
THERMO-HYDRAULIC ANALYSIS OF THE PBMR FUEL HANDLING AND STORAGE SYSTEM

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ABSTRACT

The work done for this dissertation is based on actual thermo-hydraulic design work done during 2002 to 2006 on one of the subsystems of the Pebble Bed Modular Reactor (PBMR).

The Pebble Bed Modular Reactor is a proved revolutionary small, compact and safe nuclear power plant. It operates on a direct closed Brayton cycle. One of the unique features of this concept is its ability to easily regulate the power output depending on the electricity demand.

The PBMR fuel comprises particles of enriched uranium dioxide coated with silicon carbide and pyrolytic carbon. The particles are encased in graphite to form a fuel sphere or pebble about the size of a billiard ball. The core of the reactor contains approximately 360 000 of these fuel spheres for a 400 MW design reactor.

The fuel spheres are continuously circulated through the reactor core via a closed loop helium conveying system, referred to as the Fuel Handling and Storage System (FHSS). The system is also responsible for discharging spent-fuel spheres to the spent-fuel storage area and recharging the reactor with fresh fuel spheres.

The focus of this dissertation is the thermo-hydraulic design of the FHSS system, with specific focus on the FHSS helium circulator, referred to as the FHSS blower. The FHSS blower is a single-stage centrifugal machine, submerged in an enclosed pressure boundary, which forms part of the closed-loop helium pressure boundary. The aim of the dissertation is to simulate all the operating parameters of the system to determine the volumetric flow rate and pressure rise the impeller of the blower has to deliver.

Due to the complexity of the simulation model and lack of experimental data a Sensitivity and Monte Carlo study was also done.

The output of the study is sufficient thermo-hydraulic data to design all the major components of the FHSS system. For components such as the piping and pressure boundary this includes (i) temperature, (ii) pressure and (iii) heat transfer through the material at all the operating conditions. For the blower it includes; (i) blower mass flow rate, (ii) pressure ratio, (iii) inlet pressure and (iv) inlet temperature at all the operating conditions.

UITTREKSEL

Die basis vir hierdie verhandeling is die termo hidroliese ontwerp wat uitgevoer is gedurende die periode vanaf 2002 tot 2006 op een van die Kieselbed Kern Reaktor (KKR) se substelsels.

Die Kieselbed Kern Reaktor (KKR) is 'n revolusionêre klein, kompakte en veilige kernaanleg. Dit word deur middel van 'n direkte geslote Brayton siklus aangedryf. Een van die unieke kenmerke van hierdie konsep is die vermoë om kraglewering te reguleer soos wat die elektrisiteitsaanvraag varieer gedurende bedryfstoeestande.

Die KKR brandstof bestaan uit partikels verrykte uraandioksied met 'n silikon karnied en 'n pyrolitiese koolstoflaag rondom. Die partikels word bedek met grafiet en gevorm om 'n brandstofsfeer omtrent die grootte van 'n snoekbal aan te neem. Die kern van die reaktor bevat ongeveer 360 000 van hierdie brandstofsfeere.

Die brandstofsfeer word deurlopend deur die reaktorkern gesirkuleer via 'n geslote helium vervoerstelsel, bekend as die Brandstof Hantering en Bewaring Stelsel (BHBS). Die stelsel is ook verantwoordelik om volledige ontbrande sfere te vervang met vars brandstofsfeere.

Die fokus van hierdie skripsie is die termo hidrouliese ontwerp van die BHBS stelsel, met spesifieke fokus op die BHBS gas-sirkulerings komponente, ook bekend as die BHBS waaier. Die waaier is 'n enkelstadium sentrifugale masjien binne-in die drukgrens van die totale BHBS stelsel.

Weens die kompleksiteit van die simulasiemodel en tekort aan eksperimentele data is 'n Sensitiwiteits-, asook 'n Monte Carlo-studie uitgevoer.

Die resultate van die studie sluit voldoende inligting in om al die hoofkomponente van die BHBS te ontwerp. Vir komponente soos die pype en die drukgrens sluit dit in; (i) temperatuur, (ii) druk en (iii) die hitte-oordrag deur al die materiaalwande vir alle bedryfstoeestande. Vir die waaier sluit dit in; (i) waaiermassa-vloei benodig, (ii) drukverhouding, (iii) inlaatdruk en (iv) inlaatteratuur vir alle bedryfstoeestande.

Die waaier is die hoof-fokus van die verhandeling.

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LIST OF ABBREVIATIONS

AGS	Auxiliary Gas System
AMS	Activity Measurement Sensor
ASME	American Society of Mechanical Engineers
ATL	Air Test Loop
BUMS	Burn-up Measurement Sensor
CBA	Conveying Block Assembly
CCS	Core Conditioning System
CFD	Computational Fluid Dynamics
CUD	Core Unloading Device
DSI	Double Seat Isolation
FHSS	Fuel Handling and Storage System
FRI	Flow Restricting Indexer (Drucksperre)
GRBA	Gas Return Block Assembly
GSBA	Gas Supply Block Assembly
HICS	Helium Inventory Control System
HPC	High-pressure Compressor
HVAC	Heating, Ventilation and Air-conditioning System
IBA	Isolation Block Assembly
ICS	Inventory Control System
MCR	Maximum Continuous Rating
MCRI	Maximum Continuous Rating Inventory
MPS	Main Power System
NNR	National Nuclear Regulator
NQA	Nuclear Quality Assurance
PBMR	Pebble Bed Modular Reactor (The unit, The Project or The Company)
PCU	Power Conversion Unit
PPB	Primary Pressure Boundary
PU for CHE	Potchefstroom University for Christian Higher Education
QAP	Quality Assurance Procedure
ROT	Reactor Outlet Temperature
RSS	Reserve Shutdown System
RU	Reactor Unit
SAS	Small Absorber Spheres
SFSS	Spent-fuel Storage System
SLP	Sphere Loading Pipe (in SFSS)
SRP	Sphere Return Pipe (in SFSS)
SUP	Sphere Unloading Pipe (in SFSS)

TBC	To be Confirmed
TBD	To be Determined
TD	Transfer Device (in SFSS)
TUD	Tank Unloading Device
US	User Specified Element (Flownex)

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1. INTRODUCTION

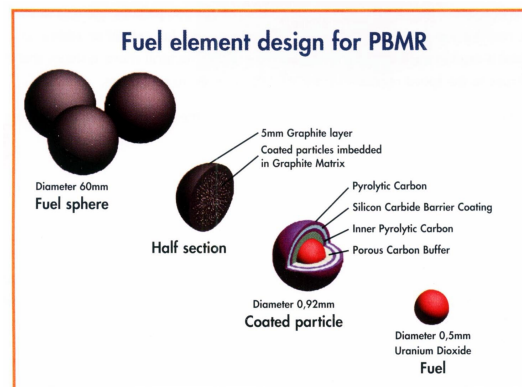
1.1 BACKGROUND

To better understand the operation of the Fuel Handling and Storage System (FHSS) it is necessary to give a brief background on the Pebble Bed Modular reactor (PBMR) project as a whole, including the operation of the entire plant.

The increasing demand for energy in the world created an extensive research field for finding alternative ways to convert energy into electricity. Nuclear power was always considered as a potential solution to the problem, although questions regarding its safety have always been raised.

The outstanding features of the PBMR concept are that it is a potentially small, safe, clean, cost-effective and robust nuclear reactor in its operation. During the initial phases of the project South Africa's power utility giant, Eskom, has committed itself to the development of the PBMR so that, in the future, it can play a leading role as a major energy provider.

The nuclear technology of the PBMR is based on a concept that was developed in Germany by Prof. Dr. Schulten. Silicon carbide-coated uranium granules are compacted into hard billiard ball sized spheres (Figure 1), to be used as fuel for a high-temperature, helium-cooled gas reactor [1].



The above picture was taken from the PBMR website, which explains in detail the physics associated with the fuel design. For more info visit <http://www.pbmr.com/index.asp?Content=224>

Figure 1: A presentation of the pebble fuel design.

This concept was transformed into a design that resulted in the AVR (“Arbeitsgemeinschaft Versuchsreaktor”), a 15 MW demonstration pebble bed reactor, built in Germany. It operated successfully for 21 years, but the intense wave of post-Chernobyl anti-nuclear sentiment that swept through Europe brought a premature end to this reactor [1].

In 1994, Eskom started with feasibility studies into the design and construction of PBMR’s in South Africa. The design and costing studies showed that the PBMR has a number of advantages over other potential power sources [2].

Most of South Africa’s coal-fired power stations are built close to the coal-producing areas. This requires long power lines from coal-rich areas to the end-user centres, which in turn, implies high capital costs and transmission losses. Due to poor support infrastructure in South Africa and the high costs involved, the option of transporting coal to distant power stations is not feasible. The opportunities in South Africa for producing hydroelectric power stations, or obtaining power from natural gas, are limited.

Eskom experiences short, sharp, demand peaks in winter that are difficult to accommodate with the slow ramping characteristics of the existing large power stations. Every modern utility will pay a premium for plants with load-following capability. Not only does it provide the utility with the ability to meet all power demands (base and peak load) with the same plant, but also there are hefty premiums attached to peak load supply [1].

These factors created the need for small electricity generation units situated near the points of large demand. The PBMR concept, which has a potentially short construction lead-time of about 4 years, low operating cost and fast load-following characteristics, is such an option. Furthermore, the pebble fuel used in this concept has inherently safe characteristics.

Research has shown that a closed loop Brayton cycle layout configuration would provide the optimal thermal efficiency for the PBMR [2]. Figure 2 shows a simplified schematic diagram of the operation of a Brayton cycle [3].

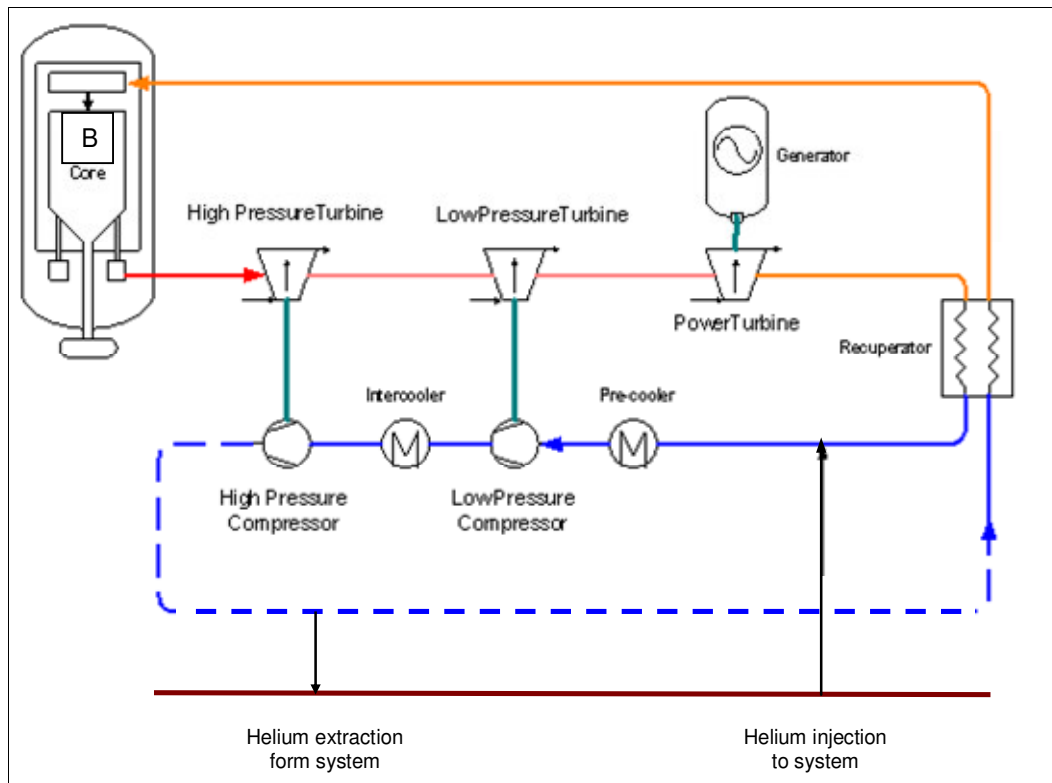


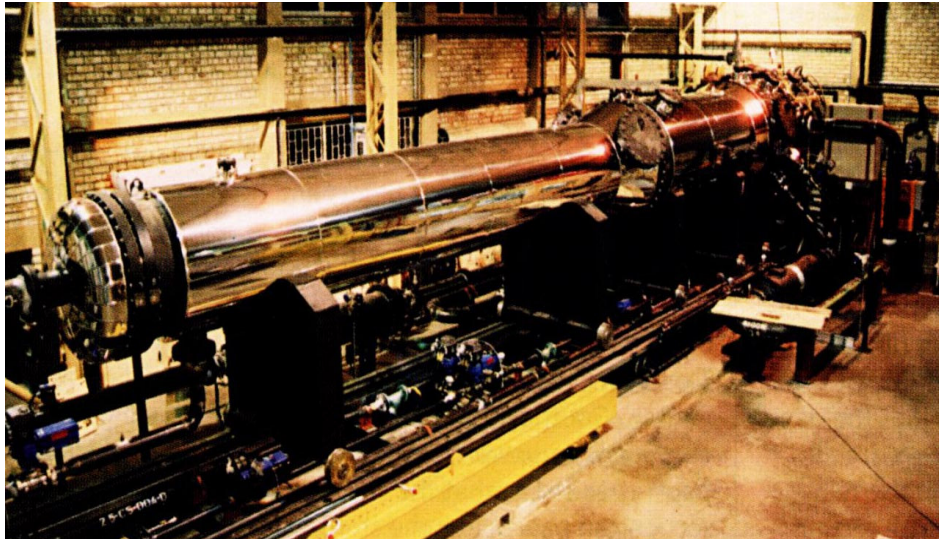
Figure 2: Simplified diagram of a direct Brayton cycle nuclear power conversion system.

The operation of the Brayton Cycle is not important for this dissertation. Note however that the output power of the generator is controlled by injecting or extracting helium from the closed-loop cycle by the Inventory Control System (ICS). This process is used to achieve load following, where the output of the cycle is increased or decreased when the required load fluctuates.

The difference in pressure levels in the closed-loop Brayton Cycle has a direct effect on the power produced by the power turbine, which is in turn connected to the generator.

This fluctuation in the system pressure levels, due to output power control, has a direct influence on the FHSS operation, as the system will be designed to operate across the spectrum of the total system operating pressures and temperatures.

One of the requirements that needed verification was whether the Brayton Cycle could be used to achieve load following. A three-shaft recuperative Brayton cycle was tested prior to this project to better understand the operation and simulation of a Brayton cycle. The test rig operating on this cycle was built at the Potchefstroom University for Christian Higher Education (PU for CHE) in 2002 (Figure 3). The project was a success and proved that this concept is feasible with the cycle being self-sustaining and controllable within the design limitations [5].



The above photo was taken at engineering department at the Faculty of Engineering at the then PU for CHE micro model.

Figure 3: The test model that was built at the PU for CHE

The system responsible for load-following of the plant, the ICS, can be seen in Figure 4.

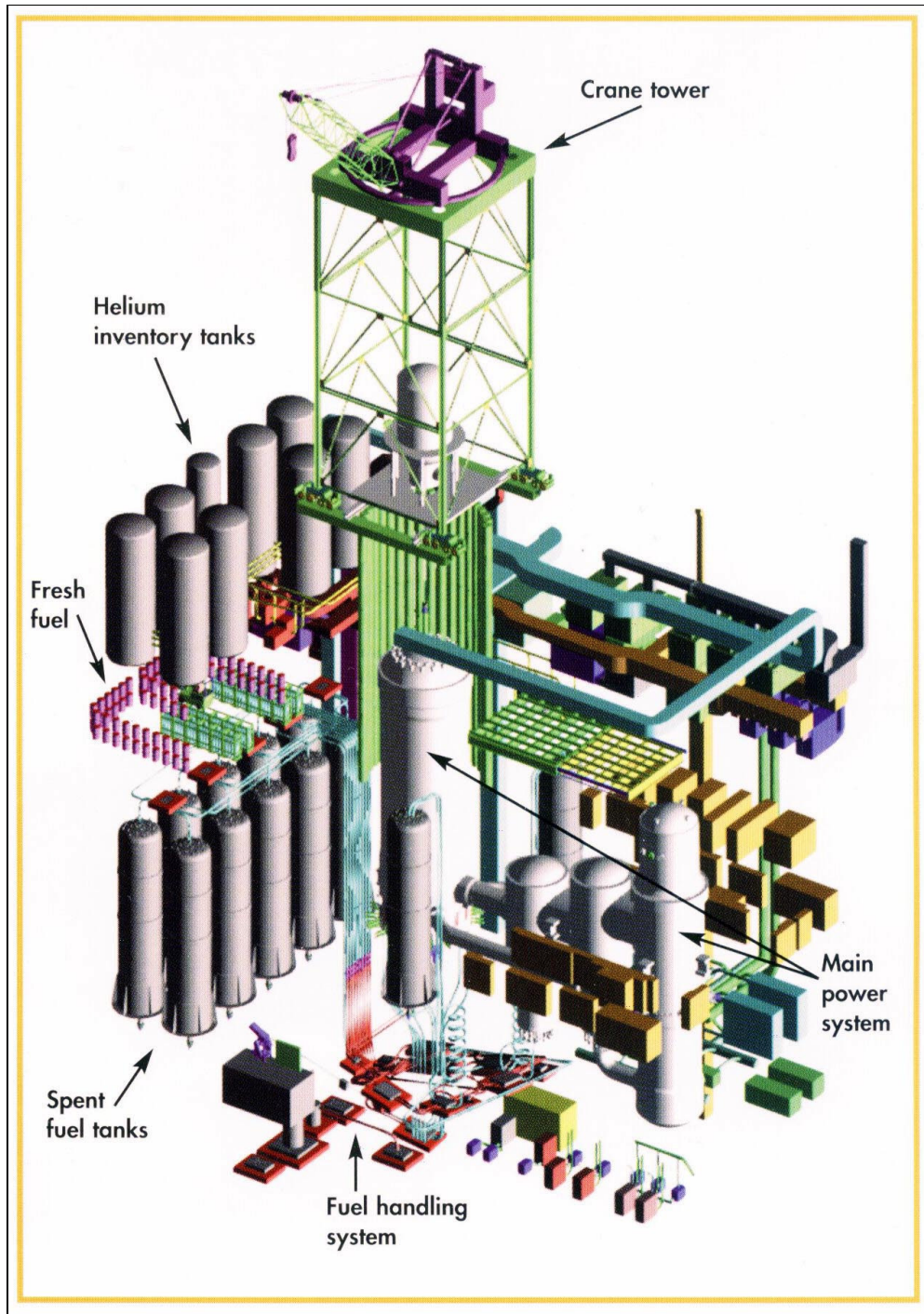


Figure 4: Layout of the PBMR

The FHSS is a support subsystem of the Main Power System (MPS) of the PBMR module. The main purpose of the FHSS is to circulate the spherical fuel elements of the PBMR through the reactor core during reactor operation. When equilibrium condition is reached in the core, an almost constant pattern of spheres with different burn-up states throughout the core is maintained with their associated flux profiles that change little over time.

The reactor core operates according to a ‘multi-pass’ fuelling scheme. This means that fuel spheres are moved through the core several times before reaching the desired burn-up and before being discharged. The fuel spheres are circulated by means of a combination of gravitational flow and pneumatic conveying, using helium as the transporting gas at MPS operating pressures.

The FHSS also stores the spent-fuel spheres discharged from the reactor after these spheres have achieved their maximum burn-up. Fresh fuel spheres are then fed into, and circulated through, the reactor core. The discharge of spent-fuel and the feeding of fresh fuel are performed while the reactor is at a steady state operation. Provision is made to remove specific spheres, identified as samples, before discharge to the spent-fuel storage tanks.

If required, the FHSS can be used to substitute the fuel spheres in the reactor core with non-nuclear graphite spheres. This is accomplished by discharging the used fuel spheres from the reactor and storing these spheres in the used fuel storage tanks outside the MPS, as shown in Figure 5. At the same time, graphite spheres, which are normally stored in the graphite storage tank outside the MPS, are fed into the reactor core. This process of changing fuel spheres forms part of the reactor shutdown sequence and takes about 24 hours to complete. The process is reversed again once the shutdown is completed, where graphite spheres are extracted from the core and filled again with the fuel pebbles.

During commissioning of the PBMR module, the FHSS is initially used to load the complete core of the reactor with graphite spheres. The graphite spheres in the core are then gradually replaced with a mixture of graphite and fresh fuel spheres supplied from the fresh fuel store, until the reactor achieves criticality.

An important aspect to understand is the criticality of the reactor core, which is achieved by the fuel and graphite sphere mixture as well as external control on the reactor via specific control rods.

The term **critical** refers to an equilibrium fission reaction (steady state or continuous chain reaction); this is where there is no increase or decrease in power, temperature, or neutron population [55].

A numerical measure of a critical mass is dependent on the neutron multiplication factor, **k**, where:

$$k = f - l$$

f is the average number of neutrons released per fission event and **l** is the average number of neutrons lost by either leaving the system or being captured in a non-fission event. When **k = 1** the mass is **critical**.

A **subcritical** mass is a mass of fissile material that does not have the ability to sustain a fission reaction. In this case, **k < 1**. A population of neutrons introduced to a subcritical assembly will decrease exponentially. A steady rate of spontaneous fissions causes a proportional steady level of neutron activity. The constant of proportionality increases as **k** increases.

A **supercritical** mass is one where there is an increasing rate of fission. In the case of super criticality, **k > 1**. The material may settle into equilibrium (i.e. become critical again) at an elevated temperature/power level or destroy itself (disassembly is an equilibrium state).

At the end of life of the PBMR module, the FHSS is used to remove the used fuel spheres of the last core from the reactor. The used fuel is stored in a helium filled storage tank to prevent corrosion of the hot used fuel while dissipating its decay heat.

In summary the FHSS system is thus the system responsible to circulate both fuel and graphite spheres through the reactor core as well as transporting these spheres to various containment units. The system operates during all the plant operating conditions, except during plant maintenance, at various temperature and pressure levels.

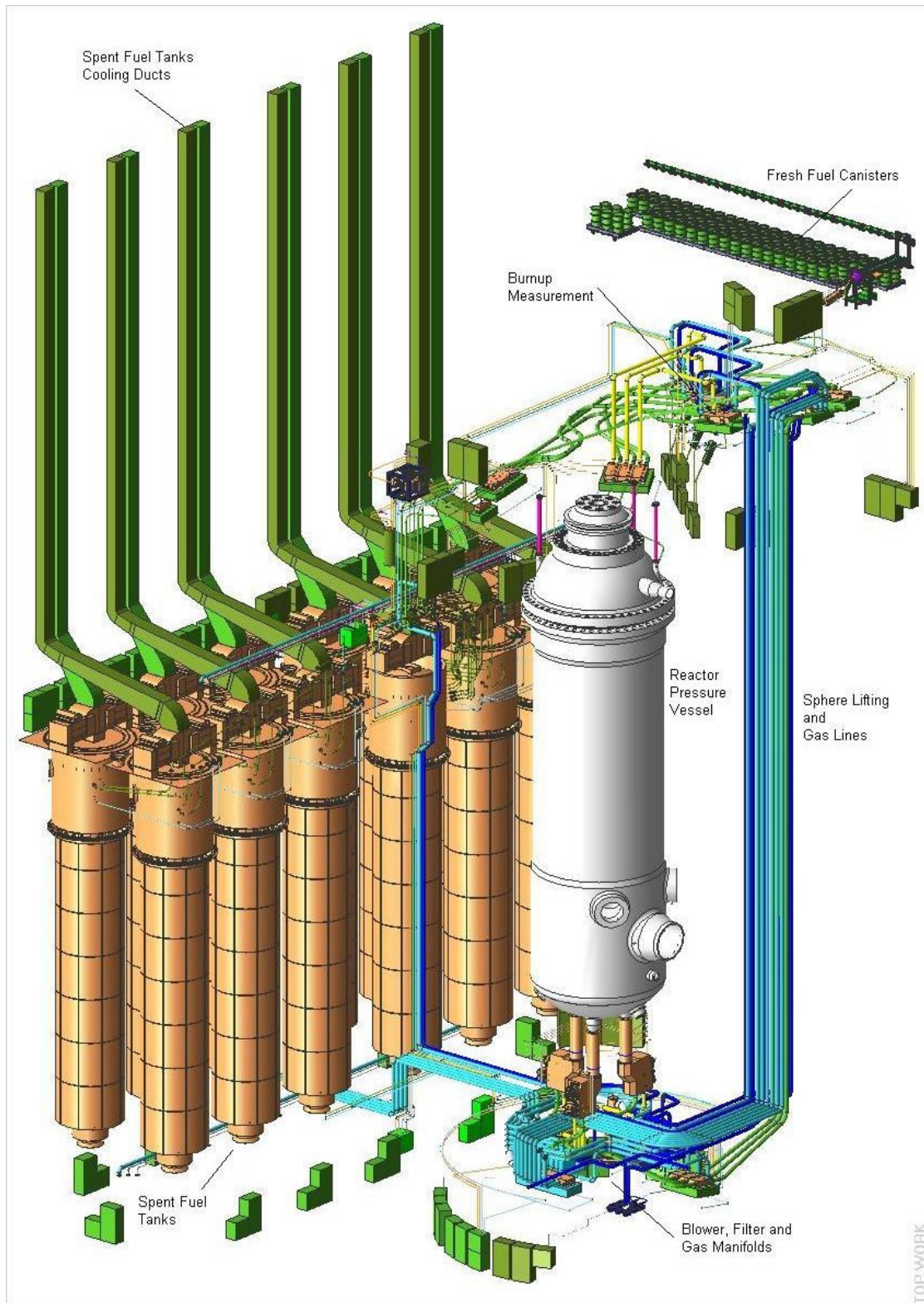


Figure 5: Layout of the PBMR Fuel Handling and Storage System

1.2 PROBLEM STATEMENT

The FHSS system performance design is largely driven by the circulation rate of the spheres through the reactor core for the various operating conditions. To achieve these circulation rates, spheres have to be transported from the bottom of the reactor to the top at a specific rate.

Specific gas flow rates, for the pneumatic conveying of the spheres are required in the FHSS sphere-transport piping to achieve the specified circulation rates of both fuel and graphite spheres, at all the operating conditions. The required gas velocities for pneumatic conveying of the spheres are achieved by using a gas blower.

The primary focus of the study is to calculate the correct gas flow rate required to achieve the correct sphere circulation rates. The secondary focus is to calculate the blower operating range for the entire operating functions of the FHSS as well as the thermo-hydraulic input data required for the design of the rest of the FHSS.

A simulation model of the entire FHSS system was constructed in order to calculate the full operating range of the blower as well as to calculate the required thermo-hydraulic input data for the design of the rest of the FHSS. A method had to be selected and a process developed which could be used to perform a complete thermo-hydraulic analysis of the FHSS. The required sphere velocities calculated during the pneumatic and gravity transport had to be shown to be accurate and conservative. To this end, a sensitivity and Monte Carlo study was carried out on the sphere velocity calculations.

1.3 LITERATURE SURVEY ON BLOWERS

To better understand the limitations and application in the industry for gas blowers a literature study was carried out.

1.3.1 HELIUM/GAS BLOWERS USED BY INDUSTRY

Helium is widely used in industrial gas-cooling applications. One example is a 74kW gas blower where an improved low-pressure-drop internal furnace and a fin-and-tube heat exchanger are used for quenching processes [25].

The design of a power plant based on the Spherical Tokamak (ST), is being developed in order to explore its potential advantages [27]. The pebbles are transferred to an upper tank by a pneumatic conveyor, also known as a helium blower.

3rd and 4th generation high-temperature gas-cooled nuclear reactors will be used in the near future to harness nuclear power safely. Helium blowers have become widely used in the following projects:

1. The High Temperature Gas Cooled Reactor Programme in China [25].
2. The AVR (Arbeitsgemeinschaft Versuchsreaktor - German for Jointly-developed Prototype Reactor), a 15MWe experimental pebble bed reactor operated for 21 years in Germany [1].
3. THTR, a 300MWe German demonstration pebble bed reactor with steam turbine operated for five years [1].
4. Fort St Vrain, a 330 MWe US HTGR operated for 14 years [1].
5. HTTR, a 30 MWth Japanese HTGR reached criticality in 1998 [1].
6. HTR-10, a 10 MWth Chinese HTGR under construction reached criticality in 2000 [1].
7. HTR-100, a 100 MWe German modular pebble bed reactor design by HRB/BBC [1].
8. GT-MHR, a 300 MWe US HTGR, direct-cycle design [1].

Initial research done, before the development of the FHSS started, indicated that the most probable solution would be a single stage axial or centrifugal blower.

There are various types of other blowers and uses in the industry. Table 1 provides an indication of the vast variety of blower types available on the market [24], but not considered for this study.

Table 1: Blower types and uses in the industry

Blower Type	Use/Characteristics
Axial Blower	Acceleration of the gas is followed by diffusion to convert kinetic energy into pressure energy; very high flow rates.
Centrifugal Blower	High-speed impeller produces radial airflow; velocity converted to pressure energy. Evacuated air flows radially outward as opposed to axial flow in axial blowers.
FURTHER LITERATURE STUDY WAS DONE ON THE FOLLOWING BUT NOT INCLUDED IN THIS STUDY	
Circumferential Piston	Multiple-rotor configuration where two rotors, each with two "wings" that trap air against the outside wall during rotation and compress it in their rotary stroke towards the outlet. The wings of the two rotors alternate in making compression strokes.
Claw	Claw or rotary-claw pumps use precision-designed intermeshing hooked claws with very tight tolerances and clearances for highly efficient internal compression. There is typically no contact, thus minimising or eliminating friction and wear.
Diaphragm	Oscillating diaphragm driven by a reciprocating or eccentric "rocking" rod; no sliding seals or parts. This design isolates the pumped fluid from any contact with the pumping mechanism. Diaphragm pumps exhibit a much lower compression ratio than piston pumps, but frequently offer quiet, economical performance.
Linear	The stroke of a sliding compression piston is generated with electromagnetic oscillation; clean and quiet.
Liquid Ring	Eccentrically mounted rotor and vanes utilise liquid ring on inside of chamber to compress air. The liquid also absorbs compression heat and entrained particles in the air.
Lobed Rotor	Air is trapped and compressed by the diminishing volume caused by the meshing of oppositely rotating lobes.

Reciprocating Piston	Piston mechanically reduces air volume inside cylinder. These pumps may have one or several pistons being driven by a motor. The vacuum levels produced by this pump style are higher than for other types of mechanical pumps.
Regenerative Blower	Similar to centrifugal, with airflow chamber designed to generate higher pressure. Air flows in a radial direction outward along a blade to the housing wall, whereupon it flows down to the root of the next blade gap and repeats the cycle. The airflow thus creates several "stages" of compression.
Rocking Piston	Similar to reciprocating piston but is not articulated; "rocks" with eccentric motion of drive.
Rotary Piston	Rotary piston or cam is rotating eccentrically; evacuates air through check valve on the "compression" or evacuation stroke while air from the vacuum application fills in behind it.
Rotary Vane	Eccentrically mounted rotor and sliding vanes compress air in diminishing volume compartments.
Rotary Screw	Two or more spindles with intermeshing screws rotate in opposite directions, creating axially progressing "chambers," moving the air from suction to discharge. Larger pumps often have double suction, where air is let in from both ends to a central discharge port.
Scroll	Air is moved as intake air is compressed between the surfaces of mating involute spirals, one of which is moving to push the evacuated air out to the exhaust progressively.

1.3.2 REQUIRED INPUTS FOR A BLOWER DESIGN

To ensure that all the correct inputs are calculated for the ultimate blower design, a literature study was done to establish what industry standards require.

For a simple blower design with the blower operating at a fixed input/output or pressure ratio pressure and flow rate, catalogue designs are usually adequate. The relevant inlet pressure, flow rate and working fluid are given to the supplier. From this information an off-the-shelf item can usually be selected to meet the required flow or pressure variations.

Figure 6 shows a typical example where a required blower output is used to select the blower [28].

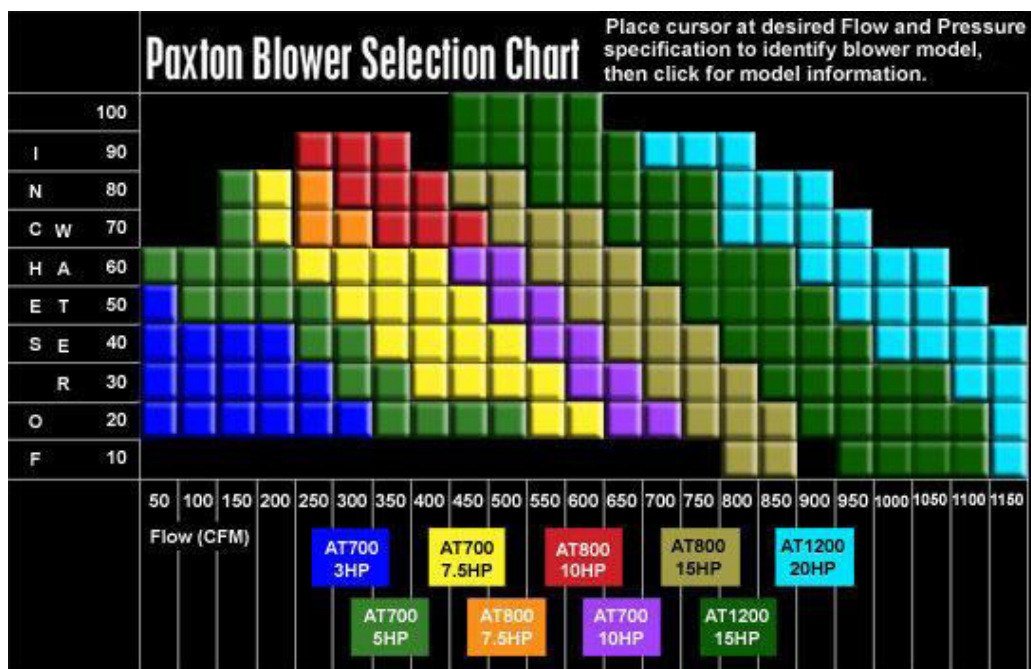


Figure 6: Blower selection guide from Paxton Blower Selection Chart

This chart is typically used to select the blower for the required performance.

