximum speed. During shutdown the SBS is again activated at maximum power and speed. Notice the corresponding injection of gas to compensate for the inlet pressure loss. There is a small increase in power drawn by the SBS during shutdown as seen in figure 49. When the SBS is initially activated during the cool down cycle, the gas still has a significant amount of energy. The SBS, running at maximum speed, draws enough power to support this speed. The gas is still hot and the SBS easily supports the cycle. As the gas slowly loses temperature the SBS maintains a maximum speed. With the gradual decrease in gas temperature, the SBS requires increasingly more power to support the cycle in maintaining speed and therefore the resulting gradual increase in power during shutdown.

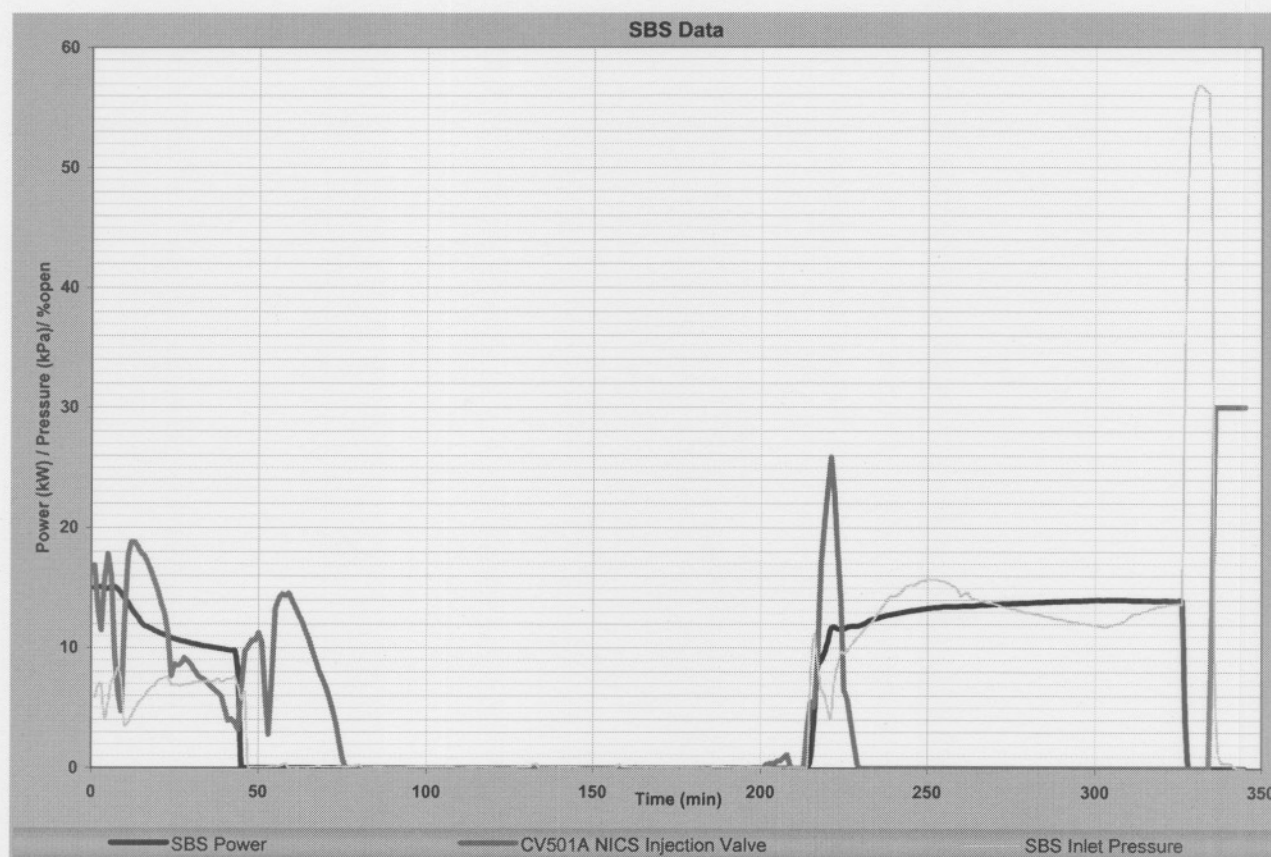


Figure 49: SBS data with no acceleration

To reduce the inlet pressure effect during SBS activation, a system was installed in the physical PBMM which allowed for gradual acceleration of the SBS. This reduced the effect of the pressure drop at the inlet of the SBS when activating the SBS. The reason is that when gradually accelerated,

the pressure drop is gradual allowing for effective injection which could not be performed without gradual SBS acceleration.

Shown in figure 50 is SBS data generated by the physical PBMM illustrating the effect of accelerating the SBS during start-up and shutdown. Notice that during start-up the heaters are activated only after the SBS has reached its maximum speed. This is done to ensure that gas is already passing through the heaters when activated.

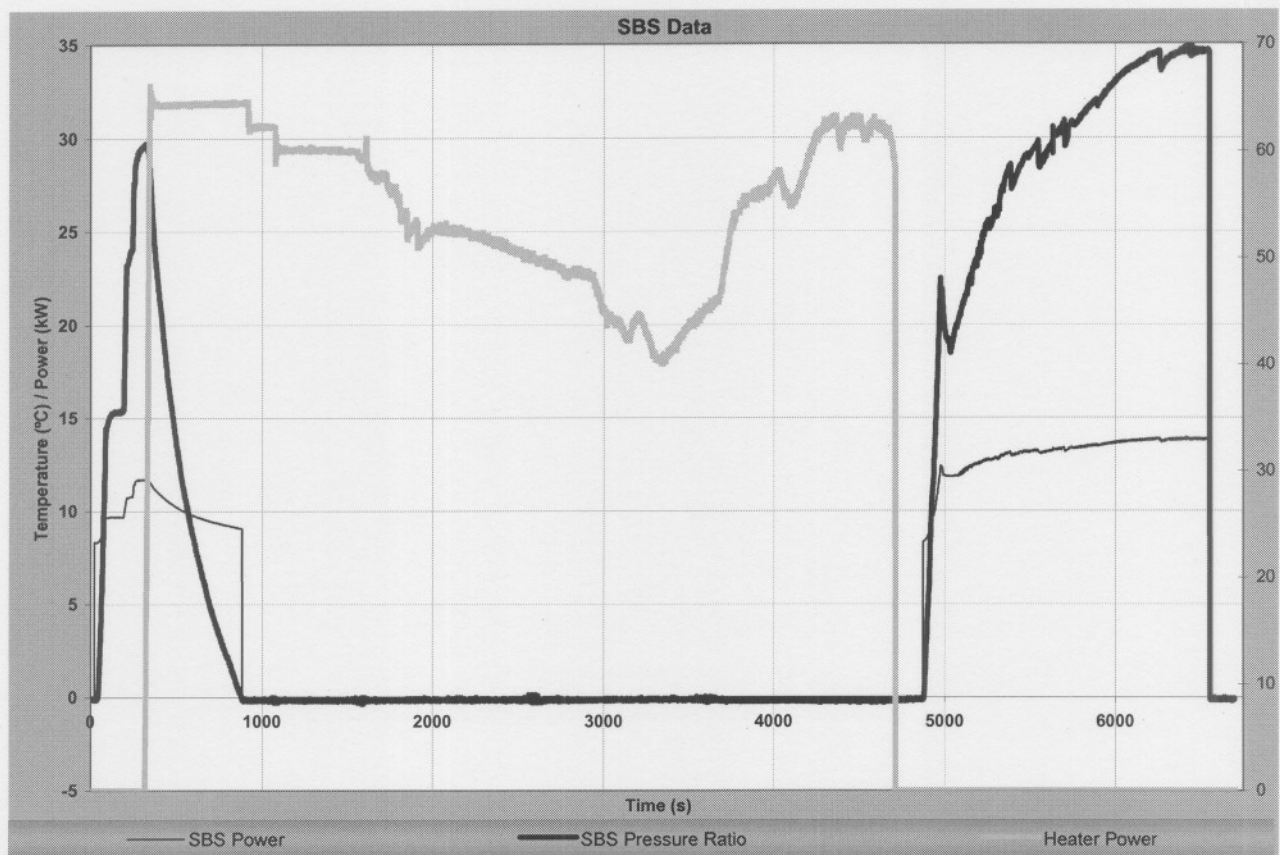


Figure 50: Actual PBMM data with acceleration of SBS

6.4.2 Flownex Simulation Model Data

Shown in figure 51 is the most important SBS characteristics as generated by the Flownex/Simulink simulation model. When the heaters are initially deactivated at around 45 seconds the pressure at the SBS inlet gradually increases as the turbomachinery gradually loses rotational speed. Notice the pressure drop when the SBS is activated at about 105 seconds. The pressure drop effect can clearly be seen from the time the SBS is initially accelerated at about 500 seconds until it reaches a

maximum speed at 570 seconds. There was deliberately no gas injected to observe the effect acceleration will have on the SBS inlet pressure.

