

APPLICATION OF MONTE CARLO ANALYSIS IN THE SIMULATION OF THERMAL-FLUID NETWORKS

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Philippians 4:13, "I can do all things through Christ who strengthen me."

I praise God for the strength and courage He has given me over the past year. His greatness cannot be expressed in words.

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Thank you to my parents for the opportunity they gave me to study; for trusting me and believing in me.

ABSTRACT

Title : Application of Monte Carlo analysis in the simulation of thermal-fluid networks

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Large thermal-fluid network simulations are usually conducted for fixed input steady-state conditions without accounting for statistical variations of these variables. This is not realistic and gives no indication of possible deviations in results. A typical example of a large thermal-fluid network is the Pebble Bed Modular Reactor (PBMR) power plant. To accurately predict the electricity that is going to be generated, all the variations of the input variables must be accounted for in the simulation. Therefore a need was identified to derive a suitable Monte Carlo type algorithm that can be applied to large thermal-fluid network simulations.

An extensive literature survey was conducted and it was also found that Monte Carlo methods in general were used extensively to predict or forecast certain events. However, it also revealed that little previous work has been done specifically on Monte Carlo techniques applied to large thermal-fluid networks. Other sampling techniques could also been used to conduct the sensitivity analysis, but these are usually more complicated than the Monte Carlo technique.

This study deals with the derivation, validation and verification of a suitable Monte Carlo type algorithm as well as an investigation into the extent of uncertainties typically found in thermal-fluid component simulation. The latter is required as input to the algorithm. The new algorithm was implemented in different software models and successfully verified and validated using problems with varying degrees of complexity. Following this, the methodology was implemented into the Flownex software and applied to simulate a comprehensive network case study namely the Micro Model of the PBMR project.

The results of Flownex along with the results of the sensitivity analysis were used to do certain comparisons to determine the integrity of the algorithm. The Flownex steady state results were well within the range obtained from the Monte Carlo analysis. The results of the comparison obtained from the steady state and Monte Carlo analysis provide more confidence in the actual steady state results obtained from thermal-fluid network simulations. With the aid of the Monte Carlo analysis, it is now possible to simulate thermal fluid networks, while considering all the uncertainties involved for each component.

OPSOMMING

Titel	:	Toepassing van Monte Carlo-ontleding in die simulاسie van termo vloeinetwerke
Outeur	:	Johan Labuschagne
Promotor	:	Prof. P.G. Rousseau
Skool	:	Meganiese en Materiaal Ingenieurswese
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Groot termo-vloeinetwerk simulاسies word gewoonlik gedoen vir 'n vaste werkpunt by gestadigde toestande sonder om statistiese variasies in die veranderlikes in ag te neem. Dit is onrealisties en gee geen indikاسie van moontlike variasies in resultate nie. Die Korrel Bed Modulêre Reaktor (PBMR) is 'n tipiese voorbeeld van 'n groot termo vloeinetwerk. Om akkuraat te voorspel hoeveel elektrisiteit opgewek gaan word moet al die variasies in die insette in ag geneem word in die simulاسie. Die behoefte is dus geïdentifiseer om 'n Monte Carlo tipe algoritme af te lei wat op groot termo vloeinetwerk simulاسies toegepas kan word.

'n Uitgebreide literatuurstudie is onderneem en daar is gevind dat min werk spesifiek op Monte Carlo applikasies vir groot termo vloeinetwerk simulاسies gedoen is. Daar is wel gevind dat Monte Carlo-metodes in die algemeen op groot skaal gebruik word in die voorspelling van sekere gebeurtenisse. Ander tegnieke kan ook gebruik word om die sensitiwiteit te ontleed, maar is gewoonlik meer ingewikkeld.

Hierdie studie handel oor die afleiding, verifikاسie en validاسie van 'n geskikte Monte Carlo tipe algoritme asook 'n ondersoek na die onsekerhede wat tipies in termo vloeikomponente gevind word. Die laasgenoemde word benodig as inset tot die algoritme. Die nuwe algoritme is in verskillende sagtewaremodelle geïmplementeer en suksesvol geverifieer en gevalideer deur dit toe te pas op probleme met verskillende vlakke van kompleksiteit. Die verbeterde Flownex program is hierna gebruik om 'n omvattende netwerk gevallestudie, naamlik die Mikro Model van die PBMR projek te doen.

Die Flownex gestadigde resultate tesame met die resultate van die sensitiwiteitsanalise is gebruik en met mekaar vergelyk. Die Flownex waardes het almal in die bereik van die Monte Carlo ontleding se resultate geval. Die resultate van die vergelykings wat verkry is van die gestadigde simulاسie en Monte Carlo ontleding verskaf meer vertroue in die resultate van die termovloeinetwerk simulاسies. Met die hulp van die Monte Carlo ontleding is dit nou moontlik om termovloeinetwerke te simuleer en tegelykertyd die onsekerheid in die veranderlikes van al die komponente in ag te neem.

NOMENCLATURE

Symbol	Description	Unit
A	Area	m ²
c	Circumference	m
d	Diameter	m
e	Local error	-
E	Global error	-
f	Friction factor	-
K	Secondary Losses	-
L	Length	m
$\dot{m}$	Mass flow rate	kg/s
P	Pressure	kPa
P	Power Input	kW
Δp	Pressure drop	Pa
Q_e	Cooling capacity	kW
R^2	Coefficient of determination	-
$\bar{R}$	Mean	-
Re	Reynolds number	-
T_c	Condensing temperature	°C
T_e	Evaporating temperature	°C
Greek Symbols		
E	Inside Pipe Roughness	μm
μ	Mean	-
ρ	Density	kg/m ³
σ^2	Variance	-
Subscripts		
E	Outlet	-
I	Inlet	-

ABBREVIATIONS

Abbreviation	Description
BE	Best Estimate
BM	Box-Muller
CAD	Computer Added Design
CSD	Corrected Standard Deviation
CT	Cooling Tower
CWP	Cooling Water Pump
ELC	External Load Cooler
GUI	Graphical User Interface
GBP	General Bypass Valve
HPB	High Pressure Bypass
HPC	High Pressure Compressor
HPT	High Pressure Turbine
HS	Heat Source
IC	Inter-cooler
LHS	Latin Hypercube Sampling
LPB	Low Pressure Bypass
LPC	Low Pressure Compressor
LPT	Low Pressure Turbine
NEV	Nitrogen Extraction Valve
NIV	Nitrogen Injection Valve
PBMM	Pebble Bed Modular Reactor Micro Model
PBMR	Pebble Bed Modular Reactor
PBR	Pebble Bed Reactor
PC	Pre-cooler
PT	Power Turbine
PTCV	Power Turbine-Compressor Valve
RX	Recuperator
SBS	Start Up Blower System
SBSIV	Start Up Blower System Inlet Valve
SBSOV	Start Up Blower System Outlet Valve

Abbreviation	Description
SD	Standard Deviations
SHS	Shifted Hamersley Sampling
SIV	System Inline Valve
SV	Simulation Variable
V&V	Verification and Validation

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CHAPTER 1

INTRODUCTION

- 1.1 Preface
 - 1.2 Uncertainty analysis
 - 1.3 Sensitivity analysis
 - 1.4 Purpose of this study
 - 1.5 Impact of this study
-

1.1 PREFACE

Man uses mathematical and computational models for a variety of purposes, often to gain insight of possible outcomes of one or more courses of action. This may concern a financial investment, the choice on whether and how much to insure, the assessment of industrial practices and environmental impacts.

For engineers it is important to correctly simulate and accurately predict plant performance, before any physical construction of a plant can begin. This may be the deformation of the wing of an airplane due to certain stresses, or pressures and temperatures involved in thermal-fluid systems. There are literally hundreds of programmes to aid engineers in doing a variety of simulations of physical situations and processes.

In the case of thermal-fluid problems, one such programme is Flownex. Flownex is a general network analysis code that solves the flow, pressure and temperature distribution in large arbitrary-structured thermal-fluid networks. Flownex can handle a wide variety of network components, such as pipes, pumps, orifices, heat exchangers, compressors, turbines, controllers and valves.

Although Flownex can do all off this it does not allow for uncertainties that could exist in the input values of a system. This can be the uncertainty of the length of a pipe due to installation problems, the efficiency of a turbine or compressor, etc. The need therefore arose to derive a suitable Monte Carlo type algorithm to be implemented into existing thermal-fluid network simulation software to determine the sensitivity of a system due to existing uncertainties. This will be called a sensitivity analysis in the rest of the study. The following section will show the connotation between an uncertainty and a sensitivity analysis. This study will also show the importance of conducting the two together.

1.2 UNCERTAINTY ANALYSIS

An uncertainty analysis aims to quantify the overall uncertainty associated with the response of a system as a result of uncertainties in the inputs. The uncertainty associated with thermal-fluid networks is an important factor for risk analysis and performance studies. Consequently, this topic is very important in decision making in process safety and economic profitability analysis.

Normally, in actual process design and simulation operations, the associated uncertainty is addressed by using safety factors, which can increase cost and investment without a quantitative measure of avoidable risk. Uncertainty analysis can be used for studying the safety factors involved in design. Decreasing the magnitude of uncertainties increases the efficiency and financial attractiveness of the global process.

1.3 SENSITIVITY ANALYSIS

A sensitivity analysis is the study of how the variation in the output of a model (numerical or otherwise) can be apportioned, qualitatively or quantitatively, to different sources of variations. A sensitivity analysis aims to ascertain how a model depends upon the information fed into it, upon its structure and upon the assumptions made to build it. This information can be invaluable, since:

- Different levels of acceptance (by the decision-makers and stakeholders) may be attached to different types of uncertainty.
- Different uncertainties impact differently on the reliability, robustness and efficiency of the model.

There are three different ways to do this sensitivity analysis according to Press *et al.* (1997):

- One may perturb the boundary conditions in addition to the perturbations of the observations (input parameters). One then obtains an impression of the combined sensitivity to the uncertainties in the observations and boundary conditions.
- One may also perturb the parameters used by the model in addition to the perturbations of the observations and boundary conditions.
- In general one may perturb any aspect of the forecasting system of which the uncertainty is expected to be of some importance.

It is thus clear that an uncertainty analysis aims to quantify the uncertainties involved whereas sensitivity analysis use these values to determine the sensitivity of the network due to the existence of the uncertainties.

1.4 PURPOSE OF THIS STUDY

The purpose of this study is to develop an algorithm to conduct sensitivity analysis on thermal-fluid network simulations. A secondary outcome is to implement this algorithm into a software code like Flownex to do such an analysis. In order to develop this algorithm, the following steps were taken:

- A literature survey was done on different statistical methods used to do sensitivity analysis to obtain information on what has been done up to now, so that work that has already been done can be implemented.
- Development of the algorithm.
- Implementation of the algorithm into a software code and the Flownex simulator.
- Verifying the algorithm against experimental simulation data.

The Pebble Bed Modular Reactor Micro Model (PBMM) was used as a case study and the data generated from the Flownex network was used in the verification and validation process.

1.5 IMPACT OF THE STUDY

On completion of this study a complete algorithm is available to conduct a sensitivity analysis on thermal-fluid network simulations. This algorithm was implemented into the Flownex software and will be available for use to determine the sensitivity of a thermal-fluid network such as the PBMM. The sensitivity analysis routine will become a handy tool in designing thermal-fluid systems and will increase confidence in the network and its predictions by providing an understanding of how the model's output variables are affected by uncertainties in the input variables.

CHAPTER 2

LITERATURE SURVEY

- 2.1 Introduction
 - 2.2 Monte Carlo methods
 - 2.3 Taguchi methods
 - 2.4 Other sampling techniques
 - 2.5 Uncertainty and sensitivity analysis
 - 2.6 Conclusion
-

2.1 INTRODUCTION

An extensive literature survey was conducted into the field of statistical methods to do sensitivity analysis on thermal-fluid network simulations. The focus fell mainly on Monte Carlo, Taguchi and other sampling methods.

The survey was divided into the following three main groups:

- Statistical methods:
 - Monte Carlo
 - Taguchi
- Other sampling techniques.
- Uncertainty and sensitivity analyses.

The literature was evaluated on the basis of the following questions:

1. What was the aim of the work?
2. Why was the work done?
3. How was the work done?
4. What are the most important results that have been obtained?
5. What conclusions can be drawn from the work?

Because of the general nature of the subject, little or no literature was found specifically on the application of the Monte Carlo method on thermal-fluid network simulations. In the following sections it will be shown that the proposed method is commonly used and is suitable for application in this study.

2.2 MONTE CARLO METHODS

Numerical methods known as Monte Carlo methods can be loosely defined as statistical simulation methods. Statistical simulations are defined in general terms to be any method that utilises sequences of random numbers to perform a simulation (Woller, 1996).

The idea of the Monte Carlo methods in these studies is to perturb all of the available observations simultaneously with random numbers of realistic amplitude. Note that the resulting forecast will be different almost every time. This is due to the fact that random numbers are used. By repeating the experiment many times with different sets of random numbers for different variables, one obtains an impression of the forecast error that is due to the uncertainty in the observation.

Statistical simulation methods may be contrasted to conventional numerical discretisation methods, which are typically applied to ordinary or partial differential equations that describe some underlying physical or mathematical system. In many applications of Monte Carlo methods, the physical process is simulated directly, and there is no need to even write down the differential equations that describe the behaviour of the system. The only requirement is that the inputs of the physical (or mathematical) system should be described by probability density functions (pdf's).

Monte Carlo methods are commonly used for the simulation of various transport phenomena as shown by Hammersley and Handscomb (1964), Howell (1969) and MacKeown (1997). The term Monte Carlo is, however, used to cover such a wide range of distinct statistical approaches that it is always a source of ambiguity to address any Monte Carlo methodology on a general basis.

Rousseau *et al.* (2001) developed a computer simulation model that combines a deterministic mathematical model with a Monte Carlo approach in order to predict the diverse factors associated with household water heating methods. This Monte Carlo model used the Box-Muller transformation. This transformation transforms two independent rectangular random numbers to an independent random variable with normal distribution with mean zero and unit variance. This random number is then multiplied with a standard deviation of a particular input variable and added to the value calculated mathematically for the input variable. The above method is used to generate the perturbations and a good estimate of the mean and standard deviation can be deduced from the values generated.

Zhou *et al.* (2002) developed a Monte Carlo model for predicting the effective emissivity of a silicon wafer in rapid thermal processing furnaces. Yang *et al.* (2001) did a Monte Carlo simulation of hyper-thermal physical vapour deposition. They developed an energy-dependent kinetic Monte Carlo method to simulate sputter deposition on a flat substrate. Du Toit (1991) used a Monte Carlo technique to determine the deflection direction and particle velocity after collision with a solid surface in a flow field. Baguer *et al.* (2002) presented some of the fundamental characteristics of the hollow cathode glow discharge for different discharge conditions. Based on a hybrid Monte Carlo model to describe the movement of the fast electrons as particles, while in the fluid model, the slow electrons and positive ions are treated as a continuum.

De Lataillade *et al.* (2002) showed that, starting from any existing Monte Carlo algorithm for estimation of a physical quantity A , it is possible to implement a simple additional procedure that simultaneously estimates the sensitivity of A to any problem parameter. The corresponding supplementary cost is very low as no additional random sampling is required. These authors presented the principle on a formal basis and used simple radiative transfer examples as illustration. They address the question of estimating parametric sensitivities with Monte Carlo algorithms. Parametric sensitivity estimates are required in numerous physical contexts, as stated by Tomovic (1963) and Beck and Arnold (1977), in particular that of inverse radiative transfer problems as basis for numerous retrieval algorithms. For their purposes, sensitivities are mainly considered as a way of deriving first-order radiative transfer models for unstationary coupling with other complex phenomena such as natural convection or chemical reactions in combustion systems. Although they used radiative transfer examples for illustration this approach can be extended to a wider range of applications.

Another subject commonly used in Monte Carlo methods is acceptance-rejection methods. Pang *et al.* (2002) and Du Toit (1991) showed that by using the acceptance-rejection method one can generate a uniform distribution in a certain domain. The method only has to satisfy the definition as stated in section 4.3.4 to qualify as an acceptance-rejection method.

The last major question in conducting a Monte Carlo simulation is the number of runs to be conducted or in other words, the convergence criteria to use when simulating the flow in thermal-fluid networks. After consulting with Prof. H.S. Steyn (2002) of the Statistical Consulting Bureau

at the PU for CHE, some methods used by statisticians were proposed by him. The following criteria were suggested:

- Conduct 10 000 runs (norm in statistics for Monte Carlo simulations).
- Use the standard deviation of the mean of the response variable as criteria. The equation used to calculate this standard deviation is $SD(\bar{x}) = \frac{SD}{\sqrt{n}}$ (Vardeman, 1993). If this is minimised one can use it as a criterion.