Because of the large operating range of the FHSS blower and the first-of-a kind engineering required to develop such a unique blower, it is necessary to do a detailed analysis of the FHSS system. The calculated parameters for all the operating conditions would then serve as an input to the FHSS blower design.

1.3.3 FHSS BLOWER REQUIREMENTS

The characteristics of compressible-flow machines are usually described in non-dimensional terms, of groups of variables given by the function [29]:

$$P_{02}/P_{01} = f((T_{02}/T_{01}), (m T_{01}^{1/2}/P_{01}), (N, T_{01}^{1/2}))$$

Where

P_{02} refers to the outlet absolute pressure of the blower.

P_{01} refers to the inlet absolute pressure of the blower.

T_{02} refers to the outlet absolute temperature of the blower.

T_{01} refers to the inlet absolute temperature of the blower.

m refers to the delivery of the blower

N refers to the rotational speed of the blower [29].

Obtaining the required component is a simple exercise because a specific flow rate at a specific pressure and temperature is required. The FHSS blower, however, operates over a large pressure range (between 1000 kPa and 9000 kPa helium and 100 kPa Nitrogen/Air).

The Nitrogen/Air operation is applicable during the system commissioning and also in a fault mode, where the system will be flushed with nitrogen.

The blower design, for these many operating conditions, is also constrained by physical limitations such as;

- *Blower surging*, in centrifugal compressors occurs at low flow rates, where the pressure ratio approaches its maximum value. Figure 7 shows a typical centrifugal compressor performance map. Surging is usually defined as axial oscillations of the airflow. Flow will occur in the reverse direction from one blade passage to the next.
- *Rotating stall*, occurs at high angles of attack to the blade. A single blade may stall, causing a reduced mass flow in the blade passage, causing a deflection of the airflow on either side of this blade. The angle of attack of the neighbouring blade, in the direction of rotation, will decrease and increase the angle of attack on the opposite side of the stalled blade. A stall condition is then propagated in the opposite direction of

rotation, blade by blade. The blades tend to stall individually. This prolonged cyclic loading and unloading of the rotor blades can lead to eventual fatigue failure or even sudden catastrophic failure.

- *Choking* can occur where at some point within the blower, sonic conditions are reached. Shock waves are formed within certain passages and the flow is said to choke. No further increase in mass flow can take place.

Indicated below is an example of the non-dimensional characteristic map of a blower [29].

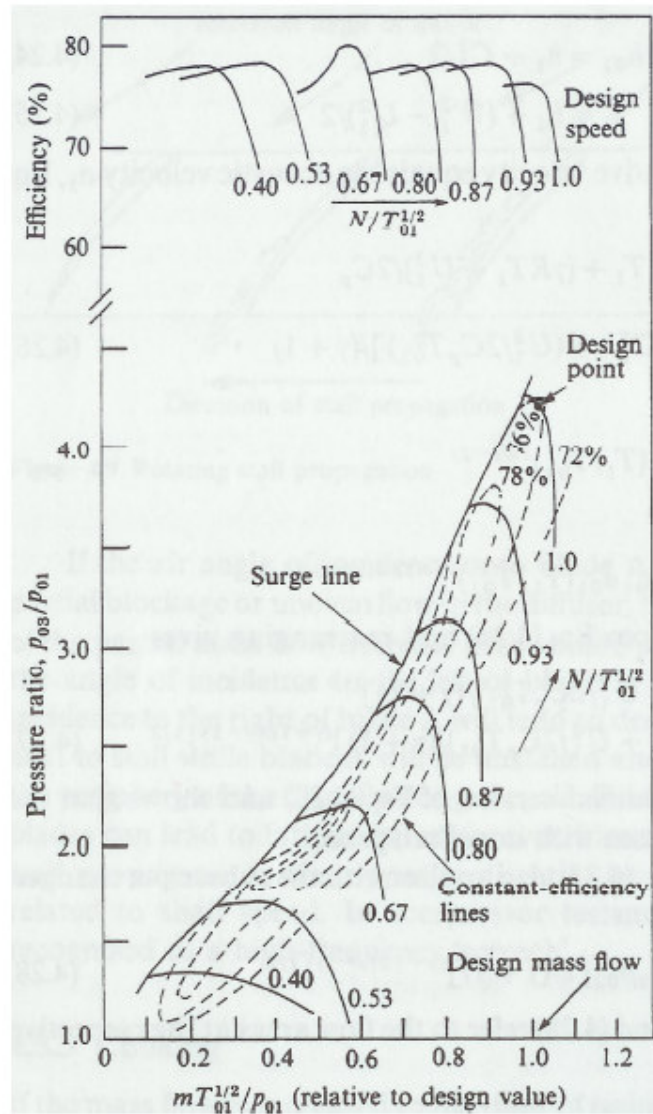


Figure 7: Blower Characteristic Map

1.3.4 LITERATURE SURVEY ON POSSIBLE METHODS FOR ANALYSIS

Three different methods were evaluated to perform the thermo-hydraulic analysis:

A. First order calculations [7]:

This would have been a tedious process to follow, considering all the different test conditions that had to be evaluated and the number of components in the test set-up.

B. Computational Fluid Dynamics (CFD)

The ability to determine the fluid flow and heat transfer in complex networks was an important prerequisite in the design process of thermal-fluid networks. Complex flows could be solved using a CFD code, which require complex meshing in three dimensions to resolve the flow and temperature fields [8].

To obtain a solution using a CFD code for a simple pipe in three dimensions would have required many hundreds or even thousands of cells to ensure an accurate solution. This was simply not practical for large network simulations consisting of a large number of different and complex components. In particular, when dynamic simulations are performed, they would require excessive computational resources that could take many hours to solve.

A CFD analysis required the generation of meshes, which would have to be altered and updated as the design progressed. Mesh generation in CFD is a complex process requiring a great deal of time and user expertise.

C. One-dimensional modelling methodology.

Simulation modelling overcame the difficulty associated with traditional CFD simulations, by employing a one-dimensional modelling methodology. This simplified the problem considerably by using average flow conditions across the flow area. Flow velocity, pressure and fluid properties would be average values for the cross-sectional area and would vary only in the direction of flow.

This assumption greatly simplified the solution procedure and eliminated the requirement for complex computational meshes. The drawback of using such a one-dimensional simulation methodology was that the detailed flow fields within a component could not be resolved. However, this assumption did not adversely affect the accuracy required for this study.

1.3.5 SELECTED METHOD FOR THE ANALYSIS - ONE-DIMENSIONAL MODELLING

The process involved setting up a thermal-fluid network, consisting of thermal-fluid components connected in an unstructured manner. Thermal-fluid networks could therefore vary in complexity from just a few different components in a network to hundreds and even thousands of components in a single network.

Flownex, a software fluid-analysis program, provides the means to design and analyse very complex unstructured thermal fluid networks [9]. This program was selected for the present analysis. The objective of a thermal-fluid network analysis was to determine the flow rates, pressures, temperatures and heat transfer rates for the components in the network. Every thermal-fluid component in the network had to comply with the system specifications and the individual components had to function correctly as part of the integrated system.

When designing a thermal-fluid network, it is essential to accurately predict the flow rates through the components. It is also essential to accurately estimate the temperature distributions and heat transfer rates throughout the network. Flownex can then be used to assess the performance and operating conditions of the thermal-fluid components in complex unstructured thermal-fluid networks [9].

1.3.6 REQUIREMENT FOR THE SIMULATION

Thermal system design involved the consideration of the technical details of the basic concept and the creation of a new or improved system for the specified task. It was important to distinguish between thermal-fluid *Design* and thermal-fluid *Simulation*.

Design refers to a situation where the characteristics of a system have to be specified so that it will enable the execution of specific functions at an acceptable level of performance.

Simulation, on the other hand, generally refers to a situation where the characteristics of the system are known. Models have to be set up that will predict its functionality and performance level under various operating conditions. Simulation therefore forms an integral part of the design process, because new design has to be analysed and evaluated to ensure that the design criteria are satisfied.

Simulation was used to calculate the required blower operating conditions. Flownex was considered a satisfactory simulation software tool and was chosen for this study. Many simulation tools are commercially available for this purpose.

1.4 OVERVIEW OF REPORT

The first Chapter of the report elaborated on the background of the PBMR plant as well as on one of its essential subsystems. The requirement for thermo-hydraulic input data to design the FHSS blower was identified. A literature survey was conducted to identify possible methods for thermo-hydraulic analysis of the FHSS to obtain the required design data.

The following two Chapters discuss the selected approach in detail. Different aspects of the concept were implemented and addressed in the solving technique. Chapter 2 is a detailed literature review on the solving method.

Chapter 3 gives a description of the method that was developed to set up the simulation model for the analysis as well as the sensitivity and Monte Carlo study. The system model for the simulation is documented in the appendices to this report.

The last two Chapters of the report contain the conclusions from this study, as well as a list of all the references used. Recommendations for future work are also given.

The appendices to this document include the distribution parameters for the Monte Carlo simulation as well as the complete model description for the FHSS Flownex model.

2. DESCRIPTION OF AN APPROPRIATE SOLVING METHOD

2.1 PREAMBLE

A component as critical as the FHSS blower, must be tested before the proposed concept can be implemented in a full-scale nuclear reactor. Designing, developing and testing an experimental model is necessary to ensure that each component produces the required results. The time and costs involved in the development and design of each component are substantial. To reduce the time involved and ensure that the required design inputs used to develop the component were accurate, it was necessary to verify the requirements and specifications of the design inputs and the required outputs of the blower.

To determine the required design parameters for the blower, the FHSS fluid flow characteristics must first be solved. A few different approaches can be followed to solve this specific type of fluid flow problem. Building and testing an experimental model would obviously have provided reliable answers. However, the time and costs involved in such an experiment would make it impractical.

Fluid flow conditions of the FHSS are governed by two system requirements. The first would be to transport fuel and graphite spheres at specific velocities and various fluid densities; the second would ensure proper dust removal from all the gravity pipe sections at selected intervals. Dust removal is an important part of maintaining the FHSS system to ensure that the dust build-up will not result in system blockages over time. The generation of dust in a nuclear system is also a sensitive parameter requiring additional safety precautions, because of the fact that the airborne dust has the ability to spread easily. Therefore the generation of dust in a nuclear system needs to be contained and maintained.

To compensate for the lack of experimental and calculation inputs to predict pneumatic sphere transport velocities in pipe sections accurately, a Monte Carlo and Sensitivity study was done. Experimental data will be used to predict the required gas velocities for dust removal.

An appropriate software package was selected and used to build the simulation model and accurately calculate the fluid flow scenario. Flownex was selected as the most suitable software package to accomplish this requirement. The procedure for setting up such a

simulation model had to be fully understood in order to create a simulation model that would reflect the actual FHSS fluid flow conditions [10].

Because the PBMR is a nuclear power plant, the model must be designed according to strict rules and regulations. It has to comply with safety standards and quality assurance codes given by the National Nuclear Regulator (NNR) in order to obtain an operating licence in South Africa. A detailed Verification and Validation (V&V) process must be performed on all software used as part of the design.

2.2 BACKGROUND ON FLOWNEX

A literature survey was conducted on both the development of Flownex and the application of the software in this relevant field. This was done to determine whether Flownex would be an acceptable tool for the required analysis.

2.2.1 GENERAL [54]



Flownex is a systems CFD code that enables users to perform detailed design, analysis and optimisation of thermal-fluid systems. These range from simple pipe networks to complex systems such as gas turbine engines and combined-cycle power plants.

“Systems CFD” refers to the approach where component models with different levels of complexity, from analytical models or lumped models to 1-D, 2-D or even 3-D CFD models are linked together in a network, to represent a complex system.

Flownex’s solution algorithm is similar to that of a conventional CFD code. The system is discretized into a number of spatial or conceptual control volumes to which a set of conservation equations are applied and then solved.

Distinguishing features of Flownex are:

- the ability to deal with both steady-state and dynamic problems
- the ability to deal with both single-phase and two-phase fluids
- the ability to deal with very large networks
- the speed of execution.

2.2.2 THE DEVELOPMENT OF FLOWNEX

Flownex is a general-systems CFD code that finds wide application in the industry. M-Tech Industrial developed the code over the past 15 years, in collaboration with the Faculty of Engineering at PU for CHE (now known as the North West University) [11].

The PBMR project has boosted the development of Flownex as a commercial product, and users include companies such as Rolls Royce, Mitsubishi Heavy Industries, Kobe Steel, Concepts NREC, Eskom, Sasol, CSIR Miningtek as well as Iscor. MIT University, Cranfield University, and Stuttgart University [11].

Flownex is used in the industry by Rolls Royce [12] for the modelling and simulation of aircraft combustion chambers. Clients such as PCA Engineers (USA) [13], Concepts NREC (USA) and Mitsubishi Heavy Industries [15] use Flownex for the modelling of turbo machines [14].

Mitsubishi Heavy Industries, Ltd (MHI) is one of the world's leading manufacturers of heavy machinery. With a vast amount of practical experience and a high level of technological capability, MHI has been active in the nuclear industry for more than three decades. Since starting research into and development of nuclear power generation in the 1950's, MHI has taken part in the design, manufacture and construction of a large number of very successful Pressurised Water Reactor (PWR) power plants [15].

MHI is the only organisation to produce such a large range of supplies for nuclear power generation. These supplies include Architectural Engineering, Nuclear Steam Supply Systems, Turbine Generator Systems, Electrical Systems, I & C Systems, Nuclear Fuel, and also the Balance of Plant.

Kobe Steel Ltd (Japan) uses the software for the simulation of air-chilling units [16]. From comprehensive power generation plants to individual machines, the Plant Engineering Sector of Kobe Steel's Plant Engineering Company has the capability to fulfil a vast range of needs in such industries as iron and steel making, cement, energy and chemical-related fields.

Integrating excellent manufacturing and plant engineering capabilities, they are expanding their operations into a variety of business fields. Kobe Steel produces the world's largest desulphurisation reactors and oxygen generation plants for oil refining and petrochemical plants. In addition, they offer a wide range of power generation and gas supply facilities, nuclear equipment, and district heating and cooling systems [16].

Flownex is also used by a number of academic institutions. The Massachusetts Institute of Technology (MIT) uses Flownex for simulating various designs of the Brayton cycle [17]. Cranfield University uses it for the simulation of compressor units [18].

These references show that Flownex is widely used in the industry and academic institutions for the modelling and simulation of various thermal-fluid systems and networks. Flownex users are all well known and respected in industry and academic fields. It can therefore be accepted that Flownex will be a reliable tool for the analysis of this particular thermal-fluid network.

2.3 PROCESS DEVELOPED FOR THE ANALYSIS

2.3.1 SETTING UP OF THE THERMAL-FLUID NETWORK

Flownex was used as the simulation tool to set up a thermal-fluid network for performing the analysis. Thermal-fluid networks are presented in Flownex by a combination of Nodes and Elements. In the Flownex Graphical User Interface (GUI), nodes are indicated with a square box symbol while elements are indicated with a circle.

A network was created by placing and connecting elements and nodes in a random fashion. Flownex caters for any number of nodes and elements per network, limited only by the available computer memory. It was therefore possible to create very complex thermo-fluid networks.

Nodes were used to connect various elements and to represent boundaries for a network. Reservoirs and tanks can also be represented by these nodes. Junction losses can also be modelled where elements meet at a common node.

2.3.2 SOLVING OF THE THERMAL-FLUID NETWORK

Flownex solves networks quickly and accurately by employing a very fast and stable implicit solver [9]. This eliminates the excessive time-step restriction imposed on explicit codes. Flownex uses dynamic memory allocation, which means that very large networks can be solved on a personal computer without re-dimensioning the code each time.

Flownex provides extensive error and warning messages. Although nodes are the endpoints of elements, a node can have a volume. Flownex can also deal with heat transfer to and from nodes. Long pipes can be subdivided into a number of smaller element lengths. This increases the accuracy and enables the user to study pressure and temperature variations over the length of the pipe. Different pipe-loss coefficients can also be specified in the forward and reverse flow directions.

2.3.3 PROCESS FOR CREATING A FLOWNEX NETWORK

Flownex is run from within the Windows environment. Elements and nodes define a network and form the basic building blocks to simulate a network.

An element is a component, such as a length of pipe, duct, orifice, fan, pump, compressor, turbine or heat exchanger, which causes a pressure variation. An element can also be a

combination component, such as a length of pipe, which includes a number of secondary pressure loss components and orifices. In the case of a combined element, the diameter of the pipe has to be constant.

Nodes are the endpoints of elements. A network is defined by joining elements at common nodes as shown in the figure 8.

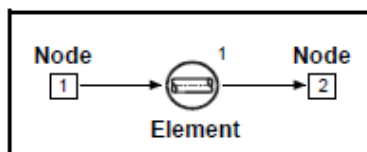


Figure 8: Basic Building Blocks of a Network

It is possible to distinguish between the following three types of nodes:

- *Boundary nodes.* A node associated with only one element is called a boundary node.
- *Fixed pressure node.* When defining a network, the pressure at any node, even that of boundary nodes, could have been fixed. Such nodes are called fixed pressure nodes. A node can therefore be both a boundary node and a fixed pressure node.
- *Internal nodes.* Nodes that are neither boundary nor fixed pressure nodes.

It is also possible to distinguish between the following two types of elements:

- *Boundary elements.* A boundary element is an element associated with a boundary node or a fixed pressure node.
- *Internal elements.* Internal elements are all elements that are not boundary elements.

In specifying a network, the following simple rules apply:

- For boundary node/element pairs, at least one of the node pressure, the node mass source or the element mass flow must be specified.
- If the pressure of an internal node was fixed, continuity would not be satisfied at the node for the network specified by the user. It is important to remember that if the

pressure of a node is fixed, Flownex will generate a mass source or sink at that node, which will cause continuity to be satisfied.

- If the mass flow of an internal element is fixed, generally, the relationship between mass flow and pressure change over that specific element will not be satisfied. An additional pressure difference will be generated in the element with the specified mass flow. If the mass flow of a boundary element as well as the pressure of the associated boundary node is fixed, the pressure of the boundary node will be ignored. If the mass flow was specified at a boundary, Flownex will calculate the pressure of the boundary node.
- Mass flows may not be fixed for all boundary elements. For at least one boundary element-node pair, the pressure and not the flow should be fixed. If two networks are connected through a single fixed-flow element, the pressure of at least one boundary node in each of the two networks should be fixed.
- The mass flow either in a boundary element or the pressure of its associated boundary node must be fixed. It is not allowed to specify both the pressure and mass source at the same node.
- If neither the node pressure nor the node mass source of a boundary node is specified, the flow in the associated boundary element will be zero.

The convergence parameters specified for the project were subdivided into two groups. The first group was where the convergence criteria and the number of iterations for each solver were specified. The second group was where the relaxation parameters were specified to ensure a stable solution. For the solution to have been considered as convergent, the conservation of mass, momentum and energy must be satisfied. To check whether continuity was satisfied, conservation of mass at each node, the sum of the continuity errors at all the nodes divided by the mean of the entire element mass flows (absolute values) was calculated.

2.4 VERIFICATION AND VALIDATION (V&V) OF THE CODE

Because the PBMR is a nuclear power plant, it has to be designed under strict rules and regulations. It has to comply with safety standards and quality assurance codes given by the NNR in order to obtain an operating licence in South Africa.

One regulatory requirement is that all applicable software codes used for the design of the PBMR must be verified and validated. To verify and validate these codes is a lengthy process. In order to meet this requirement, PBMR has dedicated personnel that are responsible for this task.

The Software V&V process for Flownex was captured in the Verification and Validation of software [20]. This document, in conjunction with the procedure for Project Management for the Design, Development and Maintenance of Software [21] and Configuration Management Process Definition for Software [22], dictated the Software V&V process.

Many of the software codes used as part of the PBMR design are commercial codes that have been developed for industry over many years. These codes however also have to undergo a strict verification and validation to ensure that all requirements are met for using these codes in a nuclear design.

Flownex Nuclear differs from other codes used on the PBMR project because it is categorised as Software Under Development (SUD). The code is being specifically developed to perform thermal-fluid analyses on a high-temperature gas-cooled reactor coupled to a direct, recuperated Brayton cycle in an implicit way. As it is the first software product of its kind various verification and validation methods, from different sources, are used to license the software.

It should be stressed that Flownex Nuclear is the first software product of its kind, because this affects the availability of codes that can be used for independent V&V activities. In order to ensure that all phenomena for each component in Flownex Nuclear are validated for the various extremities, an extensive V&V exercise must be completed.

Verification forms part of the overall Flownex Nuclear development process and includes the verification activities that form part of the software engineering process. Furthermore, all related verification is done as part of the derivation of the theory for component models or model enhancements. Validation of Flownex Nuclear is performed by comparing the results

of the implemented theoretical models in Flownex Nuclear with benchmark data obtained using appropriate methods [23].

The Nuclear Research and Consultancy Group (NRG) in Petten, the Netherlands, performs Independent Software V & V on the Flownex Nuclear software. The NRG operates technically, managerially and financially independently of PBMR and M-Tech. This V&V is managed by PBMR and data obtained is accessible to M-Tech for V&V activities.

3. SIMULATION MODEL

3.1 PREAMBLE

The FHSS makes use of pneumatic helium- and gravity conveying to circulate fuel spheres through the core of the reactor. At the same time, it will discharge spent-fuel to the spent-fuel storage area and recharge the reactor with fresh fuel. As part of the sphere conveying system there are also pneumatic brake sections included that reduce the sphere velocity as they exit the lift line sections. The sphere velocities must be reduced to prevent high impact velocities downstream of the pneumatic brake section. As a first estimate, the pneumatic brake gas velocity is set to ensure that the largest sphere, with a diameter of 60.3mm, has a terminal velocity of 1 m/s in the specific brake section. The formulae used to compute the sphere velocities and ensure adequate brake lengths must be verified. To ensure the accuracy and correctness of these computed parameters, a parametric and sensitivity study was used to calculate the sphere velocities. This also includes a Monte Carlo study of the inputs.

After the parametric and sensitivity study had been completed, the blower operating parameters were calculated for the various FHSS operating conditions. These parameters were calculated for the high pressures, (3300 kPa to 9000 kPa absolute helium pressure), low pressure, (1000 kPa absolute helium pressure), and air operation at atmospheric conditions.

The FHSS Flownex model was used to balance the sphere conveying lines gas flow velocities to achieve the required sphere velocities in the sphere lines. The blower thermo-hydraulic performance requirements could then be calculated from the overall system thermo-hydraulic calculation.

3.2 SENSITIVITY AND MONTE CARLO STUDY FOR SPHERE VELOCITY CALCULATION

3.2.1 PARAMETRIC STUDY

Sphere velocity vs. pneumatic brake distance is calculated for the following operational conditions in helium:

1. 1000 kPa and 250 °C, lifting velocity of 10 to 15 m/s
2. 3300 kPa and 150 °C, lifting velocity of 2 to 4 m/s
3. 9000 kPa and 150 °C, lifting velocity of 2 to 4 m/s

The sphere sizes simulated range between 59.3 mm to 60.3 mm spheres. The lift line gas velocity is calculated for the average sphere size. The pneumatic brake line gas velocity is calculated to ensure that the largest sphere has a 1 m/s velocity. The calculations are done for a 10° pneumatic brake section. The outputs are presented in brake distance vs. sphere velocity graphs.

Note that the calculations do not compensate for the rotation energy of the sphere. The effect of the sphere rotation energy is not taken into account and is discussed in section 3.2.4.

3.2.2 SENSITIVITY STUDY

The sensitivity of the input parameters is compared to the sphere terminal velocity. This study also includes the effect of the sphere rotation energy that is normally ignored in the calculations.

The input parameters are varied with a normal distribution as indicated in the appendix of the document for the Monte Carlo study. The study is repeated with the sphere rotation energy taken into account.

3.2.3 SPHERE ROTATION AND VELOCITY CALCULATION

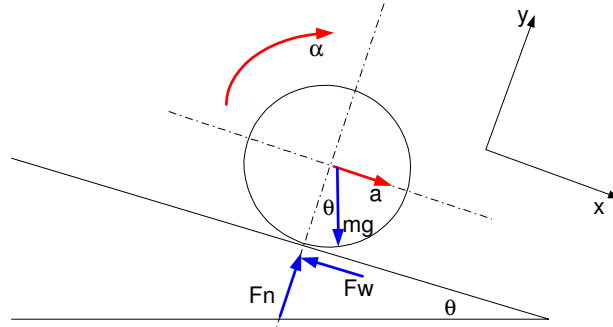


Figure 9: Sphere Roll and Slip Diagram

Table 2: Force Balance on Sphere

Equation	Variables	Description	Units
$\Sigma F_y: F_n - m.g.\cos(\theta) = 0$ $\therefore F_n = m.g.\cos(\theta)$	F_y	Force in y-direction	N
$\Sigma F_x: m.a = m.g.\sin(\theta) - F_w$ $\therefore = m.g.\sin(\theta) - \mu F_n$ $\therefore = m.g.(\sin(\theta) - \mu.\cos(\theta))$ $a = g.(\sin(\theta) - \mu.\cos(\theta))$	F_x	Force in x-direction	N
Equation 1 $I.\alpha = r.F_w$ $\therefore \frac{2}{5}m.r^2\alpha = \mu.r.F_n = \mu.r.m.g.\cos(\theta)$ $\alpha = \frac{5}{2}\mu.g.\cos(\theta)/r$ Equation 2	F_n	Normal Force acting in on sphere	N
	F_w	Drag Force acting in on sphere	N
	m	Sphere Mass	Kg
	G	Gravitational acceleration	m/s^2
	a	Sphere linear acceleration	m/s^2
	α	Sphere rotational acceleration	rad/s^2
	μ	Rolling co-efficient of Friction	-
	θ	Angle between horizontal and x-axis	$^\circ$
	I	Sphere moment of inertia	$kg.m^2$
	r	Sphere radius	m

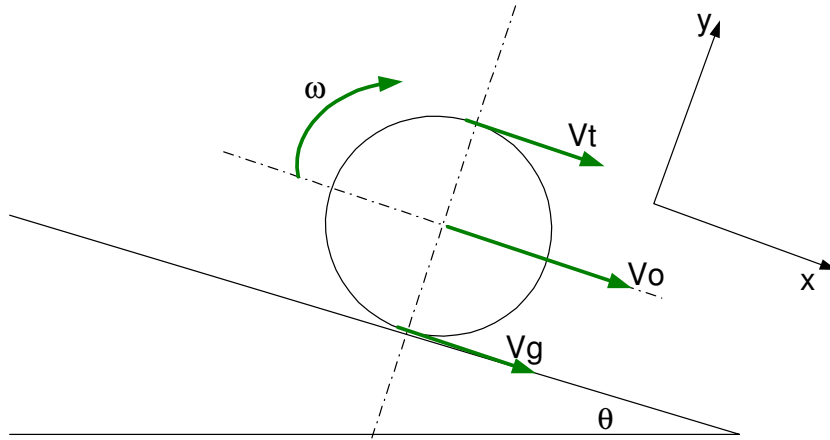


Figure 10: Sphere velocity diagram

Table 3: Sphere Velocity Equations

Equation	Variables	Description	Units
$V_t = V_o + r\omega$	V_t	Sphere Tip Velocity	m/s
$V_g = V_o - r\omega$	V_o	Sphere Velocity	m/s
$\mu = -\frac{V_g}{ V_g } \cdot \mu$	V_g	Sphere Velocity relative to surface	m/s
No Slip: $V_g = 0$	ω		rad/s
$\therefore V_o - r\omega = 0 \Rightarrow \omega = \frac{V_o}{r}$			
Slip: $V_g \neq 0$			
$\therefore V_o - r\omega \neq 0 \Rightarrow \omega \neq \frac{V_o}{r}$			
No Slip: $\mu = \mu_{static}$			
Slip: $\mu = \frac{V_g}{ V_g } \cdot \mu_{dynamic}$			
Equation 3			

Table 4: Sphere Energy Balance

Equation	Variables	Description	Units
$I.\omega^2 + m.v^2 + mgh = E_{\text{total}}$	E	Energy	Joule
$E_{t+\Delta t} = E_t - F_w / s _{\Delta t}$	h	Height	m
No Slip : $\alpha = \frac{a}{r}$	s	Distance	m
$\therefore \frac{5}{2} \mu . g . \cos (\theta) / r = g(\sin (\theta) - \mu . \cos (\theta)) / r$	t	Time	sec
$\frac{5}{2} \mu . \cos (\theta) = \sin (\theta) - \mu . \cos (\theta)$			
$\frac{7}{2} \mu . \cos (\theta) = \sin (\theta)$			
$\mu = \frac{2}{7} \tan (\theta)$			
But $\mu \leq \mu_{\text{static}}$			
Equation 4			

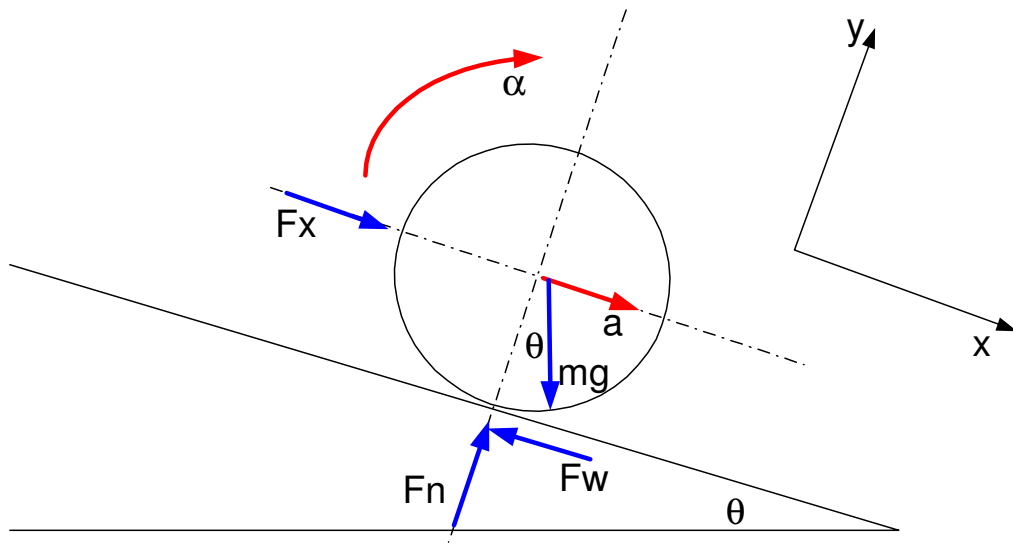


Figure 11: External Force on Sphere

$$\begin{aligned}
\sum F_x : m.a &= m.g.\sin(\theta) - F_w + F_x \\
&= m.g.\sin(\theta) - \mu F_n + F_x \\
&= m.g(\sin(\theta) - \mu \cos(\theta)) + F_x \quad \text{Equation 5} \\
\therefore a &= g(\sin(\theta) - \mu \cos(\theta)) + \frac{F_x}{m}
\end{aligned}$$

From the above calculations and the equations noted in [30]:

Table 5: Required gas flow for Sphere terminal velocity calculation

Equation	Variables	Description	Units
<i>Sphere Velocity Calculation ignoring rotation energy of the sphere</i>			
$V_g = V_s + \sqrt{\frac{2.g.m_s.\sin(\alpha)}{A_s.C_{dp}.\rho}}$ Equation 6	V_g	Gas velocity	m/s
	V_s	Sphere terminal velocity	m/s
	g	Gravitational acceleration – (9.81)	m/s ²
	m_s	Sphere mass	Kg
	α	Pipe angle with horizon	°
	A_s	Sphere cross sectional area	m ²
	C_{dp}	Drag coefficient for a sphere in a pipe	-
	ρ	Gas density	kg/m ³
<i>Sphere Velocity Calculation</i>			
$V_g = V_s + \sqrt{\frac{2.g.m_s.\sin(\alpha - \mu.\cos(\alpha))}{A_s.C_{dp}.\rho}}$ Equation 7	All variables are depicted as above		
	μ	Friction Force Coefficient $\mu = 2/7.\tan(\alpha)$	-
<i>Sphere Drag Coefficient Calculation</i>			
$C_{dp} = C_{ds} + \frac{D_p}{(1 - D_p)^2}$ Equation 8	C_{ds}	Free Flow Sphere Drag Coefficient	-
	D_p	Pipe/Sphere Area Ratio, with $D_p = (\text{Sphere Diameter}/\text{Pipe Diameter})^2$	-

From the equations of table 2 it is possible to calculate the required gas velocity to achieve a specific sphere terminal velocity. To calculate the sphere acceleration, velocity and displacement vs. time, a force balance on the sphere is applied.