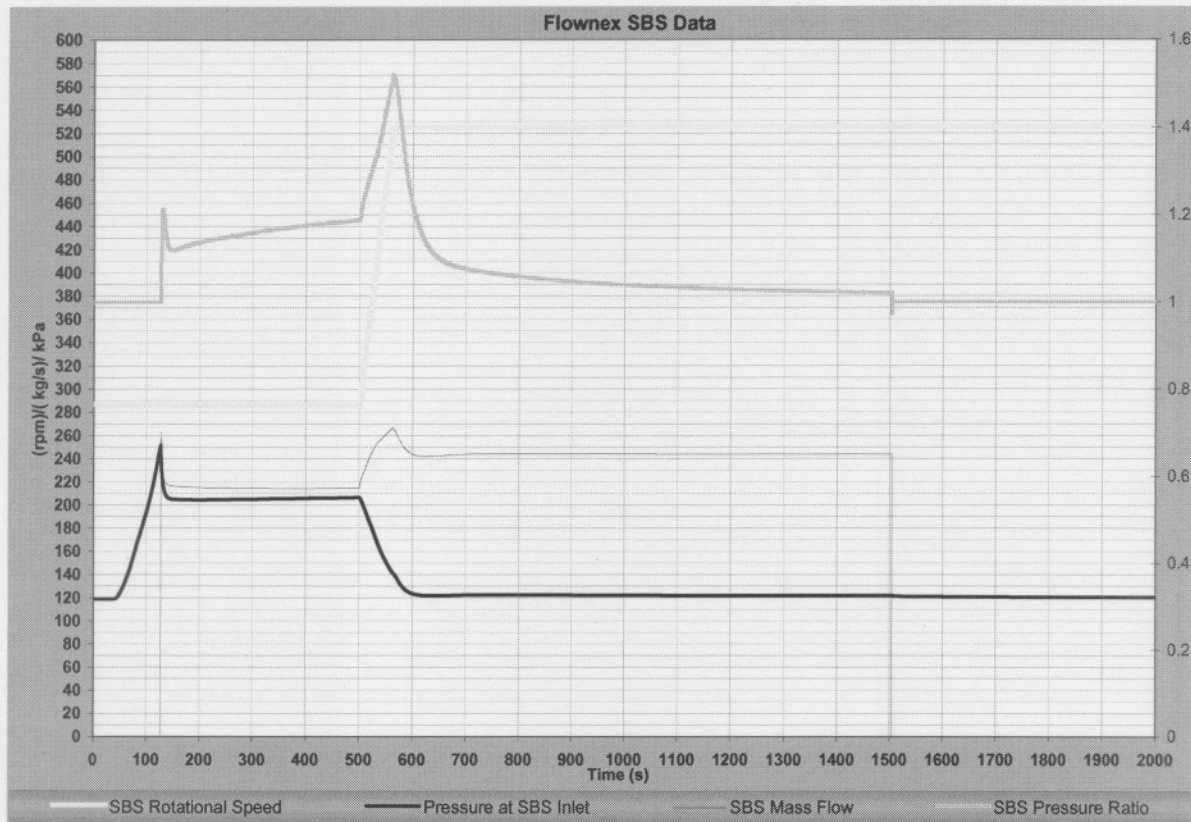


Figure 51: Flownex simulation model SBS data

6.5 Conclusion

Various sets of data of both the actual PBMM and the Flownex/SIMULINK[®] PBMM simulation model were considered in this chapter with special emphasis on acceleration of the SBS. Previously when the SBS was activated, it immediately ran at maximum speed. This produced an unwanted decrease in SBS inlet pressure. Coolant gas then needed to be injected at the inlet side to compensate for this pressure decrease. To relieve this problem, a system which allows for gradual acceleration of the SBS, was installed in the physical PBMM. This caused gradual decrease in inlet pressure when the SBS is gradually accelerated to maximum speed. This in turn meant that gas can be slowly introduced to compensate for pressure loss.

During shutdown the SBS was deliberately not accelerated to maximum speed. SBS deactivation during shutdown has only one purpose and that is to sustain the system so that Flownex would not

experience errors. The SBS is only accelerated during start-up where the pressure variation at the inlet side is observed. As a direct consequence of this means of operation of the SBS an idea arose to start the SBS before the turbo machinery come to a standstill. This will eliminate the need to blow off gas which is the case when the turbo machinery are at a standstill.

This idea might form the basis of a future study to prove the validity behind the reasoning, consider the following data captured by the Flownex simulation model. The idea is to monitor the mass flow through the inline SBS valve during deceleration of the turbo machinery, then to activate the SBS at the moment the valve closes. The rotational speed of the SBS must then be controlled to establish the same mass flow that was flowing through the inline valve prior to when it was closed. This will then, in theory, substitute as the cooling cycle eliminating gas being blown off during shutdown and decreasing the need to inject gas during start-up as all the gas is still trapped in the system. Gas blown off during shutdown is lost in the atmosphere. Consider the situation in figure 52. Here the mass flow through the SBS is exactly the same as before the valve was closed. In figure 53 it can be seen that the heater was deactivated at 20 seconds.