It is clear that Monte Carlo models are widely used for predicting and forecasting.

2.3 TAGUCHI METHODS

The Taguchi method was developed for designing experiments by optimising the input variables so that the variance of the response variable is a minimum. Its main objective can be divided into two categories namely to optimise the experiment and to determine the variables with the biggest impact on the response. The Taguchi method has been well described by Phadke (1989) in his book, *Quality engineering using robust design*. A brief explanation of the method follows.

In the method proposed by Taguchi, orthogonal arrays are used to sample the domain of input variables. For each input variable, either two or three levels are taken. Suppose μ_i and σ_i^2 are the mean and variance respectively for the input variable of x_i . Taking two levels, we then choose

them to be $\mu_i + \sigma_i$ and $\mu_i - \sigma_i$. Similarly, taking three levels, we choose them to be $\mu_i - \sqrt{\frac{3}{2}}\sigma$ and $\mu_i + \sqrt{\frac{3}{2}}\sigma$. Here also, the mean and variance of the three levels are μ_i and σ_i^2 respectively.

We then assign the input variables to the columns of an orthogonal array to determine testing conditions (sampling points) for evaluating the response. From these values of response, we can estimate the mean and variance response. Note that orthogonal array-based simulation can be performed with hardware experiments as well, provided that experimental equipment allows one to set the levels of the input variables.

Wang and Pan (1998) showed how the method can be used to increase the stability of the two-phase flow experiment in a natural circulation loop, by determining the inputs with the biggest impact on the response variable's variance. They found that the variables suggested by Taguchi did in fact improve the stability and that they saved a great deal in experimental time.

Taguchi is also used in optimisation. Bilen *et al.* (2001) used the Taguchi method to determine the effect of the geometric position of wall-mounted blocks on the heat transfer from a surface. They determined the optimum conditions for heat transfer from the surface, as well as the parameters with the largest effect. The results showed that the Taguchi method can be successfully applied to this kind of study, and the prediction of the method was in very good agreement with the experimental results.

Similar studies were conducted by Chen and Du (2000) in developing a methodology for managing the effect of uncertainty in simulation-based design. Again the limitations were one of the aspects that make this method difficult to implement into simulations of systems with large numbers of input variables.

2.4 OTHER SAMPLING TECHNIQUES

Vasquez and Whiting (2000) found that a major concern in uncertainty analysis is to obtain reliable results for the output distribution of the variable being studied or analysed. This problem mainly relies on the sampling technique used to get the samples and the criteria employed to assign the probability distributions of the input parameters in a given stochastic model. The latter is a topic of wide discussion because the complexity involved is specific for each case. A more detailed discussion about this topic can be found in Haimes *et al.* (1994) and Seiler and Alvarez (1996).

Whiting and Vasquez (1998) also suggest sampling techniques such as the Latin hypercube (LHS) and shifted Hamersley sampling (SHS). They also state that this is much more complicated than the basic Monte Carlo method that is used when one knows the probability density function used to describe the system.

Generally, LHS will require fewer samples than Monte Carlo for similar accuracy. However, due to the stratification method, it may take longer to generate a value than for Monte Carlo sampling. Similarly, with the Hamersley sampling technique it was found that the Monte Carlo model will be the best and fastest sampling technique because of its simplicity.

2.5 UNCERTAINTY- AND SENSITIVITY ANALYSIS

As mentioned earlier, sensitivity and uncertainty analyses are very similar and closely linked to the Monte Carlo analysis. As mentioned above, the Monte Carlo method is only one of many sampling techniques. Clarke *et al.* (2001) used the LHS method to study the sensitivity and uncertainty of heat exchanger design to physical properties' estimation.

Previous work has also shown that the uncertainty associated with thermodynamic models can be significant. Reed *et al.* (1993) showed how the uncertainty in the Soave-Redlich-Kwong equation of state affects the reflux ratio and reboiler heat duty in a superfractionator. A similar analysis for the number of stages in a distillation column is presented in Reed and Whiting (1993).

2.6 CONCLUSION

Little literature was found on the application of Monte Carlo models in thermal-fluid network simulations. However, many Monte Carlo models were used in other applications. Most of these models were used to forecast or predict events due to different input parameters.

It was also found that there are many different statistical methods proposed in the literature to do sensitivity and uncertainty analyses. The Box-Muller transformation was successfully used along with a Monte Carlo model. It is also clear that one can integrate the Monte Carlo model with sensitivity analysis in order to conduct such an analysis.

Acceptance-rejection methods are commonly used in determining whether or not a certain value satisfies a certain specification. No concrete criteria for such models were found though. The information that was obtained on convergence criteria of Monte Carlo models was from persons in statistical consulting professions.

Other sampling methods such as the LHS and SHS gives the same accuracy with fewer samples but is more complicated. The Taguchi method was found to be very stable but its limitations on the number of input variables suggested that a multiple regression method would be more suitable to determine the input variables with the most impact on the response variables.

CHAPTER 3

UNCERTAINTIES IN THERMAL FLUID SYSTEMS

- 3.1 Introduction
 - 3.2 Uncertainties in pipes
 - 3.3 Uncertainties in shell-and-tube heat exchangers
 - 3.4 Uncertainties in turbines and compressors
 - 3.5 Uncertainties in other equipment
 - 3.6 Conclusion
-

3.1 INTRODUCTION

This chapter will discuss the uncertainties involved in thermal-fluid systems/components. Uncertainties exist in virtually all computational, analytical, or experimental engineering activities. The quantification of uncertainties in experimentation is a relatively mature subject and is well-documented in Coleman and Steele (1989). The quantification of uncertainties in computational field simulations is a rapidly growing segment of that discipline as stated by Roache (1997). In topical areas such as structural and mechanical design for reliability, the uses of statistical and probability-based methods are powerful tools that are well-integrated into engineering practice. However, procedures for the quantification of uncertainties in thermal-fluid network analysis and design are not well developed; indeed, thermal system design procedures are generally based on ad hoc safety factors with little appeal to probability or statistics.

In this chapter, detailed discussions on uncertainties of thermal components will help in quantifying some of these values. Not all components involved in thermal-fluid networks will be discussed in this study, however the components that will be discussed are the following:

- Pipes;
- Shell-and-tube heat exchangers;
- Turbines and compressors;
- Other components such as valves and orifices.

Each component will be discussed under the following topics. First and foremost it is necessary to understand which variables are involved in simulating the component and what effect the uncertainties of these variables have on the operation of the component. Secondly, the variables

that will be used in the case study (see Chapter 6) will be tabled as well as the physical values of these uncertainties. Note that this chapter is based on component models found in Flownex.

3.2 UNCERTAINTIES IN PIPES

Pipes are the primary source of conveying a fluid from component to component in a thermal fluid system. In fluid dynamics there are a few ways in which one can simulate a pipe. This study will only look at the most common one, namely the Darcy-Weisbach pipe simulation. The equations that are necessary to calculate the pressure drop in a pipe is given in Chapter 5 section 5.2.4. The schematic diagram below shows the variables involved in simulating the pipe.

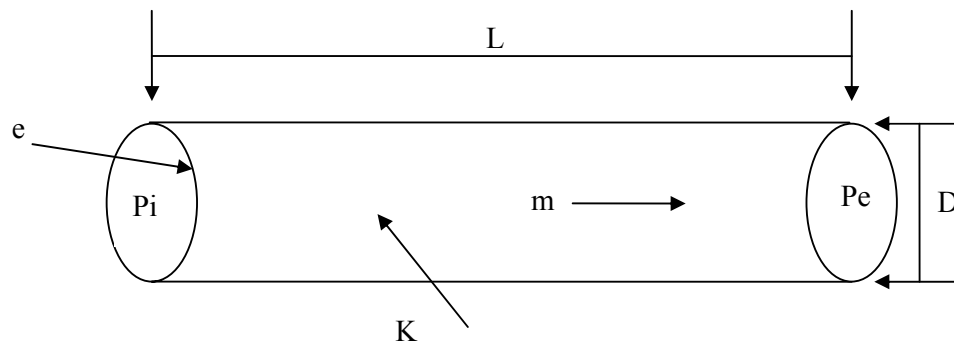


Figure 3.1: Schematic illustration of a pipe

Variables

Table 3.1 shows all the variables that are used in the equations mentioned above as well as the effect they have on the pressure drop in the pipe if they are varied. Note that not all of the variables can be varied, some are values that have no uncertainty or are fixed. It is necessary to understand the effect of each input variable on the output parameter, in this case the pressure drop. This also shows that if you have an uncertainty in a variable your simulation can and mostly will give you answers that will not correlate with experimental data of the same system.

Variables	Description	Affect on ΔP
Diameter (D) Circumference (C) & Area (A)	Pipe inside diameter, circumference and area.	Large value results in smaller ΔP ; smaller value results in higher ΔP .
Length (L)	Length of pipe including all fittings.	Larger value results in higher ΔP ; smaller value results in lower ΔP .
Roughness (ε)	Roughness of pipe.	Larger value results in higher ΔP ; smaller value results in lower ΔP .
Secondary Losses (K)	Loss coefficients of all the fittings as well as inlet and outlet losses.	Larger value results in higher ΔP ; smaller value results in lower ΔP .

Variables	Description	Affect on ΔP
Inlet Pressure (P_i)	Total inlet pressure.	Is usually a fixed value and has a direct proportional effect on the ΔP .
Mass Flow Rate (m)	The rate at which the flow flows through the element.	Is usually a response variable and has a direct proportional effect on the ΔP .
Outlet Pressure (P_e)	Total outlet pressure.	Is usually a fixed value and has an inversely proportional effect on the ΔP .

Table 3.1: Variables used in Darcy-Weisbach pipe simulations and the effect they have on the pressure drop in the pipe

Note that all of these variables are variable when one is simulating a pipe theoretically, however practically this is not always the case. For instance, the inlet and outlet pressure are usually fixed or are calculated in a system, the same as for the mass flow. In the next section, only the variables that have uncertainties will be discussed. Values for these uncertainties will be assigned and the method of doing this will also be discussed.

Uncertainty of variables

This section will discuss the most difficult and most important part of the study, namely assigning values for the uncertainty of the variables. If the values assigned were not realistic, the algorithm will generate values with unrealistic standard deviations and the study will not be successful.

In most cases the uncertainty can be defined as the tolerance that is specified in the specifications of the component. The tolerance as a percentage of the nominal value is used as the uncertainty for the variable. Table 3.2 shows the values for the uncertainties for the pipes used in the case study (See Chapter 6) as well as the originating source.

Variables	Uncertainty	Source
Diameter (D)	8 %	Manufacturing specification. (ASTM)
Length (L)	0.1 %	Implementation
Roughness (ϵ)	50 %	Article by R.P Taylor <i>et al.</i> (1999)
Secondary Losses (K)	50 %	Same as above

Table 3.2: Values for uncertainties in Darcy-Weisbach pipes

As stated in the table above, the diameter's tolerance is found in the specification from which it was manufactured. In the case of stainless steel pipes, the tolerance is not a uniform distributed function, the specification only allows for tolerance in the positive direction. This, however, is not implemented in the current code (See suggestions for further work in Chapter 7). The way to

handle a phenomenon like this in the current algorithm is to set the uncertainty on the highest value allowed in each direction. Although the diameter normally has a small uncertainty, it has a large effect on the output of the network.

The only specification set on the length of a pipe is the design specification. In practice it is difficult to build a plant and stay exactly within the design length. An uncertainty of 0.1 % is thus estimated for all pipe lengths. It is possible to identify certain pipes where the length can have a larger uncertainty that could transpire from installation problems. This value is relatively small, because the length of the pipe will usually not vary much. The estimation of this value is dependent on the amount of variance allowed for the length of pipe in the plant. In many cases it is not even necessary to incorporate this in one sensitivity analysis, because the effect it has on the whole system is negligible. However, this value is included for the sake of completeness of the study.

Taylor *et al.* (1999) did a study on estimating uncertainty in thermal system analysis and design. They stated that by conducting many experiments, the value of the uncertainty for the roughness of a pipe is estimated at 50%. The same study showed that the uncertainty for loss coefficients is also 50%. These values will have the biggest effect on the system and are very important in the sensitivity study. The next section will discuss the uncertainties involved in shell-and-tube heat exchangers.

3.3 UNCERTAINTIES IN SHELL-AND-TUBE HEAT EXCHANGERS

Shell-and-tube heat exchangers are by far the most common type of heat exchanger to encounter in the chemical process and power plant industry. This type of heat exchanger is available in a variety of configurations with numerous construction features and with differing materials for specific applications. The primary function of a heat exchanger is to cool down or heat up a primary fluid (tube-side) with a secondary fluid (shell-side). A typical example of such a heat exchanger is shown in Figure 3.2. In this arrangement, the tube-side fluid enters the header through the nozzle at the upper extreme left of the unit makes two passes through the shell via the U-shaped tubes and leaves via the bottom nozzle in the header. The second fluid enters the shell-side of the heat exchanger through the second nozzle at the lower left of the unit. From there it passes in cross-flow across the tubes, around the upper edge of the first baffle and returns toward the bottom of the shell, making a second pass across the outside surface of the tubes. The shell-

side fluid continues a serpentine flow across the tubes and exits through the nozzle at the upper right-hand side.

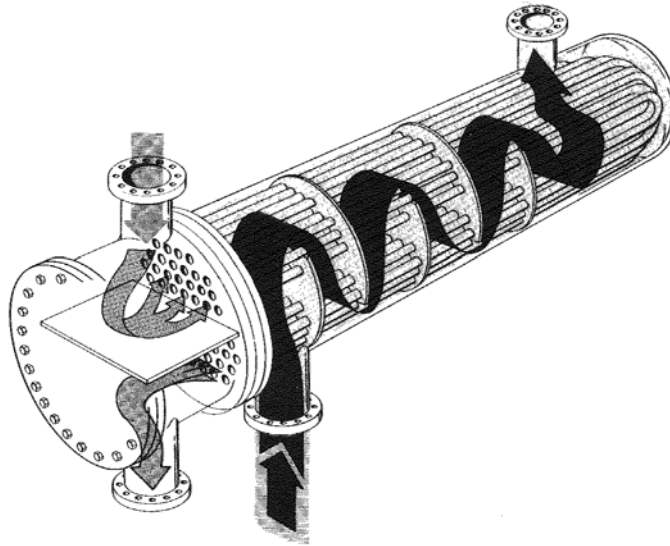


Figure 3.2: Typical U-tube shell-and-tube heat exchanger

The modelling of compact heat exchangers such as shell-and-tube heat exchangers, requires careful attention when the numerical model is set up. The equations used to numerically model a shell-and-tube heat exchanger are given by Kays and London (1984). The E-type shell-and-tube heat exchanger as shown in Figure 3.3 is used in the case study. It is now necessary to inspect the variables involved in simulating such a heat exchanger and the effect that the variation of the input variables has on the heat exchanged in the process.

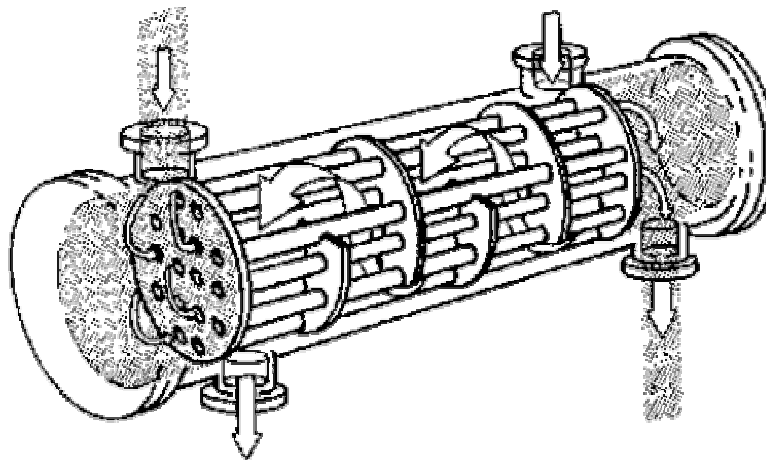


Figure 3.3: Typical E-type shell-and-tube heat exchanger

Flownex simulates a shell-and-tube heat exchanger by dividing the heat exchanger into a number of cross-flow heat exchangers. The heat transfer is solved for each of these sub heat exchangers. Figure 3.4 shows a schematic representation of the tube layout of a typical shell-and-tube heat exchanger. The figure shows some of the important dimensions of the tube bundles required by Flownex. Both the gas and liquid flow paths are serpentine-shaped.