Table 6: Sphere acceleration, velocity and displacement calculation

Equation	Variables	Description	Units
Gravitational force on sphere			
$F_g = \sin(\alpha).m_s.g$ Equation 9	All variables are depicted as above		
	F_g	Gravitational Force, which is the component of the force in the x direction.	N
Gravitational force on sphere including sphere roll			
$F_g = (\sin(\alpha) - \mu.\cos(\alpha)).m_s.g$ Equation 10	All variables are depicted as above		
Drag force on sphere			
$F_d = \frac{1}{2}.\rho.C_{dp}.A_s.(V_g - V_s)$ Equation 11	All variables are depicted as above		
	F_d	Drag Force on Sphere	N
Resultant force on sphere			
$F_{res} = F_g - F_d$ Equation 12	All variables are depicted as above		
	F_{res}	Resultant Force on Sphere	N
Sphere acceleration as			
$a = \frac{F_{res}}{m_s}$ Equation 13	All variables are depicted as above		
	a	Sphere acceleration	m/s ²
Sphere Velocity			
$V_s = V_s(t - 1) + a.t$ Equation 14	All variables are depicted as above		
	t	Time interval (taken as 0.01s)	S
Sphere Displacement			
$x = x(t - 1) + V_s.t$ Equation 15	All variables are depicted as above		
	x	Sphere Displacement	M

Note that the sphere velocity drag coefficient does not have to be adjusted for the Reynolds number range of simulations done, as the flow is laminar for both cases. For calculations including the rotation energy of the sphere, it is assumed that there is no slip between the sphere and the pipe surface. It is also assumed that the sphere rotation velocity is zero as it enters the pneumatic brake section.

3.2.4 EFFECT OF SPHERE ROTATION ENERGY

The current equations used to calculate the sphere velocity profile do not compensate for friction forces between the sphere and pipe wall. It also does not include the energy dissipated by the sphere rotation.

If it is assumed that the sphere is not rotating when it enters the pneumatic brake and that there is zero friction between the sphere and pipe wall, the sphere friction coefficient can be defined as

$$\mu = \frac{2}{7} \tan(\theta) \quad \text{from Equation 4}$$

The sphere acceleration calculation becomes:

$$a = g(\sin(\theta) - \mu \cos(\theta)) + \frac{F_x}{m}, \quad \text{from Equation 5}$$

when the wall friction and sphere rotation are taken into account.

From the simulations, which include the sphere rotation energy, it was evident that at low pressure the system is more sensitive to sphere rotation. The greater the pipe angle (relative to vertical) becomes, the larger the difference between the calculated sphere velocities (including and excluding the sphere slip and rotation) becomes, as indicated below:

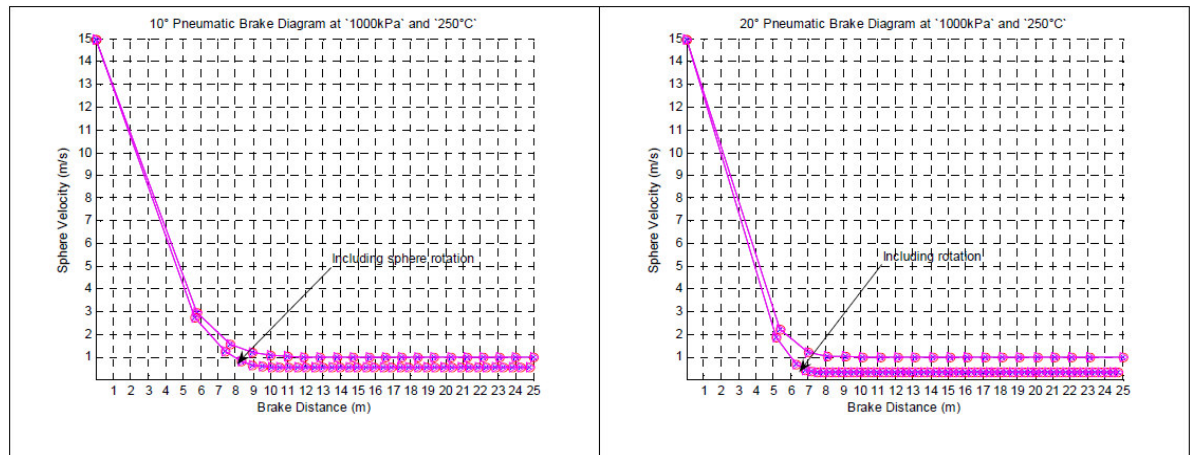


Figure 12: Example of Sphere rotation included in sphere velocity calculation

From Figure 12 sphere rotation results in a lower exit velocity. For the purpose of the study the effect of the sphere rotation is ignored, therefore the exit velocity calculated is considered conservative relative to the sphere exit velocity.

3.2.5 FHSS SIMULATION SET-UP PARAMETERS

This section explains the boundary values used and simulation parameters for the following FHSS operation conditions:

- High Pressure/Normal Operation
- Low Pressure/Defuel and Refuel Operation

3.2.6 HIGH PRESSURE/NORMAL OPERATION

The required helium and air gas velocity was calculated using Equation 7. During this mode of operation, the plant is at a varying power level, controlled by the helium inventory. It is required that spheres are circulated between 9000 kPa and 3300 kPa helium at about 150 °C.

Sphere velocities are calculated with the average sphere lifting velocity 90° upwards (vertically) between 2 - 4 m/s and the sphere brake velocity at a 10° slope, having a terminal velocity of about 1 m/s.

The following assumptions were made for the analysis:

- The sphere storage tanks are isolated from the FHSS.
- Continuous dust pocket cleaning is included for only the IBA FRI's. 10 mm Internal Diameter (ID) piping for horizontal dust pocket extraction pipes and 12.7 mm ID piping for vertical sections are used.
- Sphere lifting is controlled to only one sphere per lift line at any moment and three spheres simultaneously in the separate lift lines.
- Should the blower exit temperature exceed 250 °C for any analysis, the heat exchanger will be used to control the blower exit temperature to 250 °C. It is assumed that the heat exchanger exit temperature is 50 °C.
- Sphere weight for simulation purposes is calculated using a density of 1.75 g/cm³.
- All the control valves utilised in the simulations contribute at least 30% of the total system pressure loss as required for controllability.
- For dust cleaning the required gas velocity is:

$$\text{Velocity (m/s)} = 24.3 \times [\text{Gas Density (kg/m}^3\text{)}]^{-1/2} \text{ [30]}$$

3.2.6.1 CIRCULATE EQUILIBRIUM CORE

The following boundary temperature and pressures conditions were used for the simulation [49]:

Table 7: Circulation Operation System Boundary Conditions

Steady State Nr	Operational Steady State	Node 2 – Reactor Core Outlet		Node 78 – Manifold		Node 98 – Void above reactor core	
		T (°C)	P (kPa)	T (°C)	P (kPa)	T (°C)	P (kPa)
MPS-SS0052	100%MCR 100%MCRI 900°C ROT 18°C CWT	946	8673	93	9000	487	8881
MPS-SS0065	15%MCR 40%MCRI 900°C ROT 18°C CWT	939	3277	71	3389	500	3348

Note that the MPS steady state numbers, i.e. MPS-SS0052, refer to a particular steady state operating simulation of the PBMR plant. The boundary values from these simulations were used as input to the FHSS simulations.

The system gas mass balance and blower design points calculated were derived from two philosophies. The first philosophy is described in 1A and 1B below and the second philosophy in 2C and 2D.

Sphere Velocity Limit philosophy 1:

1A. The FHSS brake and gas supply valves were set to ensure that a 58.5 mm sphere has a lifting line terminal velocity of 2 m/s and brake line terminal velocity of 1.2 m/s at MPS-SS0065. This condition represents the allowable limits of 2 - 4.5 m/s for lifting line sphere velocities and 0.5 - 1.2 m/s for sphere velocities at the brake exit.

1B. The same valve settings were used as calculated for the mass balance at MPS-SS0065, sphere velocity limit philosophy 1-A. System temperatures and pressures were set to MPS-SS00052. The blower speed was adjusted in the simulation to ensure a 58.5 mm sphere lifting line terminal velocity of 2 m/s.

Sphere Velocity Limit philosophy 2:

2C. The system temperatures and pressures are set to MPS-SS00052. The blower speed is adjusted to ensure a 58.5 mm sphere lifting line terminal velocity of 2 m/s. The same lift line supply valve settings are still used as calculated in philosophy 1 above. The brake line supply

valve settings are adjusted to ensure that a 61 mm sphere will have a brake line terminal velocity of 0.5 m/s.

2D. The same valve settings are used as calculated above for the mass balance at sphere velocity limit philosophy 2-C. The system temperatures and pressures are set to MPS-SS00065. The blower speed is adjusted to ensure a 58.5 mm sphere lifting line terminal velocity of 2 m/s.

The blower design parameters are presented in section 4. All the control valves utilised in the simulations contribute 30% or more of the total system pressure loss as required for controllability.

3.2.7 LOW PRESSURE/DEFUEL AND REFUEL OPERATION

The defueling operation takes place at a lower system pressure of about 1000 kPa. Spheres get withdrawn from the reactor and diverted to storage tanks, where it will be temporarily stored. This is done to prepare the reactor for maintenance and inspection. Once the maintenance and inspection is complete the reactor vessel is refuelled with the spheres again.

The required helium and air gas velocity was calculated using Equation 7. During this mode of operation, the plant is at a minimum pressure of 1000 kPa helium and a maximum temperature of 250 °C.

The following assumptions were made for the analysis:

- The storage tanks have an absolute pressure of 1 MPa.
- The influence of continuous dust pocket cleaning for all FRI's is investigated and included in this document.
- The pressure drop across all control valves actively used for controlling the gas flow during the specific simulation shall be at least 30% of the total system pressure drop.
- Sphere lifting is controlled to only one sphere per lift line at any moment.
- Heat input of 100 spheres per buffer is accounted for.
- The density of a sphere (fuel or graphite) is assumed to be 1.7g/cm³.
- The blower bypass line shall never determine the system total resistance. If the bypass line resistance is larger than the system resistance, the line size shall be increased and noted as such.
- The current Helium Test Facility (HTF) blower characteristics, which are very similar the FHSS in theory, shall be used to represent the FHSS blower for simulation purposes [53]. Once the study is complete specific characteristic will be derived for the FHSS system and will then be used in future to simulate the FHSS system more accurately.

The required sphere velocities for the different required modes of operation are calculated below:

There are two options for the Refuel Process, which is reliant on the preceding process.

If refuel follows a Used Core Graphite Load, the core is initially considered to contain only graphite. Graphite spheres are removed from the core whilst being filled with fuel spheres transported from the fuel storage area. If refuelling follows a de-fuel operation, the core contains a mix of graphite and fuel. The remaining graphite spheres are separated from the fuel spheres.

For the Flownex simulations, the pressure to node 2095, representing the *graphite tank assembly*, has been fixed at 1000 kPa, (maximum allowable tank pressure). The reactor exit temperature is fixed at 250 °C, which is the maximum allowable sphere temperature before entering the FHSS.

3.2.7.1 SPHERE LINES FLOW RATE CALCULATION FOR REFUELLING OPERATION

The required circulation rate of spheres is given as approximately 1000 spheres/hour [47].

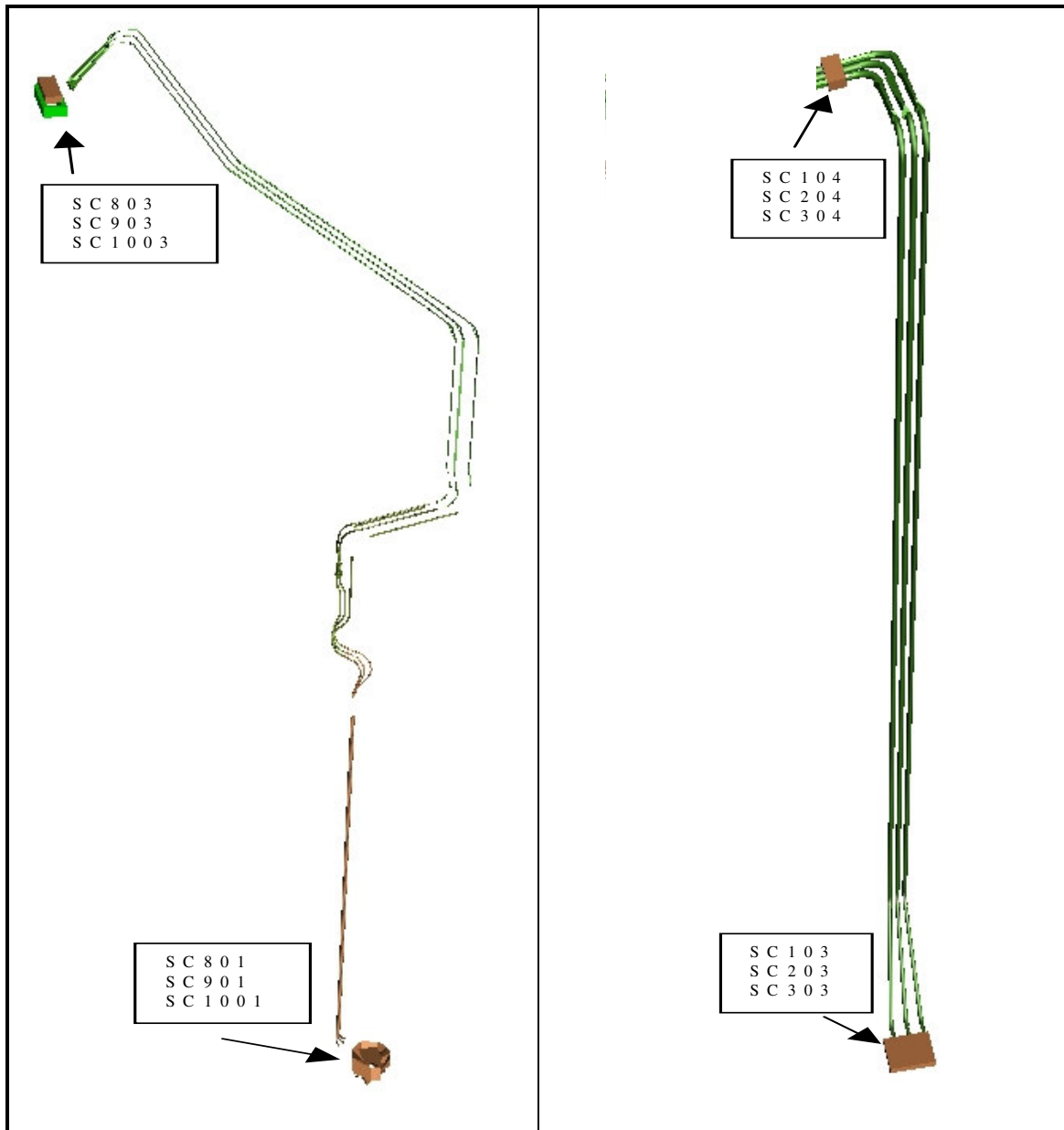
Thus:

$$\begin{aligned}
 1000 \text{ Spheres/hour} &= 0.278 \text{ Spheres/second} \\
 &= 3.6 \text{ seconds/Sphere} \\
 &\text{There are 3 sphere-conveying lines} \\
 \therefore &= 10.8 \text{ seconds/Sphere for an individual line}
 \end{aligned}$$

This assumption is considered to be conservative due to the actual circulation rate stated in [47] being slightly less than 1000. The mass flow rate required in the sphere conveying lines is calculated to lift a 58.5 mm sphere in 10.8s for the following sections as taken from the FHSS layout model. Larger spheres will thus circulate at a faster rate.

Table 8: Sphere flow path for mass flow rate calculation

Used Fuel/Graphite Spheres lifting from storage area:		Fuel/Graphite Spheres removed from reactor:	
From Sphere Counter	To Sphere Counter	From Sphere Counter	To Sphere Counter
SC801	SC803	SC103	SC104
SC901	SC903	SC203	SC204
SC1001	SC1003	SC303	SC304



As an estimate, the mass flow rate is only calculated for one line in each section and then used as the required flow rate in the other two lines.

Using the sphere conveying equations as previously described, the piping layout is simulated and a lift mass flow rate is calculated to ensure that a 58.5 mm sphere is conveyed in approximately 10.8 seconds. From the simulations, it is also evident that the pneumatic brake sections are too short for the spheres to reach terminal velocity, as can be seen in figures 12,

13 and 14. The brake line mass flow is therefore adjusted to ensure that a 61 mm sphere will leave the brake at about 0.5 m/s.

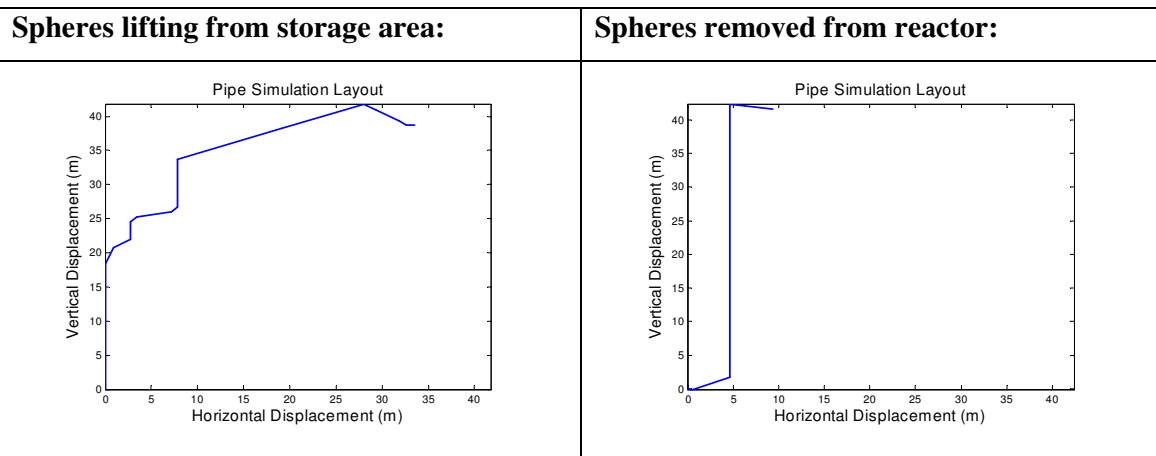


Figure 13: Side view of sphere conveying piping simulated

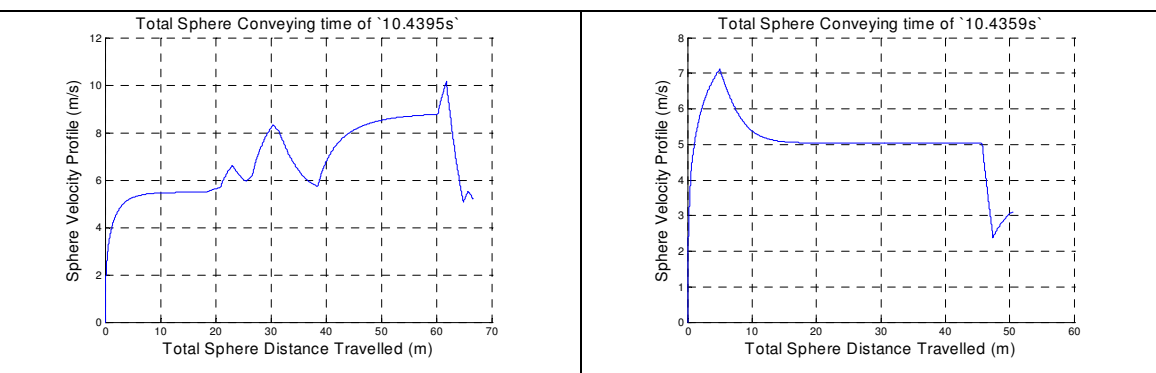


Figure 14: Sphere Velocity Profile for a 58.5 mm sphere

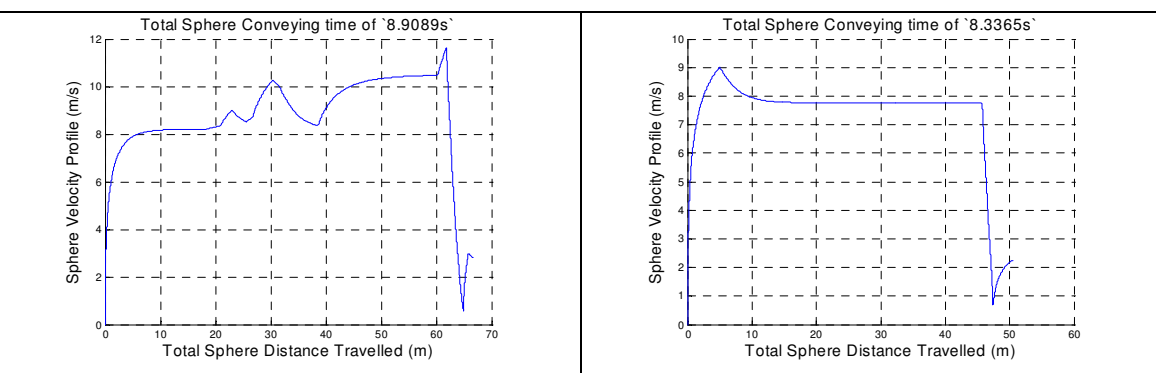


Figure 15: Sphere Velocity Profile for a 61 mm sphere

From the above results, the mass flow rates calculated to lift a 58.5 mm sphere in less than 10.8s and ensure that a 61 mm sphere exits the pneumatic brake at 0.5 m/s, are as follow:

Used Fuel/Graphite Spheres lifting from storage area lift line mass flow rate = 0.054kg/s

Used Fuel/Graphite Spheres lifting from storage area brake line mass flow rate = 0.0159kg/s

Fuel/Graphite Spheres removed from reactor lift line mass flow rate = 0.0523kg/s

Fuel/Graphite Spheres removed from reactor brake line mass flow rate = 0.0148kg/s

3.2.7.2 FHSS PNEUMATIC BRAKE ANALYSIS DURING REFUELLING OPERATION

The thermo-hydraulic data obtained were for simulations without continuous dust pocket cleaning. The sphere impact velocities were also calculated from this data.

There are three pneumatic brake sections active during the refuelling operation (shown in figures 16, 17 and 18), namely:

- a. 10° Pneumatic brake section at the top of the reactor before the spheres enter the measurement block section.

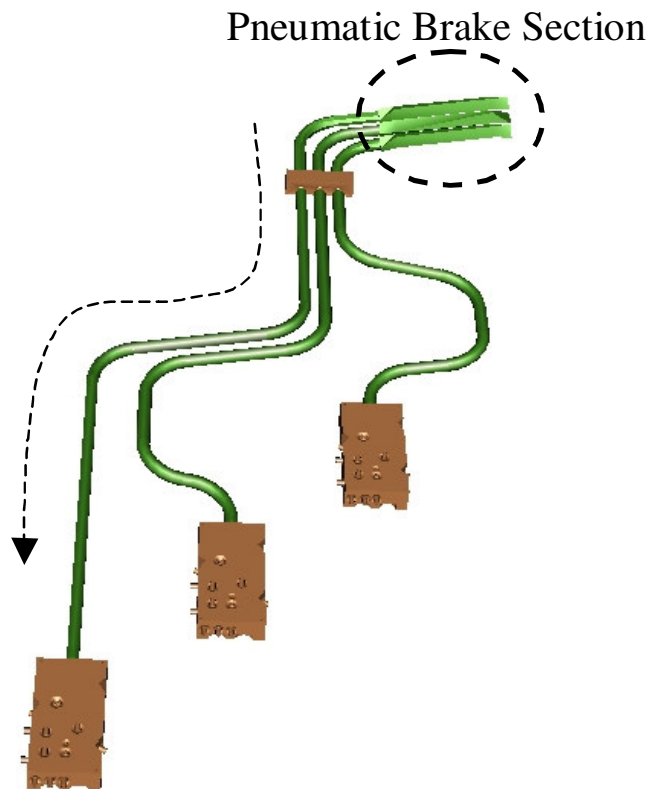


Figure 16: 10° Pneumatic Brake Section

- b. 33.4° Pneumatic brake section before the charge lock outlet assembly coming from the sphere storage area.

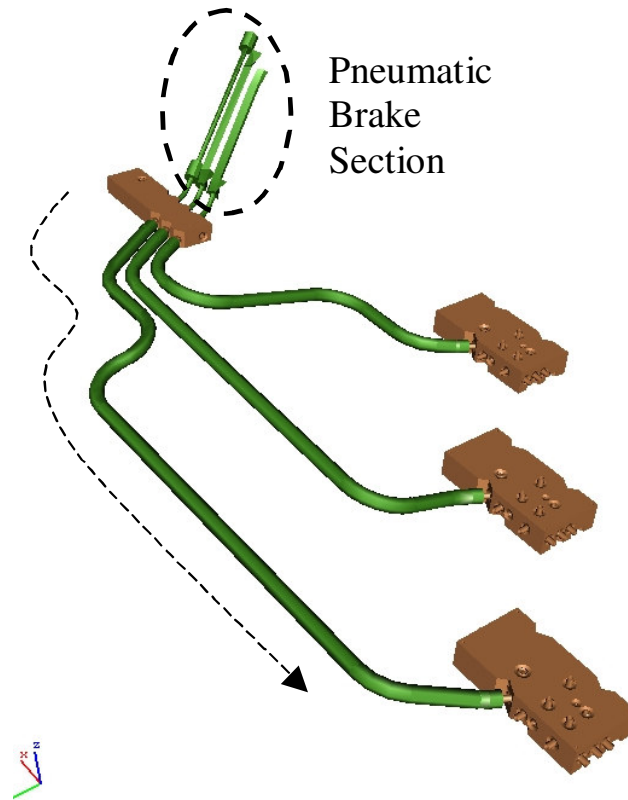


Figure 17: 33.4° Pneumatic Brake Section

- c. Multi angled pneumatic brake section for spheres transported to the sphere storage area

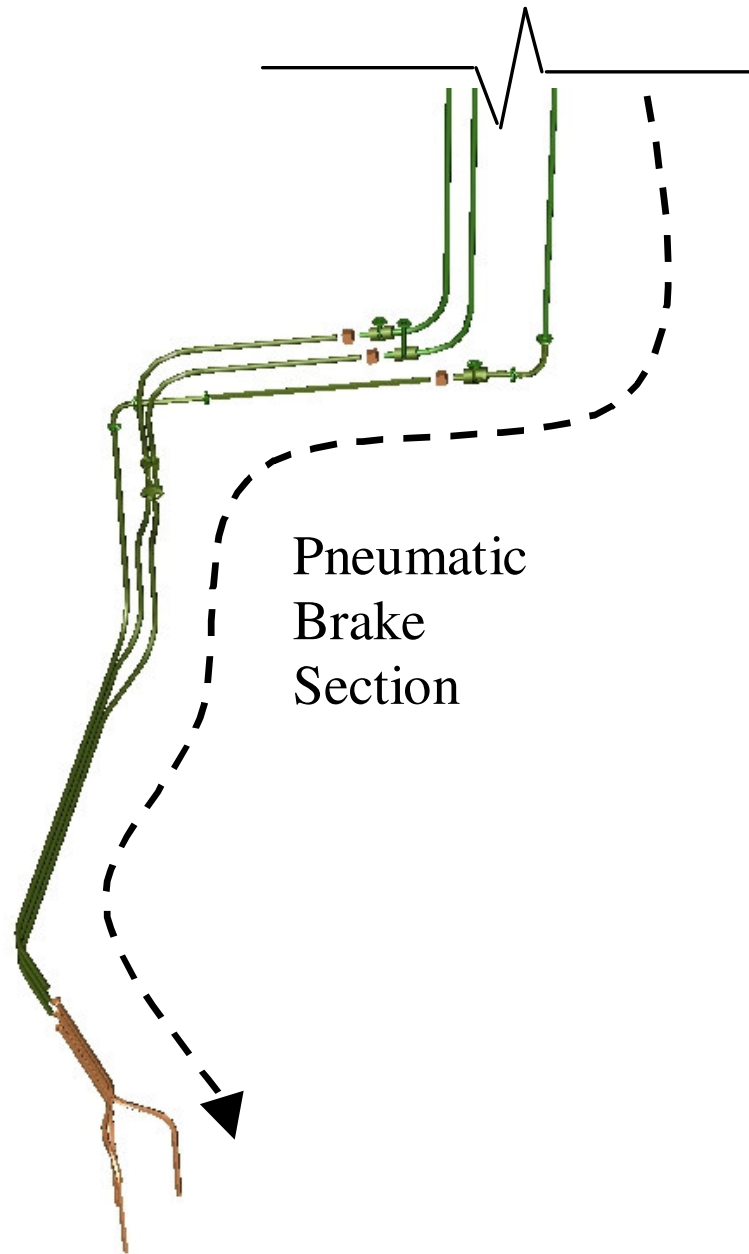


Figure 18: Pneumatic Brake Section before sphere storage area

The following FHSS Pneumatic Brake Analysis results indicate the velocity profile for both 58.5 and 61 mm spheres in the relevant pneumatic brake section. Also displayed are the sphere impact velocities after the spheres exit the pneumatic brake sections and roll under gravity downstream to the relevant Flow Restricting Indexer (FRI).

Note that the sphere velocity profile is only for the relevant pneumatic brake section and not the entire flow path, which includes the sphere lifting profile, etc. The graphs shown in figure 19, 20 and 21 are also for all three-line sections, superimposed on one another, every time.

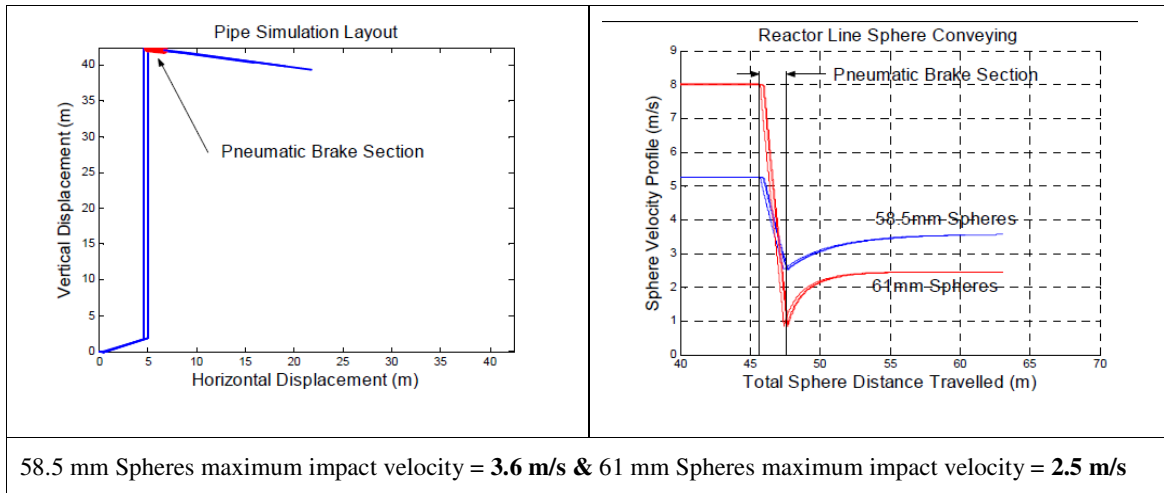


Figure 19: 10° Pneumatic Brake Section Analysis

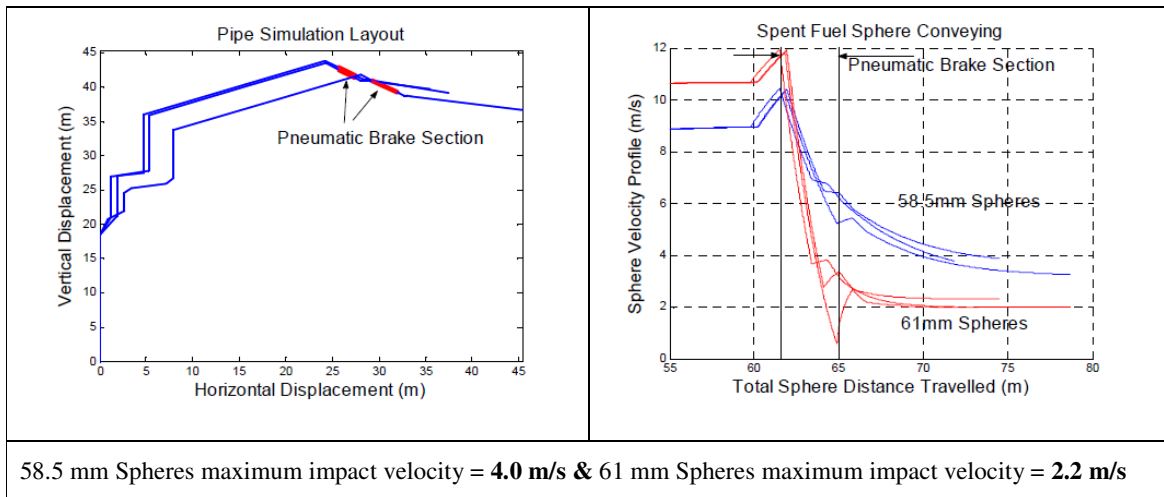


Figure 20: 33.4° Pneumatic Brake Section Analysis

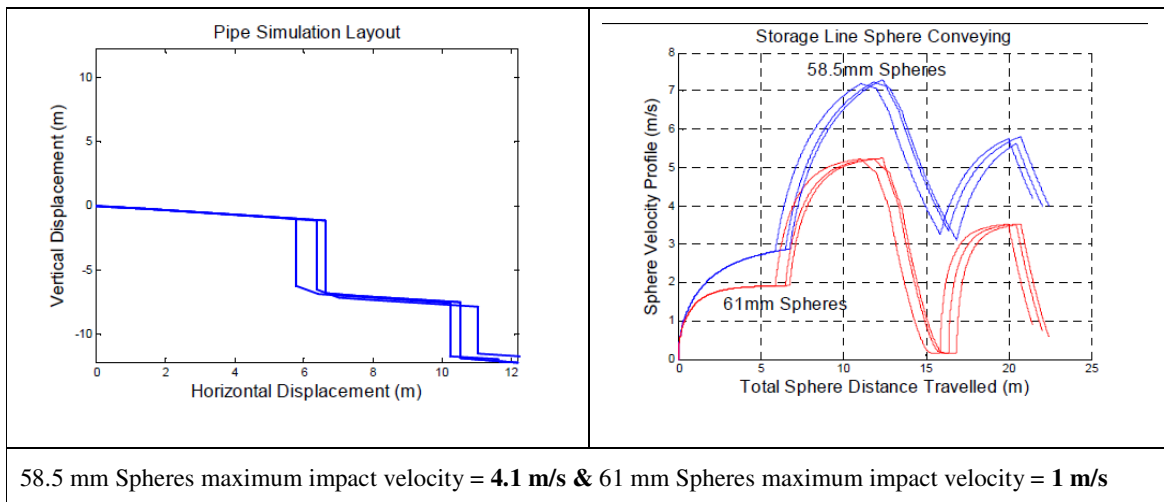


Figure 21: Multi Angled Pneumatic Brake Section Analysis

4. INTERPRETATION AND VERIFICATION OF RESULTS

4.1 PREAMBLE

This chapter describes the interpretation of the simulation results. The process that was followed for the analysis as well as the experimental modes, are also described.