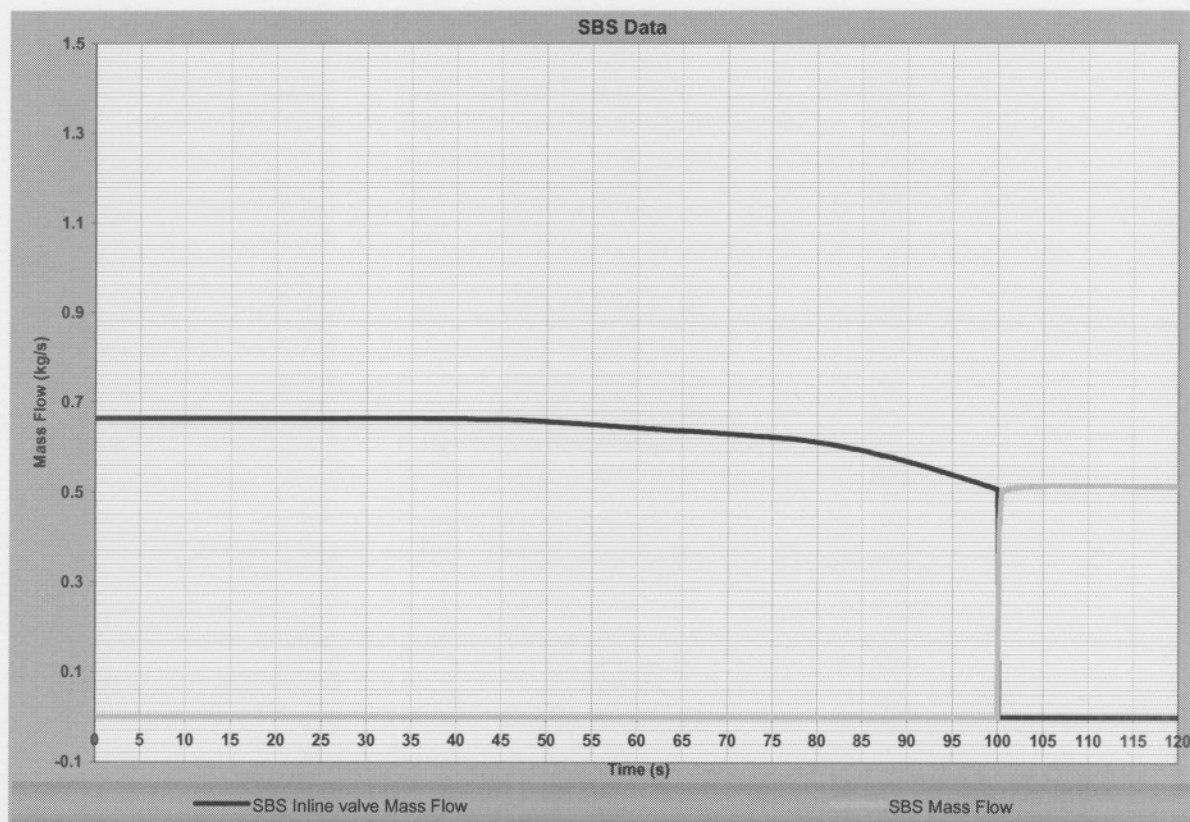


Figure 52: SBS and inline valve mass flow

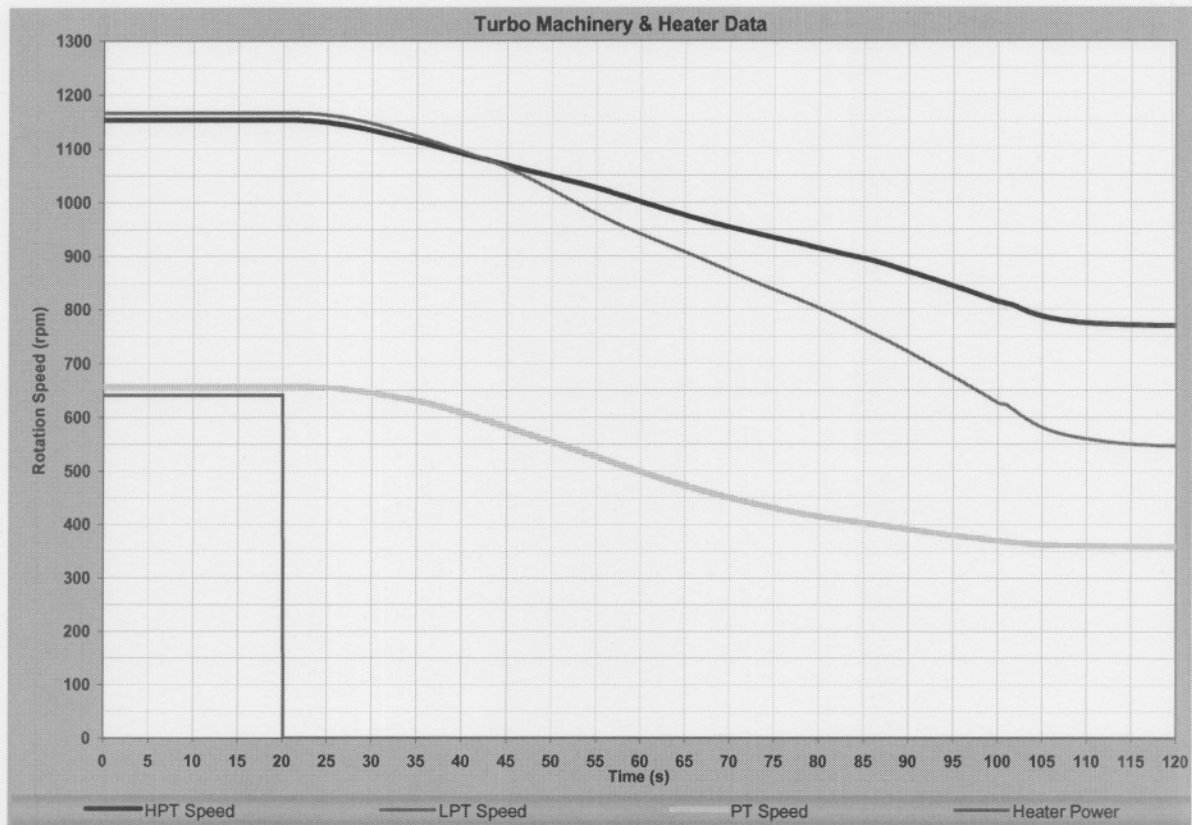


Figure 53: Turbomachinery and heater characteristics

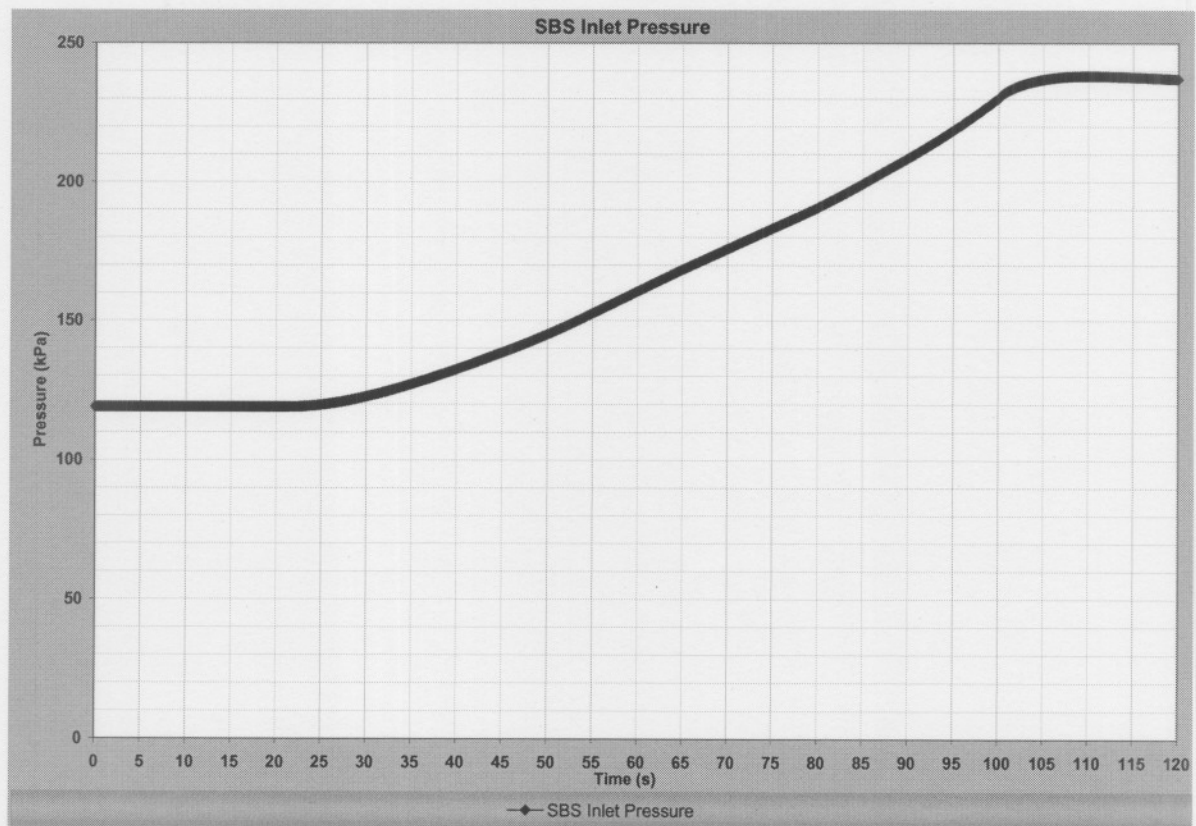


Figure 54: SBS inlet pressure

Shown in figure 54 is the SBS inlet pressure. Notice the small pressure variation when the SBS is activated at 100 seconds. This can be compared to the pressure decrease due to SBS activation of figure 48. There is no pressure decrease when the SBS rotational speed is controlled to establish the same mass flow as in the inline valve prior to when it is closed. Also no gas will be lost because no gas is now needed to be blown off to atmosphere. Future study may evaluate this type of activation which might eventually be implemented in the actual PBMM system.

Chapter 6 gave a detailed consideration of data captured by the Flownex/Simulink control interface. This data was then compared to data captured during actual start-up and shutdown. The chapter was concluded by an idea of future simulation that might benefit the operation of the actual system.