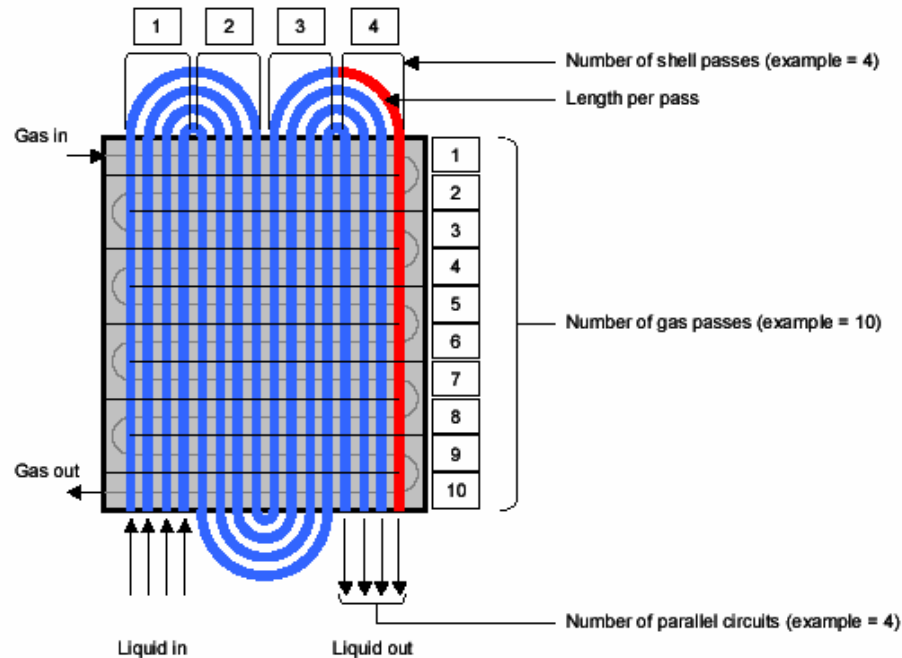


Figure 3.4: Tube layout of a shell-and-tube heat exchanger (Flownex User Manual Version 6.4, 2003)

A cross-sectional view of a typical shell-and-tube heat exchanger is shown in Figure 3.5.

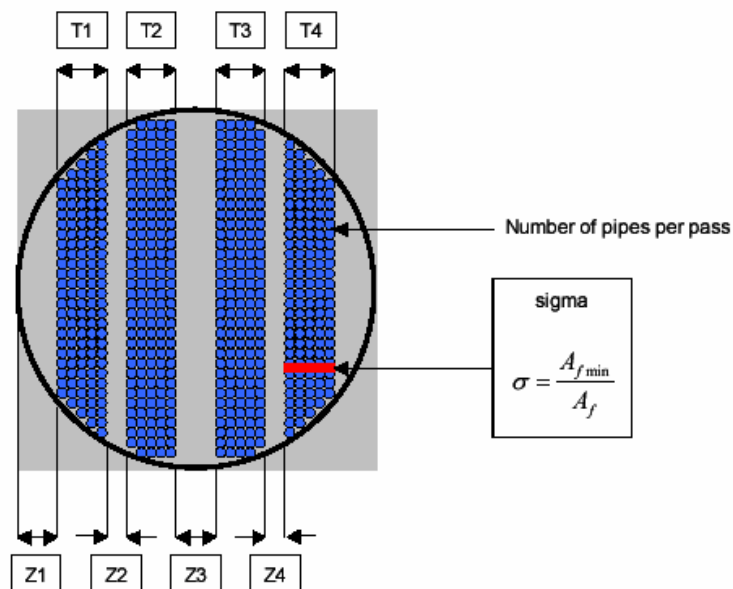


Figure 3.5: Cross-sectional view of shell-and-tube heat exchanger (Flownex User Manual Version 6.4, 2003)

Variables

Table 3.3 shows all the variables that are used to simulate a shell-and-tube heat exchanger as well as the effect they have on the heat transfer and pressure drop if they were varied. Not all the variables have uncertainties, some are fixed in the heat exchanger other is results of the simulation.

Variables	Description	Effect on heat transfer and ΔP
General		
Gas heat area	Heat transfer area on the gas-side.	Larger area results in more heat transfer and higher ΔP ; smaller area results in less heat transfer and lower ΔP .
Area ratio	Area ratio of the gas-side heat transfer area to the liquid-side heat transfer area.	Larger area ratio results in less heat transfer; smaller area ratio results in more heat transfer. No effect on ΔP .
Metal coefficient	Metal heat transfer coefficient.	Has little or no effect on the heat transfer and ΔP .
Heat capacity	Product of mass and specific heat.	Has little or no effect on the heat transfer and ΔP .
Shell-side (Gas)		
Number of gas passes	Number of gas passes in shell-and-tube heat exchanger.	Fixed value; number of baffles determine number of gas passes.
Shell diameter	Inside diameter of heat exchanger shell.	Larger diameter results in less heat transfer and lower ΔP ; smaller shell diameter results in more heat transfer and higher ΔP . *Note: Cannot be much smaller because bundle will not fit into shell.
Shell length	Inside length of heat exchanger shell.	Longer shell results in less heat transfer and lower ΔP ; shorter shell results in more heat transfer and higher ΔP .
Void fraction	Fraction not occupied by the tubes in the shell of the heat exchanger.	Have little or no effect on the heat transfer and ΔP .
Sigma	Ratio of minimum flow area to frontal flow area.	Larger sigma results in less heat transfer and lower ΔP ; lower sigma results in more heat transfer and higher ΔP .
K_{in}	Inflow loss factor	Fixed value for inlet losses
Z_{1-4}	Shell space width between tube bundles. (See Figure 3.5)	Larger and smaller space results in more heat transfer. Larger space results in lower ΔP and smaller space results in lower ΔP . *Note: Can't be much bigger because bundle will not fit into shell.
T_{1-4}	Width of tube bundle per pass. (See Figure 3.5)	Larger and smaller space results in more heat transfer and larger ΔP . *Note: Cannot be much bigger because bundle will not fit into shell.

Variables	Description	Effect on heat transfer and ΔP
Tube side (Liquid)		
Number of parallel circuits	See Figure 3.4	Fixed number of circuits
Number of shell passes	See Figure 3.4	Fixed number of shell passes
Number of pipes per pass	See Figure 3.4	Fixed number of pipes
Pipe inside diameter	Tube inside diameter.	Larger diameter results in less heat transfer and higher ΔP ; smaller diameter results in more heat transfer and higher ΔP .
Length per pass	Total tube length per pass. (See Figure 3.4)	Has little or no effect on the heat transfer and ΔP . Usually fixed value.
Inside roughness	Inside surface roughness of tube.	Has little or no effect on the heat transfer and ΔP .
K_{in}	Inflow loss factor.	Fixed value for inlet losses
K_{out}	Outflow loss factor	Fixed value for outlet losses

Table 3.3: Variables used in shell-and-tube heat exchanger simulations and the effect they have on the heat transfer

It is clear from the table above that many variables have a small or even no effect on the heat transfer of the heat exchanger. Other variables are fixed and have no uncertainty at all. In the next section only those variables that have uncertainties will be discussed. Values for these uncertainties will be assigned and the method of how this is done, will be discussed.

Uncertainty of variables

Table 3.4 shows the values for the uncertainties for the shell-and-tube heat exchanger used in the case study (see Chapter 6) as well as the source where these values were obtained from.

Variables	Uncertainty	Source
General		
Gas heat area	8 %	Dependent on pipe diameter
Area ratio	8 %	Dependent on pipe diameter
Shell side (Gas)		
Shell diameter	1 %	Design specifications
Shell length	0.1 %	Design specifications
Sigma	8 %	Dependent on pipe diameter
Z_{1-4}	8 %	Dependent on pipe diameter
T_{1-4}	8 %	Dependent on pipe diameter
Tube side (Liquid)		
Pipe inside diameter	8%	Manufacturing specification (ASTM)

Table 3.4: Values for uncertainties in shell-and-tube heat exchangers

As stated previously, the value of the diameter's uncertainty is found in the specification from which it was manufactured from. All the variables with regard to the area and area ratios are directly dependent on the uncertainty of the pipe diameter.

The uncertainty of the shell inside diameter and shell length is the tolerance that the manufacturing specification allows. Note that almost all the variables in a heat exchanger are dependent on each other; however, they are varied independently from each other to ensure that every uncertainty has been covered. The next section will discuss the uncertainties involved in a turbocharger unit.

3.4 UNCERTAINTIES IN TURBINES AND COMPRESSORS

Different types of compressors and turbines are used in the industry for different applications. Centrifugal compressors and turbines are usually used in a turbocharger unit in the automotive industry. The details of how a centrifugal turbo unit works, can be found in Cohen *et al.* (1996).

For the purpose of this study, only a brief description will follow of how such a unit works in a closed cycle. Gas enters the compressor unit and the compressor adds energy to the gas, the gas passes through a heat source, which adds even more energy. The energy in the gas in turn drives the turbine that supplies the compressor of energy to turn. As a result, the system is self-sustaining.

Compressors and turbines are simulated as separate units in Flownex and only use the performance maps supplied by the manufacturers. The next section will show the variables involved in simulating a turbine and compressor. Figure 3.6 shows the layout of a typical turbocharger consisting of a centrifugal compressor and turbine.

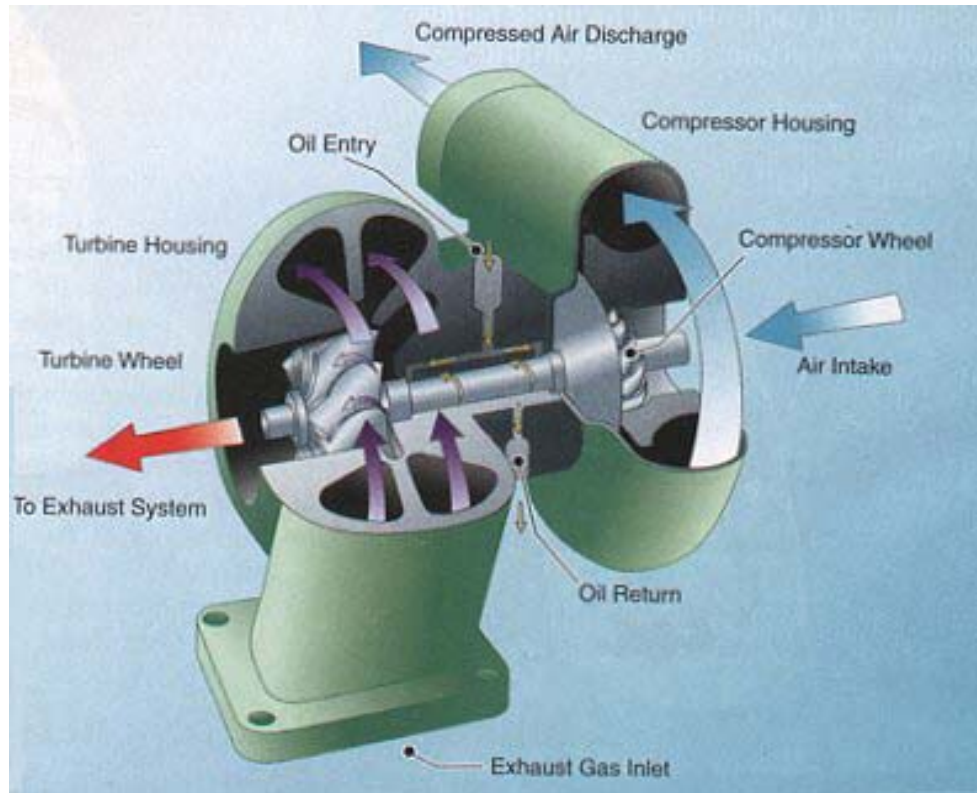


Figure 3.6: Schematic illustration of turbocharger

Variables

To be able to understand the method of how one can vary the parameters involved when simulating a turbo-charger in Flownex, one must first investigate the used variables. Table 3.5 shows the variables or in this case the geometric scaling factors that can be varied to conduct the sensitivity analysis on a compressor. The variables are the same for the turbine although different maps are used.

Variables	Description	Uncertainty
A-Factor ($N/\sqrt{T_{01}}$)	The geometrical scaling factor for the corrected speed.	Not applicable
B-Factor ($\dot{m}\sqrt{T_{01}}/p_{01}$)	The geometrical scaling factor for the corrected mass flow.	Not applicable
C-Factor (p_{02}/p_{01})	The scaling factor for the pressure ratio.	Not applicable
E-Factor (η_c)	The scaling factor for the efficiency fraction.	1%

Table 3.5: Variables used in compressor and turbine simulations

The variation of the factors mentioned above will ensure that many different work points will be simulated. If all the variables/factors were varied in a complex system like the one in the case study, the effect can be too much and the compressor and turbine will no longer be on the performance maps. This can be prevented by only varying the E-factor, which actually includes all the other variables. This factor will be only varied with by 1%.

3.5 UNCERTAINTIES IN OTHER EQUIPMENT

Other components used in the case study are orifices and valves. Figure 3.7 and Figure 3.8 schematically illustrates the two components.

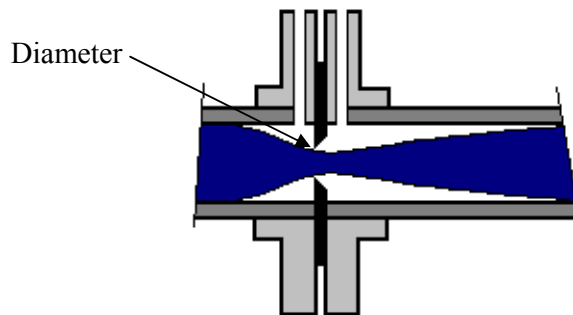


Figure 3.7: Schematic illustration of an orifice

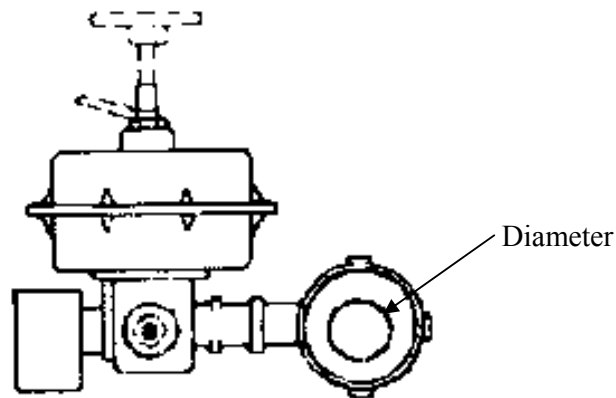


Figure 3.8: Schematic illustration of control valve

From the illustrations it is clear that the only uncertainty the components could have is the size of the diameter. This value, as in all the other cases, is obtained from the manufacturing specification.

3.6 CONCLUSION

In this chapter an in-depth look was taken at the variables involved when simulating pipes, shell-and-tube heat exchangers, compressors, turbines, valves and orifices in Flownex. The effect that these variables have on certain responses of the components, if varied, was also stated. Almost all the variables had an effect on the component's response variables. This implies that if uncertainties were involved, one would surely get an answer that would not correspond with the experimental values.

Physical values were assigned to the variables that will be used in the case study in Chapter 6. In most instances, the value of the uncertainty involved can be obtained from the manufacturing specifications, but sometimes a well thought of educated guess is the only value one can get hold of. In the next chapter an algorithm will be derived on how to incorporate these uncertainties in thermal-fluid network simulations. The governing theory will also be discussed in detail.

CHAPTER 4

ALGORITHM AND THEORY

- 4.1 Introduction
 - 4.2 Algorithm
 - 4.2.1 Input parameters
 - 4.2.2 Random numbers
 - 4.2.3 Box-Muller transformation
 - 4.2.4 Simulation variable calculation
 - 4.2.5 Acceptance-rejection
 - 4.2.6 Governing equations
 - 4.2.7 Cumulative statistics
 - 4.2.8 Output variables
 - 4.2.9 Convergence criterion
 - 4.2.10 Standard deviation correction
 - 4.2.11 Basic statistics
 - 4.3 Conclusion
-

4.1 INTRODUCTION

In this chapter the relevant theory necessary to develop the sensitivity analysis model will be discussed. An algorithm will be derived and a detail discussion will be provided on each part of the algorithm. The algorithm is derived in a general form and not for a specific software code. All the essential equations will also be given for each part of the algorithm.

4.2 ALGORITHM

A schematic illustration of the algorithm is shown in Figure 4.1. A short systematic explanation is given below to understand the logic behind the derivation of the algorithm:

- The input parameter/s, i.e. best estimate, uncertainty and range of the variable to be varied must be specified. The response variable/s to be evaluated must also be specified.
- Two random numbers for each input variable must be generated.
- The Box-Muller transformation must be imposed on the two random numbers for each variable.
- The simulation variable/s must be calculated for each run of the Monte Carlo analysis.
- An acceptance-rejection method inspects if the simulation variable/s is within the range specified.
- The simulation variable/s is substituted into the governing equations and the response variable/s specified is calculated.
- The mean and standard deviation for each variable is calculated cumulatively.