A number of assumptions were made during the analysis. These assumptions are given and motivated to verify that valid results were obtained. The convergence criteria and relaxation parameters that were selected are given and verified to be acceptable.

The detailed results that were obtained are also given and discussed in this chapter.

4.2 SENSITIVITY AND MONTE CARLO STUDY RESULTS

4.2.1 SENSITIVITY STUDY OF CALCULATION PARAMETERS

A sensitivity and Monte Carlo study was conducted to establish whether any key parameters or variables might significantly influence the calculations. This will also ensure that there is sufficient confidence in the calculated sphere velocity profiles. Otherwise, additional calculations or research may have to be conducted.

The aim of the sensitivity study was to vary single calculation input parameters one at a time and compare the various sphere computed terminal velocities. This procedure would determine which single parameter had the largest effect on the calculated sphere velocity. All the results were varied randomly with a normal distribution for the Monte Carlo study. From these results, a sphere velocity exit band profile could be determined for each operating condition. 10 000 different runs were made for the Monte Carlo study.

For the sensitivity study, the computed sphere drag coefficient was varied by $\pm 10\%$. This was done to compensate for the uncertainty of the drag coefficient calculation. For the Monte Carlo study, the free flow drag coefficient of 0.4 was varied by 10%. The other parameters were varied as follows:

1. Pipe diameter by $\pm 1\%$
2. Sphere diameter between 59.3 - 60.3 mm
3. Gas velocity by $\pm 5\%$
4. Gas density by $\pm 2\%$

5. Sphere density between 1.75 - 1.85g/cm³

6. Pipe angle by $\pm 1^\circ$ for the series of simulations.

All the sensitivity studies were conducted in helium at:

a) 250 °C and 1000 kPa,

b) 150 °C and 3300 kPa,

c) 150 °C and 9000 kPa,

for a 10° pneumatic break. The counter flow calculated is for a 60.3 mm sphere with a terminal brake exit velocity of 1 m/s.

Table 9 refers to a, b and c for the helium temperatures and pressures as referenced above.

4.2.2 SENSITIVITY STUDY RESULTS

Table 9: Parameter Input Sensitivity Study

	Parameters									
Nr	Cd			ϕ Pipe			ϕ Sphere			TERMINAL VELOCITY
	-			(mm)			(mm)			(m/s)
1a	18.4	20.4	22.4	66.7			59.3			1.69
1b										1.50
1c										1.34
2a	20.4	65.64	66.70	66.69			59.3			1.35
2b										1.25
2c										1.17
3a	20.4	66.7					58.5	59.3	60.3	1.22
3b										1.15
										1.10
										1.82
										1.50
										1.19
										1.14
										1.09
										1.26
										1.15
										1.06
										1.90
										1.50
										1.00
										1.46
										1.25
										1.00

3c						0.075			9.959				1.29	1.16	1.00
4a	20.4	66.7	59.3	1.95	2.05	2.15	0.918			1.75	1.60	1.50	1.40		
4b				0.49	0.52	0.54	3.716				1.28	1.25	1.22		
4c				0.071	0.075	0.078	9.959				1.16	1.15	1.15		
5a	20.4	66.7	59.3	2.048			0.90	0.92	0.94	1.75	1.54	1.50	1.47		
5b				0.515			3.64	3.72	3.79		1.27	1.25	1.23		
5c				0.075			9.76	9.96	10.16		1.17	1.15	1.14		
6a	20.4	66.7	59.3	2.048			0.918			1.75	1.80	1.85	1.60	1.55	1.50
6b				0.515			3.716						1.30	1.28	1.25
6c				0.075			9.959						1.18	1.17	1.15

From these results, it is evident that at low operating pressures, resulting in low helium densities, the parameter input sensitivity has the highest percentage difference between the varied input parameters as depicted in Table 7.

Table 10: Sensitivity study summary

Parameter	% Difference at:		
	<i>1000 kPa 250 °C Helium</i>	<i>3300 kPa 150 °C Helium</i>	<i>9000 kPa 150 °C Helium</i>
Cd	12.67 -10.67	8.0 -6.4	6.09 -4.35
ϕ Pipe	23.33 -20.67	8.68 -12.8	9.04 -8.52
ϕ Sphere	26.94 -33.28	16.97 -20.05	11.27 -13.42
Gas Velocity	6.87 -6.87	2.01 -2.05	0.33 -0.32
Gas Density	2.45 -2.31	1.38 -1.41	0.95 -1.01
Sphere Density	3.30 -3.27	1.96 -2.07	1.23 -1.33

Table 11: Pipe angle sensitivity

	1000 kPa and 250 °C Operation			3300 kPa and 150 °C Operation			9000 kPa and 150 °C Operation		
<i>Angle</i>	<i>9 °</i>	<i>10 °</i>	<i>11 °</i>	<i>9 °</i>	<i>10 °</i>	<i>11 °</i>	<i>9 °</i>	<i>10 °</i>	<i>11 °</i>
V_{exit}	1.52	1.50	1.48	1.26	1.25	1.24	1.16	1.15	1.15
%Dif	1.62	0.00	1.63	0.92	0.00	0.96	0.57	0.00	0.59

From these results, it is evident that the pipe diameter and sphere diameter have the highest sensitivity compared to the sphere terminal velocity calculated. This is because these two inputs are used to calculate the sphere drag coefficient (see **Equation 8**), which is an exponential equation.

4.2.3 MONTE CARLO STUDY OF CALCULATION PARAMETERS RESULTS

The aim of the Monte Carlo study was to calculate the exit velocity distribution at the pneumatic break sections. The gas mass balance in the sphere break lines has to ensure that the spheres do not change direction, thus becoming a blockage in the sphere line.

Ultimately the gas mass balance would influence the blower design parameters.

The graphs below will indicate the normally calculated result displayed in red with the various simulated results from the Monte Carlo analysis spread in blue.

4.2.3.1 MONTE CARLO STUDY RESULTS AT 1000 KPA AND 250 °C

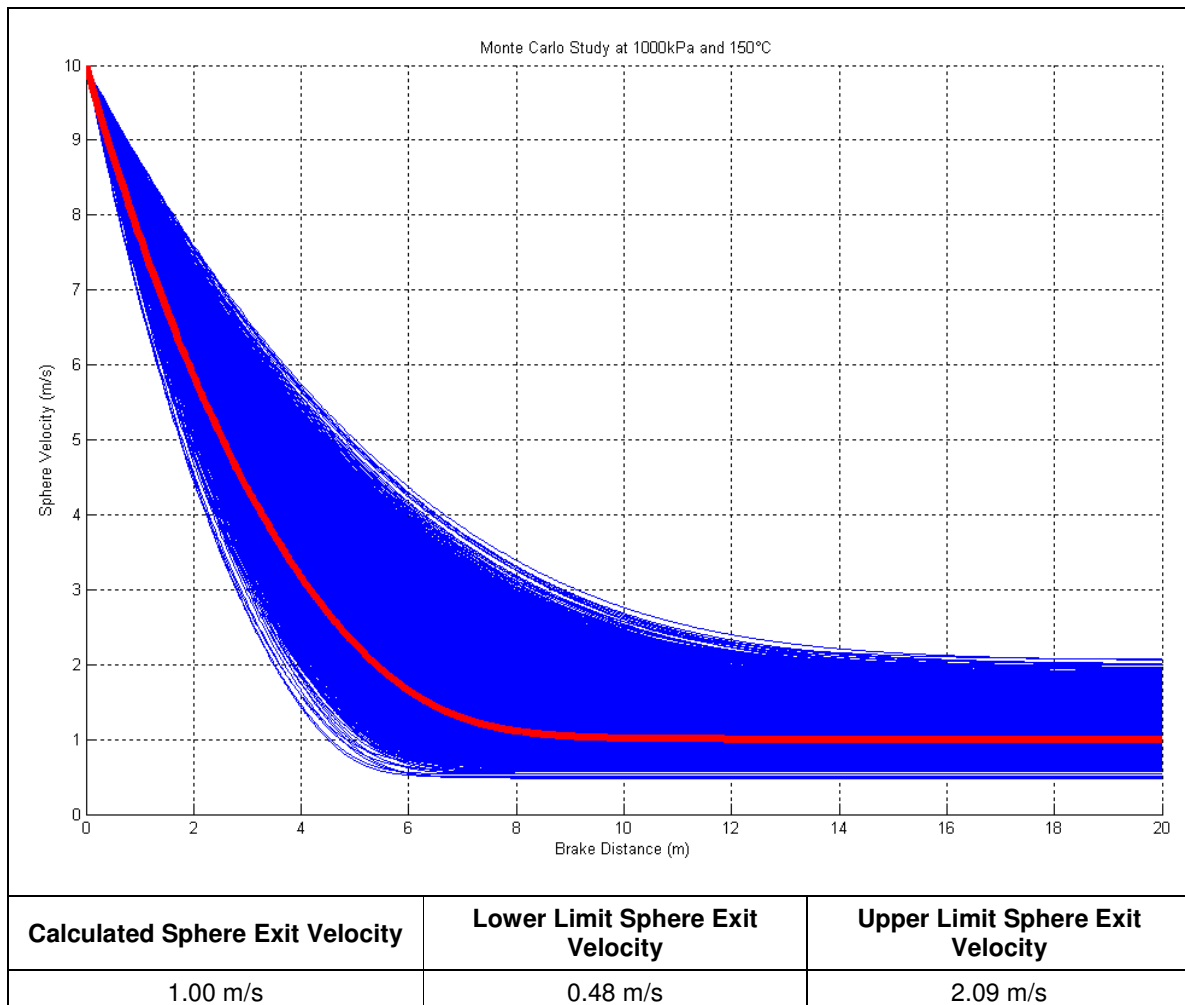


Figure 22: Monte Carlo Results at 1000 kPa and 250°C

4.2.3.2 MONTE CARLO STUDY RESULTS AT 1000 KPA AND 250 °C WITH NO COUNTER FLOW

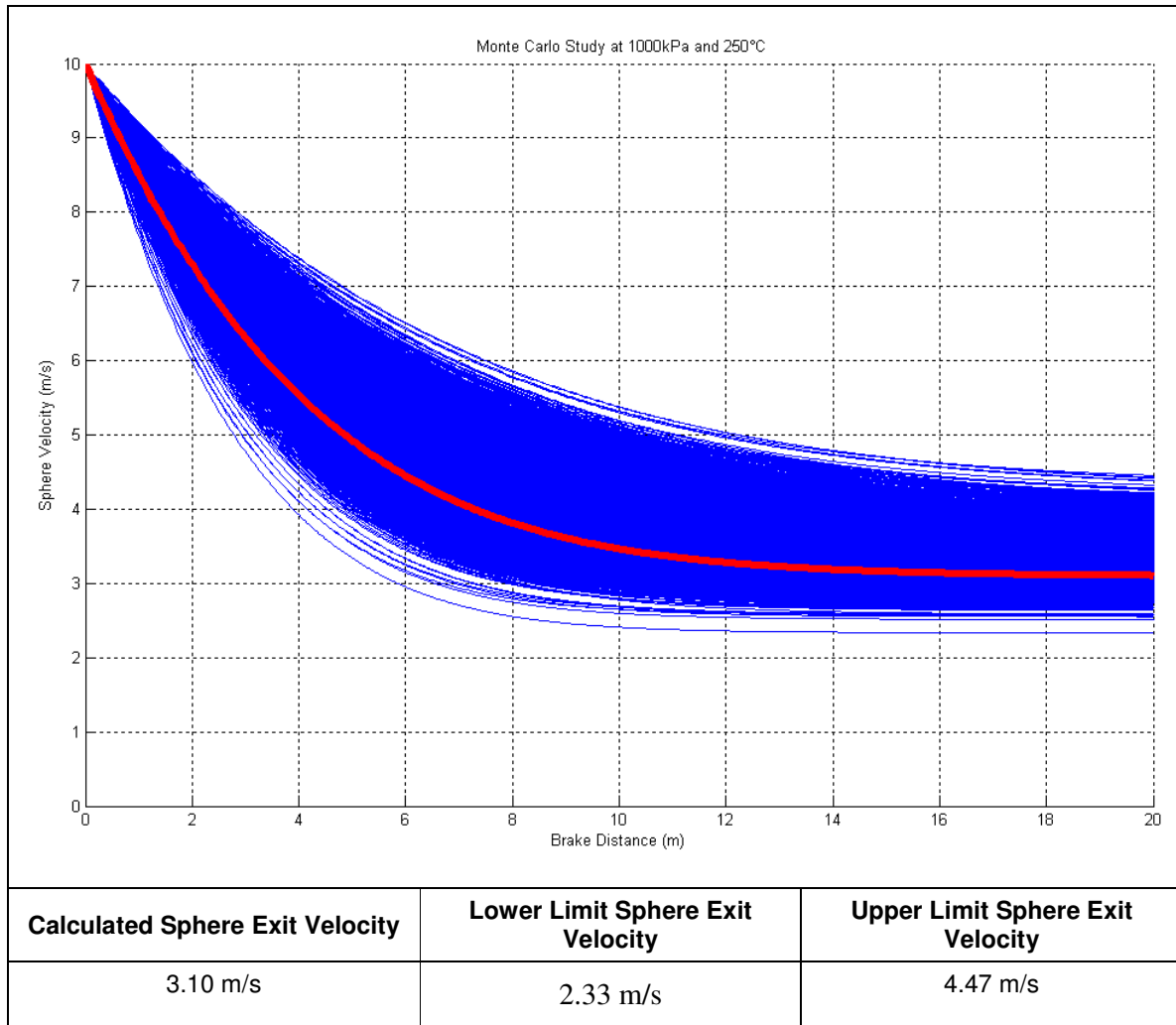


Figure 23: Monte Carlo Results at 1000 kPa and 250°C with no counter flow

4.2.3.3 MONTE CARLO STUDY RESULTS AT 3300 KPA AND 150 °C

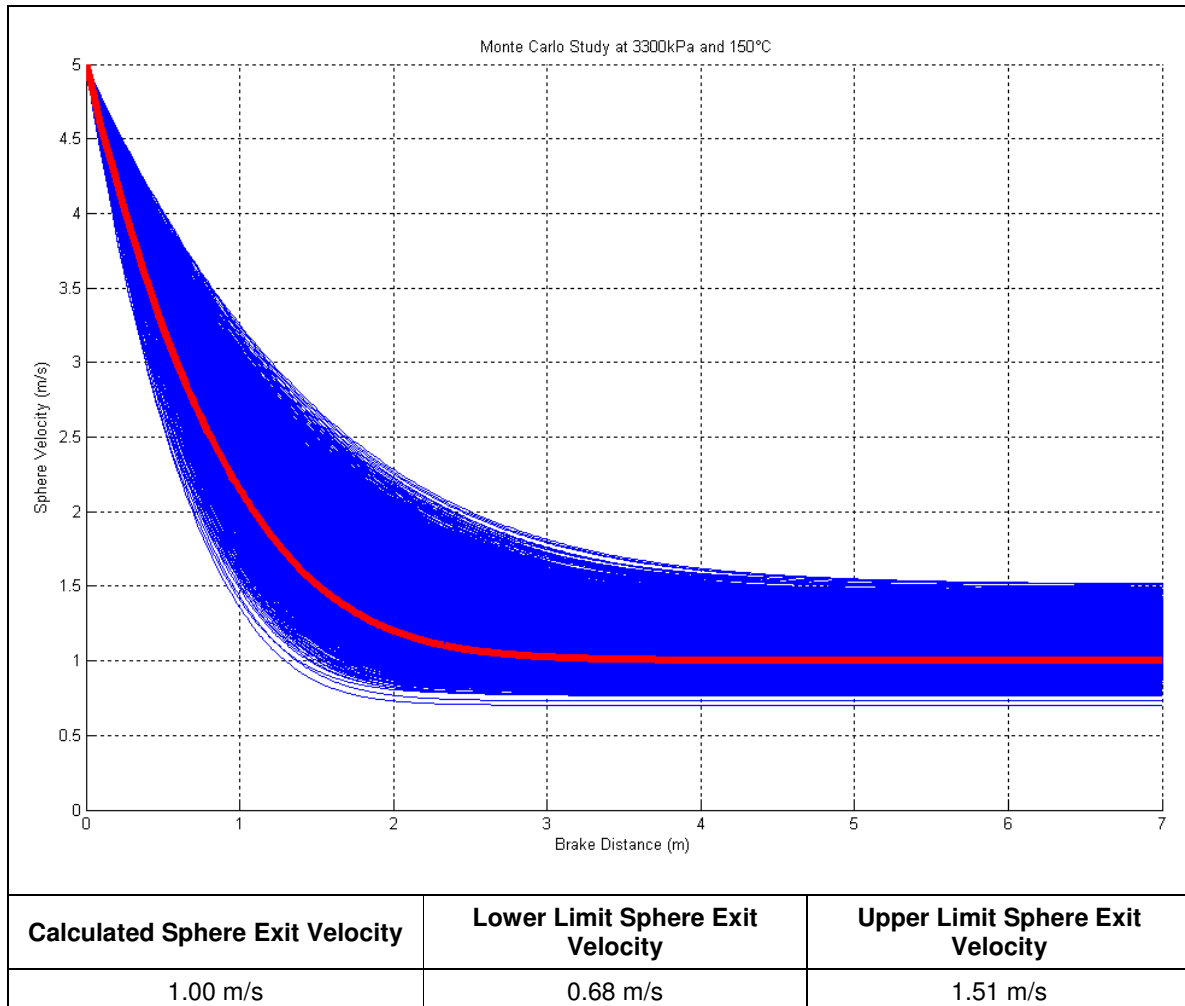


Figure 24: Monte Carlo Results at 3300 kPa and 150°C

4.2.3.4 MONTE CARLO STUDY RESULTS AT 3300 KPA AND 150 °C WITH NO COUNTER FLOW

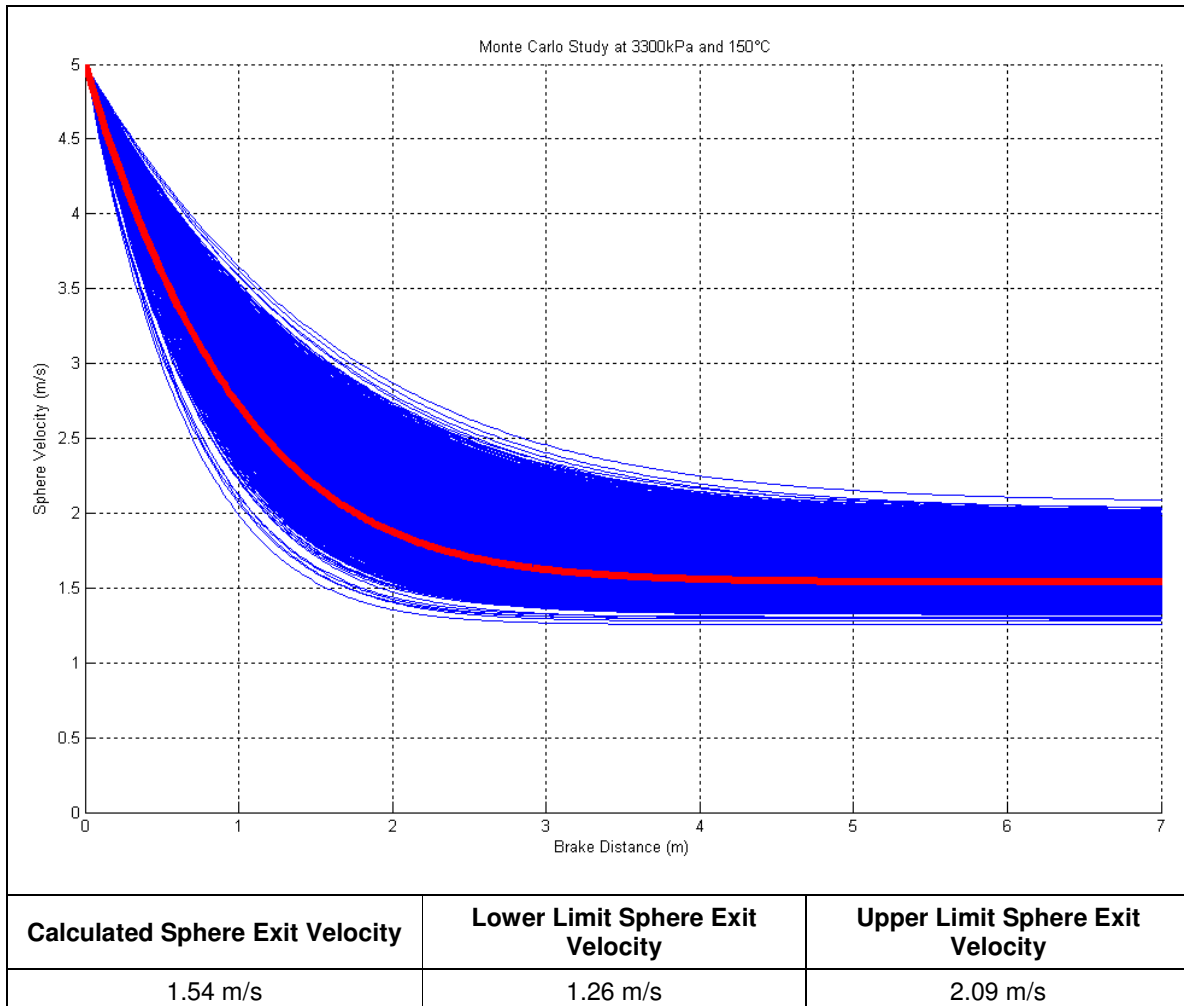


Figure 25: Monte Carlo Results at 3300 kPa and 150°C with no counter flow

4.2.3.5 MONTE CARLO STUDY RESULTS AT 9000 KPA AND 150 °C

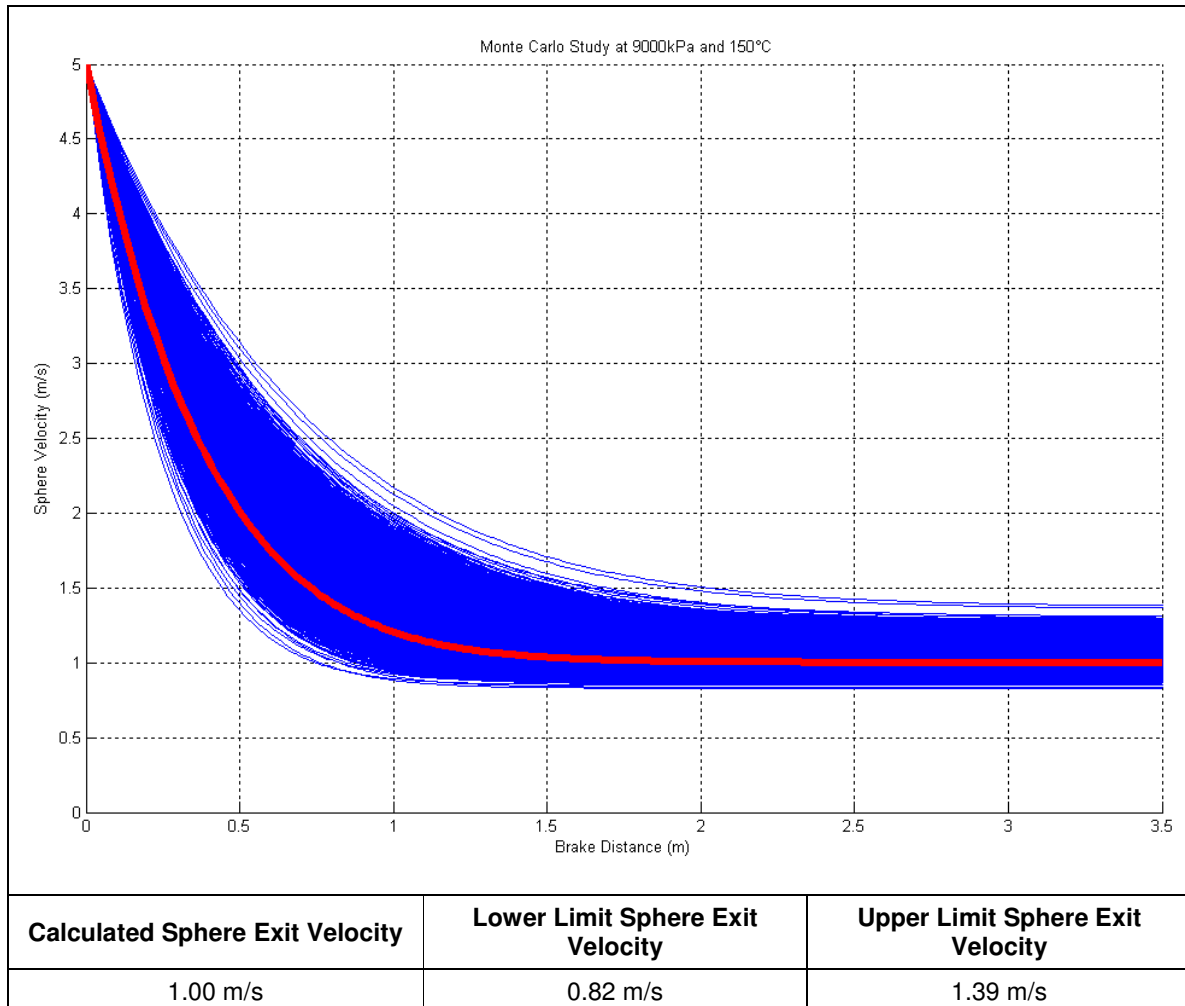


Figure 26: Monte Carlo Results at 9000 kPa and 150°C

4.2.3.6 MONTE CARLO STUDY RESULTS AT 9000 KPA AND 150 °C WITH NO COUNTER FLOW

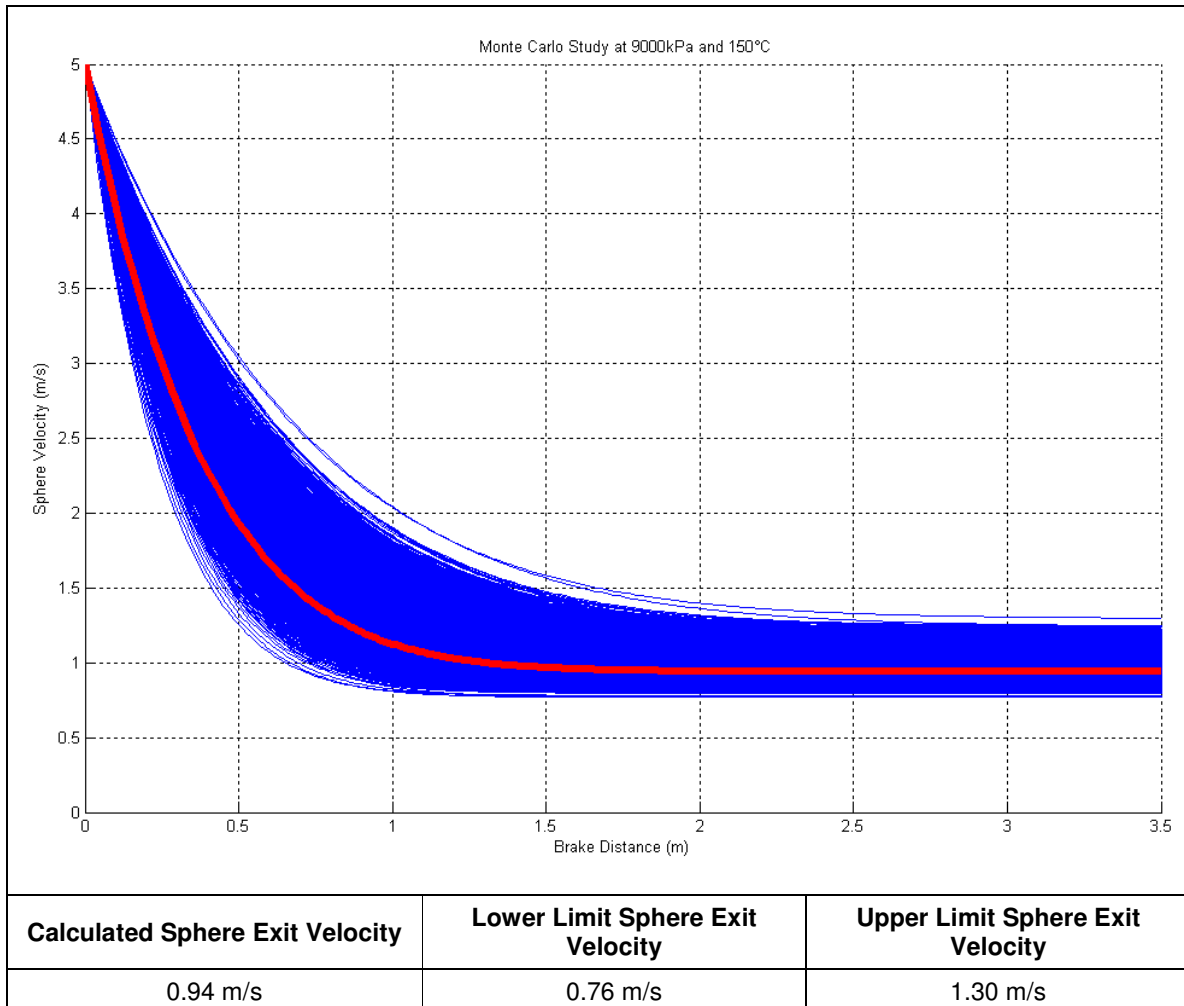


Figure 27: Monte Carlo Results at 9000 kPa and 150°C with no counter flow

From the Monte Carlo results, it is evident that at low pressures, the sphere exit velocity range is at its highest, varying between about 0.5 and 2 m/s. Important to notice is that no spheres changed direction in the brake section. For the sensitivity and Monte Carlo study sphere friction or rotation energy was not included in the sphere velocity profile calculations.

4.3 FHSS SIMULATION RESULTS

The following section describes the simulation results, based on the operating conditions at a high system pressure for normal operation and at a low pressure operation for defueling and refuelling the reactor. The tables presented in this section depict the blower operating parameters for the simulations whilst the graphs represent some operating points pressure ratio vs. the corrected mass flow rate.

4.3.1 HIGH PRESSURE/NORMAL OPERATION RESULTS

For normal circulation of spheres the required blower operating conditions are shown in the table below.

Table 12: FHSS sphere circulation required during normal blower operating conditions

Blower Parameters	Unit	Philosophy used, see pg 36			
		A	B	C	D
Total Pressure Blower Inlet	kPa	3329	8852	8854	3330
Total Pressure Blower Outlet	kPa	3370	8914	8913	3370
FHSS Blower Volume Flow Rate	kg/m ³	0.080	0.061	0.059	0.077
FHSS Blower Differential Pressure	kPa	41.36	61.99	59.53	39.78
FHSS Blower Pressure Ratio	-	1.012	1.007	1.007	1.012
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	0.199	0.148	0.142	0.192
FHSS Blower Mass Flow Rate	kg/s	0.345	0.675	0.652	0.334
Total Temperature Blower Inlet	°C	95.45	101.93	99.64	92.17
Total Temperature Blower Outlet	°C	100.82	104.96	102.47	97.17
Blower Efficiency (η)	-	33.85	34.30	34.98	34.63
Blower Bypass Mass Flow Rate	kg/s	0.00	0.00	0.00	0.00
Blower Fluidic Power	kW	9.66	10.71	9.69	8.71

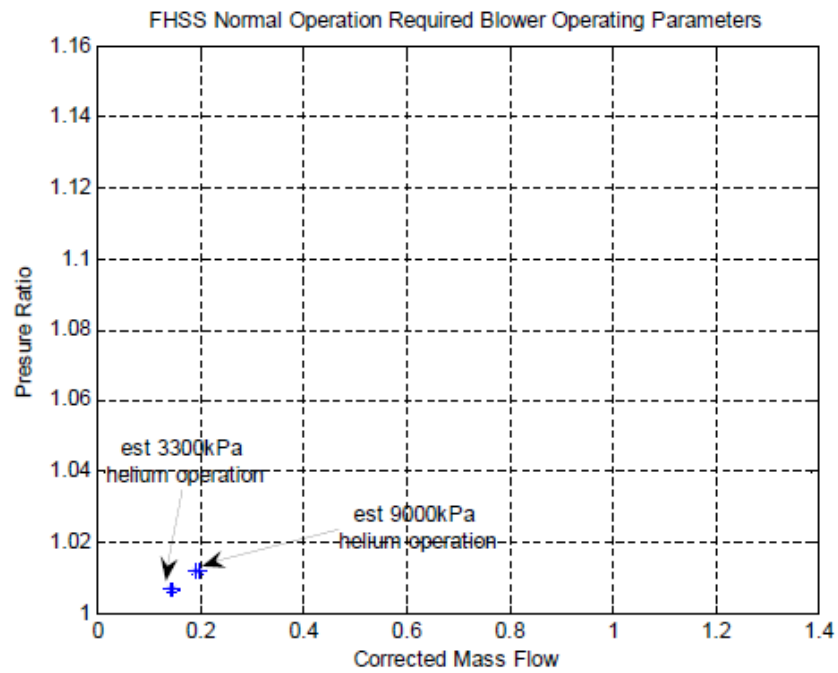


Figure 28: FHSS Normal Operation Required Blower Operating Parameters

The graph indicates the different operating points for the normal FHSSS system operation modes at two different system pressure operations.