Chapter 7 – Conclusion & Recommendations

This chapter concludes the dissertation and recommends improvements which may be applied to the designed system in order to improve overall system accuracy in comparison to data generated by the physical PBMM. Recommendations concerning the simulation capabilities of Flownex are also made in this chapter. Flownex is in a continual process of development and improvement. User input concerning improvement is considered in development of a newer version. Therefore recommendations are made here which might be incorporated in future developments of Flownex which will improve simulation results in comparison to the physical PBMM.

7.1 Conclusions

Actual data generated by the physical system was described in *Chapter 3*. This data proved immensely important and ultimately the only means of completely identifying and understanding the start-up, shutdown and basic operation of the physical PBMM. Knowledge of start-up and shutdown obtained by investigation of this data formed the basis on which the entire dissertation was completed.

The heater element was considered in section 4.2.1. The implementation was done to ensure heater response similar to the electrical heaters of the physical PBMM. This implementation of the heater was successfully used to simulate the basic operation of the physical electrical heater counterparts.

The start-up blower system SBS was considered in section 4.2.2. Activation and deactivation is fully described by the mass flow through the SBS. If the mass flow is zero the SBS is in a deactivated state. If the mass flow is a value higher than zero the SBS is said to be in an activated state. Despite this alternate means of operation which is different than the physical system, the SBS was still effectively used during start-up and shutdown as would have been the case in the real system.

Inlet pressure variations concerning the SBS activation was introduced in section 3.5.2. In this section the SBS was still operated by activating it at full speed. Gradual acceleration to maximum speed of the SBS when activated was introduced in chapter 4. Pressure variations as a result of

acceleration of the SBS were described in section 6.4.2. The developed system proved accurate in simulating these pressure variations and can be used in future to predict these pressure variations.

Injection of gas as part of the start-up procedure of the physical system was introduced in section 3.5.2. However no gas was ever injected during start-up of the Flownex/Simulink PBMM simulation model. The reason is that the turbomachinery is always running during the simulation. Therefore when the SBS is activated the gas is already passing through the system at a certain speed resulting in less but noticeable pressure variations at the SBS inlet side. No gas injection at the inlet to compensate was therefore necessary compared to actual start-up when the SBS is activated with the coolant gas at complete standstill.

The same applies to the extraction of gas during shutdown which was introduced in section 3.5.3. During normal shutdown after the turbomachinery has come to a standstill, gas is blown off to ensure that system pressure is less than what the SBS casing can handle. The reason is that during normal operation gas might have been injected to increase the power delivered by the power turbine. More gas in the system directly relates to a higher system pressure. In the simulation, with turbomachinery always running, the system pressure does not equalise as is the case in the physical system when the turbomachinery come to a standstill. The system therefore has different pressures at different points throughout the system avoiding the need for extraction of gas.

7.2 Recommendations

The procedures of start-up and shutdown ultimately help to obtain a certain operational state of the system. The start-up procedure is a procedure followed to get the system into a self-sustaining Brayton cycle state, whereas the shutdown procedure removes the system from that state and puts it into a state where the system can be completely deactivated and left alone. Although these two procedures were successfully applied to the Flownex PBMM simulation model, a number of recommendations is made that in future will improve the simulation capabilities.

The heater element was implemented using a conductive heat transfer element. Although it was used successfully as the primary heat source in the simulation, it might be investigated and improved to act more closely like its electrical counterparts.

The SBS casing of the real system can handle only lower pressures in comparison to the rest of the system. The pressure variations at the SBS inlet side as considered in chapter 6 was relatively high ranging from 100 to 200 kPa. The SBS casing of the real system can therefore be replaced by a casing which can handle higher pressures. This will allow more flexibility in the operation of the SBS and will also allow the activation of the SBS which establishes the same mass flow as the inline valve prior to when it was closed.

The PBMM Flownex model has the same layout as the real system. All the pipes of the simulation model have the same geometry as the real system. The simulation model also compensates for mass flow and pressure losses of the coolant gas flowing through the pipes. However, no heat loss through pipes to the surroundings was considered. Determining where most of the heat is lost in the real system and incorporating this loss of heat in the simulation model might form a part of a future study.

The flexibility of the simulation model was greatly impaired by the disability of Flownex to simulate a turbine and compressor at standstill. Future improvements of Flownex might include the simulation of compressors and turbines at standstill.

7.3 Closure

Flownex was successfully used as a modelling platform to simulate the normal and dynamic operation of the PBMM. Identification of start-up and shutdown was a direct result of investigation of the start-up and shutdown checklist documents as well as a detailed consideration of data captured by the PBMM. A control method was then implemented in Simulink and controls start-up and shutdown through the Flownex/ SIMULINK[®] interface. A graphical user interface allows in time system changes by a user. Data captured by the simulation model was evaluated against data captured from the real system. As a result, conclusions were drawn and recommendations concerning future improvements were made.

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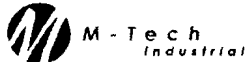
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APPENDIX A

Start-up and Shutdown Procedures and Checklists

This appendix is dedicated to the documents which describe the start-up and shutdown procedures of the physical PBMM is. Both of these documents are in the form of a checklist which has to be completed by an operator when start-up and shutdown is performed. The steps followed by the documents describe the safe and preferred operation of the PBMM.

A.1 Start-up Procedure and Checklist

		<u>START-UP PROCEDURE & CHECKLIST</u>			
PROJECT:		PBMR Micro Model			
SYSTEM / SUBSYSTEM / COMPONENT:		Starting up of the PBMM		Start-up Nr.	37
No	Component	Condition / Setting Required			Check
1.	LUB heater	Start LUB circulation pump & heater 4 hours before startup			
2.	IO Server	Start up PC and run Sixnet IO Toolkit, then Operations menu -> IO map -> Run selected IO map -> PBMM.			
3.	IO Server	Run the PBMM Tags v5 Spreadsheet and Start OPC.			
4.	UNAC PC	Run the Unac engine, and Unac Design in Unac design -> Unac engine -> Upload configuration -> Set no2.			
5.	Citect A PC	Run Citect Explorer and right click on PBMM -> run.			
6.	Citect B PC	Run Citect Runtime. (Password -> password)			
7.	HV305	Close (SBS air inlet valve)			
8.	SBS	Check SBS oil level.			

9.	Air dryer	Instrument air dryer switched on.	
10.	NSS Cylinders	All cylinder valves on both NSS banks must be open.	
11.	HV703, HV704	Both valves open (HV703-west bank & HV704-east bank isolation).	
12.	HV705	Close (Nitrogen vent to atmosphere)	
13.	HV844	Locked close (CW drain valve)	
14.	HV506	Close (Vacuum supply isolation)	
15.	HV700	Open (Nitrogen supply isolation)	
16.	HV550	Close (Instrument air supply to NICS)	
17.	HV780	Open after air dryer had a few minutes to come online (Instrument air isolation valve)	
18.	HV820 up to HV824	Open (CW supply lines)	
19.	HV830 up to HV834	Set to predetermined positions (CW return lines)	
20.	Air supply to valves	All XV's and CV's air supply open (HV781, HV782, HV783)	
21.	HV850	Open 3 full turns (HPTCU CW bypass)	
22.	HV31 & 32	HV31 locked open and HV32 locked close (Turbo machinery section oil drain)	
23.	6 of drain valves on NICS system	Locked close (HV510, HV520, HV530, HV540, HV501, HV505)	
24.	HV503 & 507	Locked close (Precom test line)	
25.	HV504	Locked open (NICS injection & extraction isolation)	
26.	PT740	Ensure instrument air supply pressure is 6 barg in Citect	
27.	Ventilation fans	Start ventilation fan service.	
28.	XV710 XV720	Open NSS valves in Citect (East and West bank)	
29.	NICS	Pressurise NICS TANKS if required	Time:
30.	CW system	Start Cooling Water service. If CW system is empty, wait for sump to fill after pump is started, then reset CW service.	
31.	Pressure vessel	Pressure vessel pressure to be at 130kPa. Activate automatic pressure control set to 130kPa.	
32.	UPS	Lub. System UPS switched on but on bypass.	
33.	Lub System	Open the lubrication system return and delivery valves.	
34.	HV760	Open (LUB isolation valve for air supply)	
35.	Lub System	Start-up lubrication service in Citect.	