- After each run all the data is written to a text file. The process continues until convergence is reached.

A detail discussion on each part of the algorithm will follow the schematic illustration.

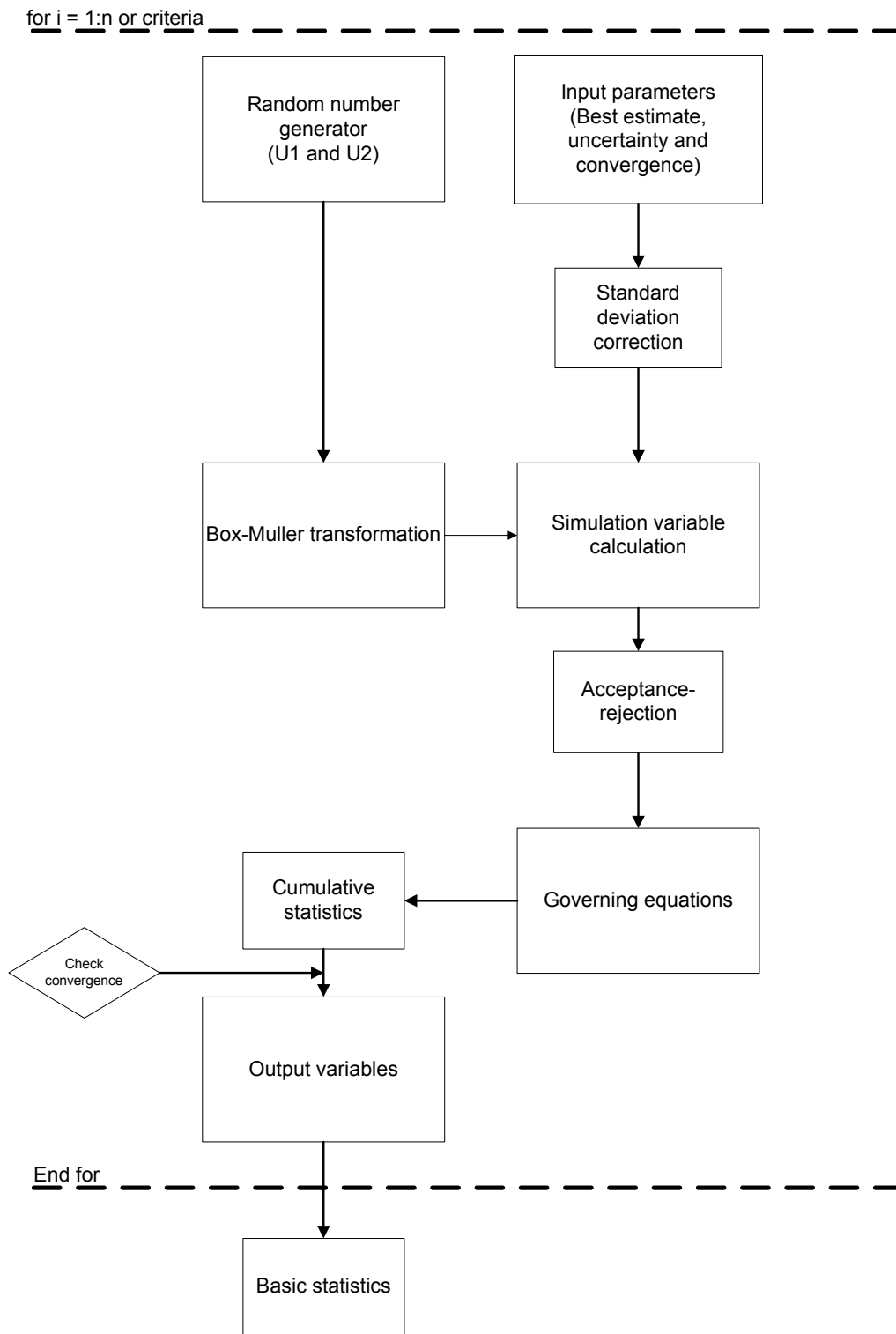


Figure 4.1: Schematic layout of algorithm

4.2.1 INPUT PARAMETERS

The input file is a text file used to define all the input parameters, i.e. the best estimate values and the uncertainties involved in the network to be simulated. It also specifies the output variables to be evaluated. In general this is all the data the sensitivity analysis needs to work. Figure 4.2 shows how a typical sensitivity analysis input file would look.

The input file must include the following sections:

- The convergence section;
- An input section; and
- The output specification section.

A brief description of the three sections named above will follow after the figure.

```

Sensitivity1.inp - Notepad
File Edit Format View Help
15.703 //Flownet
M300 //Model name
-----Monte Carlo Input-----
0/1 Convergence criteria
0 10000
# n/e VN BE SD
(0/1) (%)
1 0 6 10 20
3 1 5 10 20
0
-----Monte Carlo output-----
# n/e VN
1 0 6
3 1 5
0
  
```

Figure 4.2: Example of sensitivity analysis input file

with

- | | | |
|-----|---|---------------------------------|
| # | - | Node or element number |
| n/e | - | Node or element |
| VN | - | Variable number used by Flownex |
| BE | - | Best estimate value |
| SD | - | Standard deviation/uncertainty |

The first section gives the user the option to choose the convergence criterion. A 0 is specified to select a fixed number of runs or a 1 if convergence is to be evaluated based on the standard

deviation of the Global error as described in the Section 4.2.9. In the next section of the file all the input variables that must form part of the sensitivity analysis as well as the uncertainties associated with each are defined. The first three columns are used to define which variable to use. The last two columns define the best estimate value as well as the uncertainty of the specific variable. The third section is named the Monte Carlo output. In this section the output variables to be saved in the output file described below are defined.

In commercial software codes the user never directly uses this file but a GUI (Graphic user interface) will include all of the abovementioned input data.

4.2.2 RANDOM NUMBER GENERATOR

Random number generators are often available in mathematical programme libraries. Algorithms for random number generators can also be found on the internet, for different codes.

4.2.3 BOX-MULLER TRANSFORMATION

Now that uniformly distributed random numbers have been generated, the Box-Muller value can be obtained. For each input variable defined in the input file/ GUI, two random numbers must be generated. The BM transformation is used to transform a set of rectangular random numbers between 0 and 1 to a set of numbers with normal distribution around 0 and standard deviation equal to 1. After the transformation, approximately 68 % of the numbers will fall within the interval $(-1, 1)$ with an average value of 0.

The Box-Muller transformation is given by:

$$BM = \sqrt{-2 \ln U_1} \cos(2\pi U_2) \quad (4.1)$$

with U_1 and U_2 independent random variables from the same rectangular density function on the interval $(0, 1)$. BM will be an independent random variable with normal distribution with mean zero and unit variance (Box and Muller, 1958).

4.2.4 SIMULATION VARIABLE CALCULATION

This value was named the simulation variable because this is the value used in each run of the sensitivity analysis. For each input variable specified the following calculation will be done:

$$SV = BE + BM \left(BE \times \frac{SD}{100} \right) \quad (4.2)$$

Where BE is the best estimate value, this is the value that one will usually use in the simulation, BM the Box-Muller value and SD the standard deviation or uncertainty for each input variable.

Now that we are able to calculate the simulation variable for each input variable, we can substitute these values into the governing equations for a specific problem. In Section 4.2.6 this will be discussed in detail. Before this we must first verify if the value generated is a realistic one. This is done with the use of an acceptance-rejection method.

4.2.5 ACCEPTANCE-REJECTION

Acceptance-rejection method is defined by Rubinstein (1981) as the method accredited to von Neumann. It consists of sampling a random variate from an appropriate distribution and subjecting it to a test to determine whether or not it will be acceptable for use.

When one looks at thermal-fluid networks, there are certain variables that cannot be smaller or larger than a certain value, i.e. the length, diameter and roughness of a pipe cannot be smaller than zero. The acceptance-rejection method is brought into the algorithm to ensure that these values do not exceed the specified values. The user specifies a delta value in the input file/GUI. The delta value is the value used to determine the range of the specific variable by adding it and subtracting it from the best estimate value. The method works on the following principle:

1. Check if the simulation variable calculated in the previous section is within the range specified. (Range = (min = best estimate – delta; max = best estimate + delta))
2. If the value is in the specified range, carry on with the calculations.
3. If not, return to step 1.

This method does not change the shape of the distribution of the variable. However, when imposing the acceptance-rejection method, the results showed that the smaller the range of the variable, the bigger the effect on the actual value of the uncertainty of a simulation variable. In other words, when one changes the range to ensure that a certain variable's value is physically realistic, the uncertainty specified changes. To prevent this from happening, correction factors were generated and implemented into the code. This will be explained later in the chapter.

4.2.6 GOVERNING EQUATIONS

This is the section where the value generated in section 4.2.4 is substituted into the governing equations for the specific problem. There are two ways of doing this.

- To include all the equations needed in the code; or
- to call already existing software codes like Flownex to do the calculations.

In the next chapter both these options will be used in the validation and verification process. All the data is now generated by means of one of the methods named above. It will be necessary to apply some statistics and to give the user some visible/workable values to determine how sensitive the system that has been simulated is. The next section will illustrate how this was done.

4.2.7 CUMULATIVE STATISTICS

Two different strategies were considered in doing these calculations.

- To do the statistical calculations after all the values were generated; or
- To do the statistical calculations cumulatively.

The disadvantage of the first proposed technique was the extensive memory usage of the programme due to the large data storage. The cumulative option is much more feasible as all the data can be deleted after every step in the analysis. The equations to be used are given below.

Average

$$\hat{R}_j^k = \frac{1}{k} \sum_i^k x_{j|i} \quad (4.3)$$

with j the number of input variables and k the number of runs completed, Figure 4.3 shows a typical graph of the cumulative average of an output variable.

Standard Deviation

$$SD(x_{j|i}) = \sqrt{\frac{\sum_{i=1}^k (x_{j|i})^2 - n\hat{R}_j^k}{n-1}} \quad (4.4)$$

with j the number of input variables and k the number of runs completed; Figure 4.4 shows an example of a cumulative standard deviation for an output variable

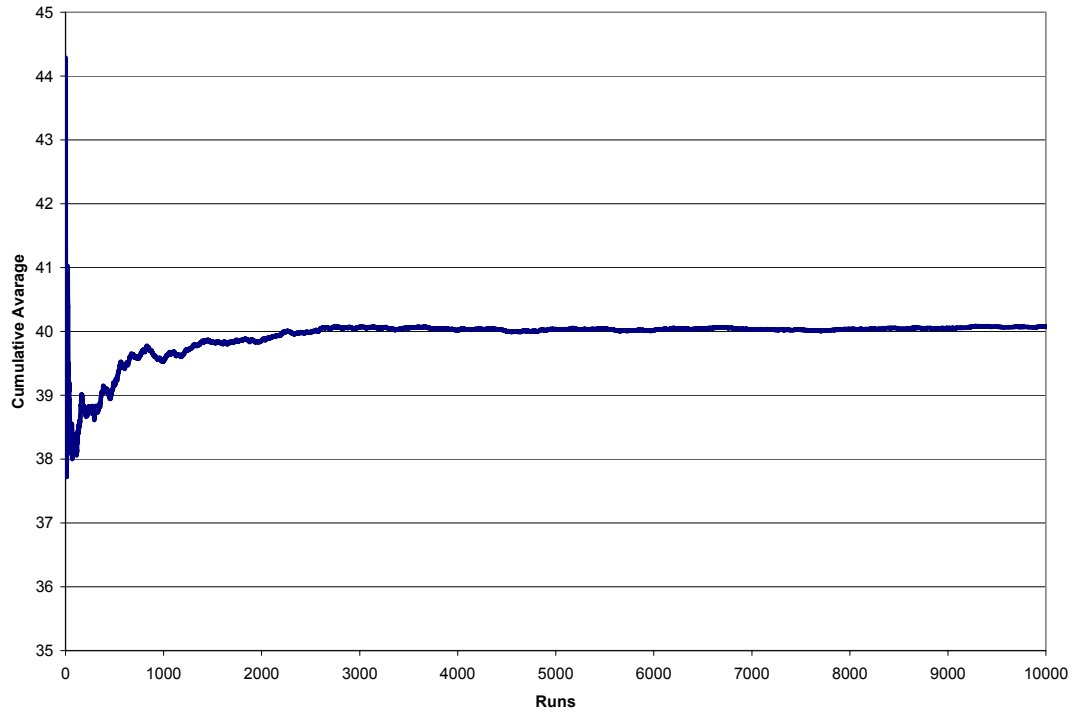


Figure 4.3: Example of cumulative average plot

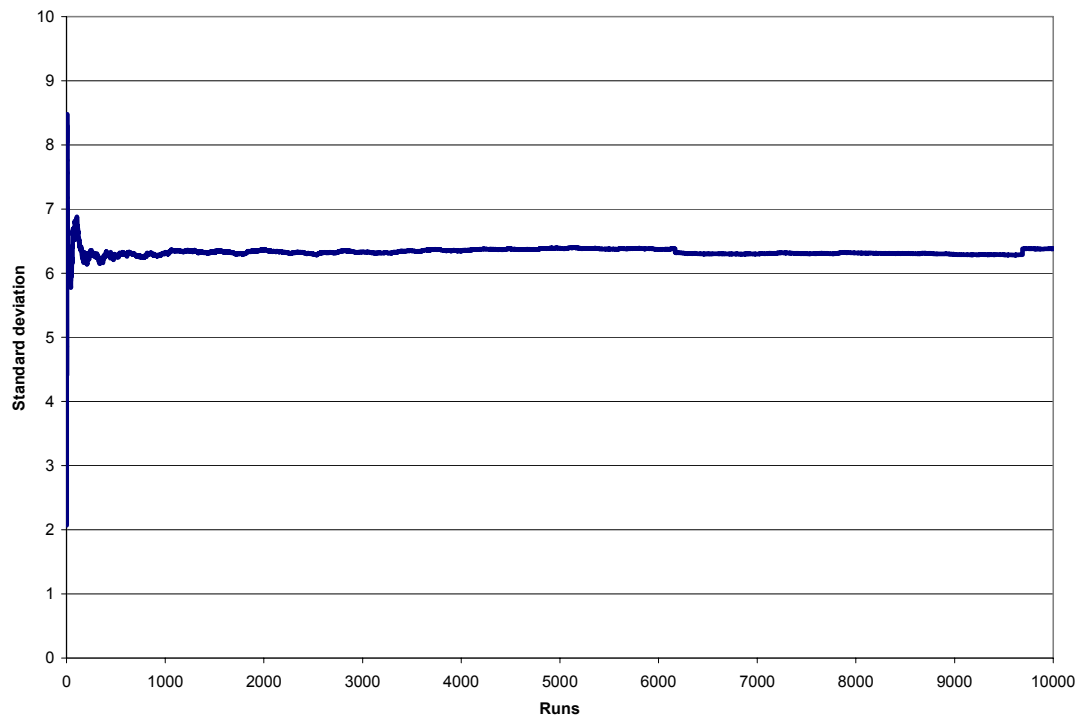


Figure 4.4: Example of standard deviation plot

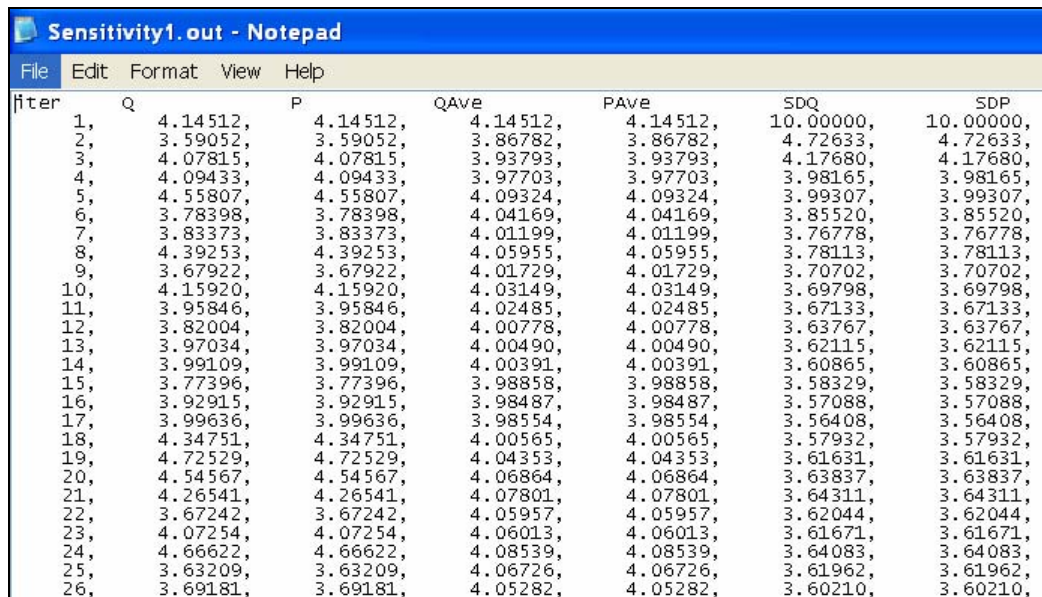
The advantage of using cumulative equations is that one uses much less memory and storage space when calculating the values. It is also clear from the graphs that the values converge to a certain value which confirms the correct implementation of the equations.