4.3.2 LOW PRESSURE/DEFUEL AND REFUEL OPERATION RESULTS

4.3.2.1 BLOWER DESIGN PARAMETERS INCLUDING AND EXCLUDING CONTINUOUS FRI DUST POCKET CLEANING FOR REFUELLING OPERATION

Table 13: Blower Design Parameters for Refuelling Operation

Blower Parameters	Unit	Excluding continuous dust pocket cleaning	Including continuous dust pocket cleaning
Total Pressure Blower Inlet	kPa	962.95	989.26
Total Pressure Blower Outlet	kPa	1007.70	1141.61
FHSS Blower Volume Flow Rate	m ³ /s	0.397	0.509
FHSS Blower Differential Pressure	kPa	44.74	152.36
FHSS Blower Pressure Ratio	-	1.046	1.154
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{K}}{100 \cdot \text{kPa}}$	0.924	1.119
FHSS Blower Mass Flow Rate	kg/s	0.432	0.507
Total Temperature Blower Inlet	°C	151.42	203.85
Total Temperature Blower Outlet	°C	163.75	250.00
Blower Efficiency (η)	-	62.99	60.83
Blower Bypass Mass Flow Rate	kg/s	0.000	0.066
Blower Fluidic Power	kW	27.71	121.75

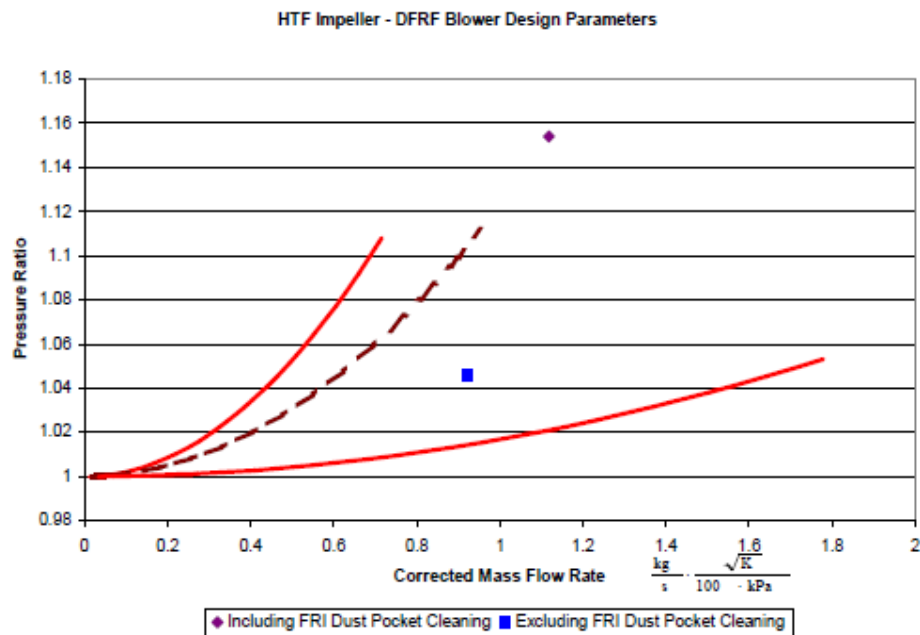


Figure 29: Blower Design Parameters overlaid on the HTF Impeller

4.3.2.2 FUEL CORE UNLOADING OPERATION

During this mode of operation, the used fuel tank is empty or has sufficient space to receive the spheres from the reactor core. The reactor and subsequent buffers are emptied of spheres,

and the spheres are stored in the appropriate tanks. The spheres are transferred to the used fuel tank, which is directly coupled to the reactor by three transfer lines, while the system pressure is below 1MPa (abs).

The Flownex simulation calculated the blower design parameters as shown in table 11:

Table 14: Blower Design Parameters for Refuelling Operation

Blower Parameters	Unit	Value
Total Pressure Blower Inlet	kPa	978.58
Total Pressure Blower Outlet	kPa	1003.40
FHSS Blower Volume Flow Rate	m ³ /s	0.179
FHSS Blower Differential Pressure	kPa	24.82
FHSS Blower Pressure Ratio	-	1.025
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	0.443
FHSS Blower Mass Flow Rate	kg/s	0.224
Total Temperature Blower Inlet	°C	101.80
Total Temperature Blower Outlet	°C	108.03
Blower Efficiency (η)	-	60.44
Blower Bypass Mass Flow Rate	kg/s	0.000
Blower Fluidic Power	kW	7.26

All these results have been computed without continuous dust pocket cleaning.

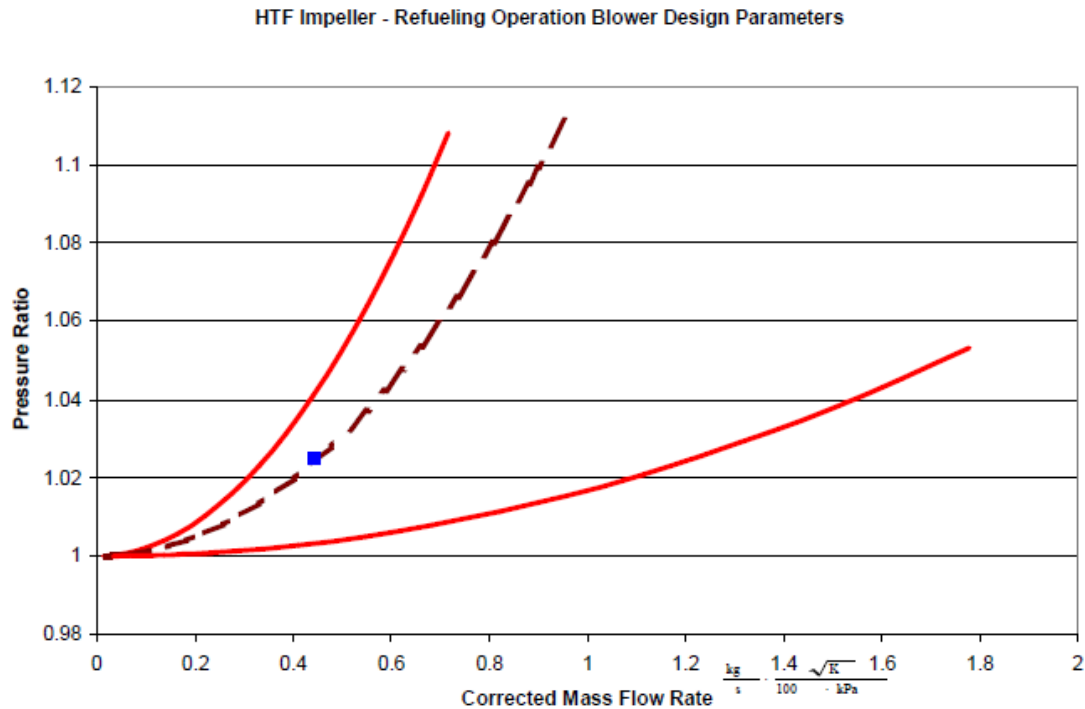


Figure 30: Blower Design Parameters overlaid on the HTF Impeller

From Figure 30 it can be seen that the blower operating point is located on the surge line of the simulated blower. Bypassing of the blower will shift the operating point to the right. This will have a minimal influence on the sphere conveying piping thermo-hydraulic data and is therefore not simulated.

4.3.2.3 DUST CLEANING OPERATION

Periodic dust removal in the sphere conveying piping is required [47]. Dust removal will be prompted after a predetermined number of spheres have passed through the lines. If dust accumulation is suspected due to slow rolling spheres, dust removal will also be conducted. Consistent periodic dust removal ensures that dust does not accumulate to unacceptable levels. This is the preferred method, rather than waiting for symptoms of dust cakes lines. When sphere rolling is retarded through dust accumulation, effective dust cleaning becomes more difficult because the caked dust is difficult to remove.

Table 15: Blower Parameters for Cleaning Operation

Blower Parameters	Unit	Forward 0% TFB*	Reverse 0% TFB*	Forward ≈68% TFB*	Reverse ≈68% TFB*	Forward Revised TFB*	Reverse Revised TFB*
Total Pressure Blower Inlet	kPa	975.41	954.05	971.07	950.36	973.24	954.65
Total Pressure Blower Outlet	kPa	1045.34	1028.08	1046.43	1029.41	1041.36	1021.48
FHSS Blower Volume Flow Rate	m ³ /s	0.101	0.105	0.268	0.277	0.382	0.393
FHSS Blower Differential Pressure	kPa	69.94	74.03	75.36	79.05	68.13	66.83
FHSS Blower Pressure Ratio	-	1.072	1.078	1.078	1.083	1.070	1.070
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	0.227	0.234	0.707	0.730	1.015	1.042
FHSS Blower Mass Flow Rate	kg/s	0.104	0.104	0.378	0.382	0.547	0.551
Total Temperature Blower Inlet	°C	179.27	187.72	56.91	57.28	53.16	53.15
Total Temperature Blower Outlet	°C	204.65	215.64	75.94	77.73	66.97	67.02
Blower Efficiency (η)	-	50.00	50.00	52.49	52.35	64.61	64.31
Blower Bypass Mass Flow Rate	kg/s	0.000	0.000	0.257	0.261	0.425	0.428

*TFB – Total Flow Bypassed. Also note the greyed out column was used for the process data generated

Summary Cleaning

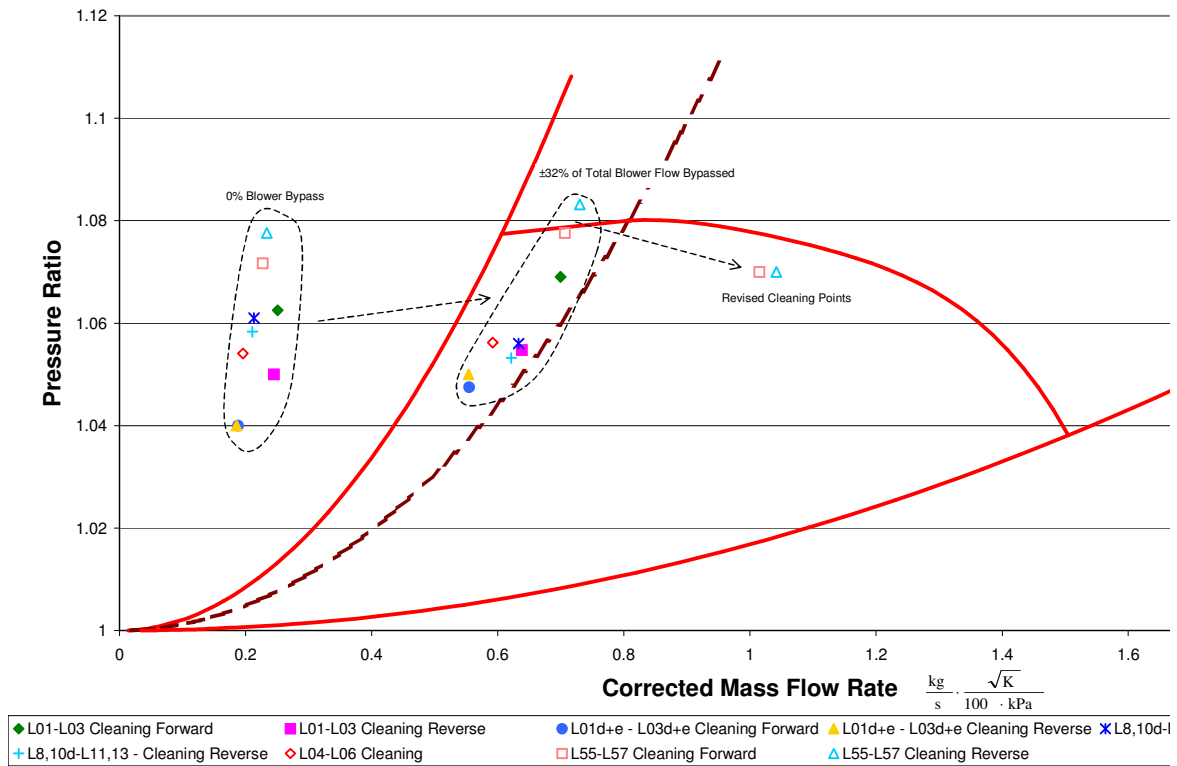


Figure 31: Dust Cleaning Operation Summary

4.3.3 AIR/COMMISSIONING OPERATION RESULTS

4.3.3.1 SPHERE CIRCULATION IN AIR:

Part of the FHSS commissioning is the circulating of spheres in air. Two different rates were simulated:

- Where the FHSS blower is operated at 100% of the designed speed and
- Where 58.5 mm spheres are lifted at 2 m/s.

For both these simulations, the 10° pneumatic brake sections are set to ensure that a 61 mm sphere has a terminal velocity of 0.5 m/s in the pneumatic brake.

When operating at 100% blower speed all the supply valves are simulated fully open and only the pneumatic brake supply valves are adjusted to ensure the correct gas flow. For 2 m/s sphere lifting both the lifting and braking supply valves are set to ensure the correct sphere velocities.

Table 16: Blower Design Parameters for Sphere Circulation

Blower Parameters	Unit	100%	2 m/s
Total Pressure Blower Inlet	kPa	87.71	95.91
Total Pressure Blower Outlet	kPa	113.23	105.52
FHSS Blower Volume Flow Rate	m ³ /s	0.267	0.140

Blower Parameters	Unit	100%	2 m/s
FHSS Blower Differential Pressure	kPa	25.51	9.61
FHSS Blower Pressure Ratio	-	1.291	1.100
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{K}}{100 \cdot \text{kPa}}$	4.629	2.669
FHSS Blower Mass Flow Rate	kg/s	0.202	0.140
Total Temperature Blower Inlet	°C	131.49	60.99
Total Temperature Blower Outlet	°C	177.84	75.17
Blower Efficiency (η)	-	65.16	64.99
Blower Bypass Mass Flow Rate	kg/s	0.000	0.000
Blower Fluidic Power	kW	9.53	2.00

Table 17: Sphere Velocities during Circulation Operation

100% Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	11.07	14.24
10° Brake Line Terminal Velocity (m/s)	1.65	0.50
2 m/s Lifting Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	2.00	4.84
10° Brake Line Terminal Velocity (m/s)	1.65	0.50

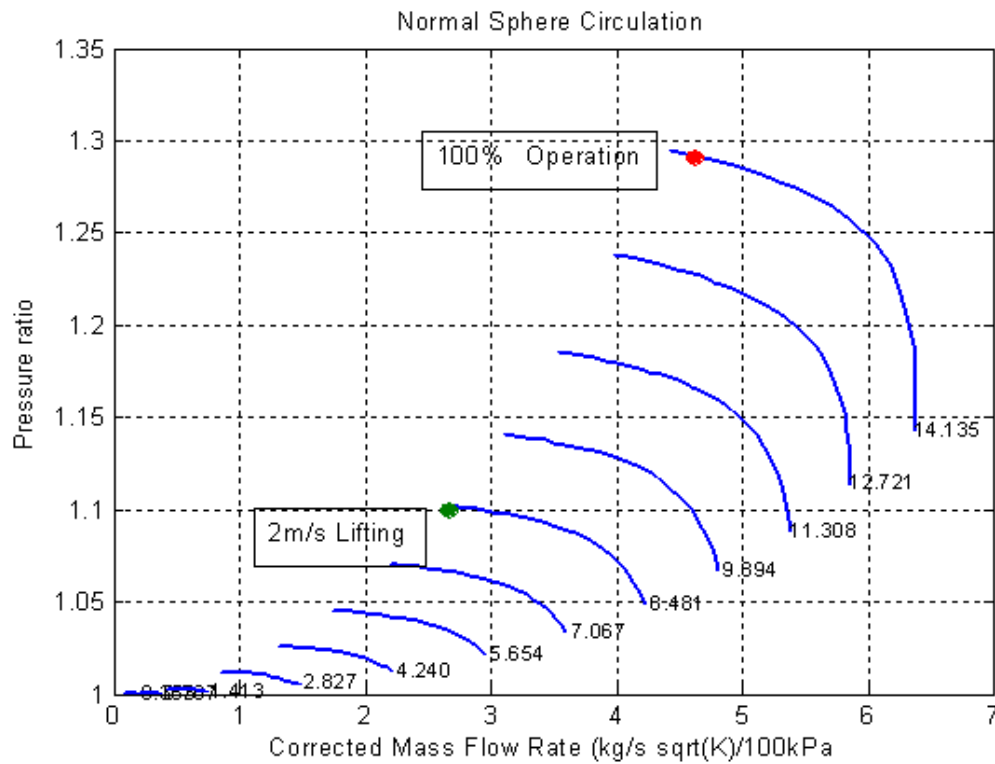


Figure 32: Blower Design Parameters for Sphere Circulation

4.3.3.2 DE-FUEL OPERATION IN AIR (REPRESENTATIVE FOR NITROGEN)

During de-fuelling the fuel spheres in the core are unloaded and transported to the fuel storage area. At the same time, the core is filled with graphite spheres transported from the storage area.

For the simulations the gas flow in the 10° and 33.4° pneumatic brake sections are set to ensure that a 61 mm sphere has a terminal velocity of 0.5 m/s in the pneumatic brake.

During this operation both lift lines from the reactor and the lift lines from the storage area are utilised. For maximum lifting velocities, the supply valves to the storage area lifting lines are fully open and the supply valves to the reactor lift lines throttled to ensure that the flow is the same in all the lift line sections. This is done only as a first estimation to see what maximum possible flow in the lift lines is achievable. All the control valves are assumed to have a cumulative pressure loss of at least 30% of the system pressure.

Table 18: Blower Design Parameters for De-fuel Operation

Blower Parameters	Unit	Value
Total Pressure Blower Inlet	kPa	94.91
Total Pressure Blower Outlet	kPa	110.57
FHSS Blower Volume Flow Rate	m ³ /s	0.327

Blower Parameters	Unit	Value
FHSS Blower Differential Pressure	kPa	15.66
FHSS Blower Pressure Ratio	-	1.165
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	6.117
FHSS Blower Mass Flow Rate	kg/s	0.312
Total Temperature Blower Inlet	°C	72.67
Total Temperature Blower Outlet	°C	105.67
Blower Efficiency (η)	-	46.41
Blower Bypass Mass Flow Rate	kg/s	0.000
Blower Fluidic Power	kW	10.42

Table 19: Sphere Velocities during De-fuel Operation

De-fuel Operation	58.5 mm Sphere	61 mm Sphere
All Lift Lines Terminal Velocity (m/s)	1.13	4.00
10° Brake Lines Terminal Velocity (m/s)	1.65	0.50
33.4° Brake Lines Terminal Velocity (m/s)	2.56	0.50

These graphs show that low lift line velocities will result in a very slow de-fuel rate during air operation.

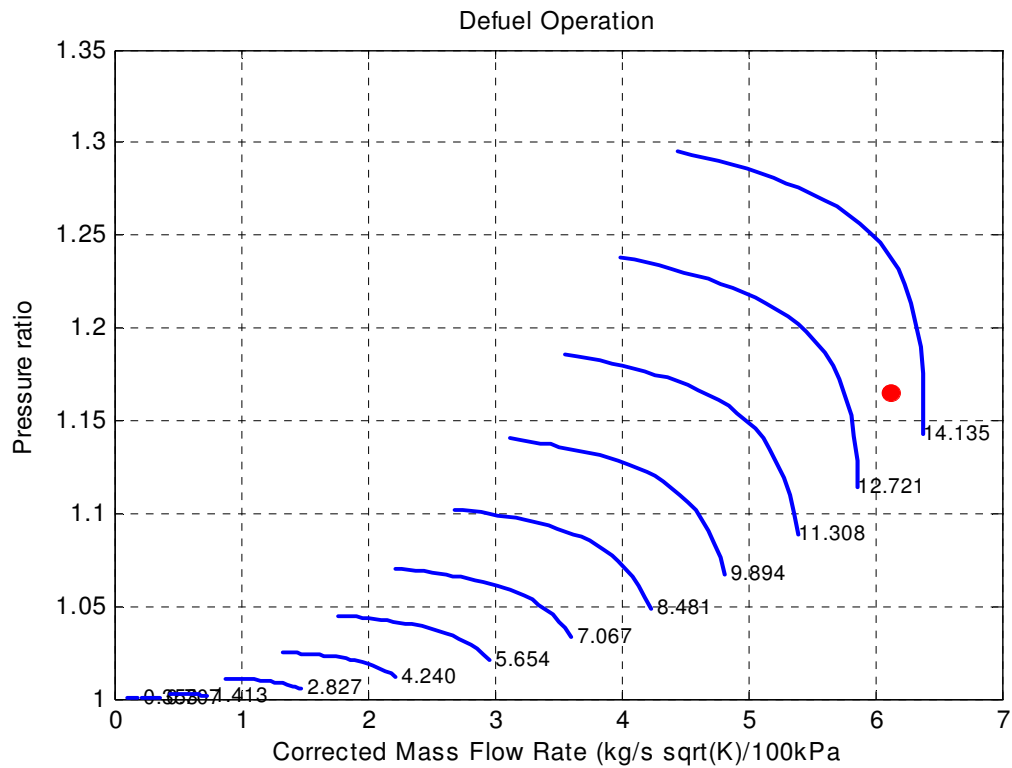


Figure 33: Blower Design Parameters for De-fuel Operation

4.3.3.3 UNLOAD OPERATION IN AIR (REPRESENTATIVE FOR NITROGEN)

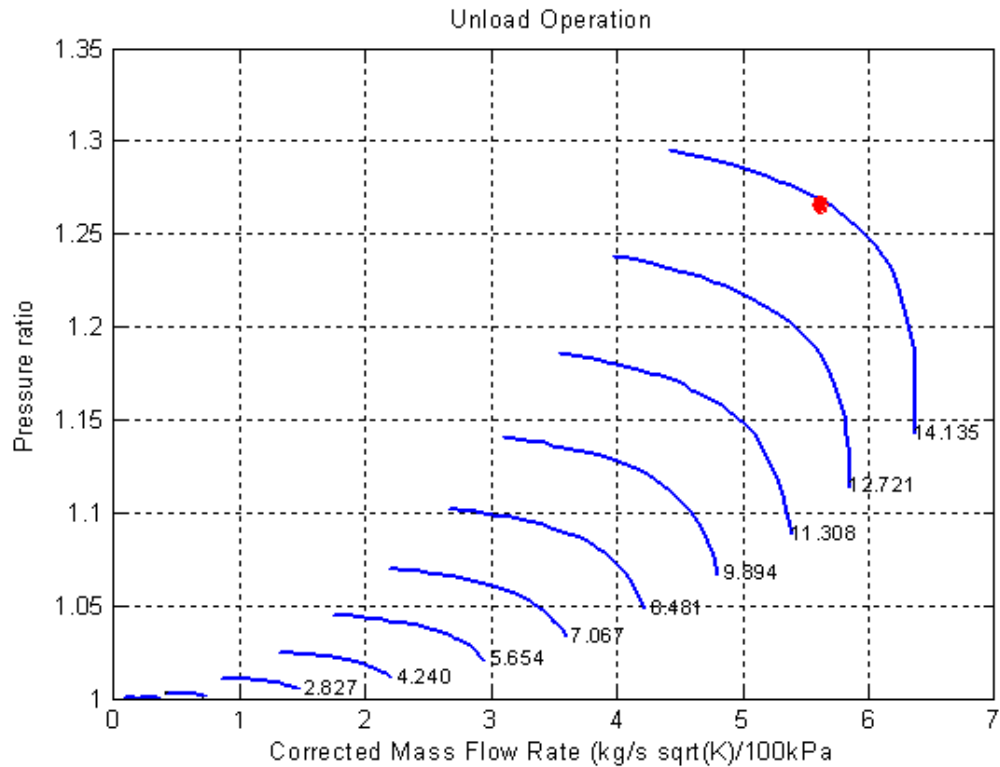
During unload operation the reactor core is emptied of all spheres. The FHSS blower is set to 100% of its maximum speed. When operating at 100% all the supply valves are simulated fully open and only the pneumatic brake supply valves are set to ensure the correct gas flow. The pneumatic brake velocity is set to ensure that a 61 mm sphere has a brake terminal velocity of 0.5 m/s.

Table 20: Blower Design Parameters for Unload Operation

Blower Parameters	Unit	Value
Total Pressure Blower Inlet	kPa	88.95
Total Pressure Blower Outlet	kPa	112.65
FHSS Blower Volume Flow Rate	m ³ /s	0.316
FHSS Blower Differential Pressure	kPa	23.70
FHSS Blower Pressure Ratio	-	1.266
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	5.620
FHSS Blower Mass Flow Rate	kg/s	0.255
Total Temperature Blower Inlet	°C	110.37
Total Temperature Blower Outlet	°C	152.67
Blower Efficiency (η)	-	62.60
Blower Bypass Mass Flow Rate	kg/s	0.000
Blower Fluidic Power	kW	10.93

Table 21: Sphere Velocities during Unload Operation

Unload Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	9.19	12.27
10° Brake Line Terminal Velocity (m/s)	1.65	0.50

**Figure 34: Blower Design Parameters for Unload Operation**

4.3.3.4 DUST CLEANING OPERATION IN AIR

As described previously the dust removal will be prompted after a pre-determined number of spheres have passed through the lines or if dust accumulation is suspected due to slow rolling spheres.

For the revised simulations, the gas piping diameters from the cleaning block to the three-way valves on the measurement blocks were increased from 2½” (63.5 mm) ID piping to 3” (76.2 mm) ID piping. The return piping to the return manifold was increased by the same ratio. The inlet nozzles inside the valve blocks connecting the sphere conveying lines to the cleaning lines were also increased from a 42 mm to a 47 mm ID hole. This was done to show that, conceptually, the FHSS piping could still be optimised by some margin to decrease the overall system pressure ratio. The required cleaning velocity is in the order of 22 m/s.

Table 22: Blower Design Parameters for Cleaning Operation

Blower Parameters	Unit	① Minimum gas velocity required	② Revised Minimum gas velocity required
Total Pressure Blower Inlet	kPa	100.62	100.85
Total Pressure Blower Outlet	kPa	172.80	155.27
FHSS Blower Volume Flow Rate	m ³ /s	0.144	0.109
FHSS Blower Differential Pressure	kPa	72.18	54.42
FHSS Blower Pressure Ratio	-	1.717	1.540
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	2.481	1.853
FHSS Blower Mass Flow Rate	kg/s	0.123	0.091
Total Temperature Blower Inlet	°C	136.69	144.40
Total Temperature Blower Outlet	°C	250.00	235.00
Blower Efficiency (η)	-	59.21	59.32
Blower Bypass Mass Flow Rate	kg/s	0.025	0.000
Blower Fluidic Power	kW	14.32	8.48

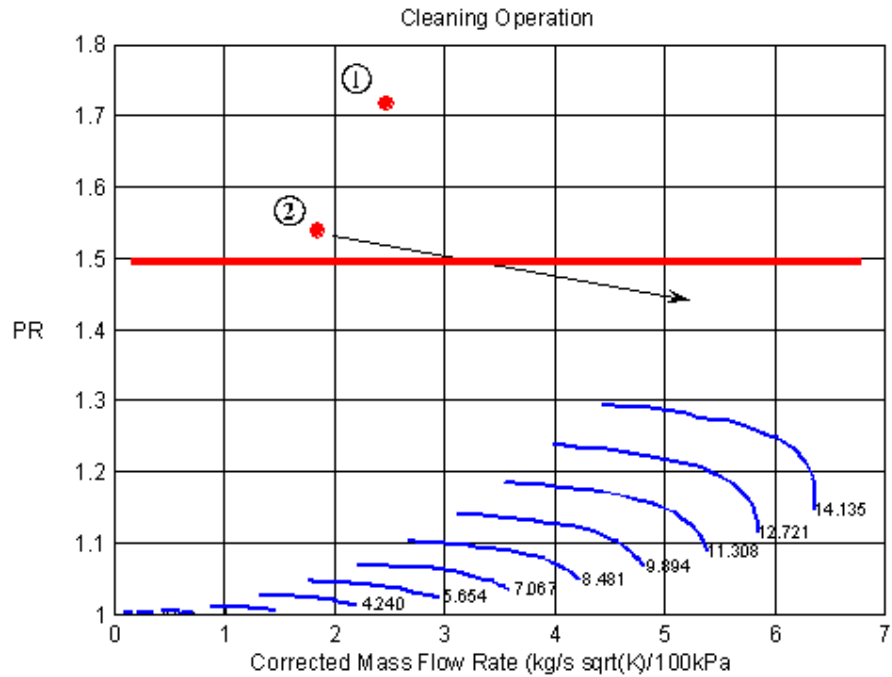


Figure 35: Blower Design Parameters for Cleaning Operation

From table 22 and figure 35 above the results indicates that an increase in the piping ID resulted in a 18 kPa decrease in the system pressure difference. The pressure difference is illustrated by point 1 and point 2 on the figure 35 above. If it is assumed that a blower pressure ratio of 1.5 is achievable in air and the system is optimised, cleaning line section L57 will be achievable at the required velocity. Some blower bypass will just have to be generated to ensure that point 2 on the figure moves within the blowers surge line capacity.

4.3.4 SUMMARY OF RESULTS FOR AIR OPERATION

Table 23: Summary of Blower Design Parameters for FHSS Air Operation

	Unit	100% Circulation	2 m/s Circulation	De-fuel	Unload	Minimum gas velocity required	Revised Minimum gas velocity required
Total Pressure Blower Inlet	kPa	87.71	95.91	94.91	88.95	100.80	100.84
Total Pressure Blower Outlet	kPa	113.23	105.52	110.57	112.65	175.64	159.05
FHSS Blower Volume Flow Rate	m ³ /s	0.267	0.140	0.327	0.316	0.102	0.097
FHSS Blower Differential Pressure	kPa	25.51	9.61	15.66	23.70	74.83	58.21
FHSS Blower Pressure Ratio	-	1.291	1.100	1.165	1.266	1.742	1.577
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{K}}{100 \cdot \text{kPa}}$	4.629	2.669	6.117	5.620	1.981	1.875
FHSS Blower Mass Flow Rate	kg/s	0.202	0.140	0.312	0.255	0.111	0.105
Total Temperature Blower Inlet	°C	131.49	60.99	72.67	110.37	50.00	50.00
Total Temperature Blower Outlet	°C	177.84	75.17	105.67	152.67	144.23	125.51
Blower Efficiency (η)	-	65.16	64.99	46.41	62.60	58.52	59.15
Blower Bypass Mass Flow Rate	kg/s	0.000	0.000	0.000	0.000	0.000	0.000
Blower Fluidic Power	kW	9.53	2.00	10.42	10.93	10.60	8.03

Table 24: Calculated Sphere Terminal Velocities for Air Operation

Normal Circulation 100% Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	11.07	14.24
10° Brake Line Terminal Velocity (m/s)	1.65	0.50
Normal Circulation 2 m/s Lifting Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	2.00	4.84
10° Brake Line Terminal Velocity (m/s)	1.65	0.50
De-fuel 100% Operation	58.5 mm Sphere	61 mm Sphere
All Lift Lines Terminal Velocity (m/s)	1.13	4.00
10° Brake Lines Terminal Velocity (m/s)	1.65	0.50
33.4° Brake Lines Terminal Velocity (m/s)	2.56	0.50
Unload 100% Operation	58.5 mm Sphere	61 mm Sphere
Lift Line Terminal Velocity (m/s)	9.19	12.27
10° Brake Line Terminal Velocity (m/s)	1.65	0.50

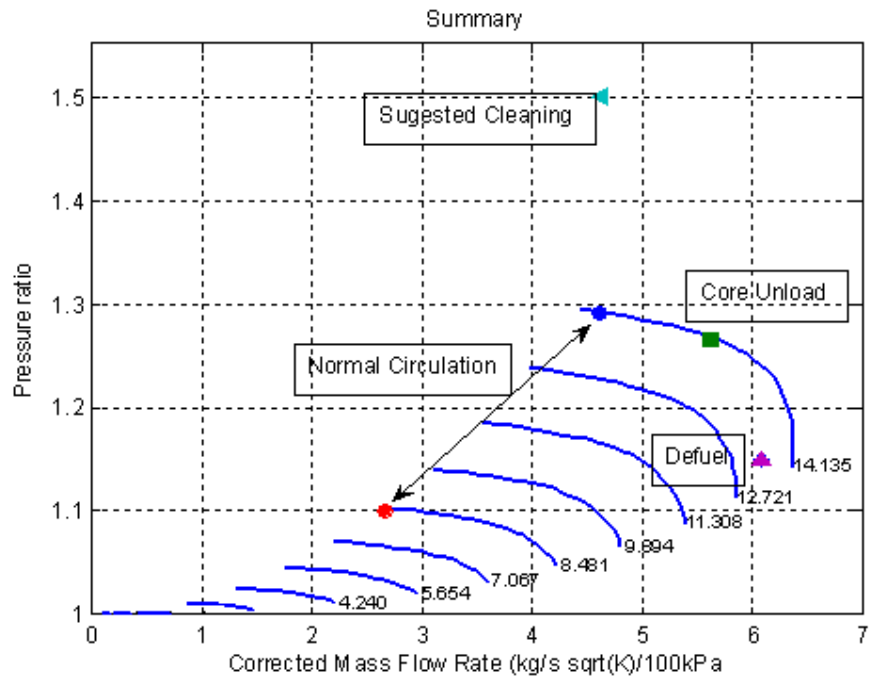


Figure 36: Summary of Blower Design Parameters for FHSS Air Operation

Maximum rate of normal circulation in air, results in an average sphere lift line velocity of 12.7 m/s.

De-fuel operation in air is possible (also representative for nitrogen) but with very slow lift line sphere velocities.

Defuel operation in air is possible (also representative for nitrogen).