36.	UPS	Switch UPS inverter on.	
37.	Lub System	Make sure accumulators are full.	
38.	Lub System	Check lub flow 5 l/min for HPC, 5 l/min for LPC & 5 l/min for ELC and pressure about 4 barg for all the turbos.	
39.	Telephone	Call University power control at ext. 2823 (Chris Jonker) and get current KVA and max KVA, if required delay heater service start until KVA is down.	
40.	SBS	Start SBS service. Pressure control on manual. Inject nitrogen to recover SBS.	Time:
41.	Heater elect.	Switch all 3 heater electrical supplies and fans on.	
42.	Heater	Start heater service, first set power to 50% power then activate temp control at	Time:
43.	Press control	Activate pressure control to maintain 95kPa.	
44.	SBS	At bootstrap, make sure SBS disengages.	Time:
45.	HV305	Open to prevent SBS casing over pressure	
46.	Lub Heater	Switch off lubrication system heater	

Sign off:

Name	Position	Signature	Date
	Inside Operator		
	Outside Operator		

A.2 Shutdown Procedure and Checklist

		<u>SHUTDOWN PROCEDURE</u> <u>& CHECKLIST</u>		 M - T e c h I n d u s t r i a l
PROJECT:		PBMR Micro Model		
SYSTEM / SUBSYSTEM / COMPONENT:		Shutting down the PBMM	Shutdown Nr.	37
No	Component	Condition / Setting Required		Check
1.	Heater	Switch off heater service.	Time:	
2.	ESS	Shut off the electrical supply to the heater controllers and their cooling fans and lock.		
3.	Turbos	Wait until the turbos come to a halt.		
4.	CV31	Bleed off gas until PV pressure is at 130kPa.		
5.	HV305	Close before cool down cycle can commence.		
6.	SBS	Start SBS for cool down cycle.	Time:	
7.	Pressure control	Pressure control on manual - inject nitrogen to recover SBS-in pressure to about 90kPa. Pressure control on auto – 95kPa.		
8.	6 of cooler gas drain valves	Open to drain accumulated oil and close again.		
9.	Recuperator	Drain oil at Recuperator dish end.		
10.	HV31 & 32	Open to drain accumulated oil and close again.		
11.	HPT casing TT50	Must be below 100°C.		
12.	Heater	Heater outlet temperature must be below 200°C.		
13.	SBS	Stop SBS service.	Time:	
14.	Lub System	Stop LUB service and close delivery valves.		
15.	HV760	Instrument air to the lubrication system closed.		

16.	CW System	Stop Cooling Water service.	Time:	
17.	HV703, HV704	Closed (west bank & east bank isolation)		
18.	HV700	Locked close (Nitrogen supply isolation)		
19.	HV705	Open (Nitrogen vent to atmosphere)		
20.	HV504	Close (NICS injection & extraction isolation valve)		
21.	HV780	Closed (Instrument air isolation valve)		
22.	Air dryer	Switch off air dryer.		
23.	Data Backup	On Citect PC go to Export trends. Enter sampling rate. Enter history time (Difference in time between Shutdown step No16 and Start-up step No 29). Enter hours backward (Difference between current time and Start-up step No 29. Click EXPORT.		
24.	Save trends	Go to c:>data on CITECTA run Export trend.xls. Click Refresh all. Copy and save file on CD and label CD accordingly.		
25.	PCs	Shut down PCs if required.		

Sign off:

Name	Position	Signature	Date
	Inside Operator		
	Outside Operator		

APPENDIX B

Data CD Content

This appendix is dedicated to the layout of the data CD. The data CD includes items such as data captured by the real system as well as data captured by the Flownex/Simulink model, Matlab and Simulink files. The layout of the data CD can be seen in figure B.1.

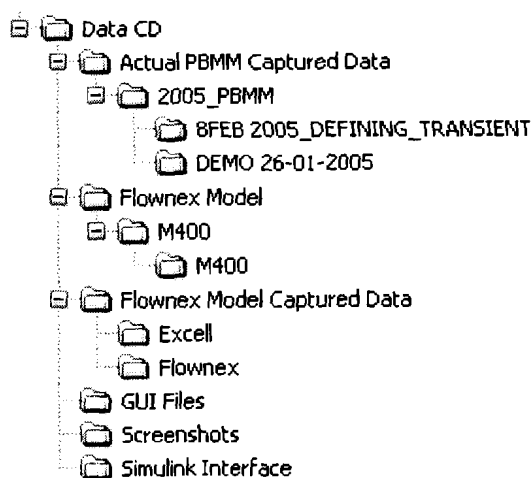


Figure B. 1: Data CD layout

APPENDIX C.1

This appendix is dedicated to describing data captured by the real PBMM system. This data can be used as a reference in conjunction with data in the text. It is given to provide a larger overview of basic operation of the PBMM. All the important components are considered, which is not the case in the text. In the text, only data applicable to the situation considered is given.

The following data was generated by the physical PBMM on 22 June 2004. At this time the SBS was operated without acceleration. When activated the SBS ran at maximum full speed. The following figures describe the data generated by the physical PBMM on the date it was operational.



Figure C. 1: Heater characteristics

Figure C.1 describes the major heater characteristics. Notice the heater inlet and outlet pressure follows each other exactly.

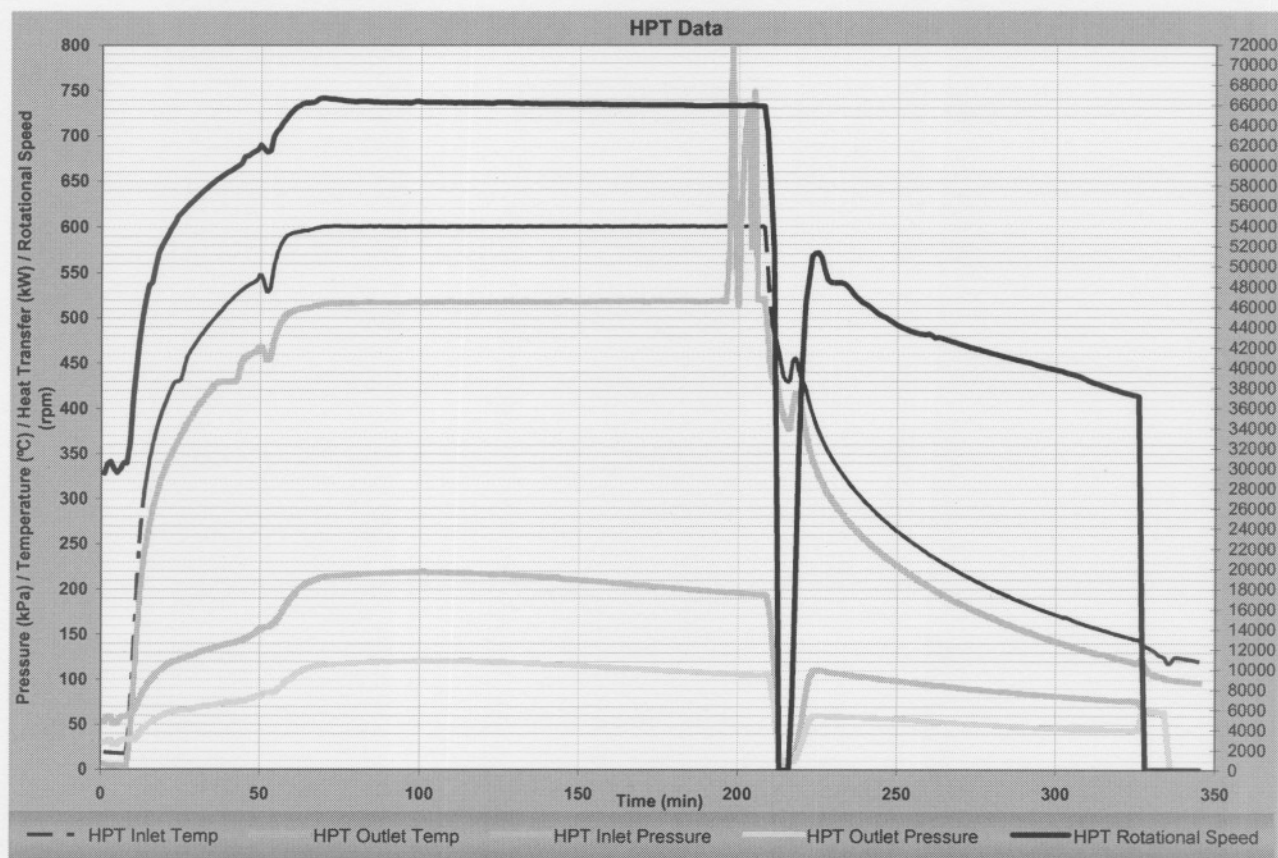


Figure C. 2: High pressure turbine characteristics

Figure C.2 illustrates the most important characteristics of the HPT. These include the inlet and outlet temperatures and pressures and the rotational speed. Notice the spikes in the outlet temperature at around 200 minutes. This occurrence is the result of operators who removed the temperature sensor at the HPT outlet, made changes and then reinserted it into the system while the system was operational.