4.2.8 OUTPUT VARIABLES

An output file is generated and saved under a specified name. This file will show the following data for each run:

- the value as calculated;
- cumulative average; and
- cumulative standard deviation for each output variable as specified in the input file.

The data can be stored for further use and calculations. This file is also a text file and look like the example in Figure 4.5:



Iter	Q	P	Qave	Pave	SDQ	SDP
1,	4.14512,	4.14512,	4.14512,	4.14512,	10.00000,	10.00000,
2,	3.59052,	3.59052,	3.86782,	3.86782,	4.72633,	4.72633,
3,	4.07815,	4.07815,	3.93793,	3.93793,	4.17680,	4.17680,
4,	4.09433,	4.09433,	3.97703,	3.97703,	3.98165,	3.98165,
5,	4.55807,	4.55807,	4.09324,	4.09324,	3.99307,	3.99307,
6,	3.78398,	3.78398,	4.04169,	4.04169,	3.85520,	3.85520,
7,	3.83373,	3.83373,	4.01199,	4.01199,	3.76778,	3.76778,
8,	4.39253,	4.39253,	4.05955,	4.05955,	3.78113,	3.78113,
9,	3.67922,	3.67922,	4.01729,	4.01729,	3.70702,	3.70702,
10,	4.15920,	4.15920,	4.03149,	4.03149,	3.69798,	3.69798,
11,	3.95846,	3.95846,	4.02485,	4.02485,	3.67133,	3.67133,
12,	3.82004,	3.82004,	4.00778,	4.00778,	3.63767,	3.63767,
13,	3.97034,	3.97034,	4.00490,	4.00490,	3.62115,	3.62115,
14,	3.99109,	3.99109,	4.00391,	4.00391,	3.60865,	3.60865,
15,	3.77396,	3.77396,	3.98858,	3.98858,	3.58329,	3.58329,
16,	3.92915,	3.92915,	3.98487,	3.98487,	3.57088,	3.57088,
17,	3.99636,	3.99636,	3.98554,	3.98554,	3.56408,	3.56408,
18,	4.34751,	4.34751,	4.00565,	4.00565,	3.57932,	3.57932,
19,	4.72529,	4.72529,	4.04353,	4.04353,	3.61631,	3.61631,
20,	4.54567,	4.54567,	4.06864,	4.06864,	3.63837,	3.63837,
21,	4.26541,	4.26541,	4.07801,	4.07801,	3.64311,	3.64311,
22,	3.67242,	3.67242,	4.05957,	4.05957,	3.62044,	3.62044,
23,	4.07254,	4.07254,	4.06013,	4.06013,	3.61671,	3.61671,
24,	4.66622,	4.66622,	4.08539,	4.08539,	3.64083,	3.64083,
25,	3.63209,	3.63209,	4.06726,	4.06726,	3.61962,	3.61962,
26,	3.69181,	3.69181,	4.05282,	4.05282,	3.60210,	3.60210,

Figure 4.5: Example of sensitivity analysis output file

4.2.9 CONVERGENCE CRITERION

A very important aspect when conducting Monte Carlo analysis is to conduct enough runs. In other words some convergence criteria must be defined to ensure convergence is reached. Two criteria were defined and implemented.

- The first criterion is the most commonly used one, namely defining a fixed number of runs to be conducted. In most cases this is sufficient; however in some cases more simulations

than initially expected may be required. With this criterion the convergence cannot be determined and is only a guess by the user.

- The objective of the second criterion is to incorporate the effect of all the response variables of a simulation to find a suitable number of runs for the specific analysis.

The user will have the choice of which criteria to use and must edit the input file/GUI correctly.

The governing equations of the second criterion are given in equation 4.5 – 4.8:

1. For each output variable, a cumulative mean is calculated with the following equation:

$$\hat{R}_j^k = \frac{1}{k} \sum_{i=1}^k x_{ij} \quad (4.5)$$

with

k = the number of runs

j = the different response variables

2. A local error value for each output variable is calculated with the following equation:

$$e_j^k = \frac{|\hat{R}_j^k - \hat{R}_j^{k-1}|}{\hat{R}_j^k} \quad (4.6)$$

3. The global error for the entire simulation is calculated with the following equation:

$$E = \sum_{j=1}^j e_j^k \quad (4.7)$$

4. A standard deviation of the global error is calculated and will serve as the convergence criteria.

The following equation was used:

$$SD(E) = \sqrt{\frac{\sum E_i^2 - n(\hat{E}_i^2)}{n-1}} \quad (4.8)$$

The typical graph for this criterion is shown in Figure 4.6.

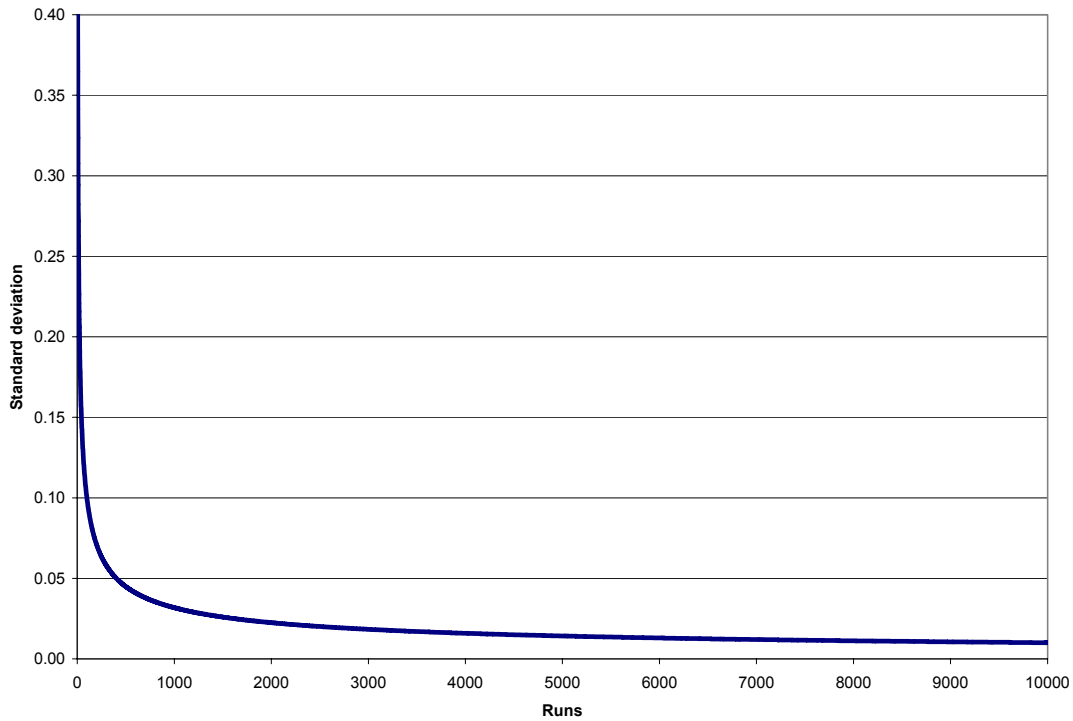


Figure 4.6: Standard deviation graph of global error

The next section will discuss the standard deviation correction as a result of the acceptance rejection as explained in Section 4.2.5.

4.2.10 STANDARD DEVIATION CORECTION

As mentioned previously, a function for the correction of the uncertainties must be found. The first step is to identify through inspection the shape of the function. This was done by plotting the standard deviation (uncertainty) specified in the input file/GUI against the standard deviation (uncertainty) obtained through experimental simulations. This was done for a wide range of deltas to ensure that the user will have significant data to work with. A typical plot would have the shape as in Figure 4.7.

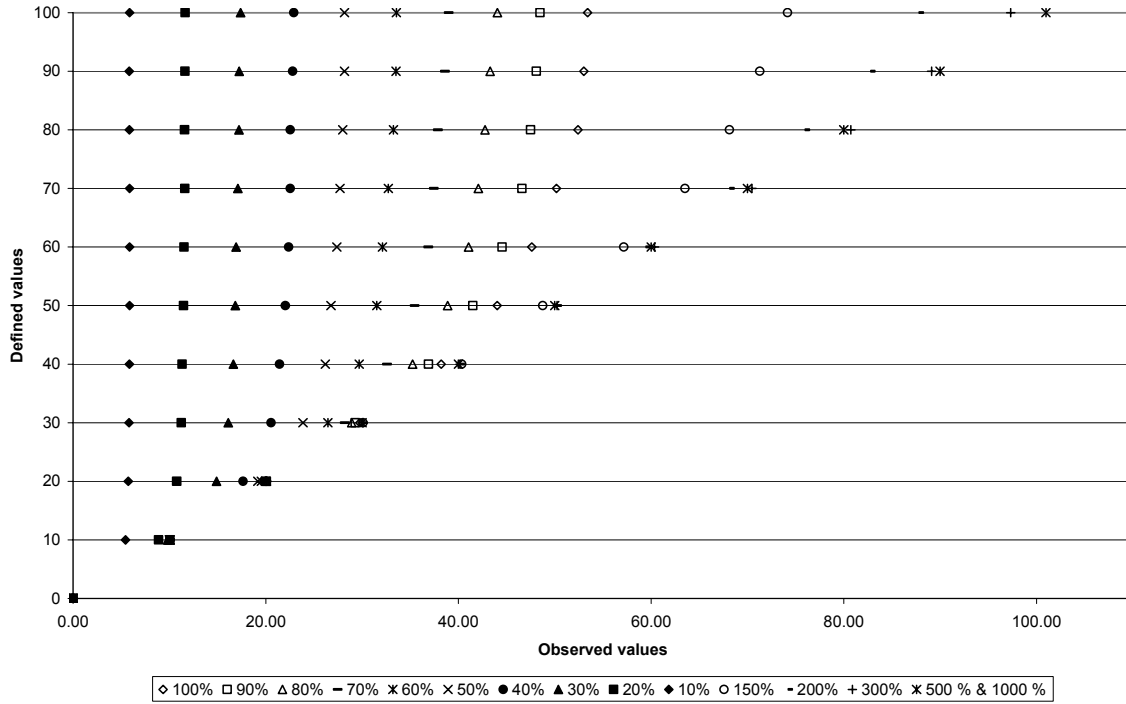


Figure 4.7: Standard deviation vs corrected standard deviation

Inspection showed that the form of a line that connected the data points is of the type

$$y = A \arctan B(SD) \quad (4.9)$$

with

$$A = f(\Delta) \text{ and} \quad (4.10)$$

$$B = f(\Delta) \quad (4.11)$$

Using the least squares method of fitting a line through a set of data points with

$$CSD = A \arctan B(SD) \quad (4.12)$$

where

$$A = a_0 + a_1\Delta + a_2\Delta^2 + a_3\Delta^3 \text{ and} \quad (4.13)$$

$$B = b_0 + b_1\Delta + b_2\Delta^2 + b_3\Delta^3 \quad (4.14)$$

the function for the corrected standard deviation is obtained. The line fitted through the data points in Figure 4.7 with the form of (4.12), (4.13) and (4.14) is plotted in Figure 4.8.

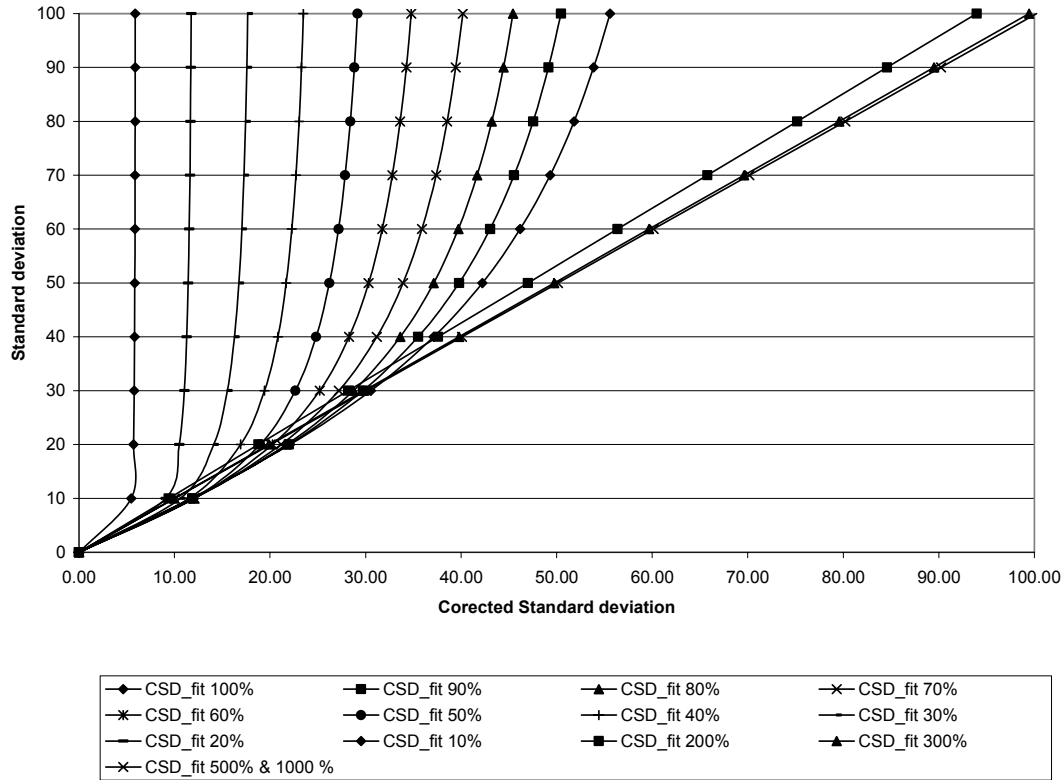


Figure 4.8: Corrected standard deviation fit for deltas ranging from 10% to 1000%

Although the line does not fit perfectly through the data points, the fit is acceptable. This was established with the coefficient of determination (R^2). If this value is above 0.98 the fits were accepted. The correction factor was determined for deltas from 10% - 1000%. The correction factors for the deltas of 200% - 1000% are zero because the two values are exactly the same. This equation is now implemented in the code and will automatically correct the standard deviation required by the user. The same had to be done to determine the maximum standard deviation for different delta. This meaning that for each delta used a maximum standard deviation is determined. Correction factors were also calculated for this and exactly the same method was used and this correction was implemented into the code. All the fits for different delta values as well as the coefficient of determination R^2 are shown in Appendix A.

4.2.11 BASIC STATISTICS

All the data is stored in the output file as described in section 4.2.10. The user is free to use statistical programmes such as Statistica to do other statistical studies on the data generated with the sensitivity analysis. The sensitivity analysis will only give an average and standard deviation for each response variable specified.

4.3 CONCLUSION

In this chapter the algorithm as well as all the relevant theory to do a sensitivity analysis was discussed in detail. Based on the practical implementation and feasibility the specific methodology and algorithm was selected.

Two important factors were identified while deriving the algorithm. The first is the importance of having an acceptance-rejection method if a Monte Carlo approach was used. If such a method is used some correction factors need to be calculated to ensure the integrity of the analysis. Another important point that was noticed is that it is much more feasible to do the statistical calculations cumulatively. These factors were identified and incorporated into the algorithm.

The algorithm was implemented into C++ and Excel to conduct validation and verification exercises by means of simple equations. Chapter 5 will give an in-depth look at the validation and verification process. After the C++ programme was thoroughly validated, it was implemented into Flownex to conduct a case study on the Pebble Bed Modular Reactor Micro Model (PBMM) in Chapter 6.

CHAPTER 5

VALIDATION AND VERIFICATION

- 5.1 Introduction
 - 5.2 Model declaration
 - 5.2.1 Linear model
 - 5.2.2 Non-linear model
 - 5.2.3 Complex non-linear model
 - 5.2.4 Thermal-fluid model
 - 5.3 Validation
 - 5.3.1 Monte Carlo validation
 - 5.3.2 Validation of cumulative statistics
 - 5.3.3 Validation of convergence criteria
 - 5.4 Verification
 - 5.4.1 Excel vs C++
 - 5.4.2 Excel vs Flownex
 - 5.5 Conclusion
-

5.1 INTRODUCTION

In the previous chapter the algorithm was derived and the relevant theory was discussed. The algorithm will now be implemented into Excel, C++ and Flownex to aid in the **Validation** and **Verification** (V&V) process. It was decided to first implement the algorithm into Excel because of the simplicity of the program. Already-defined functions such as random number generators, mean and standard deviation calculations could easily be done to aid in the V&V. The algorithm will then be implemented into C++ and functions will be hard-coded to do the random number generating and the mean and standard deviation calculations. C++ is also the source code of the Flownex simulator and consequently finally the implementation into Flownex.