Gas piping diameters from the cleaning block to the three-way valves on the measurement blocks were increased from 2½" (63.5 mm) ID piping to 3" (76.2 mm) ID piping and also the return piping to the return manifold were increased by the same ratio. The inlet nozzles inside the valve blocks connecting to the sphere conveying lines with the cleaning lines were also increased from a 42 mm to a 47 mm ID hole. From the above results, it is evident that the above changes mentioned had an 18 kPa decrease in the system pressure difference. If it is assumed that a blower pressure ratio of 1.5 is a thermo-hydraulic solution in air and the system is optimised some more for the minimum pressure difference achievable, cleaning line section L57 will be achievable at the required velocity if the blower flow is bypassed. The blower's physical constraints such as torque limitation should however also be taken into account and will be evaluated once the blower design matures.

5. CONCLUSION AND RECOMMENDATIONS

The major objective of this study was to calculate the FHSS blower thermo-hydraulic design parameters, specifically focusing on the impeller design input parameters. A sensitivity and Monte Carlo study was done to compensate for some of the uncertainty input parameters which the simulations would be based upon.

From the simulations done, the resultant input parameters for the impeller design were calculated as follow:

Table 25: FHSS Blower Design Parameters for High Pressure Operation

Blower Parameters	Unit	Mode S&GC- M070103 Blower				Mode S&GC- M030100			
		A	B	C	D	100% MCR 100% MCRI% Forward	100% MCR 100% MCRI% Reverse	16% MCR 40% MCRI% Forward	16% MCR 40% MCRI% Reverse
Total Pressure Blower Inlet	kPa	3329	8852	8854	3330	8995	8995	3385	3386
Total Pressure Blower Outlet	kPa	3370	8914	8913	3370	9117	9117	3510	3510
FHSS Blower Volume Flow Rate	kg/m ³	0.080	0.061	0.059	0.077	0.041	0.040	0.065	0.065
FHSS Blower Differential Pressure	kPa	41.36	61.99	59.53	39.78	121.88	122.35	124.70	124.20
FHSS Blower Pressure Ratio	-	1.012	1.007	1.007	1.012	1.014	1.014	1.037	1.037
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{K}}{100 \cdot \text{kPa}}$	0.199	0.148	0.142	0.192	0.099	0.099	0.167	0.166
FHSS Blower Mass Flow Rate	kg/s	0.345	0.675	0.652	0.334	0.464	0.463	0.305	0.304
Total Temperature Blower Inlet	°C	95.45	101.93	99.64	92.17	93.00	93.00	71.00	71.00
Total Temperature Blower Outlet	°C	100.82	104.96	102.47	97.17	96.60	96.61	80.24	80.20
Blower Efficiency (η)	-	33.85	34.30	34.98	34.63	53.92	53.92	53.88	53.89
Blower Bypass Mass Flow Rate	kg/s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

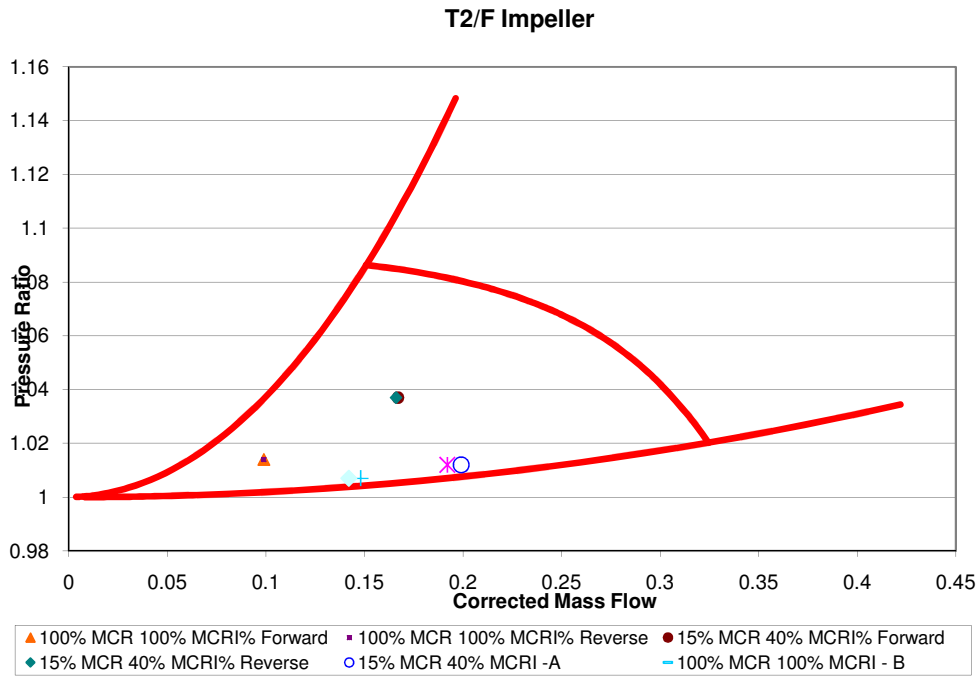


Figure 37: FHSS Blower Design Parameters for High Pressure Operation

Table 26: FHSS Low Pressure Operation Blower Design Parameters

Blower Parameters	Unit	Refuelling Operation		Fuel Core Unloading Operation	Dust Cleaning Operation			
		Excluding continuous dust pocket cleaning	Including continuous dust pocket cleaning		Forward ≈32% TFB	Reverse ≈32% TFB	Forward Revised ≈32% TFB	Reverse Revised ≈32% TFB
Total Pressure Blower Inlet	kPa	962.95	989.26	978.58	971.07	950.36	973.24	954.65
Total Pressure Blower Outlet	kPa	1007.70	1141.61	1003.40	1046.43	1029.41	1041.36	1021.48
FHSS Blower Volume Flow Rate	m ³ /s	0.397	0.509	0.179	0.268	0.277	0.382	0.393
FHSS Blower Differential Pressure	kPa	44.74	152.36	24.82	75.36	79.05	68.13	66.83
FHSS Blower Pressure Ratio	-	1.046	1.154	1.025	1.078	1.083	1.070	1.070
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{\text{K}}}{100 \cdot \text{kPa}}$	0.924	1.119	0.443	0.707	0.730	1.015	1.042
FHSS Blower Mass Flow Rate	kg/s	0.432	0.507	0.224	0.378	0.382	0.547	0.551
Total Temperature Blower Inlet	°C	151.42	203.85	101.80	56.91	57.28	53.16	53.15
Total Temperature Blower Outlet	°C	163.75	250.00	108.03	75.94	77.73	66.97	67.02

Blower Parameters	Unit	Refuelling Operation		Fuel Core Unloading Operation	Dust Cleaning Operation			
		Excluding continuous dust pocket cleaning	Including continuous dust pocket cleaning		Forward $\approx 32\%$ TFB	Reverse $\approx 32\%$ TFB	Forward Revised $\approx 32\%$ TFB	Reverse Revised $\approx 32\%$ TFB
Blower Efficiency (η)	-	62.99	60.83	60.44	52.49	52.35	64.61	64.31
Blower Bypass Mass Flow Rate	kg/s	0.000	0.066	0.000	0.257	0.261	0.425	0.428
Blower Fluidic Power	kW	27.71	121.75	7.26	37.42	40.62	39.34	39.8

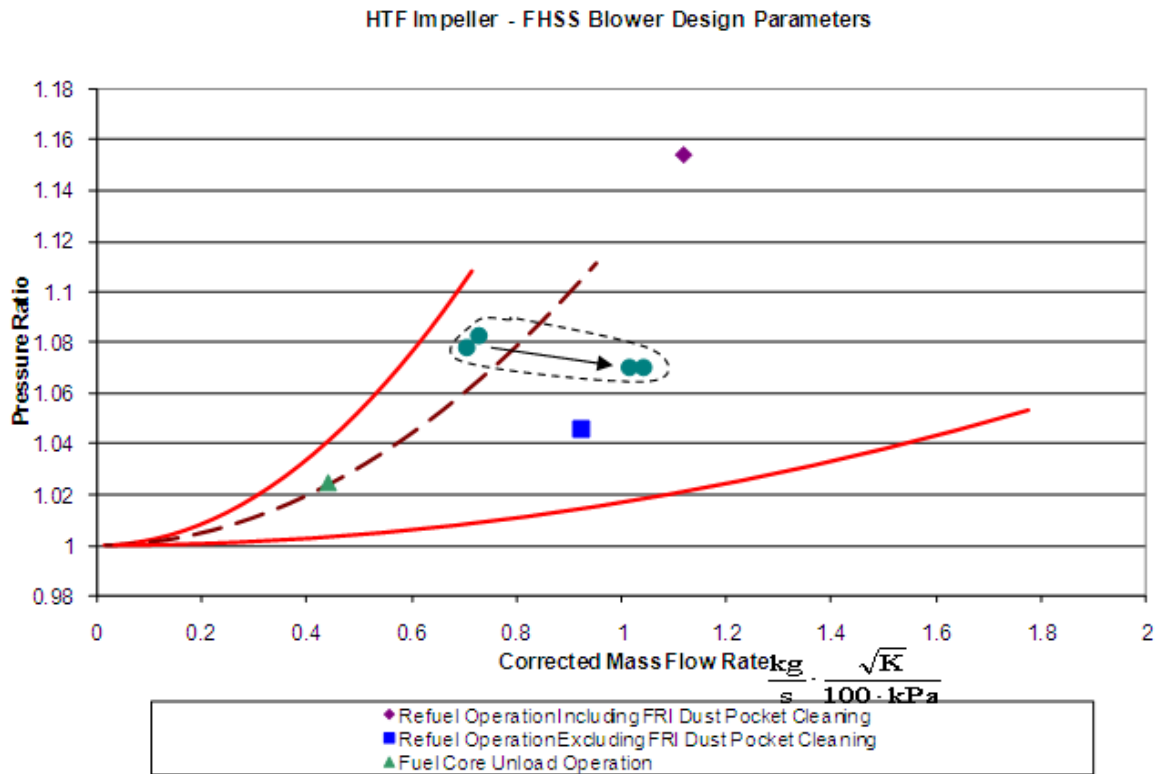


Figure 38: FHSS Low Pressure Operation Blower Design Parameters overlaid on the HTF Impeller

Table 27: Summary of Blower Design Parameters for FHSS Air Operation

Blower Parameters	Unit	100% Circulation	2 m/s Circulation	De-fuel	Unload	Minimum gas velocity required	Revised Minimum gas velocity required
Total Pressure Blower Inlet	kPa	87.71	95.91	94.91	88.95	100.80	100.84
Total Pressure Blower Outlet	kPa	113.23	105.52	110.57	112.65	175.64	159.05
FHSS Blower Volume Flow Rate	m ³ /s	0.267	0.140	0.327	0.316	0.102	0.097
FHSS Blower Differential Pressure	kPa	25.51	9.61	15.66	23.70	74.83	58.21
FHSS Blower Pressure Ratio	-	1.291	1.100	1.165	1.266	1.742	1.577
FHSS Blower Corrected Mass Flow Rate	$\frac{\text{kg}}{\text{s}} \cdot \frac{\sqrt{K}}{100 \cdot \text{kPa}}$	4.629	2.669	6.117	5.620	1.981	1.875
FHSS Blower Mass Flow Rate	kg/s	0.202	0.140	0.312	0.255	0.111	0.105
Total Temperature Blower Inlet	°C	131.49	60.99	72.67	110.37	50.00	50.00
Total Temperature Blower Outlet	°C	177.84	75.17	105.67	152.67	144.23	125.51
Blower Efficiency (η)	-	65.16	64.99	46.41	62.60	58.52	59.15
Blower Bypass Mass Flow Rate	kg/s	0.000	0.000	0.000	0.000	0.000	0.000
Blower Fluidic Power	kW	9.53	2.00	10.42	10.93	10.60	8.03

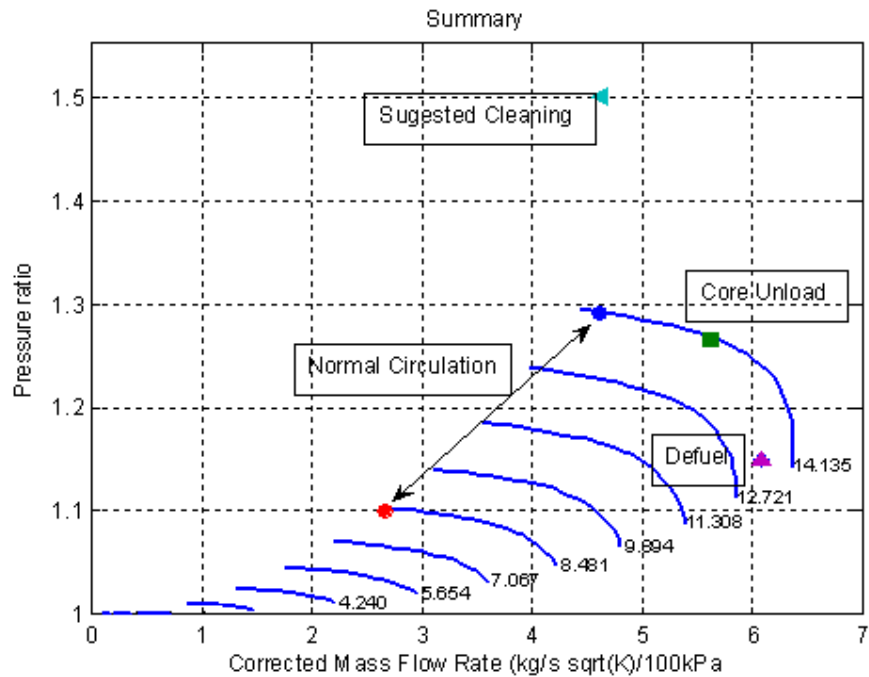


Figure 39: Summary of Blower Design Parameters for FHSS Air Operation

The thermo-hydraulic analysis of the FHSS system is only the first step in the development of the FHSS blower.

The results generated should be a sufficient source of input design parameters to use for an impeller selection that will be able to generate all the operating points simulated and presented in this section of the report.

Once the impeller selected is completed a detail blower characteristic map must be generated. The detail blower characteristic map should then be used to repeat all the simulations.

Once these simulations are complete, the generated results can be used as input to the system pressure boundary design, as the entire operating range will have been simulated, with temperatures, pressures and mass flow rates being available for the calculation of the pressure boundary conditions in all the simulated FHSS process elements.

The FHSS blower characteristic map can also be used to simulate and fix the system control philosophy. The next stage in the design process would be to complete the basic and detail design for the blower. Once fabricated, the blower can be tested to determine if the design characteristic map matches the actual performance map of the blower. If there are slight differences the simulations can be updated to verify that the system operation and control philosophy remains sufficient for the FHSS process.

The final verification will be to compare the as build FHSS system operational results with the simulation results. Variations can be investigated and resolved to ensure an accurate simulation model is available that fully represents the operational system. This verified simulation model can be used as part of a training simulator or to further develop and optimise the FHSS system.

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The following section specifically depicts the required input documents required for setting up the Flownex thermo-hydraulic model of the FHSS:

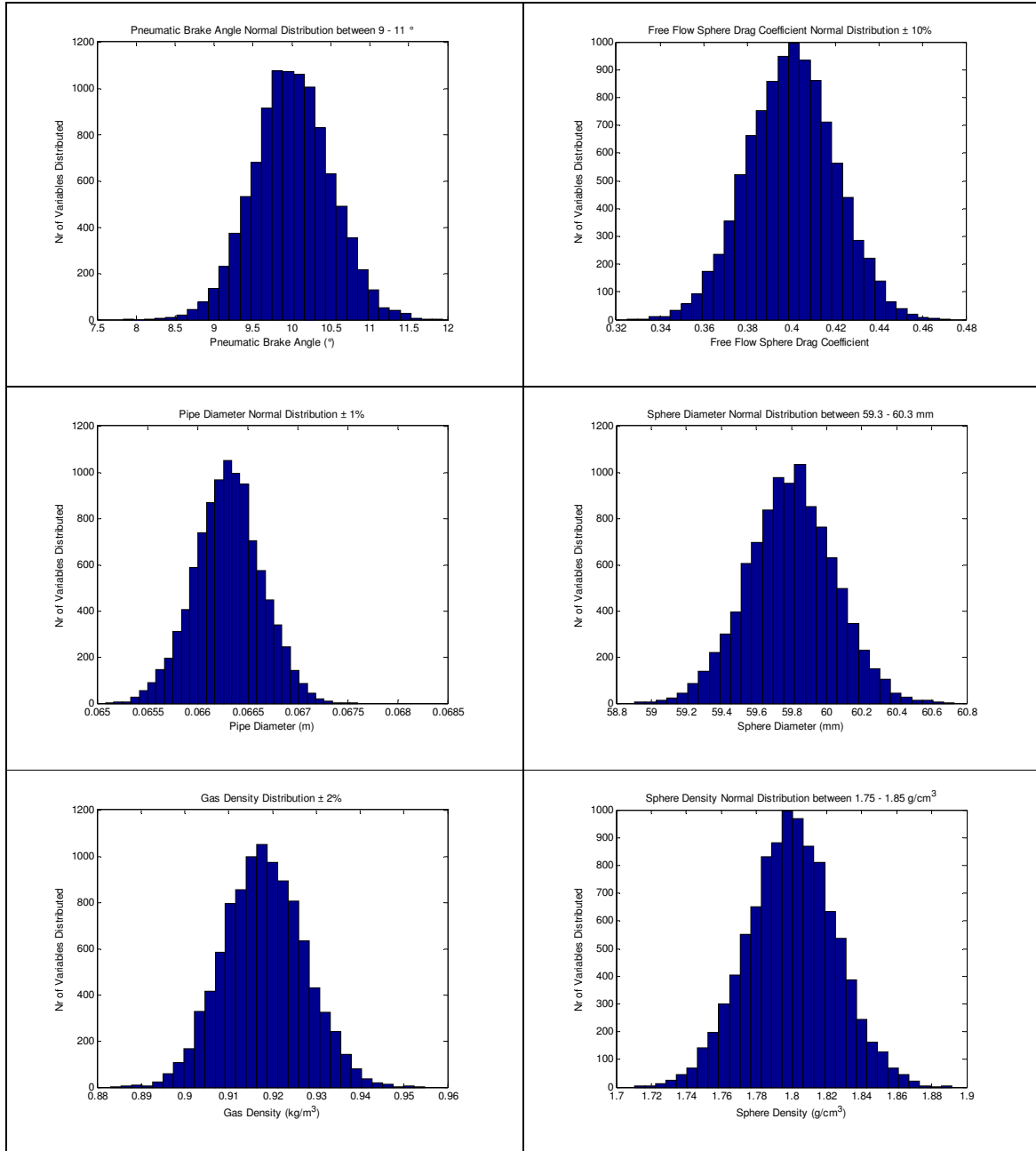
- [31] PBMR FHSS Triplex Flownex Model (work request) revision 1, PBMR Document and Data Control Centre, South Africa, 2002
- [32] FHSS UG Model, revision C, PBMR Document and Data Control Centre, South Africa, 2002
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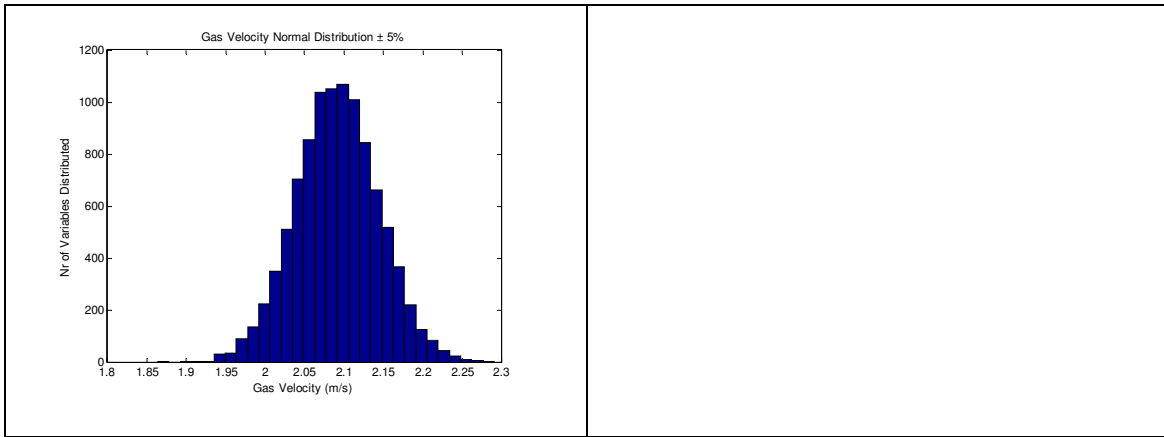
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- [53] HTF Blower Flownex System Model Report, PP150-018840-3110, PBMR Document and Data Control Centre, South Africa, 2002
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APPENDIX A

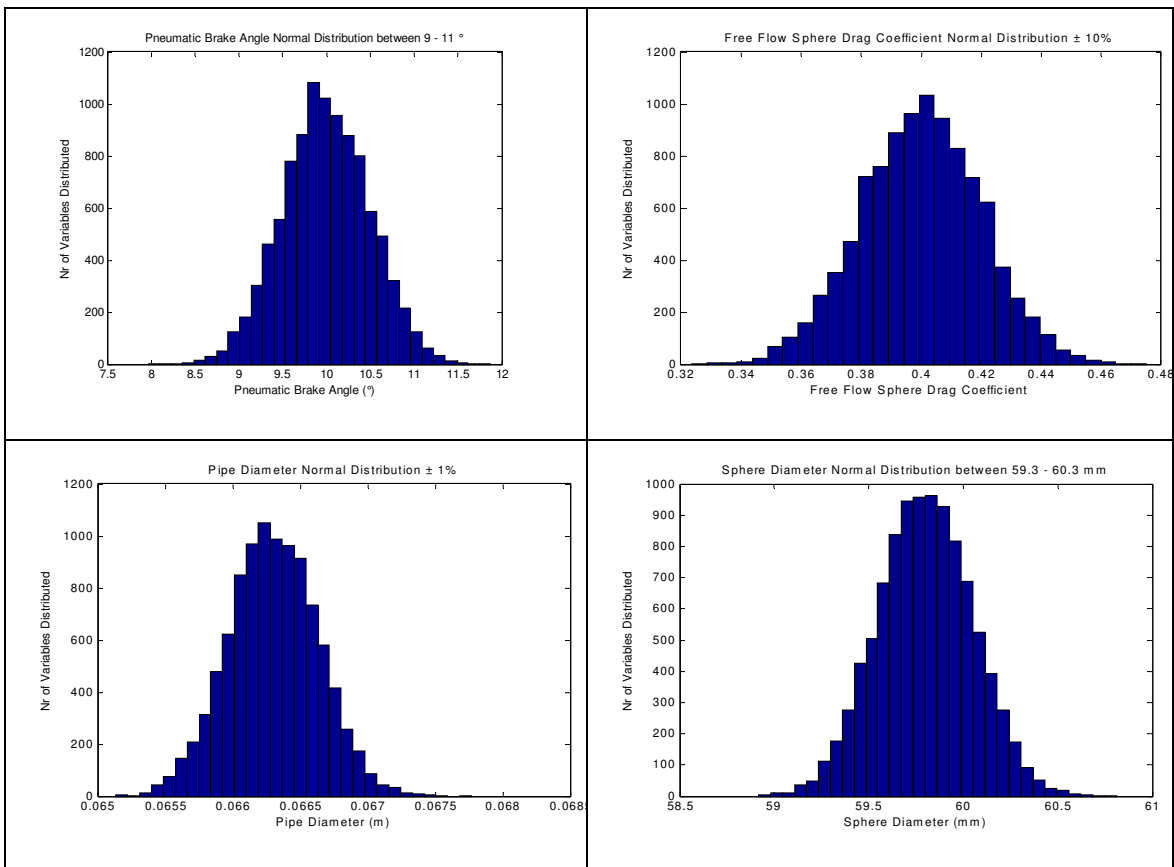
MONTE CARLO SIMULATIONS INPUT DISTRIBUTION

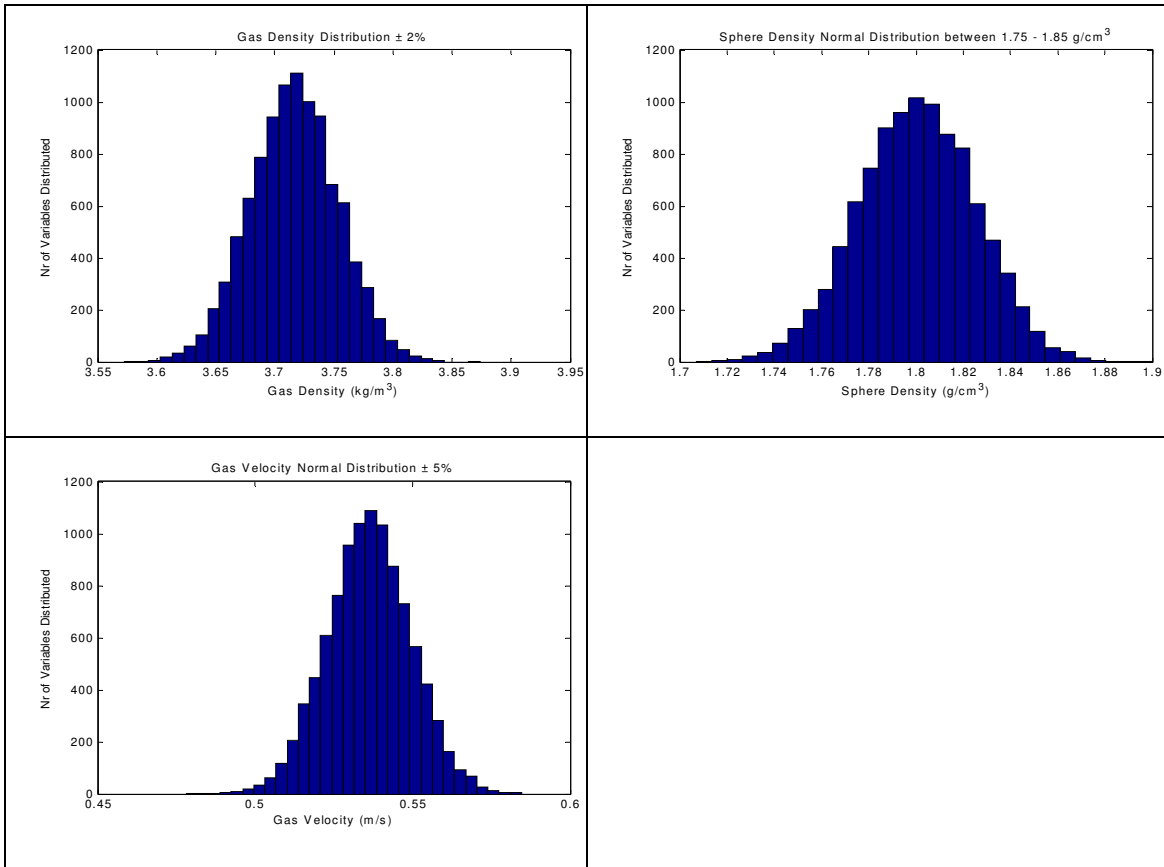
MONTE CARLO ANALYSIS INPUTS AT 1000 kPa AND 250 °C



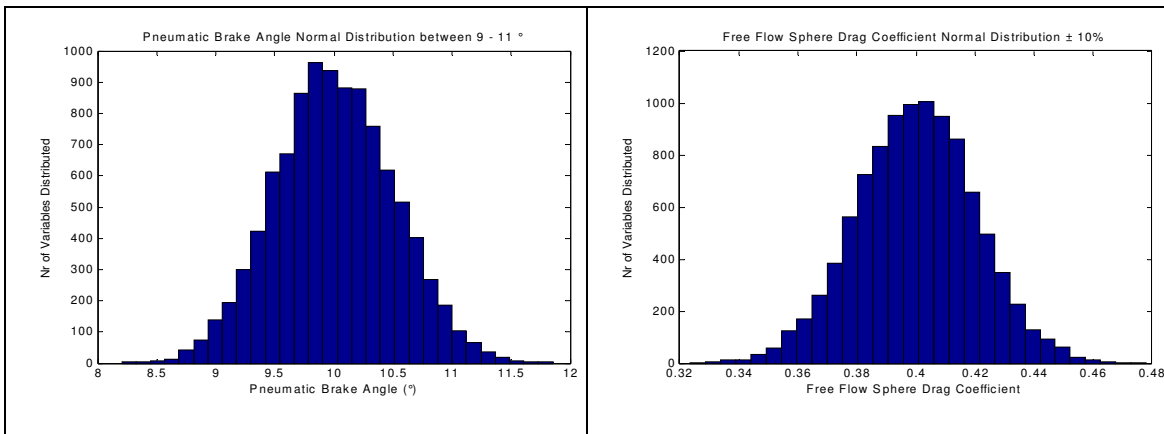


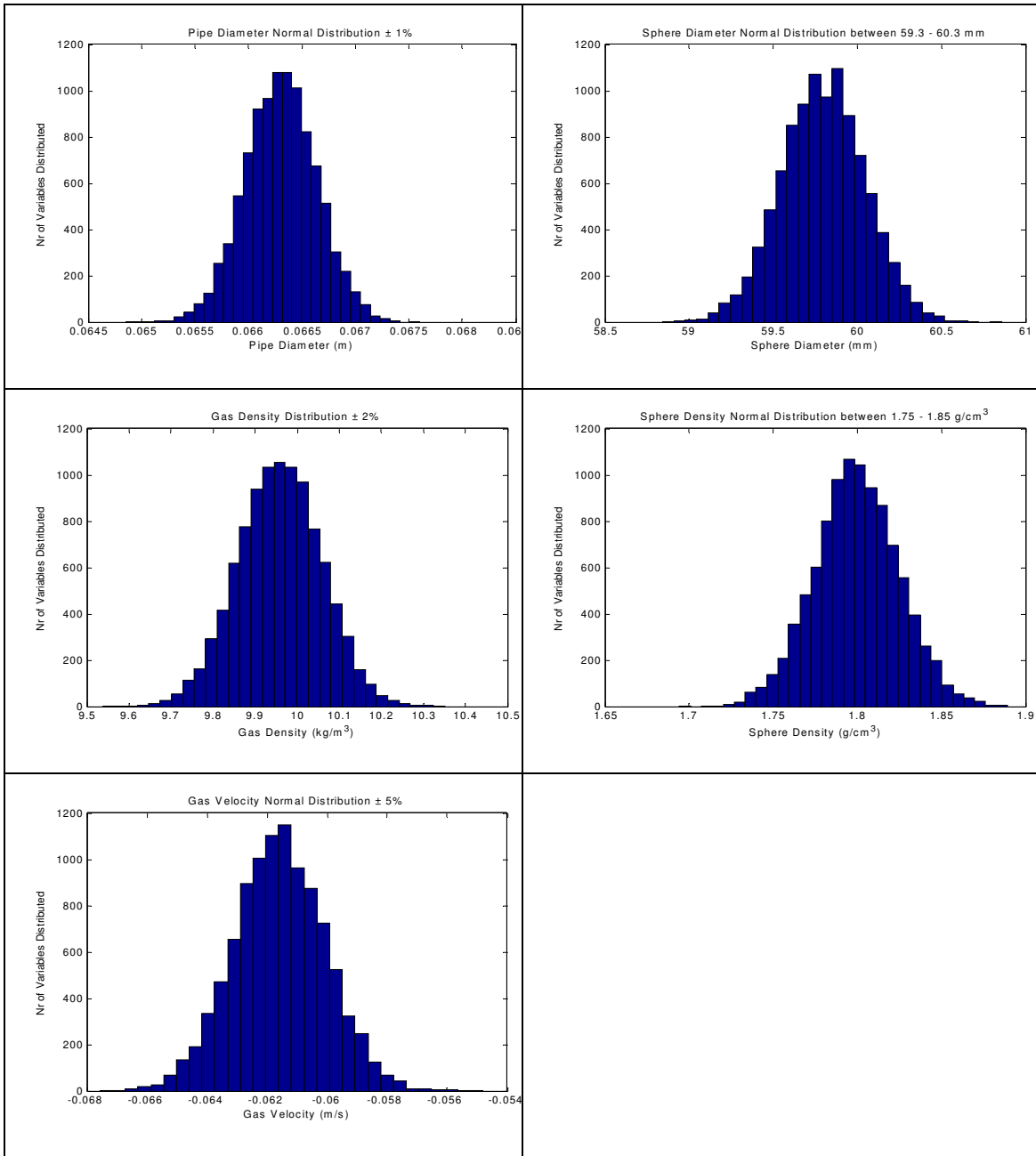
MONTE CARLO ANALYSIS INPUTS AT 3300 kPA AND 150 °C





MONTE CARLO ANALYSIS INPUTS AT 9000 kPa AND 150 °C





APPENDIX B

FHSS FLOWNEX MODEL DESCRIPTION

The following numbering convention was extracted from [52]:

Line numbers as indicated on the PFD e.g. He01 or L02a.

For block inserts the following:

E.g. ABB-CCC-DEE (Comments)

Table 28: Element Numbering Convention

Field	Name Description	Value	Value Description
ABB	Line	As per line number	As per PFD
-	Delimiter		
CCC	Block Identifier	000	Place holders where device is not associated with a block
		CB	Conveying Block
		CLD	Core Loading Device
		CLIB	Charge Lock Inlet Block
		CLOB	Charge Lock Outlet Block
		CUD	Core Unloading Device
		DLOB	Discharge Lock Outlet Block
		GRB	Gas Return Block
		GSB	Gas Supply Block
		IB	Isolation Block
		MB	Measurement Block
		SBA	Sample Block
		SSB	Sphere Sensor Block
		TUD	Tank Unloading Device
-	Delimiter		
D	Device Identifier	A	AMS or BUMS
		B	Buffer
		C	Collector
		D	Diverter
		E	Exchanger (Combined collector and diverter)
		F	Flow Transmitter
		G	Block Pitch Length
		H	Differential Pressure Transmitter
		I	Indexer
		R	FRI
		P	Pressure Transmitter
		S	Sphere Counter
		T	Temperature Transmitter

Field	Name Description	Value	Value Description
		V	Valve, including a DSI valve
		W	3-Way Valve
EE	Device Number	01 to 99	Incremental number assigned per device group. 01 is assigned to the first device in a block on the typical circulate operation route.