Figure C. 3: Low pressure turbine characteristics

Figure C.3 illustrates the most important characteristics of the LPT. These include the inlet and outlet temperatures and pressures and the rotational speed. The spikes in the data are again the direct result of operators who investigated the various sensors while the system was operational.



Figure C. 4: Power turbine characteristics

Figure C.4 illustrates the most important characteristics of the PT. These include the inlet and outlet temperatures and pressures and the rotational speed. The spikes in the data are again the direct result of operators who investigated the various sensors while the system was operational.



Figure C. 5: Recuperator characteristics

Figure C.5 illustrates the most important characteristics of the recuperator. These include the inlet and outlet temperatures and pressures.

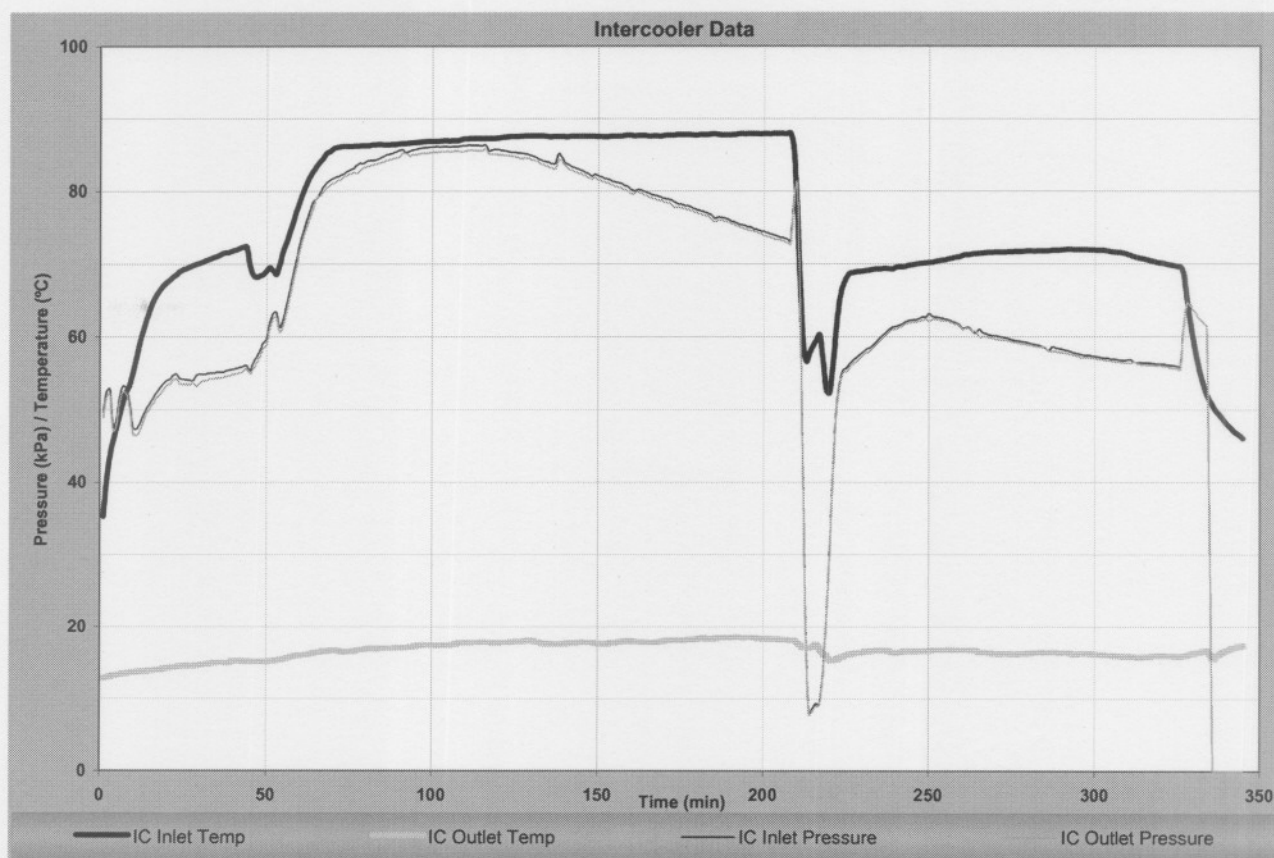


Figure C. 6: Intercooler characteristics

Figure C.6 illustrates the most important characteristics of the intercooler. These include the inlet and outlet temperatures and pressures.



Figure C. 7: Precooler characteristics

Figure C.7 illustrates the most important characteristics of the precooler. These include the inlet and outlet temperatures and pressures.

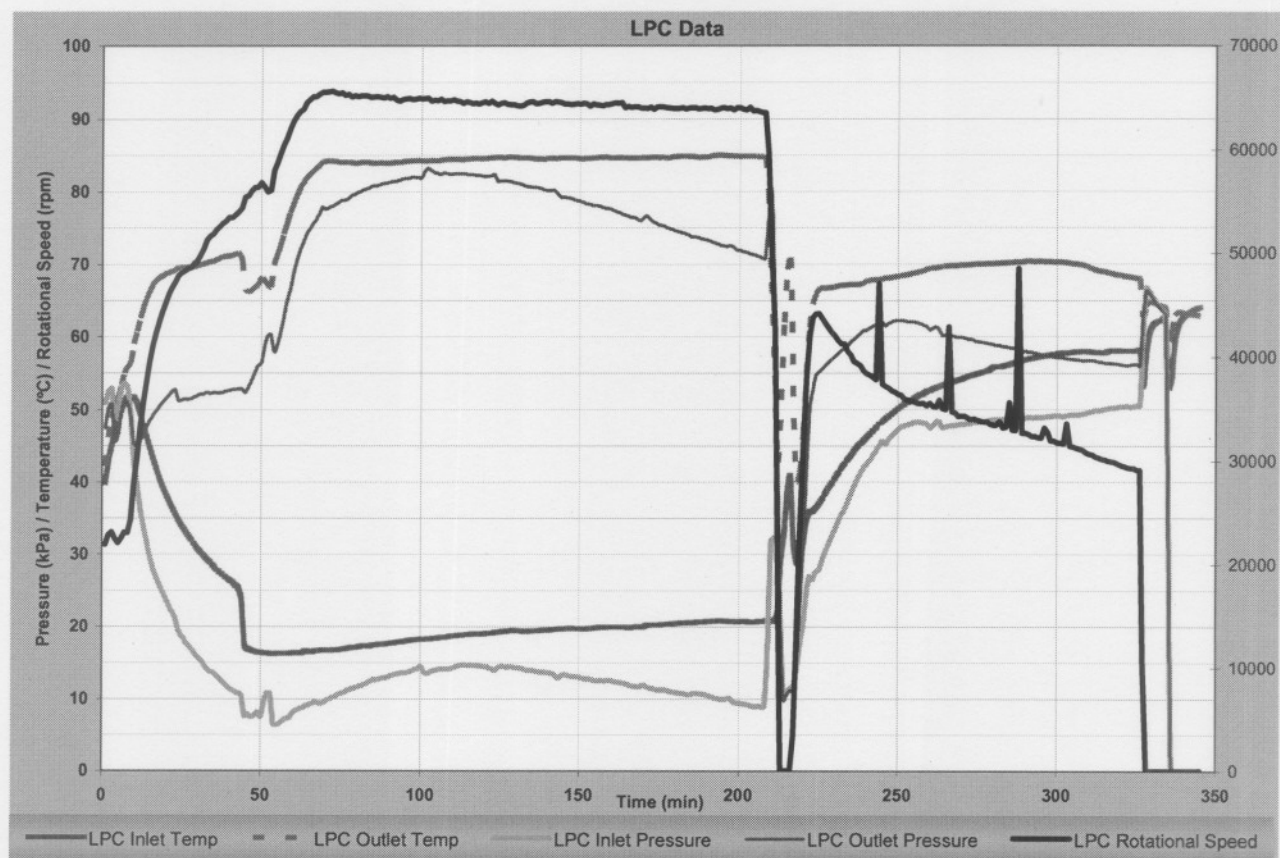


Figure C. 8: Low pressure compressor characteristics

Figure C.8 illustrates the most important characteristics of the low pressure compressor. These include the inlet and outlet temperatures and pressures and the rotational speed.