In this chapter the validation and verification of the algorithm will be done. **Validation** is defined as "Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled". In contrast with verification, validation rather focuses on the question whether a system can perform its desired functions. Another definition of **Validation** is "Answering the question whether the customer will be able to use the product in its intended manner." To validate something is to test it for use, not to check it for physical properties. Something that has failed being verified can still be declared as having fitness for purpose after validating it.

Verification is defined as the "Confirmation, through the provision of objective evidence, that specified requirements have been fulfilled". Another definition of **Verification** is: "The act of reviewing, inspecting, testing, checking, auditing, or otherwise establishing and documenting whether items, processes, services, or documents conform to specified requirements". To **verify** a product means to measure physical properties stated in the specifications for that product and compare them with the values for each requirement documented there (ANSI/ANI, 1987).

In the context of this study V&V will be done as described below.

In the validation process the following will be validated:

1. Validation of Monte Carlo values:
 - a. Validate the Box-Muller values calculated are within the range as specified in Section 4.2.3.
 - b. Validate if the simulation variables calculated over a certain number of runs still have the same mean and standard deviation as specified.
2. Validation of cumulative statistics:
 - a. Validate if the cumulative mean is calculated correctly by comparing the cumulative value against the mean of the entire population.
 - b. Validate if the cumulative standard deviation is calculated correctly by comparing the cumulative value against the standard deviation of the entire population.
3. Validation of convergence criteria:
 - a. It will be validated if the criteria converge.

In the verification process the following will be verified:

1. Verify if the algorithm was implemented correctly in Excel and C++ by checking the values of:
 - a. The cumulative average
 - b. The cumulative standard deviation
 - c. The response variable
2. Verify if the algorithm was implemented correctly in Excel and Flownex by checking the value of:
 - a. Response variable

It is important to use models of different complexity in the V&V process to confirm the stability of the algorithm. The following models will be used in the V&V process:

- A linear model;
- a non-linear model;
- a complex non-linear model; and
- a thermal-fluid model.

These models will be discussed in detail next.

5.2 MODEL DECLARATION

5.2.1 Linear model

For the linear model, the equation below was used.

$$y = 3x + c \quad (5.1)$$

The input values used are shown in Table 5.1:

	X	c
Best Estimate	10	10
Uncertainty (%)	20	20

Table 5.1: Input values for linear model

5.2.2 Non-linear model

It was decided to evaluate a polynomial model to ascertain how sensitive the analysis is to non-linearity. The polynomial model that was decided on is given in the equation below.

$$y = x^2 + c \quad (5.2)$$

The same input values that were used in the linear model were used in this model (Table 5.1).

5.2.3 Complex non-linear model

In the course notes on *Advanced Thermal-Fluid Systems* presented by Rousseau (2001), a simplified compressor model was given. The model consists of two equations, one to calculate the cooling capacity (Q_c) and the other the power input (P).

$$Q_c = a_0 + a_1 T_e + a_2 T_c + a_3 T_e^2 + a_4 T_e T_c + a_5 T_c^2 + a_6 T_e^3 + a_7 T_c T_e^2 + a_8 T_e T_c^2 + a_9 T_c^3 \quad (5.3)$$

$$P = b_0 + b_1 T_e + b_2 T_c + b_3 T_e^2 + b_4 T_e T_c + b_5 T_c^2 + b_6 T_e^3 + b_7 T_c T_e^2 + b_8 T_e T_c^2 + b_9 T_c^3 \quad (5.4)$$

with

	a	b
0	2.6352E+01	-2.3379E+01
1	1.9492E+02	-6.9429E+00
2	2.6773E+02	3.7314E+01
3	4.2998E+00	-6.6843E-01
4	4.1071E-01	4.2033E-01
5	-6.5915E+00	-3.7674E-01
6	1.6214E-02	-2.8174E-03
7	-3.3677E-02	1.0480E-02
8	-2.9048E-02	1.2821E-03
9	4.4663E-02	1.0261E-03

The only inputs necessary for these equations is the condensing temperature (T_c) and the evaporating temperature (T_e).

Typical values for T_c and T_e are shown in Table 5.2.

	T_e	T_c
Best Estimate	10	50
Uncertainty (%)	20	20

Table 5.2: Input values for Chiller model

5.2.4 Thermal-fluid model

In order to be able to simulate the flow through a pipe, an incompressible pipe model will be used to simplify the equations. In the course notes on *Simulation techniques* presented by Rousseau (2002) the equations presented on the next page were used to simulate the flow through the pipe.

Figure 5.1 shows a schematic illustration of the pipe model.

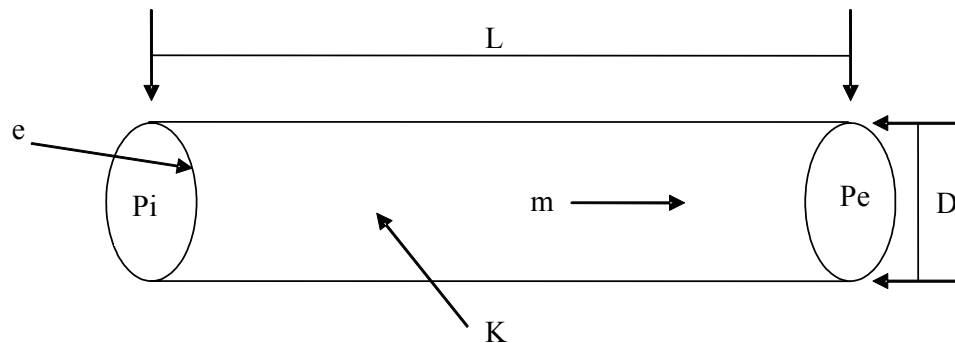


Figure 5.1: Schematic illustration of pipe

The change in pressure due to the friction in the pipe is described by:

$$\Delta P = - \left(\frac{fL}{D} + \sum K \right) \frac{\dot{m}^2}{2\rho A^2} \quad (5.5)$$

In equation (5.5) the Darcy Weisbach friction factor f is calculated, depending on the Reynolds number being laminar or turbulent. For laminar flow:

$$f = \frac{64}{\text{Re}}, \quad (5.6)$$

with $\text{Re} < 2 \times 10^3$ and for turbulent flow:

$$f = \frac{0.25}{\left(\log \left(0.27 \frac{e}{D} + \frac{5.74}{\text{Re}^{0.9}} \right) \right)^2} \quad (5.7)$$

with $5 \times 10^3 \leq \text{Re} \leq 10^8$ and $10^{-6} \leq \frac{e}{D} \leq 10^{-2}$

The following physical values were used in the pipe model:

Variable	Best Estimate	Uncertainty (%)
[L] Length (m)	2	10
[D] Diameter (m)	0.05	10
[e] Roughness (m)	0.00003	30
[K] Loss Factor	10	30
[Pi] Inlet Pressure (kPa)	100	0
[m] Mass Flow (kg/s)	1	0

Table 5.3: Input values for pipe model

5.3 VALIDATION

5.3.1 MONTE CARLO VALIDATION

The observations of the Excel and C++ codes are validated in this section. Only one of the three models had to be checked because the same algorithm was used to simulate all the models. It was decided to present the linear model's validation results. The Flownex code is indirectly also validated, considering the fact that the C++ code was implemented into Flownex. The other model's validation results are shown in the Appendix B.

Box-Muller

It is critical for this value to be calculated correctly because it is the basis of this Monte Carlo model. Note that only one Box-Muller value for each model is presented below. In order to validate this, the Box-Muller values generated from the different cases were evaluated by means of a statistical programme called Statistica. A normal distribution fit was done and will show that all the values in Excel and C++ fall within the specified range. The table for Excel and C++ respectively will show the two Box-Muller values for each of the three models.

Excel

Table 5.4 shows a summary of the normal statistical distribution fits for all the other models.

	Box-Muller	Average	Standard deviation	Frequency
Linear	1	0.0124	1.0091	68.15
	2	-0.0077	1.0086	68.31
Polynomial	1	-0.0199	0.9962	68.31
	2	0.0058	0.994	68.55
Chiller	1	0.0029	1.0043	67.83
	2	-0.0025	0.9922	68.64

Table 5.4: Excel Box-Muller summary

It is clear that the values of the Box-Muller values are very close to the values specified in the definition. It must be noted that C++ cannot automatically create random numbers in the range (0, 1) and a separate algorithm was implemented in order to ensure random numbers in this domain.

C++

The only difference between the results of C++ and those for Excel is that 70% and not 68% of the values fall in the range. The difference can be ascribed to the fact that two different random number-generators were used. Table 5.5 shows a summary of the normal distribution fits conducted on all the models in C++.

	Box-Muller	Average	Standard deviation	Frequency
Linear	1	0.0052	1.0344	70.35
	2	0.0056	1.0338	70.36
Polynomial	1	0.0052	1.0326	70.37
	2	0.0061	1.0337	70.38
Chiller	1	0.0059	1.0332	70.35
	2	0.0062	1.0337	70.36

Table 5.5: C++ Box-Muller summary

Although the frequencies of the C++ Box-Muller values are slightly different, it can be accepted as correct and the simulation variables of the two programmes can now be validated. The next section will show a detail validation of the simulation variables for the three models.

Simulation variables

To validate that the simulation variables were calculated correctly, a normal statistical analysis on each input variable was also done and compared to the values defined in Table 5.1. The analysis should indicate that the mean value of all the simulation variables for a specific input variable has to be the same as the best estimate value defined. The standard deviation has to be equal to the uncertainty defined and approximately 68% of the values must fall in the specified range. It should be noted that the simulation variables in the C++ will have frequencies of 70% because of the phenomena described in the previous section.

Excel

Table 5.6 shows a summary of the statistical analysis conducted on all the models.

	Input	Average	Standard deviation	Frequency
Linear	X	10.0249	2.018	68.15
	C	9.9847	2.0173	68.31
Polynomial	X	9.9602	1.9924	68.76
	C	10.0166	1.988	68.55
Chiller	Tc	10.0057	2.0087	67.83
	Te	49.975	9.9219	68.64

Table 5.6: Excel run variable summary

All the Excel simulation variable values are within specification and the C++ code can now be validated.

C++

Table 5.7 shows a summary of the distribution analysis conducted on all the models.

	Input	Average	Standard deviation	Frequency
Linear	x	10.0104	2.0688	70.35
	c	10.0111	2.0677	70.36
Polynomial	x	10.0104	2.0652	70.37
	c	10.0123	2.0673	70.38
Chiller	Tc	10.0118	2.0604	70.35
	Te	50.0624	10.3371	70.36

Table 5.7: C++ run variable summary

5.3.2 VALIDATION OF CUMULATIVE STATISTICS

The reason why cumulative statistics were used was explained in Chapter 4. Equation (4.13) and Equation (4.14) must be validated to ensure that the same values are calculated as when it was not done cumulatively. This validation will only be done for the linear model in Excel and C++.

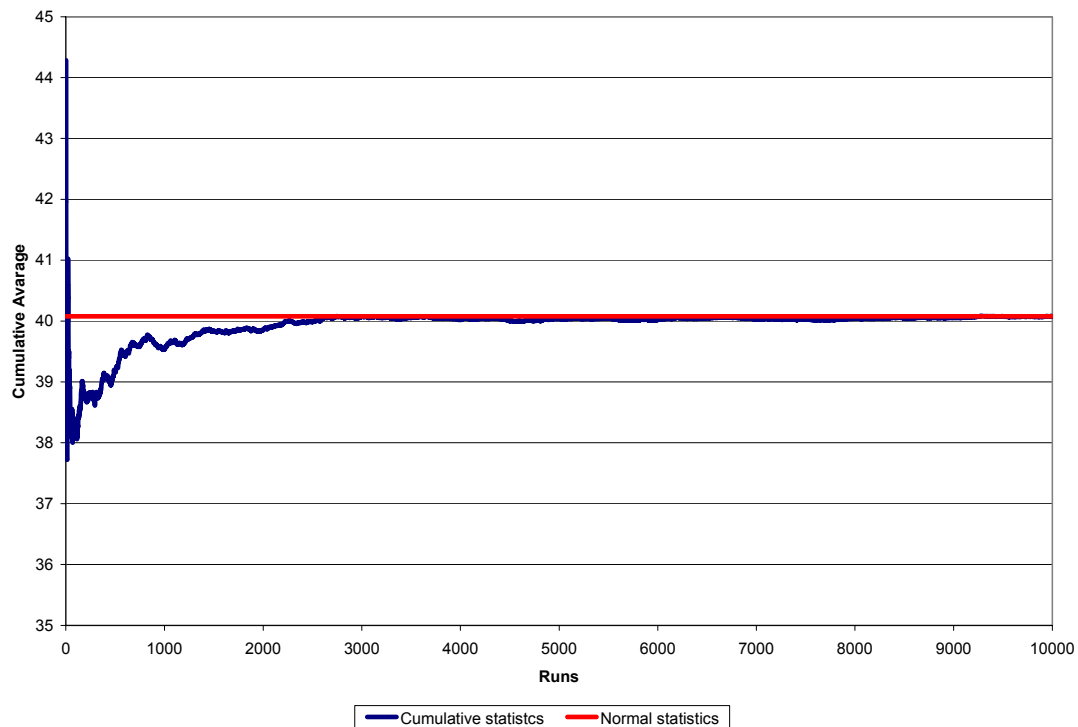


Figure 5.2: Cumulative average validation

It is clear from Figure 5. that the normal and cumulative statistic equations for calculating the average, give exactly the same answer. The same result can be seen in Figure 5.3 for the standard deviation.

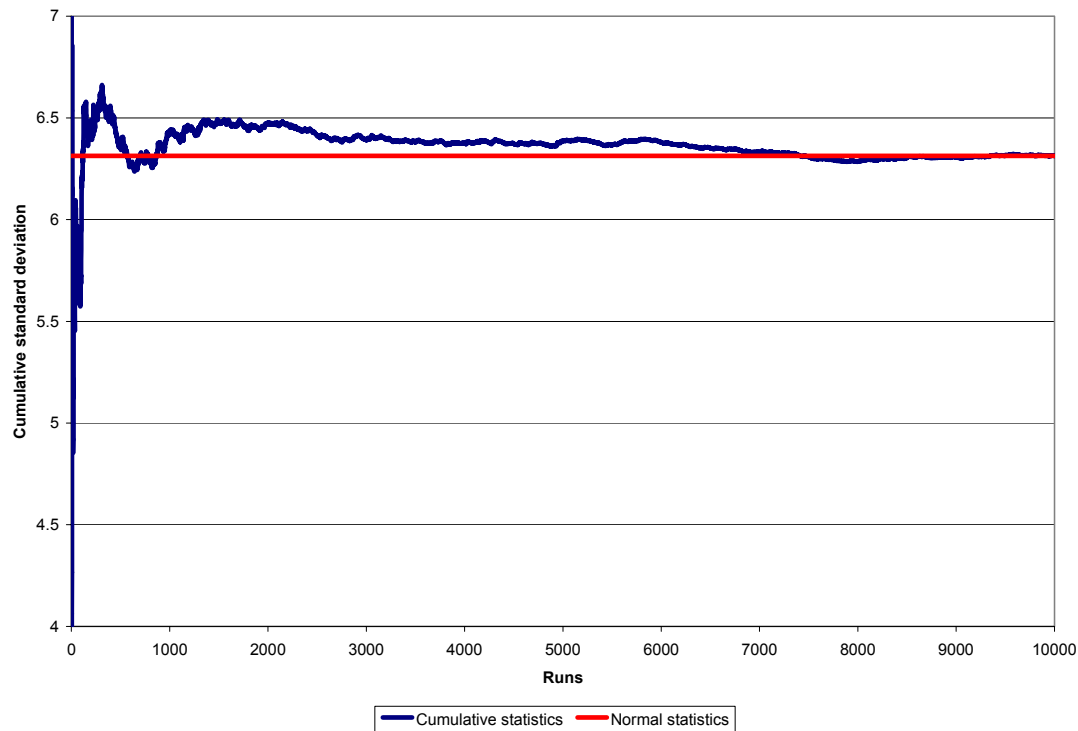


Figure 5.3: Cumulative standard deviation validation

In the next section the simulation criteria presented in chapter 3 will be verified.