GENERIC INPUTS AND ASSUMPTIONS

This model was generated primarily for the purpose of sizing the FHSS blower and to obtain a fluid mass balance for the FHSS.

GENERIC PIPE INPUTS

Generic pressure loss coefficients assumed for gas pipe bends and sphere pipe bends are shown in **Table 29**. It is assumed that the Reynolds number effect on the loss coefficients does affect these loss coefficients and a correction factor of 2 is assumed from [40].

Table 29: Generic Pipe Bend Losses

Parameter	Pressure Loss Coefficient (K) Refer	r/D	Comment
90° Gas pipe bend (long radius)	0.36	1.61	r = 0.095 m
45° Gas pipe bend (long radius)	0.18	1.61	r = 0.095 m
90° Sphere pipe bend (650 mm radius)	0.48	9.7	D = 0.0653 m
45° Sphere pipe bend (650 mm radius)	0.28	9.7	D = 0.0653 m
90° Long bends for sphere and gas pipes	0.48	10	Assumed

The pressure loss coefficients assume 30 diameters up and downstream straight piping. This assumption is not valid for the gas flow paths inside the FHSS blocks and the influence thereof needs to be quantified.

All pipe elements are modelled with a roughness of 40 μm . See [40] for reference.

A generic loss coefficient of 0.5 is assumed in the forward and reverse flow directions for all reduction gas flow paths (See **Figure 40**) connecting to sphere lines. This assumption needs to be verified.

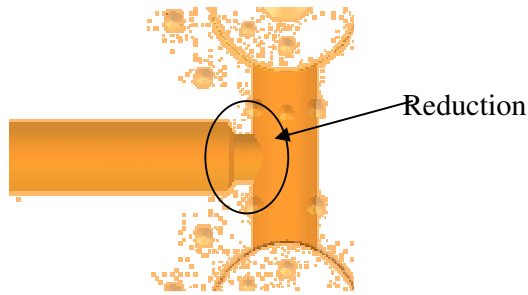


Figure 40: Reduction Gas Flow Path

A pressure loss coefficient of 1 is assumed for a dump loss and 0.5 for a sudden reduction in diameter [39].

GENERIC JUNCTION LOSS FACTORS

Junctions are simplified by introducing secondary pressure loss coefficients. Although these loss coefficients do not account for different main and branch flow ratios, it is a conservative approach and simplifies the model. **Table 30** presents the assumed loss coefficients for the junctions. From [39] p.221 the same correction factor for Reynolds number effects used in pipe bends can be used for junctions, hence the same strategy as described in 0 for Reynolds number correction is used.

The pressure loss coefficients assumed for modelling junctions are conservative and need to be updated for detailed analyses where more accurate losses are required.

Table 30: Implemented Junction Losses

Parameter	Pressure Loss Coefficient (K) Refer	Area Ratio
90° Branch Loss	2.4 (p.232)	1
60° Branch Loss	1.4 (p.225)	1
120° Branch Loss	3.5 (p.227)	1
Straight Loss	0.8 (p.239)	1

HEAT TRANSFER TO AMBIENT ASSUMPTIONS

The model includes heat transfer to ambient through insulated piping. Elements not included because of their insignificant influence on the system temperature are: process blocks, gravity conveying sphere pipes and short gas pipes. Heat transfer for these elements can be included in later versions of the model to accommodate temperature profile analyses.

The following assumptions were made about the insulation used:

Standard SA335 P1 steel is assumed for piping and pipe insulation property information was obtained from [42].

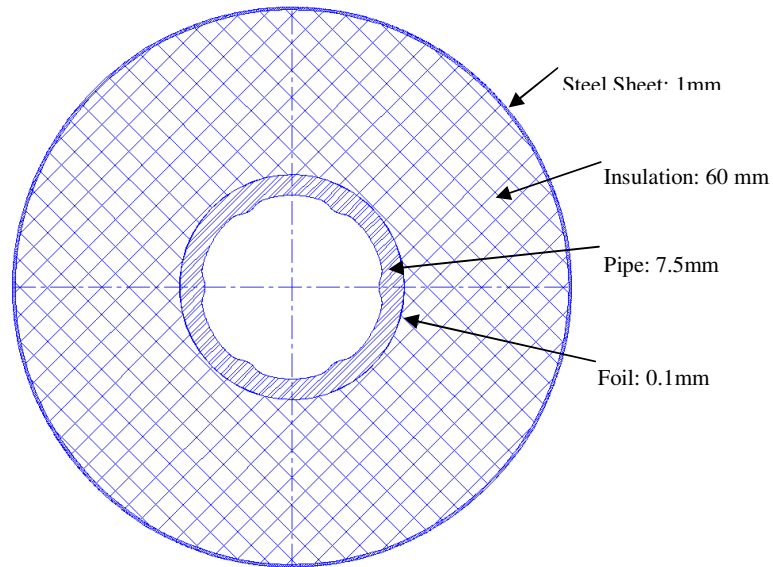


Figure 41: Cross Section of Insulated Pipe

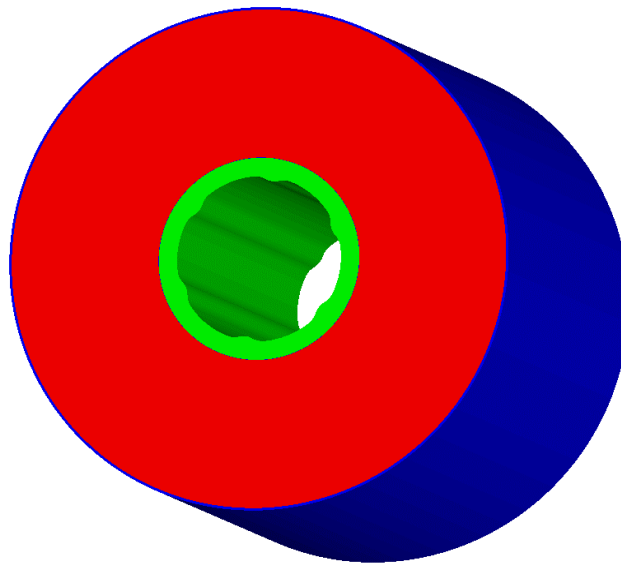


Figure 42: 3D Section of Insulated Pipe

Heat transfer parameters as shown in **Table 31** were chosen such that heat loss from the FHSS would be conservatively low.

Table 31: Generic values for insulated pipe elements.

Parameter	Unit	Value	Reference:
Conductivity for Pipe with Insulation	W/mK	0.1	-
Convection Coefficient for pipe outside wall	W/m ² K	0.5	Assumed
Ambient Temperature provided by HVAC	°C	45	Assumed

The heat transfer from the outside of the pipes is assumed to comprise convection only, which implies that heat radiation is neglected. All pipes are assumed to reside in HVAC conditions and a convection coefficient of 0.5 W/m² K is assumed.

Table 32 describes the elements with heat transfer to ambient. "Outside Area" is the outer surface area of the element. Only one layer for each element has been specified. For pipes with insulation, the different layer properties have been combined to simplify the model.

Table 32: Elements presented with Heat Transfer to Ambient

Number	Description	Length [m]	Wall Thickness [m]	Inner Diameter [m]	Outside Area [m ²]	Insulation
2002	He06	66.7	0.06701	0.05898	40.442	yes
2012	He14	10.9	0.06701	0.05898	6.609	yes
2020	CL12	51.1	0.06455	0.01	22.330	yes
2028	He13	12.8	0.06701	0.05898	7.761	yes
2032	L03b	46.1	0.0675	0.067	29.255	yes
2034	L01b	46.1	0.0675	0.067	29.255	yes
2042	He05	66.1	0.06701	0.05898	40.078	yes
2048	L08b+L08a+L24+TD+SRP1+SUP1	65.3	0.0675	0.067	41.439	yes
2050	CO05	63.8	0.06701	0.05898	38.684	yes
2052	CO11	28.6	0.06701	0.05898	17.341	yes
2054	CO07	63.8	0.06701	0.05898	38.684	yes
2056	CO09	63.7	0.06701	0.05898	38.623	yes
2064	CL08	12.5	0.06701	0.05898	7.579	yes
2066	CO03	11.9	0.06701	0.05898	7.215	yes
2076	L01a	11.8	0.0675	0.067	7.488	yes
2080	CO06	51.3	0.06701	0.05898	31.105	yes
2086	L02a	12.3	0.0675	0.067	7.806	yes
2088	L17a+L17b+L17c+L23+TD+SLP2	12.2	0.0675	0.067	7.742	yes
2090	CL13	15.1	0.06455	0.01	6.599	yes
2092	CL10	51.1	0.06455	0.01	22.330	yes
2098	CO14	67.5	0.06701	0.05898	40.927	yes

Number	Description	Length [m]	Wall Thickness [m]	Inner Diameter [m]	Outside Area [m ²]	Insulation
2100	CO19+CO19/5	32.5	0.06701	0.05898	19.706	yes
2120	CO20	47.9	0.06701	0.05898	29.043	yes
2128	He11a	14.7	0.06701	0.05898	8.913	yes
2130	CO16	67.7	0.06701	0.05898	41.048	yes
2132	CO12	28.4	0.06701	0.05898	17.220	yes
2134	CO18	67.8	0.06701	0.05898	41.109	yes
2140	CL09	15.8	0.06701	0.05898	9.580	yes
2154	CL11	51.1	0.06455	0.01	22.330	yes
2156	CO10	28.9	0.06701	0.05898	17.523	yes
2160	L16a+L16b+L16c+L22+TD+SLP1	11.8	0.0675	0.067	7.488	yes
2162	L03a	13.1	0.0675	0.067	8.313	yes
2174	L18/12+L18i+L18b+L18a+SLP	12.7	0.0675	0.067	8.059	yes
2180	L03d+L03e	12.2	0.0675	0.067	7.742	yes
2190	L55	13.3	0.0675	0.067	8.440	yes
2192	L02b	46.2	0.0675	0.067	29.319	yes
2206	CL07	11.6	0.06701	0.05898	7.033	yes
2208	L57	10.7	0.0675	0.067	6.790	yes
2210	CO02	14.6	0.06701	0.05898	8.852	yes
2216	CO21+CO24	46.3	0.06701	0.05898	28.073	yes
2230	CL15	15.1	0.06455	0.01	6.599	yes
2232	L56	10.5	0.0675	0.067	6.663	yes
2234	L02d+L02e	15.2	0.0675	0.067	9.646	yes
2236	CL14	15.1	0.06455	0.01	6.599	yes
2238	CO01	15.1	0.06701	0.05898	9.156	yes
2246	L10d+L13	12.6	0.0675	0.067	7.996	yes
2260	CO15	55.3	0.06701	0.05898	33.530	yes
2262	L19/6+L19j+L19b+L19a+SLP	12.5	0.0675	0.067	7.933	yes
2268	He16	11.8	0.06701	0.05898	7.155	yes
2276	L29/5+L30a+L30b+L30c+L30e+L19a+L29e+L29m+L29n+SRP+SUP	37.4	0.0675	0.067	23.734	yes
2278	He07b	16.7	0.06701	0.05898	10.126	yes
2282	CO13	55.6	0.06701	0.05898	33.712	yes
2284	CO17	54.9	0.06701	0.05898	33.287	yes
2292	L09b+L09a+L25+TD+SRP3+SUP3	65.8	0.0675	0.067	41.757	yes
2294	CO04	51.4	0.06701	0.05898	31.165	yes
2306	He15	13.8	0.06701	0.05898	8.367	yes
2312	L10b+L10a+L28/11+L28e+L28i+L28m+SRP2+SUP2	67.3	0.0675	0.067	42.709	yes
2553	He07a	50.0	0.06455	0.0243	24.096	yes
2594	CO32/6	19.2	0.06701	0.05898	11.641	yes
2628	CO32/12	21.1	0.06701	0.05898	12.794	yes
2630	CO08	51.1	0.06701	0.05898	30.983	yes

COMPONENT ASSUMPTIONS

FHSS VENTURI

The venturi used in the FHSS for flow measurement is described in [37]. This venturi is currently based on the ATL venturi since no better information is available.

FHSS FILTER

The primary filter used in the FHSS is described in [7]. This filter is based on conceptual design information and was characterised for the FHSS Flownex model as described in [7].

The document referenced in [7] is not yet an approved document but is regarded as sufficiently accurate for blower sizing and gas mass balance calculations since the filter pressure loss is a very small portion of the total system resistance.

FHSS BLOWER NON-RETURN VALVE

This valve is situated in the gas line connecting the blower to the gas supply manifold. Physically the valve might form part of the gas supply block assembly. The valve is not modelled in this version of the model due to a lack of information, but is represented through a pipe element with a restriction in the gas supply manifold.

The restriction is modelled as follows:

A pressure loss coefficient of 50 is added to the first pitch of the gas supply block assembly. This will cause a pressure drop of ± 1.5 kPa when 0.719 kg/s helium gas (approximately the required gas flow rate to lift one sphere at 2 m/s in three lift lines at 9MPa) flow through the pipe section.

The valve was modelled using the check valve option in Flownex in order to simulate the closing of the valve for reverse flow. Although this is not the ideal approach for simulating the non-return valve, it is nevertheless regarded as an acceptable first attempt to simulate the valve in the absence of more accurate valve characteristic information.

FHSS HEAT EXCHANGER

The FHSS heat exchanger is located in the blower bypass line and is modelled as a pipe element with a fixed exit temperature, for the time being until more detailed information becomes available. This assumption can be justified if it is assumed that the heat exchanger pressure loss will never exceed the circuit pressure loss, which is a reasonable assumption if only a small amount of bypass flow is required. The constant exit temperature can be justified if it is assumed that the heat exchanger has sufficient capacity to remove the required heat at all times. This is not a realistic assumption and needs to be verified.

The following assumed characteristics are applicable:

Table 33: Heat Exchanger Input Parameters (element 2320)

Parameter	Unit	Value	Comments
Diameter	m	0.6	Assumed
Length	m	0.1	Assumed
Secondary Loss Coefficient	-	1.5	Assumed
Exit Temperature	°C	50	Assumed 15 °C higher than the worst specified coolant temperature. See [52].

With the inputs as in **Table 33**, the heat exchanger pressure drop for the 9MPa operating pressure case is presented in **Figure 43**.

The characteristic shown in **Figure 43** is only an assumption and needs to be verified.

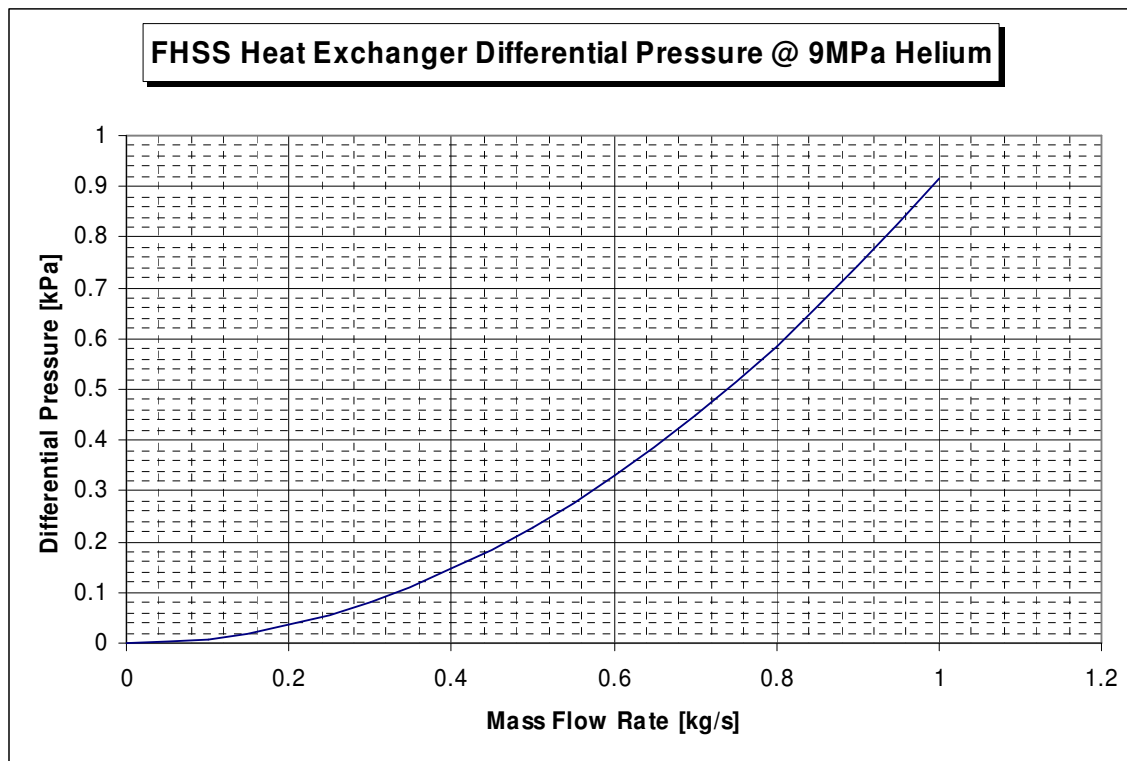


Figure 43: FHSS Heat Exchanger Characteristic

FHSS FLOW RESTRICTING INDEXER

The purpose of the FRI in the FHSS is to index spheres without allowing a full flow gas flow path. Only a small gas leak flow path exits which is modelled in Flownex and described in this section. **Figure 44** shows a picture of the FRI with labyrinths to restrict the leak flow.

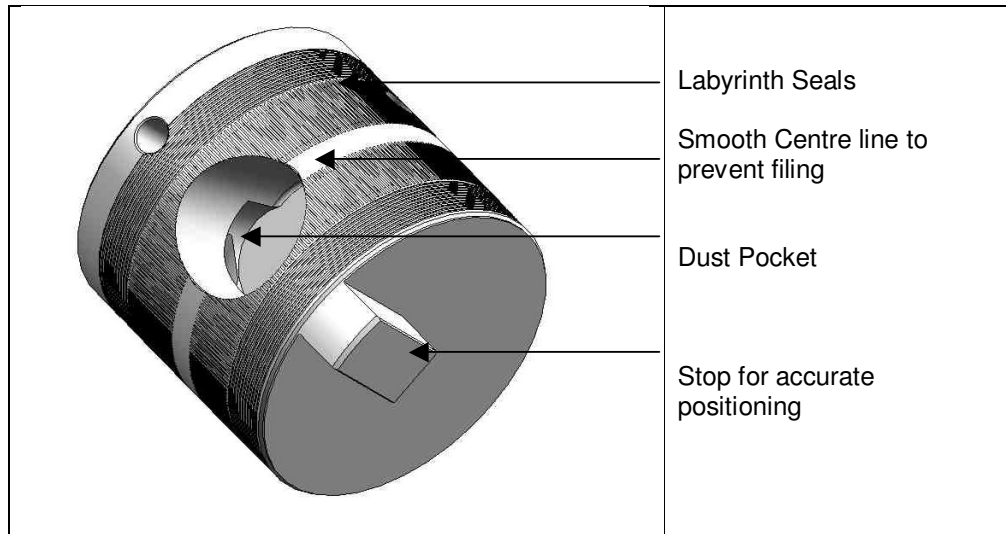


Figure 44: View of the FRI Head

The flow restricting indexers (FRI) used in the FHSS are modelled using user specified elements. The characteristic curve of the FRI is shown in **Figure 45**. No valid reference for the characteristic, which was obtained from THTR literature, is available and the data should therefore be verified. The proposed FRI design for the PBMR FHSS differs from the THTR design and should be characterised for implementation in Flownex to increase the credibility of the thermo-hydraulic model. This valve is expected to have a significant impact on the FHSS performance. The characteristic for helium and air can be found in [52].

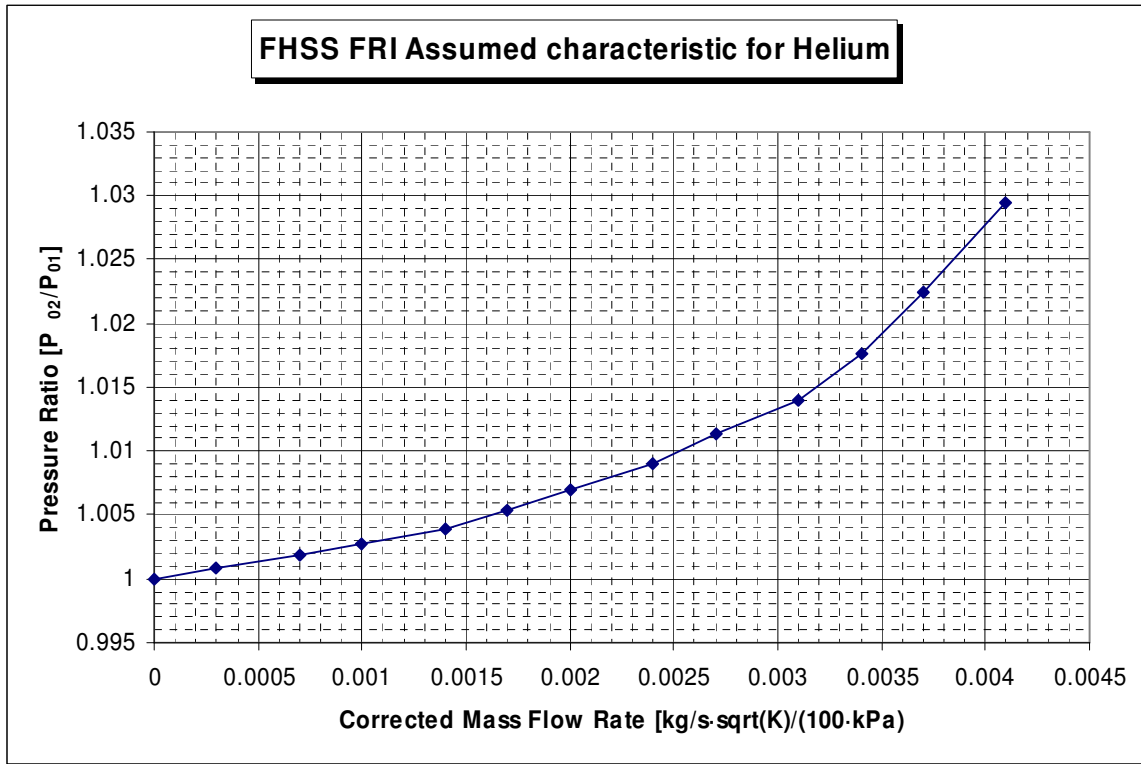


Figure 45: FHSS FRI Characteristic for Helium

The characteristic curve of the FRI for use in air, as shown in **Figure 46**, was obtained by multiplying the characteristic for use in helium with the gas constant ratio of helium and air. This is necessary since the corrected mass flow rate characteristic does not account for different fluids.

$$\dot{m}_{c,air} = \dot{m}_{c,He} \cdot \sqrt{\frac{R_{He}}{R_{air}}} \quad \text{with}$$

$\dot{m}_c$ = Corrected Mass Flow Rate

R = Fluid Gas Constant

The use of this correlation for fluid scaling of the FRI characteristic curve needs to be verified.

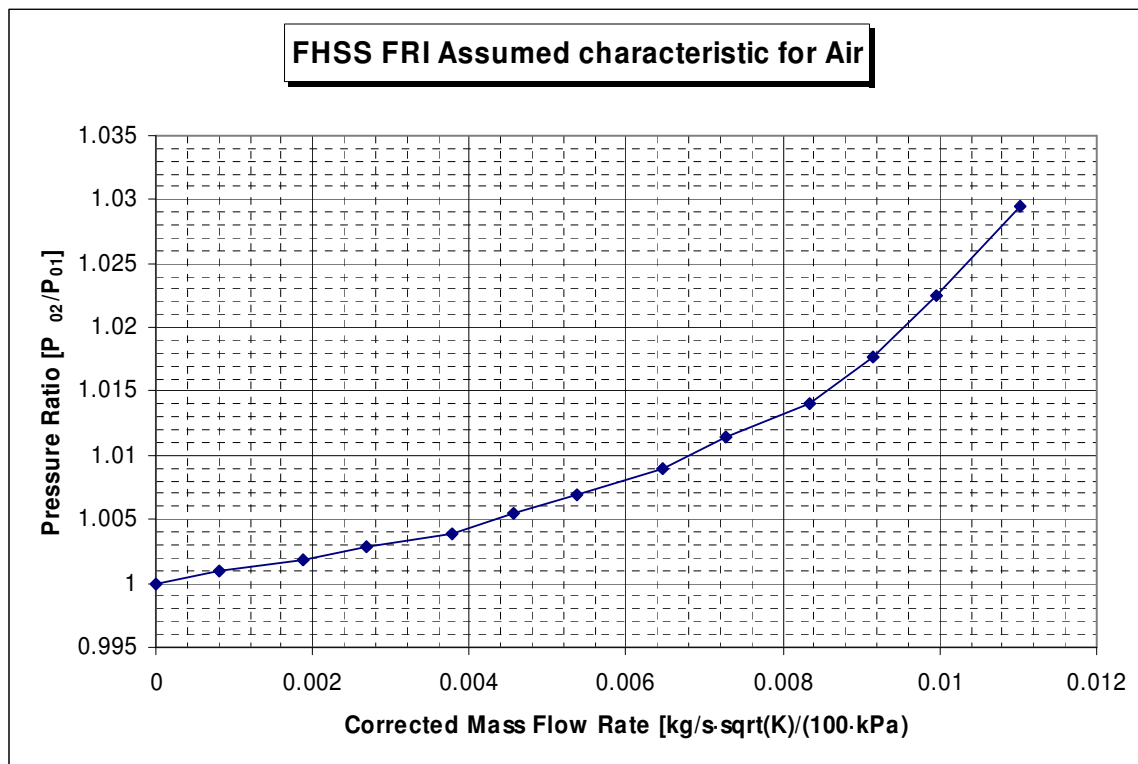


Figure 46: FHSS FRI Characteristic for Air

FHSS THREE WAY VALVE

The three-way valve in the FHSS is modelled using the same pressure loss characteristic as that used for the FRI discussed in 0, but with 20% more flow at the same pressure ratio. The 20% added to the flow rate is to account for the differences in geometry to that of the FRI. No formal reference for adding 20% is available and this is only an assumption, which needs to be verified.

The three way valve is modelled using five elements. Three of the elements represent the leak flow paths while two elements represent the full flow path if the valve is open.

FHSS DIVERTER

The diverter in the FHSS is modelled using the same pressure loss characteristic philosophy as described in 0 for the three way valve, hence the same characteristic curve is used than that used for the three way valve.

This characteristic is applicable to the restricted gas flow path in the diverter. For the free flow path of the diverter or the path conveying spheres, a gas flow pressure loss coefficient of:

$K=0.28$ is used for a diverting path (ref. 0 for 45° bend) and

$K=0.01$ is used for a straight through path (assumed).

FHSS GAS FLOW VALVES

The FHSS makes use of various gas valves to control, isolate and divert gas inside the FHSS. At present, no valve characteristic information is available for any of the valves to be used in the FHSS and the following assumptions were made for modelling purposes:

- a. The three-way valve is discussed in 0.
- b. The Double Seat Isolation (DSI) valves used to isolate the FHSS from the MPS are assumed to have the same flow characteristics than that of a ball valve. These valves are modelled as valve elements in Flownex using the experimentally derived characteristic curve of the FHSS ATL ball valve. It is assumed that the valve characteristics will not have a significant impact on operating modes where the valve is fully open or fully closed, because of the low flow resistance of the valve. For the analysis of transient events where the valve closes in a finite period during the transient, the assumed characteristic needs to be verified.
- c. Trim valves, isolation valves and flow control valves are all modelled in Flownex as valve elements with a valve characteristic curve. This characteristic curve described in [52] is obtained from a CFD analysis compiled on a THTR designed needle and seat valve.

The xT values assumed for these valves are 0.7. No valid reference exists for this assumption and this needs to be verified.

FHSS BLOWER

The FHSS blower will be described in [53]. No blower is currently available. The purpose of the model described in this document is to size the FHSS blower. To achieve this, the blower is modelled using a pipe element. The pipe element used to model the blower is described in section 0 and is used by specifying a mass flow rate through the pipe with an assumed heat input to the transported fluid. The results will be a pressure rise over the pipe element and an exit temperature.

TANK UNLOADING DEVICE

The tank unloading device (TUD) unloading spheres from the used fuel storage tank (and the graphite storage tank) is thermo-hydraulically connected to the sphere conveying lines. This causes a shortcut for the gas flow from one sphere lifting line to the other. The TUD is designed to minimise this cross flow by implementing very small gas flow paths. These small flow paths are modelled in Flownex using pipe elements with small flow areas. No reference exists for the flow path geometry and the geometry should be verified.

Table 34: Elements Representing the TUD

Number	Description	Circumference [m]	Area [m ²]	Length [m]
2110	L24-TUD-Flow_Restriction	0.606	0.0006	0.3
2314	L25-TUD-Flow_Restriction	0.606	0.0006	0.3
2316	L28/11-TUD-Flow_Restriction	0.606	0.0006	0.3

GENERAL ASSUMPTIONS

In modelling the FHSS the following general assumptions were made:

- a. All gas piping is assumed 2½" NB schedule 80 piping, which results in a pipe with a 59 mm inner diameter. The reasoning behind this assumption is that in order to prevent dust settling in gas pipes, the gas velocity needs to be at least as high or higher than the velocity needed to clean the sphere piping. Thus, the gas pipe diameter should be equal or smaller than the sphere pipe diameter. To reduce the pressure drop through gas piping, the gas pipe diameter should in turn be as large as possible. With this taken into account, the 2½" NB schedule 80 pipe is the closest standard pipe to the sphere pipe with a 65.3 mm hydraulic diameter, with regards to hydraulic diameter.
- b. The gas supply block assembly main gas flow path, gas return block assembly main gas flow path and the piping preceding and following the FHSS filter and blower are assumed to be 0.194m ID. This corresponds to 8" NB schedule 80 piping. The 0.194m ID pipe contradicts the philosophy described in (a) above and needs to be investigated.
- c. All gas paths in blocks are assumed bored to a 0.065m diameter. All bored gas paths connecting onto sphere lines are reduced to a 0.043m diameter at the point where it connects to the sphere line.
- d. Sphere conveying lines inside blocks are assumed to be round (not ribbed) with a diameter of 0.065m.
- e. The model boundary nodes are:
 - The MPS manifold – the FHSS is connected to the high pressure compressor outlet (node nr. 78)
 - The void above the reactor core (node nr. 98)
 - The reactor defueling chute (node nr. 2)
 - The RSS gas supply and return lines (node nr. 2535 and 2537)
 - Used fuel storage tank assembly (node nr. 2449)
 - Graphite storage tank assembly (node nr. 2095)
 - AGS for the dust extraction lines (node nr. 2277)

Note that the gas supply and return lines to and from the RSS are not modelled. The FHSS boundaries to the RSS are modelled as the isolation valves at the FHSS heat exchanger and the mixing chamber.

The FRI dust pocket cleaning lines situated in the conveying block unit beneath the reactor

are modelled such that these lines do not return to the GRBA but to a system thermo-hydraulically independent from the FHSS. This system is modelled by use of a node. The reason for this modelling approach is to be able to obtain a higher negative pressure in relation to the gas return block assembly, using the node as a mass sink.

Pipe lengths do not include block pitches although the pipes are modelled to run to the first gas flow obstruction or junction in a block. Pipe elements may sometimes include loss factors for bends inside a block.

The FHSS Spent-fuel Storage System (SFSS) can have physically different layouts for different modes of operation. This model is created to accommodate the refuelling operating mode and redistribution of spent-fuel from spent-fuel tank 5 to 6. Since the layout for refuelling does not differ much thermo-hydraulically from the defueling operating mode, only modelling the refuelling mode will not have a significant impact on blower analyses. For component specific or very detailed analyses, the model might have to be updated to accommodate for all operating modes.

In the Discharge Lock Outlet Block (DLOB), diverters and collectors connect the three different sphere lines. Since the system is designed to have no significant gas flow inside these lines that cause pressure differences between the lines, the leak flow paths between these lines are not modelled. This is an effort to keep the model as simple yet comprehensive as possible.

Ribbed sphere conveying pipes are modelled using the cross flow area and the inner circumference from which Flownex calculates a hydraulic diameter.

Note that for sphere conveying calculations the hydraulic diameter will not provide the correct gas flow velocity, to simulate sphere conveying if the pipe is ribbed.

Heat transfer is assumed as discussed in section 0. It is assumed that the HVAC system can remove all the heat dissipated by the FHSS piping.

Secondary pressure loss coefficients for pipes assume low Reynolds number flow conditions at all times.

The height of pipes is not included in the model and although this is not foreseen to have a significant impact on foreseen analyses, the effect of this assumption needs to be quantified.

Only one indexer was modelled with a flow restriction. The indexer holding the sphere for burn-up measurement was modelled for the three measurement blocks. The pressure loss coefficient assumed for this indexer is $K=0.1$.

Note: The gas flow through this indexer is to be verified and has to be a magnitude that will keep the sphere stable in the indexer without movement, so that the burn-up measurement is not influenced.

Element Numbering: Dust pocket cleaning lines are currently not numbered on the FHSS PFD [33]. Numbers assumed for modelling are:

- i. CL10 for L55-IB-R01 pocket cleaning
- ii. CL11 for L56-IB-R01 pocket cleaning
- iii. CL12 for L57-IB-R01 pocket cleaning

- iv. CL13 for L01-CB-R01 pocket cleaning
- v. CL14 for L03-CB-R01 pocket cleaning
- vi. CL15 for L02-CB-R01 pocket cleaning

DETAILED ELEMENTS DESCRIPTION

In this section, all Flownex elements will be described in detail. The section is divided into smaller sections describing functional and physical identical elements.