Figure C. 9: High pressure compressor characteristics

Figure C.9 illustrates the most important characteristics of the high pressure compressor. These include the inlet and outlet temperatures and pressures and the rotational speed.

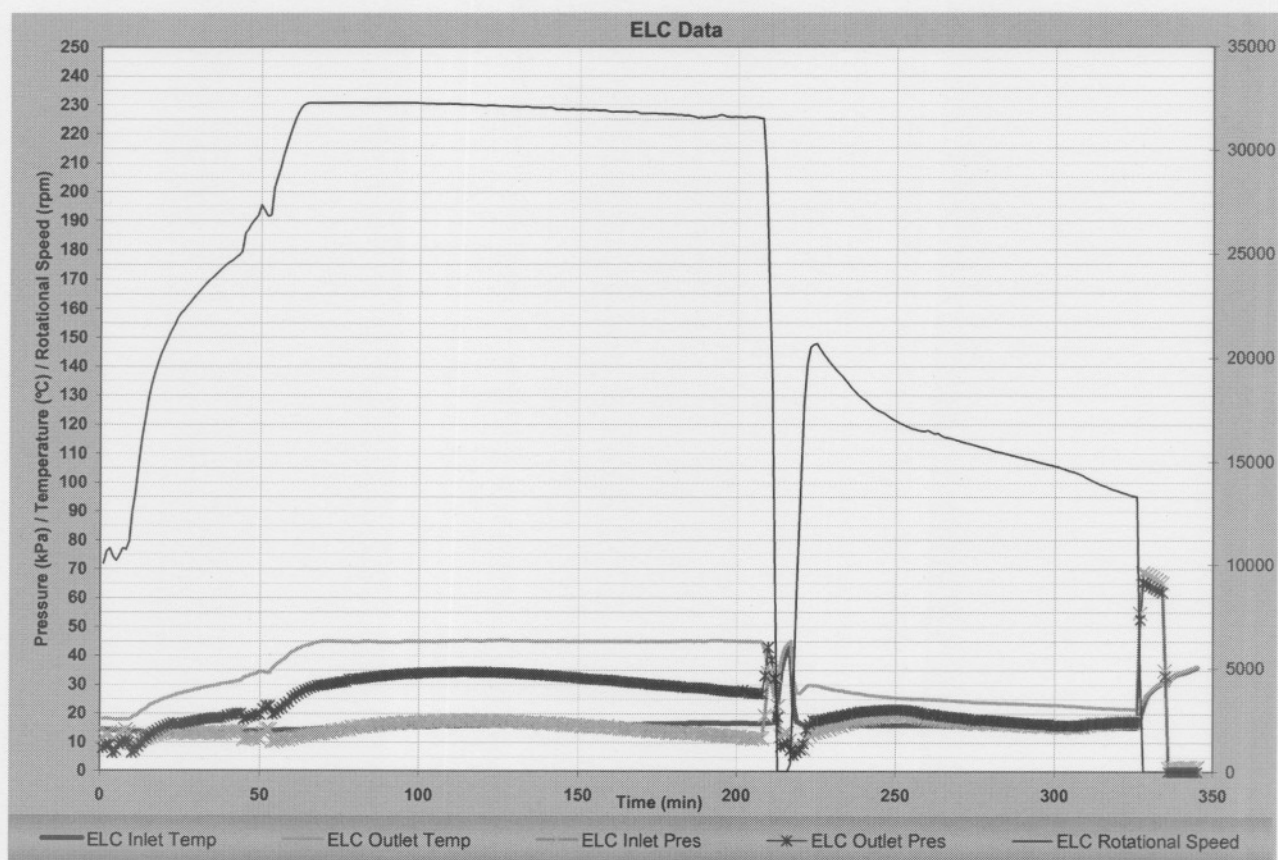


Figure C. 10: Electrical load compressor characteristics

Figure C.10 illustrates the most important characteristics of the electrical load compressor. These include the inlet and outlet temperatures and pressures and the rotational speed.

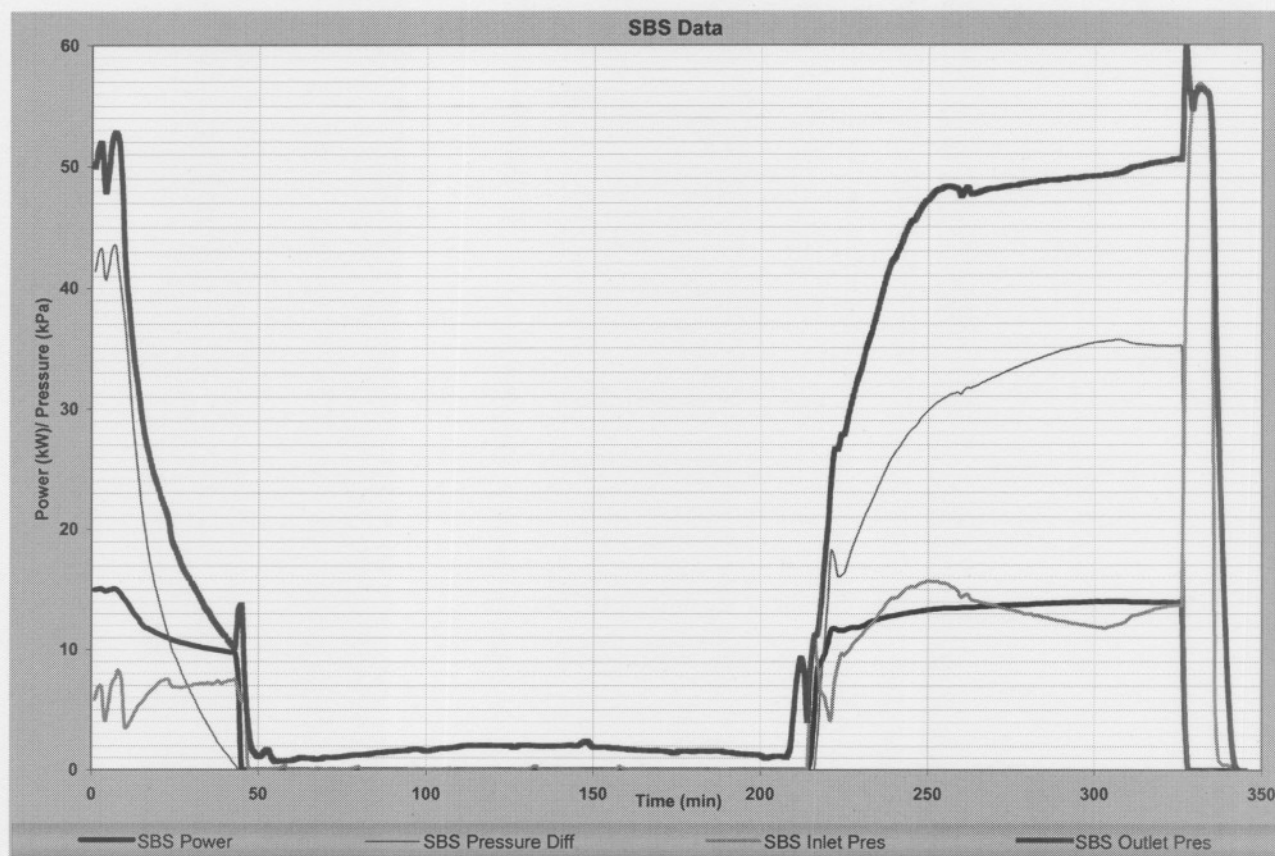


Figure C. 11: Start-up blower system characteristics

Figure C.10 illustrates the most important characteristics of the start-up blower system. These include the inlet and outlet pressures, the pressure difference and the power drawn by the SBS.