5.3.3 VALIDATION OF CONVERGENCE CRITERIA

The convergence criteria cannot be validated against other criteria because no other criteria were found, as stated in Chapter 2. The two models implemented into Excel and C++ were compared against each other. Figure 5. shows that the two programs give exactly the same results.

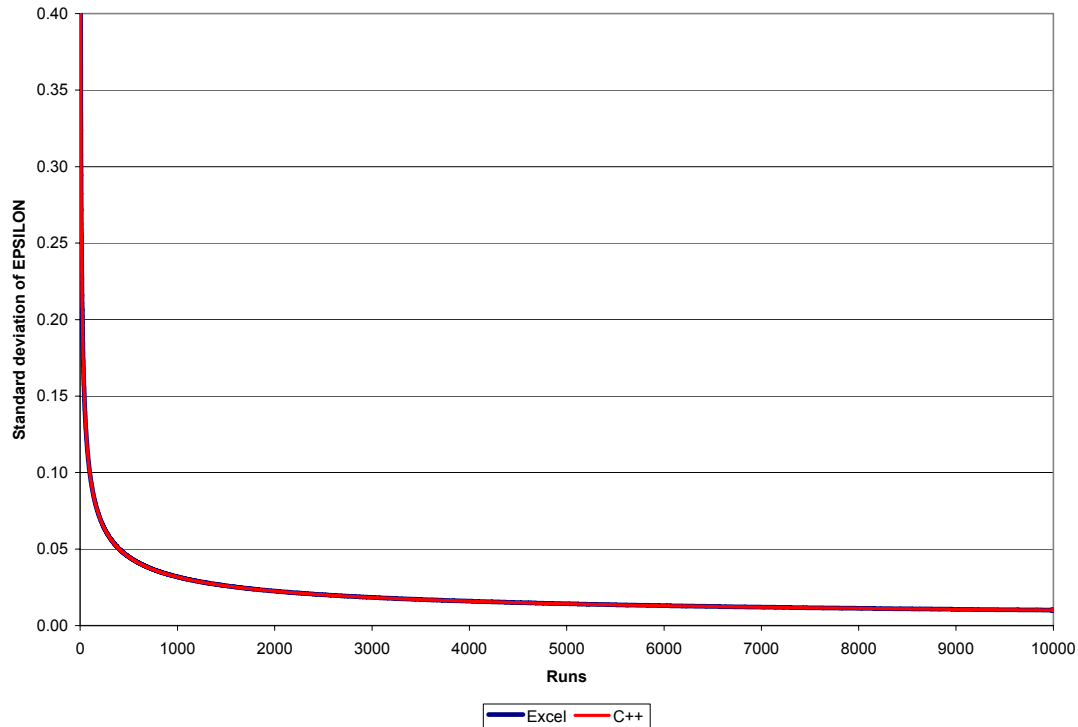


Figure 5.4: Convergence criteria validation

5.4 VERIFICATION

In the verification process a comparison of the two different programmes with the same algorithm were made. The three models implemented into C++ and Excel was compared. The following section will show the comparison of the C++ and Excel programmes for the linear model and a pipe model in Flownex and Excel. The validation of the other models appears in the Appendix B.

5.4.1 Excel vs C++

To verify if the cumulative statistics equations were implemented correctly into Excel and C++, each equation must be checked manually. The equations being checked are those stated in section 4.2.7. These equations were checked and the following figures will show that the equations were correctly implemented. Figure 5.5 shows the cumulative average as calculated in Excel and C++.

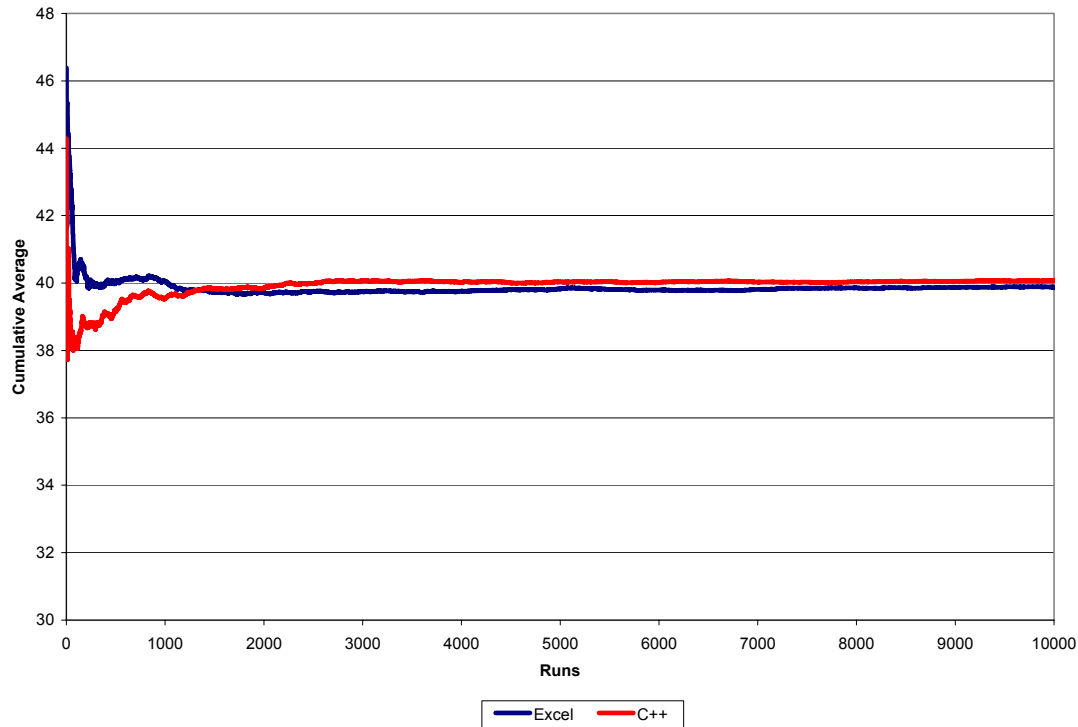


Figure 5.5: Cumulative average verification

Figure 5. shows that both the Excel and C++ programmes converge to the nearly the same value for the average of the response variable that was calculated cumulatively in the linear model. The difference can be attributed to the fact that different random number-generators were used. This will apply to any model simulated with these two programmes. The calculation of the standard deviation will be verified in the same manner.

Figure 5. show that both the Excel and C++ programmes have calculated the standard deviation correctly.

To verify the stability and the assumption made earlier that at least 10 000 runs of the Monte Carlo method is necessary the following verification was done:

- The Monte Carlo analysis was conducted on the linear model (10 000 runs were done).
- This was done ten times.

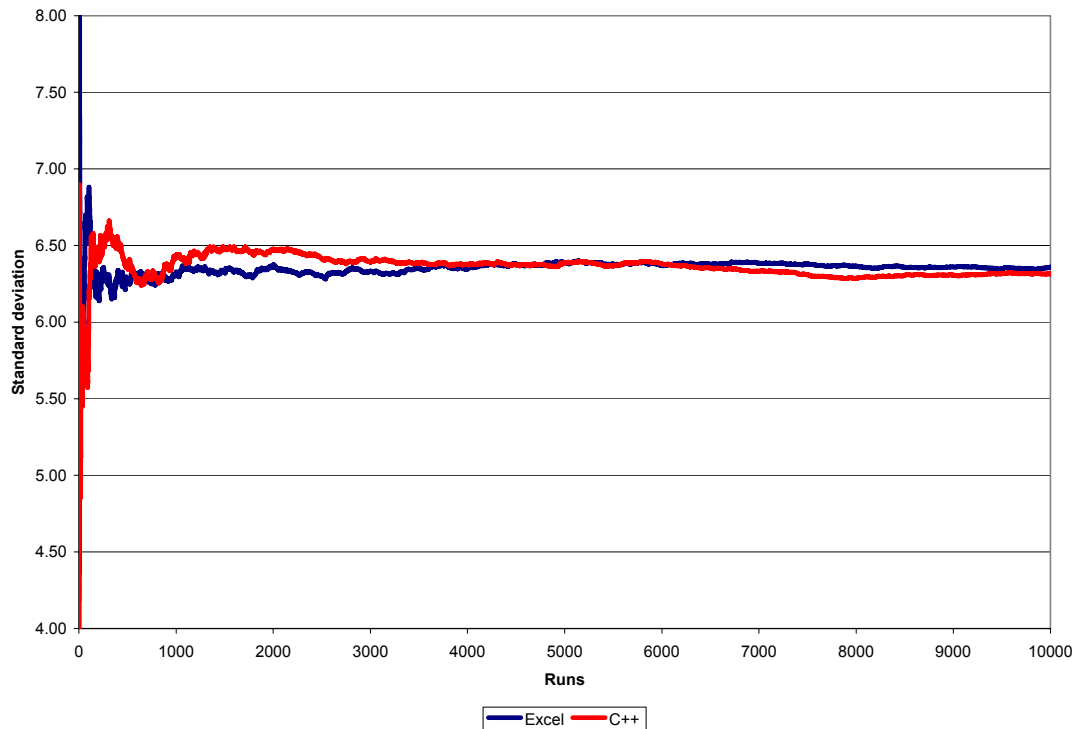


Figure 5.6: Cumulative standard deviation verification

Figure 5.6 and Figure 5. shows the comparison between the Excel and C++ code of the linear model for 10 000 runs of the Monte Carlo analysis.

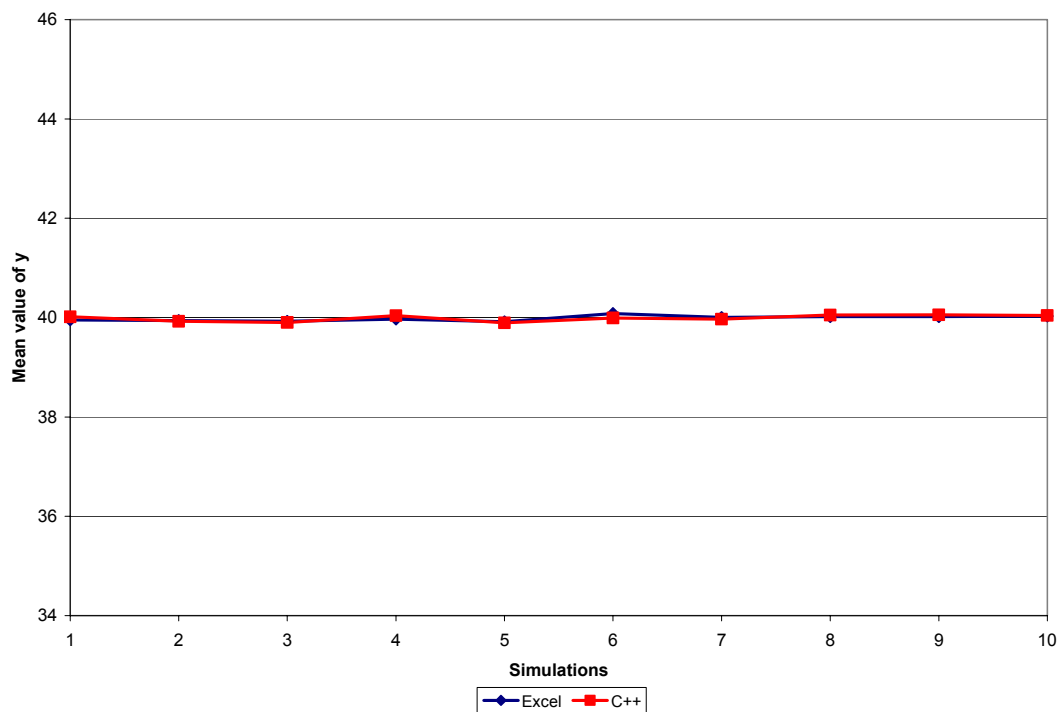


Figure 5.7: C++ and Excel comparison of linear model

It is clear that the values generated by Excel and C++ compared well. It is also visible how stable the answer generated is over ten different simulation of the same network. The time needed for such an analysis is also relative fast compared to normal steady state simulation times.

5.4.2 Excel vs Flownex

The Flownex code is actually the same as the C++ one. It is still necessary to compare the response variable value of the different codes. This will be done by conducting the analysis on a simple pipe simulation as stated in Section 5.2.4. Figure 5.8 show that the two codes again give exactly the same value for the response variable over ten separate analyses as described above.

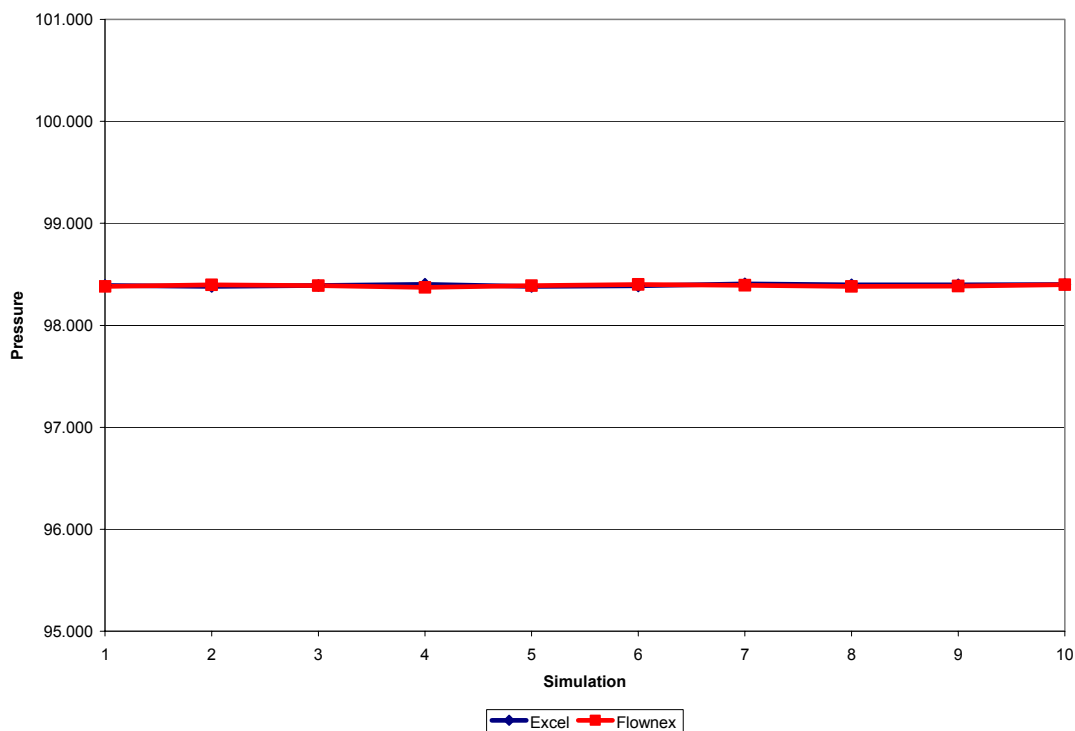


Figure 5.8: Flownex and Excel validation of pipe model

5.5 CONCLUSION

In this chapter the validation and verification of the algorithm that was implemented into three different codes, namely Excel, C++ and Flownex, was discussed in detail. Four different models were used in the process to ensure that a wide range of complexity was covered. All the verification and validation results showed that the algorithm had been successfully implemented into the different codes and that sensitivity analysis can now be done on large thermal-fluid networks in Flownex. The algorithm can also be implemented into any other existing code to do such an analysis.

In both the validation and verification processes not all the answers are exactly the same. The reason for this is that two different random number-generators were used. Meaning that the number of decimals of the different generators differs. A further reason is that the values of Monte Carlo analyses will only be exactly the same if an infinite number of runs were done. The answers are very close to each other and are, for the reasons mentioned above, accepted as correct.

In the next chapter a sensitivity analysis of the PBMM will be conducted in Flownex with the algorithm as explained in Chapter 4. The values obtained from the sensitivity analysis will be compared with the steady state results obtained from Flownex.

CHAPTER 6

CASE STUDY

- 6.1 Introduction
 - 6.2 Background
 - 6.2.1 Pebble Bed Modular Reactor
 - 6.2.2 Three-shaft recuperative Brayton cycle
 - 6.2.3 Micro Model of Pebble Bed Modular Reactor
 - 6.3 Steady state simulation
 - 6.4 Sensitivity analysis
 - 6.5 Conclusion
-

6.1 INTRODUCTION

In the previous chapters the following was done:

- Uncertainties in thermal-fluid network components were identified;
- A suitable algorithm was derived and discussed in detail;
- Implemented, verified and validated thoroughly.

The sensitivity analysis is now available as a tool that could be used to determine the sensitivity of a complex thermal-fluid system due to the uncertainties in its inputs.