GAS FLOW VALVE ELEMENTS

This section describes the Flownex elements used as valve elements. All valves are modelled as control valves with loss coefficients (Flownex Type CLC).

No.	Description	Valve Diameter [m]	Fraction Open [/]	Pipe Inlet Diameter [m]	Pipe Outlet Diameter [m]	xT Forward [/]	xT Backward [/]	Valve Chart
2518	He07-GRB-V01	0.065	0	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2526	He12-GRB-V01	0.065	0	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2554	He10-GSB-V01	0.065	0	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2690	L01-CUD-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2692	L03-CUD-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2694	L02-CUD-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2696	L55-IB-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2698	L56-IB-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2700	L57-IB-V01	0.065	1	0.065	0.065	1E+30	1E+30	ATL Ball Valve_2004-03-10.vl2
2186	CL11-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2512	CO02-GSB-V01	0.065	0.34	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2514	CO13-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2516	CO21-GRB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2520	CO06-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2522	CL12-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B

No.	Description	Valve Diameter [m]	Fraction Open [/]	Pipe Inlet Diameter [m]	Pipe Outlet Diameter [m]	xT Forward [/]	xT Backward [/]	Valve Chart
2524	CO04-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2528	CO17-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2534	CO03-GSB-V01	0.065	0.34	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2536	CO05-GSB-V01	0.065	0.027	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2538	CO15-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2540	CO18-GSB-V01	0.065	0.022	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2542	CO07-GSB-V01	0.065	0.032	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2544	CO20-GSB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2546	CO01-GSB-V01	0.065	0.29	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2548	CO14-GSB-V01	0.065	0.0146	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2550	CO12-GSB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2552	CO11-GSB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2555	He07A-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2556	CO10-GSB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2558	He11-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2560	CO19-GSB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2562	CO09-GSB-V01	0.065	0.034	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2564	He03-GSB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2566	CO16-GSB-V01	0.065	0.0179	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2568	CL02-CUD-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2570	CL03-CUD-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2572	CL01-CUD-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2574	L02-CB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2576	L03-CB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2578	L02-CB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2580	L55-IB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B

No.	Description	Valve Diameter [m]	Fraction Open [/]	Pipe Inlet Diameter [m]	Pipe Outlet Diameter [m]	xT Forward [/]	xT Backward [/]	Valve Chart
2582	L56-IB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2584	L57-IB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2586	CL10-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2638	He04-GRB-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2640	CO08-GRB-V01	0.065	0.9	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2702	He09-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B
2704	He17-000-V01	0.065	0	0.065	0.065	0.7	0.7	FHSS German Trim Valve Rev B

VENTURI ELEMENTS

This section describes the elements used to model the FHSS venturis

No	Description	Chart
2382	CO01-000-F01	fhss_venturi_he_rev1.usp
2384	CO17-000-F01	fhss_venturi_he_rev1.usp
2386	CO02-000-F01	fhss_venturi_he_rev1.usp
2388	CO18-000-F01	fhss_venturi_he_rev1.usp
2392	He03-000-F01	fhss_venturi_he_rev1.usp
2396	CO21-000-F01	fhss_venturi_he_rev1.usp
2400	CO04-000-F01	fhss_venturi_he_rev1.usp
2402	He12-000-F01	fhss_venturi_he_rev1.usp
2406	CO12-000-F01	fhss_venturi_he_rev1.usp
2410	He10-000-F01	fhss_venturi_he_rev1.usp
2412	CO14-000-F01	fhss_venturi_he_rev1.usp
2414	CO20-000-F01	fhss_venturi_he_rev1.usp
2420	CO06-000-F01	fhss_venturi_he_rev1.usp
2422	CO16-000-F01	fhss_venturi_he_rev1.usp
2460	CO03-000-F01	fhss_venturi_he_rev1.usp
2462	He07-000-F01	fhss_venturi_he_rev1.usp
2480	CO11-000-F01	fhss_venturi_he_rev1.usp
2482	CO05-000-F01	fhss_venturi_he_rev1.usp
2484	CO09-000-F01	fhss_venturi_he_rev1.usp
2490	CO10-000-F01	fhss_venturi_he_rev1.usp
2498	CO13-000-F01	fhss_venturi_he_rev1.usp
2500	CO15-000-F01	fhss_venturi_he_rev1.usp
2502	CO07-000-F01	fhss_venturi_he_rev1.usp
2504	CO19-000-F01	fhss_venturi_he_rev1.usp
2632	CO08-000-F01	fhss_venturi_he_rev1.usp
2642	He04-000-F01	fhss_venturi_he_rev1.usp

THREE WAY VALVE AND DIVERTER ELEMENTS

This section describes the elements used to model the three way valves and diverter leak flow paths.

No.	Description	Chart
2374	L11 to L55 (Restricted)	3_way_valve_v00.usp
2376	L12 to L56 (Restricted)	3_way_valve_v00.usp
2378	L13 to L57 (Restricted)	3_way_valve_v00.usp
2394	CL06-MB-W01 (LP to CL06 Leak)	3_way_valve_v00.usp
2408	L02 to L57 (Restricted)	3_way_valve_v00.usp
2418	L03e to L56 (Restricted)	3_way_valve_v00.usp
2424	CL02-CLB-W01 (HP to CL02 Leak)	3_way_valve_v00.usp
2426	CL06-MB-W01 (HP to CL06 Leak)	3_way_valve_v00.usp
2428	CL01-CLB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2430	CL01-CLB-W01 (HP to CL01 Leak)	3_way_valve_v00.usp
2432	CL01-CLB-W01 (LP to CL01 Leak)	3_way_valve_v00.usp
2434	CL05-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2436	CL05-MB-W01 (HP to CL05 Leak)	3_way_valve_v00.usp
2438	CL05-MB-W01 (LP to CL05 Leak)	3_way_valve_v00.usp
2440	CL02-CLB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2442	L01e to L55 (Restricted)	3_way_valve_v00.usp
2446	CL03-CLB-W01 (LP to CL03 Leak)	3_way_valve_v00.usp
2448	CL02-CLB-W01 (LP to CL02 Leak)	3_way_valve_v00.usp
2450	CL04-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2452	CL04-MB-W01 (HP to CL04 Leak)	3_way_valve_v00.usp
2454	CL04-MB-W01 (LP to CL04 Leak)	3_way_valve_v00.usp
2456	CL03-CLB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2458	CL03-CLB-W01 (HP to CL03 Leak)	3_way_valve_v00.usp
2464	CL06-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2468	L03e to L05 (Restricted)	3_way_valve_v00.usp
2472	CL07-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2474	CL07-MB-W01 (HP to CL07 Leak)	3_way_valve_v00.usp
2476	L01e to L04 (Restricted)	3_way_valve_v00.usp
2478	L02e to L06 (Restricted)	3_way_valve_v00.usp
2486	CL08-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp
2488	CL08-MB-W01 (HP to CL08 Leak)	3_way_valve_v00.usp
2494	CL07-MB-W01 (LP to CL07 Leak)	3_way_valve_v00.usp
2496	CL08-MB-W01 (LP to CL08 Leak)	3_way_valve_v00.usp
2506	CL09-MB-W01 (LP to CL09 Leak)	3_way_valve_v00.usp
2508	CL09-MB-W01 (HP to CL09 Leak)	3_way_valve_v00.usp
2510	CL09-MB-W01 (HP to LP Leak)	3_way_valve_v00.usp

FLOW RESTRICTING INDEXER ELEMENTS

This section describes the elements used to model the flow restricting indexers.

No.	Description	Chart
2390	L57-IB-R01	Drucksperr.usp
2398	L56-IB-R01	Drucksperr.usp
2404	L02-CB-R01	Drucksperr.usp
2416	L55-IB-R01	Drucksperr.usp
2444	L01-CB-R01	Drucksperr.usp
2466	L03-CB-R01	Drucksperr.usp

GSBA AND GRBA

This section describes the elements making up the GSBA and GRBA internal gas flow paths.

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = $90^\circ \times 0.36 + 45^\circ \times 0.18 + \text{Sharp} \times 2.4 + \text{Other (ref. 0 and 0)}$							Comments
					K_{fw}	K_{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2338	CO04-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2336	CO06-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2644	CO08-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2344	CO13-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2342	CO15-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2340	CO17-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2368	CO21-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2636	He04-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2370	He07-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2366	He12-GRB-V01 (to He19)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2200	He19-GRB-G01	0.16	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2240	He19-GRB-G02	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2184	He19-GRB-G03	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2188	He19-GRB-G04	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2196	He19-GRB-G05	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2222	He19-GRB-G06	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2646	He19-GRB-G07	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2592	He19-GRB-G08	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2590	He19-GRB-G09	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2358	CO01-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2360	CO02-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2220	CO03-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2352	CO05-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2354	CO07-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2356	CO09-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2326	CO10-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2328	CO11-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2330	CO12-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2346	CO14-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2348	CO16-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2350	CO18-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2296	CO19-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2332	CO20-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	
2286	He01-GSB-G01	0.16	0.194	NS	50.8	0.0	0	0	0	50.8	0.0	Non-Return Valve (ref. section 0) & Straight junction loss
2288	He01-GSB-G02	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2310	He01-GSB-G03	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2324	He01-GSB-G04	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2304	He01-GSB-G05	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2302	He01-GSB-G06	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2214	He01-GSB-G07	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2244	He01-GSB-G08	0.32	0.194	NS	0.8	0.8	0	0	0	0.8	0.8	Straight junction loss
2274	He03-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2334	He10-GSB-V01 (to He01)	0.06	0.065	NS	2.4	2.4	0	0	1	0.0	0.0	

FILTER AND BLOWER ASSEMBLY

This section describes the elements presenting the FHSS blower, filter and the piping connecting these components.

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2202	He19	5.4	0.194	NS	1.44	1.44	4	0	0	0	0	
2258	He20	3.3	0.194	NS	0.72	0.72	2	0	0	0	0	
2000	FHSS Blower	0.1	1.000	0.42	0.00	0.00	0	0	0	0	0	Including 14kW **
2256	He01	7	0.194	NS	1.44	1.44	3	2	0	0	0	

** → Refer [47] p.173 equation 8.25. Assumed blower efficiency of 70%.

Details for the FHSS filter are as follows:

No.	Description	Chart
2380	FHSS Filter	FHSS_Filter_He_RevA.usp

BLOWER BYPASS

This section describes the blower bypass line and heat exchanger.

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2108	He10	3.2	0.05898	NS	1.44	1.44	4	0	0	0.0	0.0	
2320	FHSS Heat-Exchanger	0.1	0.60000	NS	1.50	1.50	0	0	0	1.5	1.5	Refer section 0
2128	He11a	14.7	0.05898	NS	1.98	1.98	5	1	0	0.0	0.0	
2648	He11b	4.0	0.05898	NS	3.48	3.48	3	0	1	0.0	0.0	
2242	He12	1.0	0.05898	NS	0.72	0.72	2	0	0	0.0	0.0	

MEASUREMENT BLOCK INTERNALS

The measurement block (MBA) internals comprise of the gas flow paths through the diverter in the MBA and the dust cleaning paths.

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2470	CL04-MB-E01 (Gas_Inlet)	0.10	0.043	NS	2.90	2.90	0	0	1	0.50	0.50	Reduction (Ref. 0)
2030	CL04-MB-W01 (to He05)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2022	CL04-MB-W01 (to He14)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2530	CL05-MB-E01 (Gas_Inlet)	0.10	0.043	NS	2.90	2.90	0	0	1	0.50	0.50	Reduction (Ref. 0)
2068	CL05-MB-W01 (to He13)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2270	CL05-MB-W01 (to He16)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2588	CL06-MB-E01 (Gas_Inlet)	0.10	0.043	NS	2.90	2.90	0	0	1	0.50	0.50	Reduction (Ref. 0)
2272	CL06-MB-W01 (to He15)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2264	CL06-MB-W01 (to He16)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2018	CL07-MB-W01 (to He05)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2024	CL07-MB-W01 (to He14)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2026	CL08-MB-W01 (to He13)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2074	CL08-MB-W01 (to He16)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2280	CL09-MB-W01 (to He15)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2290	CL09-MB-W01 (to He16)	0.01	0.065	NS	2.40	2.40	0	0	1	0.00	0.00	
2004	He05-MB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss
2014	He13-MB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss
2040	He14-MB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss
2016	He15-MB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = $90^\circ \times 0.36 + 45^\circ \times 0.18 + \text{Sharp} \times 2.4 + \text{Other (ref. 0 and 0)}$							Comments
					K_{fw}	K_{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2266	He16-MB2-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss
2322	He16-MB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.80	0.80	Straight junction loss
2010	L01 to L04 (Open)	0.64	0.065	0	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter
2070	L01 to L55 (Open)	0.64	0.065	NS	0.28	0.28	0	1	0	0.00	0.00	Sphere line loss factor
2250	L01-MB-I01	0.10	0.065	NS	0.10	0.10	0	0	0	0.10	0.10	Assumed for indexer
2006	L02 to L06 (Open)	0.64	0.065	0	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter
2038	L02e to L57 (Open)	0.64	0.065	NS	0.28	0.28	0	1	0	0.00	0.00	Sphere line loss factor
2114	L02-MB-I01	0.10	0.065	NS	0.10	0.10	0	0	0	0.10	0.10	Assumed for indexer
2008	L03 to L05 (Open)	0.64	0.065	0	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter
2078	L03 to L56 (Open)	0.64	0.065	NS	0.28	0.28	0	1	0	0.00	0.00	Sphere line loss factor
2148	L03-MB-I01	0.10	0.065	NS	0.10	0.10	0	0	0	0.10	0.10	Assumed for indexer
2228	L11 to L55 (Open)	0.64	0.065	NS	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter
2226	L12 to L56 (Open)	0.64	0.065	NS	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter
2144	L13 to L57 (Open)	0.64	0.065	NS	0.01	0.01	0	0	0	0.01	0.01	Assumed for straight diverter

CONVEYING BLOCK INTERNALS

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2072	L01-CB-R01 (Bypass)	1.28	0.065	NS	4.8	4.8	0	0	2	0.0	0.0	
2596	L01-CB-R01 (Bypass_Exit)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2598	L01-CB-R01 (Bypass_Inlet)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2084	L02-CB-R01 (Bypass)	1.28	0.065	NS	4.8	4.8	0	0	2	0.0	0.0	
2606	L02-CB-R01 (Bypass_Exit)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2602	L02-CB-R01 (Bypass_Inlet)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2096	L03-CB-R01 (Bypass)	1.28	0.065	NS	4.8	4.8	0	0	2	0.0	0.0	
2604	L03-CB-R01 (Bypass_Exit)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2600	L03-CB-R01 (Bypass_Inlet)	0.10	0.043	NS	2.9	2.9	0	0	1	0.5	0.5	Reduction (Ref. 0)
2547	CO01-CB-G1 (Gas Inlet)	0.10	0.043	NS	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction
2549	CO02-CB-G1 (Gas Inlet)	0.10	0.043	NS	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction
2551	CO03-CB-G1 (Gas Inlet)	0.10	0.043	NS	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction

ISOLATION BLOCK INTERNALS

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2364	CL07-IB-R01 (Gas_Inlet)	0.10	0.065	0.00	0.00	0	0	0	0.0	0.0	
2492	CL08-IB-R01 (Gas_Inlet)	0.10	0.065	0.00	0.00	0	0	0	0.0	0.0	
2532	CL09-IB-R01 (Gas_Inlet)	0.10	0.065	0.00	0.00	0	0	0	0.0	0.0	
2152	L55-IB-R01 (Bypass)	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	
2614	L55-IB-R01 (Bypass_Exit)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2608	L55-IB-R01 (Bypass_Inlet)	0.32	0.043	5.80	5.80	0	0	2	1.0	1.0	2xReduction (Ref. 0)
2122	L56-IB-R01 (Bypass)	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	
2616	L56-IB-R01 (Bypass_Exit)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2610	L56-IB-R01 (Bypass_Inlet)	0.32	0.043	5.80	5.80	0	0	2	1.0	1.0	2xReduction (Ref. 0)
2124	L57-IB-R01 (Bypass)	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	
2618	L57-IB-R01 (Bypass_Exit)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2612	L57-IB-R01 (Bypass_Inlet)	0.32	0.043	5.80	5.80	0	0	2	1.0	1.0	2xReduction (Ref. 0)

CLEANING BLOCK INTERNALS

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2654	CL01-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2656	CL01-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2118	CL01-CLB-W01 (to He03)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2166	CL01-CLB-W01 (to He06)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2658	CL02-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2660	CL02-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2172	CL02-CLB-W01 (to He03)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2164	CL02-CLB-W01 (to He06)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2662	CL03-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2664	CL03-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2168	CL03-CLB-W01 (to He03)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2158	CL03-CLB-W01 (to He06)	0.01	0.065	NS	2.40	2.40	0	0	1	0.0	0.0	
2668	CL04-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2680	CL04-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2672	CL05-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2684	CL05-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2676	CL06-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2688	CL06-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2666	CL07-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2678	CL07-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2670	CL08-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	

No.	Description	Length [m]	Diameter [m]	Mass Flow Rate "NS"=Not Specified [kg/s]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
					K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2682	CL08-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2674	CL09-CLB-W01 (HP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2686	CL09-CLB-W01 (LP Open)	0.2	0.065	0	0.36	0.36	1	0	0	0.0	0.0	
2116	He03-CLB-G01	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss
2176	He03-CLB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss
2170	He03-CLB-G03	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss
2178	He06-CLB-G01	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss
2372	He06-CLB-G02	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss
2138	He06-CLB-G03	0.32	0.065	NS	0.80	0.80	0	0	0	0.8	0.8	Straight junction loss

CORE UNLOADING DEVICE INTERNALS

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2104	CL01-CUD-V01 (Gas_Inlet to L1)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2362	CL02-CUD-V01 (Gas_Inlet to L3)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2150	CL03-CUD-V01 (Gas_Inlet to L2)	0.10	0.043	2.90	2.90	0	0	1	0.5	0.5	Reduction (Ref. 0)
2198	L01-CUD-G01	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	
2318	L02-CUD-G01	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2194	L03-CUD-G01	0.64	0.065	2.40	2.40	0	0	1	0.0	0.0	

CONVEYING LINES

No.	Description	Length [m]	Circumference [m]	Area [m ²]	Loss Coefficient = 90° x 0.48 + 45° x 0.28 + Other (ref. 0)							
					K _{fw}	K _{bw}	90°	45°	Other Fw	Other Bw	Comments	
2076	L01a	11.8	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2034	L01b	46.1	0.211488	0.003452184	1.24	1.24	2	1	0.00	0.00		
2046	L01c	1.704	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00		
2204	L01d+L01e	8.8	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2086	L02a	12.3	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2192	L02b	46.2	0.211488	0.003452184	1.24	1.24	2	1	0.00	0.00		
2224	L02c	1.7	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00		
2234	L02d+L02e	15.2	0.211488	0.003452184	1.44	1.44	3	0	0.00	0.00		
2162	L03a	13.1	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2032	L03b	46.1	0.211488	0.003452184	1.24	1.24	2	1	0.00	0.00		
2044	L03c	1.704	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00		
2180	L03d+L03e	12.2	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2252	L04	15.2	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2254	L05	14.9	0.211488	0.003452184	2.40	2.40	5	0	0.00	0.00		
2126	L06	12.1	0.211488	0.003452184	1.44	1.44	3	0	0.00	0.00		
2048	L08b+L08a+L24+TD+SRP1+SUP1	65.3	0.211488	0.003452184	5.16	5.16	8	3	0.48	0.48	1xLong Bend	

No.	Description	Length [m]	Circumference [m]	Area [m ²]	Loss Coefficient = 90° x 0.48 + 45° x 0.28 + Other (ref. 0)						
					K _{fw}	K _{bw}	90°	45°	Other Fw	Other Bw	Comments
2082	L08c	1.9	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00	
2058	L08d+L11	7.3	0.211488	0.003452184	1.80	1.80	2	3	0.00	0.00	
2292	L09b+L09a+L25+TD+SRP3+SUP3	65.8	0.211488	0.003452184	5.16	5.16	8	3	0.48	0.48	1xLong Bend
2182	L09c	2.183	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00	
2248	L09d+L12	9.2	0.211488	0.003452184	1.04	1.04	1	2	0.00	0.00	
2312	L10b+L10a+L28/11+L28e+L28l +L28m+SRP2+SUP2	67.3	0.211488	0.003452184	4.28	4.28	6	5	0.00	0.00	
2218	L10c	2.465	0.211488	0.003452184	0.00	0.00	0	0	0.00	0.00	
2246	L10d+L13	12.6	0.211488	0.003452184	2.00	2.00	3	2	0.00	0.00	
2102	L15a+L15b+L30b+L18a	12.7	0.211488	0.003452184	1.44	1.44	3	0	0.00	0.00	
2136	L16a	11.45	0.211488	0.003452184	1.44	1.44	3	0	0.00	0.00	
2160	L16a+L16b+L16c+L22+TD+SLP1	11.8	0.211488	0.003452184	3.48	2.98	4	2	1.00	0.50	Line entrance into tank
2112	L17a	10.6	0.211488	0.003452184	1.44	1.44	3	0	0.00	0.00	
2088	L17a+L17b+L17c+L23+TD+SLP2	12.2	0.211488	0.003452184	3.48	2.98	4	2	1.00	0.50	Line entrance into tank
2174	L18/12+L18i+L18b+L18a+SLP	12.7	0.211488	0.003452184	3.68	3.18	5	1	1.00	0.50	Line entrance into tank
2262	L19/6+L19j+L19b+L19a+SLP	12.5	0.211488	0.003452184	3.48	2.98	4	2	1.00	0.50	Line entrance into tank
2276	L29/5+L30a+L30b+L30c+L30e +L19a+L29e+L29m+L29n+SRP+SUP	37.4	0.211488	0.003452184	3.44	3.44	6	2	0.00	0.00	
2190	L55	13.3	0.211488	0.003452184	2.00	2.00	3	2	0.00	0.00	
2232	L56	10.5	0.211488	0.003452184	1.52	1.52	2	2	0.00	0.00	
2208	L57	10.7	0.211488	0.003452184	1.32	1.32	1	3	0.00	0.00	
2142	L58	9.3	0.211488	0.003452184	0.56	0.56	0	2	0.00	0.00	
2094	L59	9.7	0.211488	0.003452184	0.56	0.56	0	2	0.00	0.00	

No.	Description	Length [m]	Circumference [m]	Area [m ²]	Loss Coefficient = 90° x 0.48 + 45° x 0.28 + Other (ref. 0)						
					K _{fw}	K _{bw}	90°	45°	Other Fw	Other Bw	Comments
2146	L60	6.6	0.211488	0.003452184	0.28	0.28	0	1	0.00	0.00	

CLEANING LINES

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2060	CL01	4.1	0.05898	0.72	0.72	2	0	0	0	0	
2212	CL02	7	0.05898	1.26	1.26	3	1	0	0	0	
2308	CL03	7.1	0.05898	1.44	1.44	4	0	0	0	0	
2300	CL04	1	0.05898	0.72	0.72	2	0	0	0	0	
2036	CL05	1	0.05898	0.72	0.72	2	0	0	0	0	
2062	CL06	1	0.05898	0.72	0.72	2	0	0	0	0	
2206	CL07	11.6	0.05898	1.80	1.80	5	0	0	0	0	
2064	CL08	12.5	0.05898	1.80	1.80	5	0	0	0	0	
2140	CL09	15.8	0.05898	1.44	1.44	4	0	0	0	0	
2090	CL13	15.1	0.01	2.16	2.16	6	0	0	0	0	
2230	CL15	15.1	0.01	2.16	2.16	6	0	0	0	0	
2236	CL14	15.1	0.01	2.16	2.16	6	0	0	0	0	
2092	CL10	51.1	0.01	2.34	2.34	6	1	0	0	0	
2154	CL11	51.1	0.01	2.34	2.34	6	1	0	0	0	
2020	CL12	51.1	0.01	2.34	2.34	6	1	0	0	0	

GAS SUPPLY AND RETURN LINES FOR SPHERE LIFTING AND BRAKING

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2238	CO01	15.1	0.05898	2.16	2.16	6	0	0	0.00	0.00	
2210	CO02	14.6	0.05898	2.16	2.16	6	0	0	0.00	0.00	
2066	CO03	11.9	0.05898	2.16	2.16	6	0	0	0.00	0.00	
2294	CO04	51.4	0.05898	2.70	2.70	7	1	0	0.00	0.00	
2050	CO05	63.8	0.05898	2.76	2.76	5	0	0	0.96	0.96	Including 2 long bends (ref. Table 29)
2080	CO06	51.3	0.05898	2.70	2.70	7	1	0	0.00	0.00	
2054	CO07	63.8	0.05898	2.76	2.76	5	0	0	0.96	0.96	Including 2 long bends (ref. Table 29)
2630	CO08	51.1	0.05898	2.34	2.34	6	1	0	0.00	0.00	
2056	CO09	63.7	0.05898	2.64	2.64	6	0	0	0.48	0.48	Including 1 long bend (ref. Table 29)
2156	CO10	28.9	0.05898	5.28	5.28	8	0	1	0.00	0.00	
2052	CO11	28.6	0.05898	5.28	5.28	8	0	1	0.00	0.00	
2132	CO12	28.4	0.05898	5.28	5.28	8	0	1	0.00	0.00	
2282	CO13	55.6	0.05898	2.70	2.70	7	1	0	0.00	0.00	
2098	CO14	67.5	0.05898	2.94	2.94	5	1	0	0.96	0.96	Including 2 long bends (ref. Table 29)
2260	CO15	55.3	0.05898	2.52	2.52	6	2	0	0.00	0.00	
2130	CO16	67.7	0.05898	2.94	2.94	5	1	0	0.96	0.96	Including 2 long bends (ref. Table 29)
2284	CO17	54.9	0.05898	2.52	2.52	6	2	0	0.00	0.00	
2134	CO18	67.8	0.05898	2.94	2.94	5	1	0	0.96	0.96	Including 2 long bends (ref. Table 29)
2100	CO19+CO19/5	32.5	0.05898	8.40	8.40	10	0	2	0.00	0.00	
2120	CO20	47.9	0.05898	6.36	6.36	9	4	1	0.00	0.00	
2216	CO21+CO24	46.3	0.05898	3.42	3.42	6	7	0	0.00	0.00	

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2650	CO22	4.6	0.05898	0.54	0.54	1	1	0	0.00	0.00	
2106	CO23	2.9	0.05898	0.72	0.72	2	0	0	0.00	0.00	
2652	CO24	3.5	0.05898	3.66	3.66	3	1	1	0.00	0.00	
2628	CO32/12	21.1	0.05898	10.18	9.68	5	1	3	1.00	0.50	Line entrance into tank
2594	CO32/6	19.2	0.05898	9.64	9.14	3	2	3	1.00	0.50	Line entrance into tank

GENERAL GAS LINES

No.	Description	Length [m]	Diameter [m]	Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							Comments
				K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	
2298	He03	3.9	0.05898	0.72	0.72	2	0	0	0	0	
2634	He04	2.4	0.05898	0.36	0.36	0	2	0	0	0	
2042	He05	66.1	0.05898	4.32	4.32	10	4	0	0	0	
2002	He06	66.7	0.05898	3.96	3.96	10	2	0	0	0	
2278	He07b	16.7	0.05898	2.52	2.52	7	0	0	0	0	
2553	He07a	50.0	0.0243	4.50	4.50	10	5	0	0	0	Assumed All Line Details
2028	He13	12.8	0.05898	2.16	2.16	6	0	0	0	0	
2012	He14	10.9	0.05898	2.16	2.16	6	0	0	0	0	
2306	He15	13.8	0.05898	2.16	2.16	6	0	0	0	0	
2268	He16	11.8	0.05898	2.16	2.16	6	0	0	0	0	

TANK UNLOADING DEVICE

					Loss Coefficient = 90° x 0.48 + 45° x 0.28 + Other (ref. 0)						
No.	Description	Length [m]	Circumference [m]	Area [m ²]	K _{fw}	K _{bw}	90°	45°	Other Fw	Other Bw	Comments
2316	L28/11-TUD-Flow_Restriction	0.3	0.606	0.0006	0.5	0.5	0	0	0.5	0.5	Assumed coefficient
2110	L24-TUD-Flow_Restriction	0.3	0.606	0.0006	0.5	0.5	0	0	0.5	0.5	Assumed coefficient
2314	L25-TUD-Flow_Restriction	0.3	0.606	0.0006	0.5	0.5	0	0	0.5	0.5	Assumed coefficient

				Loss Coefficient = 90° x 0.36 + 45° x 0.18 + Sharp x 2.4 + Other (ref. 0 and 0)							
No.	Description	Length [m]	Diameter [m]	K _{fw}	K _{bw}	90°	45°	Sharp	Other Fw	Other Bw	Comments
2541	CO11-TUD-G01 (Gas Inlet)	0.1	0.043	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction
2543	CO12-TUD-G01 (Gas Inlet)	0.1	0.043	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction
2545	CO10-TUD-G01 (Gas Inlet)	0.1	0.043	1.9	1.9	0	0	0	1.9	1.9	60° Junction + Reduction

NODES

No.	Description	Volume [m ³]	Pressure [kPa]	Temperature [°C]
2	Reactor Core Outlet	5.203	1000	100
78	Manifold	96.736	1000	100
98	Void Above Reactor Core	5.875	1000	100
2095	Graphite Tank Assembly	140	Not Specified	Not Specified
2449	Used Fuel Tank Assembly	140	Not Specified	Not Specified

OUTSTANDING ISSUES

- a. The pressure loss characteristics of the FRI, three way valve, diverter and indexer are currently assumed and need to be verified for both helium and air.
- b. The pressure loss characteristics of the filter need to be verified for both helium and air.
- c. The heat exchanger pressure loss and heat transfer characteristics are outstanding and assumptions need to be verified.
- d. Pressure losses in the gas flow paths inside the FHSS Cleaning Block, Conveying Block, Measurement Block, Isolation Block and CUD are assumed and need to be verified.
- e. Flow characteristics for the trim valve, double seat isolation valve, isolation valve, flow control valve, three way valve and diverter are assumed and need be verified.
- f. Assumed xT values for valves need to be verified.
- g. Pressure loss characteristics for the venturis used for flow measurement are assumed and need to be verified.
- h. The blower non-return valve characteristics are assumed and need to be verified.
- i. No blower characteristics are available for the FHSS blower and assumptions need to be verified.
- j. Pressure losses in the GRBA and GSBA are assumed and need to be verified.
- k. Information on the HVAC system is outstanding and it is assumed that HVAC can remove all heat dissipated from the piping. It is further assumed that the HVAC system can provide a convection coefficient of at least $0.5 \text{ W/m}^2\text{K}$ on the outer surface of the piping.
- l. Insulation on the FHSS piping needs to be verified regarding the piping, which should be insulated if any at all.
- m. The insulation characteristics are assumed and need to be verified.
- n. Heat transfer to ambient is currently modelled for piping longer than 10m only. No heat transfer is modelled for gravity lines and sphere buffers. The heat transfer to ambient should be updated and refined before detailed temperature distribution analyses can be conducted.
- o. Heat radiation to ambient is not included and the effect should be verified.
- p. Heat transfer to ambient does not account for thermal capacitance and heat transfer elements need to be updated with conductive heat transfer elements before heat transfer transient analyses can be conducted.
- q. The dust pocket cleaning lines servicing the CBA are modelled to connect to a node representing the Auxiliary Gas system. The characteristics of this system represented by a single node in the model still need to be established.
- r. The gas brake inlet and outlet slots are not modelled, and although not regarded as major pressure loss components, need to be verified.

- s. The tank-unloading device is expected to cause some gas leak flow between the sphere conveying lines. This leak path is assumed and needs to be verified.
- t. The influence of not including pressure losses due to flanges and connection points needs to be investigated.
- u. The sphere storage tanks pressure relieve system is not modelled.
- v. The cross flow stemming from leak flow over the diverters in the discharge lock outlet unit is not modelled. This is acceptable for normal operation since no flow is expected in these lines. For special analyses on upset or fault conditions, it might be necessary to include these cross flow paths.
- w. Junction losses are modelled conservatively concerning pressure loss. Detailed and accurate junction losses need to be investigated and included for detailed analyses.
- x. Fluid scaling from air to helium for the filter characteristic and helium to air for the FRI characteristic (the FRI characteristic influences both the three-way valve and the diverter characteristic) needs to be verified. This outstanding issue is not foreseen to influence the blower performance drastically since these components account for a very small portion of the total system resistance and is therefore acceptable for blower sizing calculations.
- y. User specified element characteristics are assumed applicable to all pressures and temperatures and this assumption needs to be verified.
- z. The effect of ignoring physical height in the model needs to be verified.

MODEL LIMITATIONS

This section elaborates on the Flownex model limitations. Most of the limitations to the model are discussed in the assumptions to this document.

A summary of some of the most important model limitations with regard to analyses accuracy is presented:

The US elements used to model the characteristics of the venturis, FRI, three way valve and diverter, are limited to an applicable operating envelope for the component. The acceptable operating range for each of the components can be found in the characteristic data, i.e. the corrected mass flow rate and pressure ratio.

Note that it is assumed that the corrected mass flow rate pressure ratio relationship for the US elements is applicable to all operating pressures and temperatures.

Conductive capacitance for heat transfer to ambient is not included and limits the model to steady state analyses with reference to heat transfer to ambient.

The effect of the heat exchanger effectiveness cannot be simulated with this model.

The applicable operating envelope as discussed in (a) above is such that high pressure ratios above approximately 1.03, as will be found during choking conditions for the FRI, is not included.

The controllability of control valves in the FHSS is not included in this model and it is assumed that any valve condition is controllable.