APPENDIX C.2

The following data was generated by the physical PBMM on 8 February 2005. At this time the SBS was operated with acceleration. This can be clearly seen when the SBS data is investigated. During start-up the SBS is activated and gradually accelerated to a maximum speed. When the SBS reaches its maximum speed the heaters are activated.



Figure C. 12: Heater characteristics

Figure C.12 describes the major heater element characteristics.

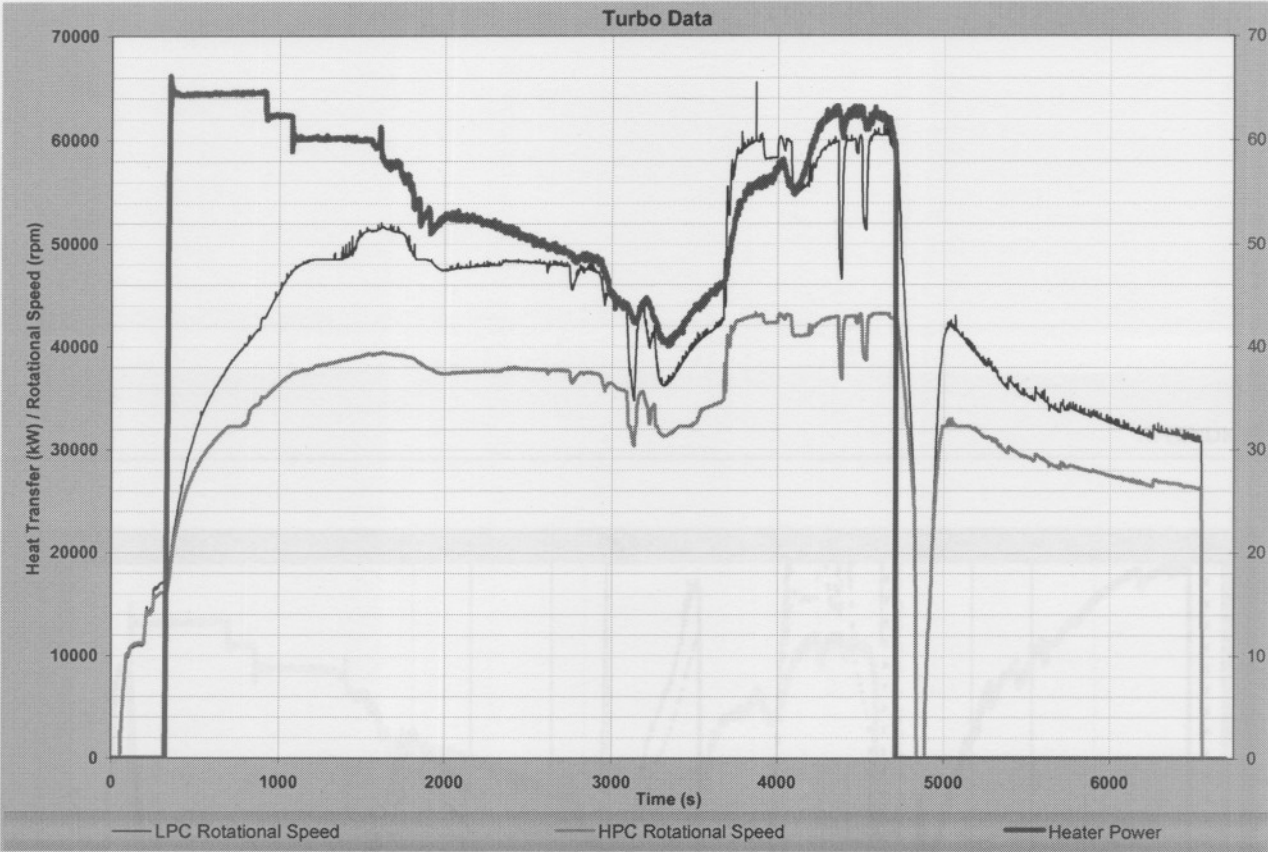


Figure C. 13: Turbomachinery characteristics

Figure C.13 illustrates the most important turbomachinery characteristics. These include the LPC and HPC rotational speed accompanied by the heater power.

Figure C. 14: SBS characteristics

Figure C.14 illustrates the important SBS characteristics. Notice that when the SBS reaches maximum power which corresponds to a maximum speed the heaters are activated.

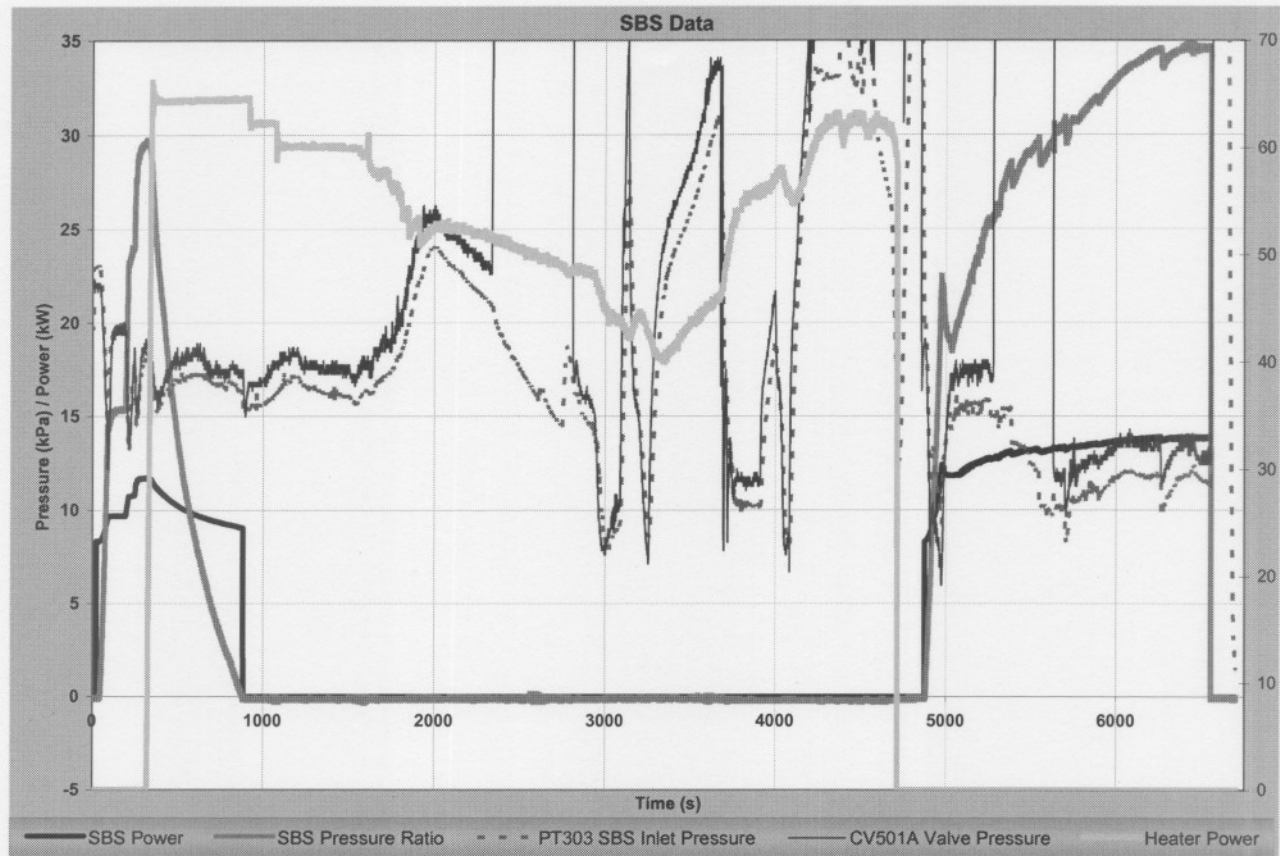


Figure C. 14: SBS characteristics

Figure C.14 illustrates the important SBS characteristics. Notice that when the SBS reaches maximum power which corresponds to a maximum speed the heaters are activated.