In this chapter the PBMM will be analysed to determine its sensitivity. To do such an analysis it is essential to have an as-built simulation-network of the plant. This network must contain the correct dimensions of all the components as well as all the losses involved due to fittings or other possible losses in the system. The final step is to identify the uncertainties involved as well as the values for these uncertainties. Only after all of this is done can one begin with a sensitivity analysis. The chapter will be divided into the following sections, namely:

- Background of Pebble Bed Modular Reactor (PBMM);
- Steady state simulation;
- Sensitivity analysis.

The next section will give a brief description of the PBMR, PBMM and the three-shaft recuperative Brayton cycle. It is necessary to have a good understanding of how this Brayton cycle works before one can start simulating such a complex system.

6.2 BACKGROUND

6.2.1 PBMR

PBMR technology was developed and demonstrated as an inherent safe nuclear technology, which could be used to generate electricity cost-effectively with the minimal impact on the environment. According to the PBMR website (<https://www.PBMR.co.za>), two demonstration plants were operated in Germany for many years to prove the reliability of this technology. The company PBMR (Pty) Ltd invested in the further development of this technology with respect to refinement of the nuclear reactor and related power generation cycles. It was decided by PBMR (Pty) Ltd to use a three-shaft recuperative Brayton cycle to transform heat energy (from the nuclear reaction) to electrical energy. The need then aroused to develop a micro model to demonstrate some of the important operational aspects of this Brayton cycle. Figure 6.1 shows a Compute aided design (CAD) illustration of the physical layout of the PBMR plant.

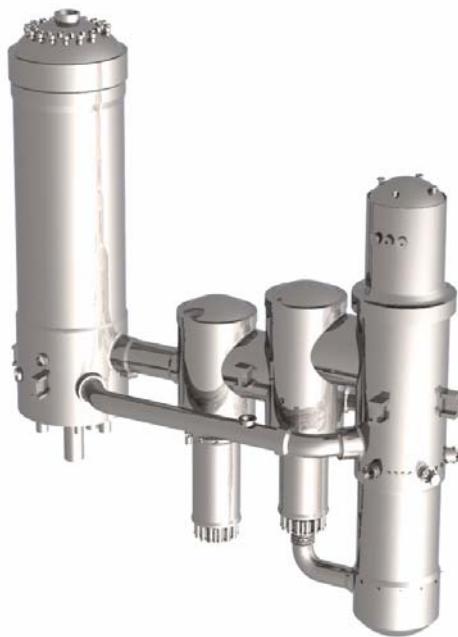


Figure 6.1: CAD illustration of PBMR 

6.2.2 THREE-SHAFT RECUPERATIVE BRAYTON CYCLE

To be able to simulate the PBMR, one must first understand the three-shaft recuperative Brayton cycle. A brief description of the working of the system is given according to the schematic layout presented in Figure 6.2.

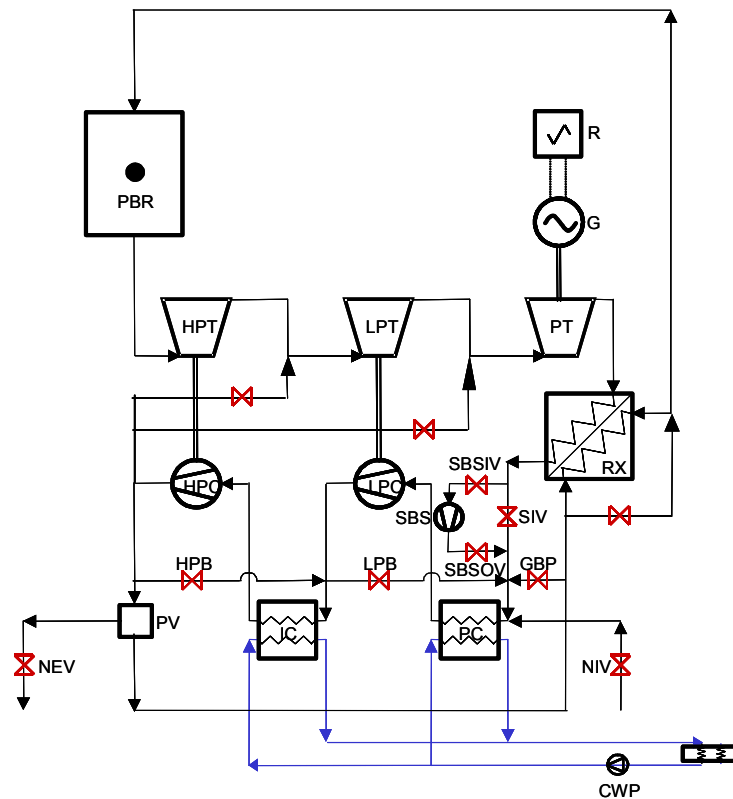


Figure 6.2: Schematic layout of PBMR (Greyvenstein and Rousseau, 2001)

The helium enters the reactor (PBR) and moves downward between the hot fuel spheres. It picks up the heat from the fuel spheres that were heated by the nuclear reaction. The helium then leaves the reactor and expands in the high-pressure turbine (HPT). This turbine forms part of the high-pressure turbo-unit. The high-pressure turbine drives the high-pressure compressor (HPC). Next, the helium flows through the low-pressure turbine (LPT), which is part of the low-pressure turbo-unit. The LPT drives the low-pressure compressor (LPC). The helium then expands in the power turbine (PT) driving the generator. At this point, the helium is still at a high temperature. It then flows through the primary side of the recuperator (RX) where it transfers heat to the low temperature gas returning to the reactor (refer also to the last step).

The helium that passed through the primary side of the RX is then cooled by means of a pre-cooler (PC). This increases the density of the helium and improves the efficiency of the compressor. The helium is then compressed by the LPC and cooled in the inter-cooler (IC). This process once again increases the density and improves the efficiency of the compressor. The HPC then compresses the helium to an even higher pressure. The cold, high-pressure helium steam then flows through the RX where it is pre-heated, after which it returns to the reactor.

6.2.3 PEBBLE BED MODULAR REACTOR MICRO MODEL

To help reduce the development risk of the actual PBMR plant, a scale model (PBMM) is needed to obtain actual operational data about the sustainability of the recuperative Brayton cycle. Data is also needed for the stability of the control strategies that would be required for operation of such a thermodynamic cycle.

The Pebble Bed Modular Reactor Micro Model (PBMM) should, however, be developed as far possible from commercial off-the-shelf units. Difficulties in the actual proposed PBMR plant such as Helium leakages should be avoided in the PBMM.

Greyvenstein and Rousseau (2001) presented a proposal for the development of a physical model of the actual PBMR plant on behalf of the Faculty of Engineering at the PU for CHE. Extensive simulations were done by the author (2002) at the School of Mechanical and Materials Engineering to predict the expected performance of such a model using the plant simulation software: Flownex. The PBMM model shown in Figure 6.3 uses the same three-shaft recuperative Brayton cycle that was discussed in section 6.2.2.2 and Figure 6.2.

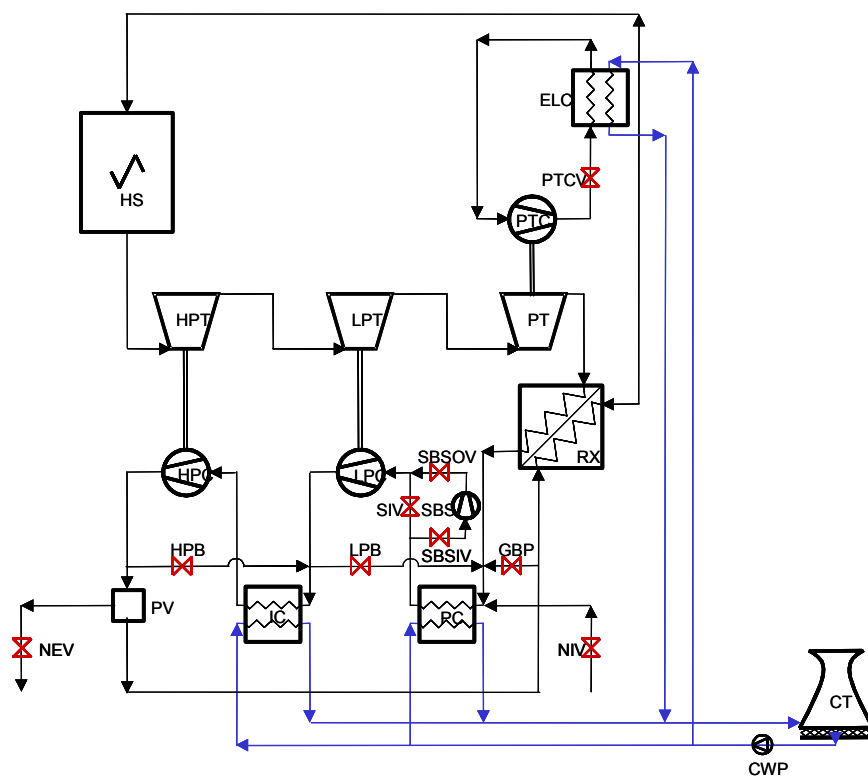


Figure 6.3: Schematic layout of PBMM (Greyvenstein and Rousseau, 2001)

There are some differences that need to be mentioned, however. The main differences between PBMR and PBMM are listed below:

- Use of nitrogen instead of helium as the working fluid;
- heat source is electrical resistance heater instead of nuclear reactor;
- use of single-stage centrifugal turbo-chargers instead of purpose-designed multi-stage axial flow turbo machines;
- heat rejection via cooling tower instead of intermediate heat exchanger;
- load on power turbine is compressor with external load cooler instead of generator with resistor bank;
- The start up blower system (SBS) is positioned differently; and
- does not contain LPT and PT cooling flows of recuperator by-pass flow.

Figure 6.4 shows a CAD illustration of the PBMM developed in the design process and Figure 6.5 a photograph of the completed PBMM.

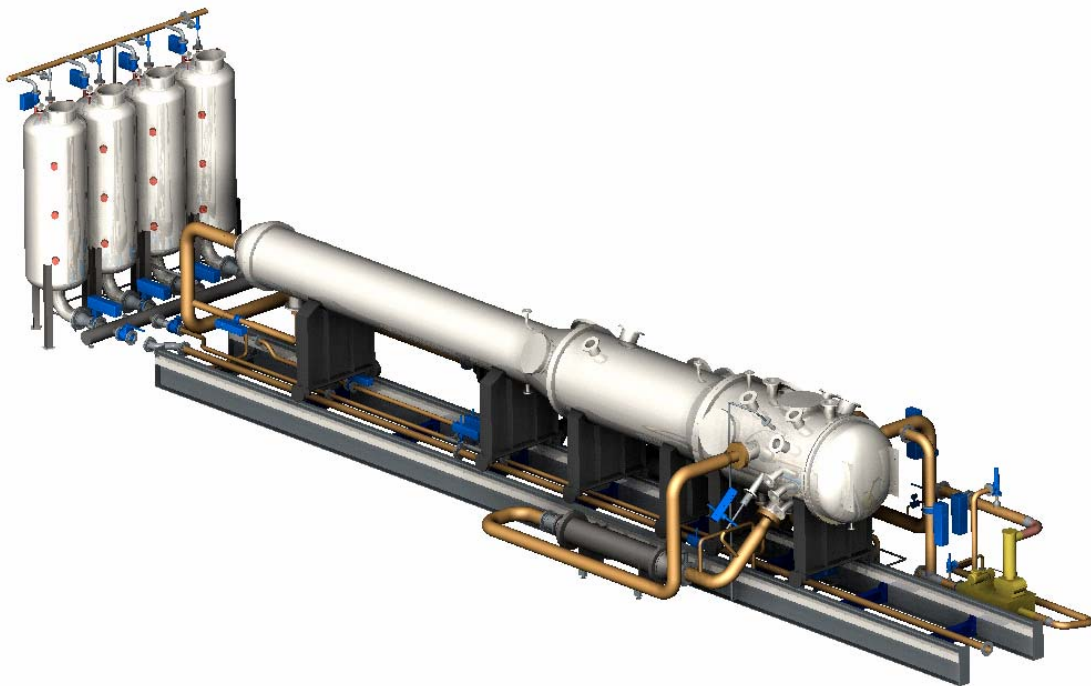


Figure 6.4: CAD illustration of PBMM 



Figure 6.5: Completed PBMM plant

In the next section the setup of the network of the PBMM in Flownex will be discussed as well as the steady state results of some important response variables.

6.3 *STEADY-STATE SIMULATION*

A steady-state simulation refers to the simulation of a plant at normal operating conditions. Steady-state is where all the components have reached a stable temperature, pressure and speed. Steady-state simulation results are handy in verifying if the operating conditions are within the design specifications of the components.

Extensive steady-state simulations were done during the development and design process of the PBMM plant. The simulations range from a very elementary (M100) network to the as-built (M400) network of the plant. The latter contains every detail of every component. The as-built network will be used in the sensitivity analysis. The following steps are very important when simulating a complex network:

- The first step when setting up a simulation like the PBMM plant is to identify all the components of the system. The exact dimensions (length, diameter, etc.) of the major components, pipes and fittings must be known. This can easily be obtained from the detail design drawings or from the manufacturers.
- The next step is to correctly calculate the losses involve in every pipe section. This calculation is a very important aspect of the modelling process and could influence the results of the network dramatically if not done correctly.

- Calculating the volume of the system is another important calculation to be done. This will aid in knowing the amount of inventory to have as this is a closed system.
- For components like turbines and compressors the performance maps must be converted into workable data files (See Appendix C). The heat exchanger characteristics are another important factor in ensuring to correctly simulate the plant (See Appendix C).

All of the above mentioned calculations can be viewed in the data pack of the PBMM network compiled by the author (2003). An extract of this report is available in Appendix C. Figure 6.6 shows the Flownex setup of the as-built model that will be used in the analysis. This Flownex model corresponds exactly with the schematic layout given in Figure 6.3.

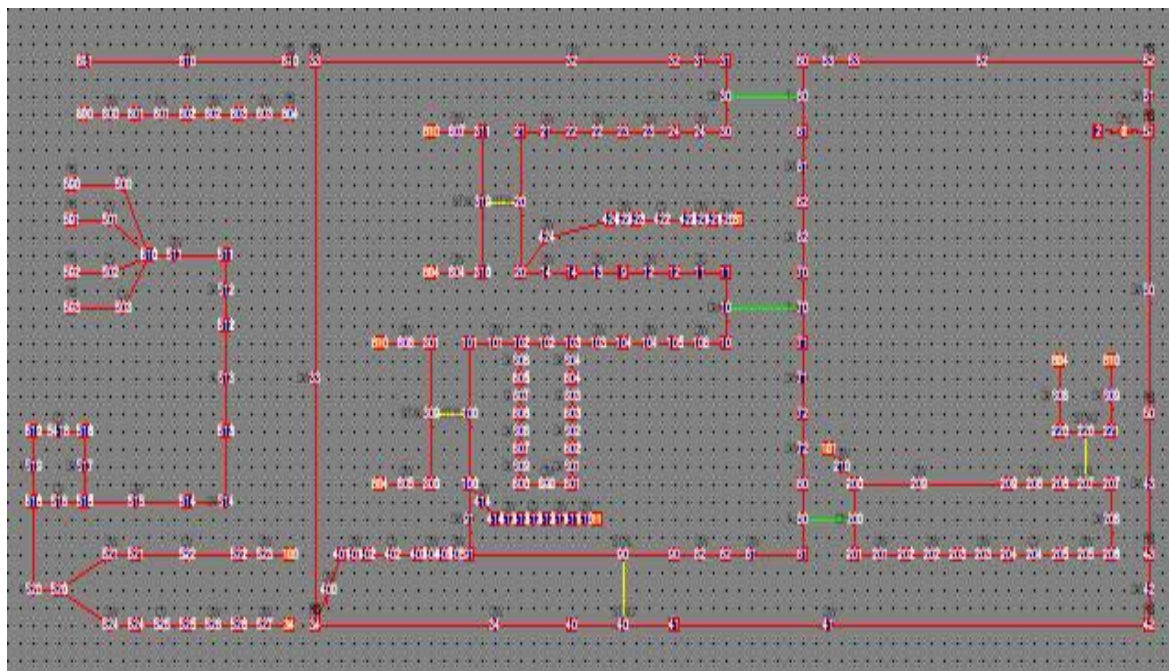


Figure 6.6: Flownet nuclear layout of as-built model of PBMM

The steady-state results obtained from all the models are discussed in the steady state result reports by the same author (2002). The pressure and temperature results before and after each major component is used to draw a temperature-entropy (T-s) and pressure-enthalpy (p-h) graphs as shown in Figure 6.7 and Figure 6.8 respectively. These results were chosen because of the ability of showing it on a graph rather than a table of values. Any of the other response variables could have been chosen. The results of the steady-state simulation will be compared with the results obtained from sensitivity analysis in section 6.4.

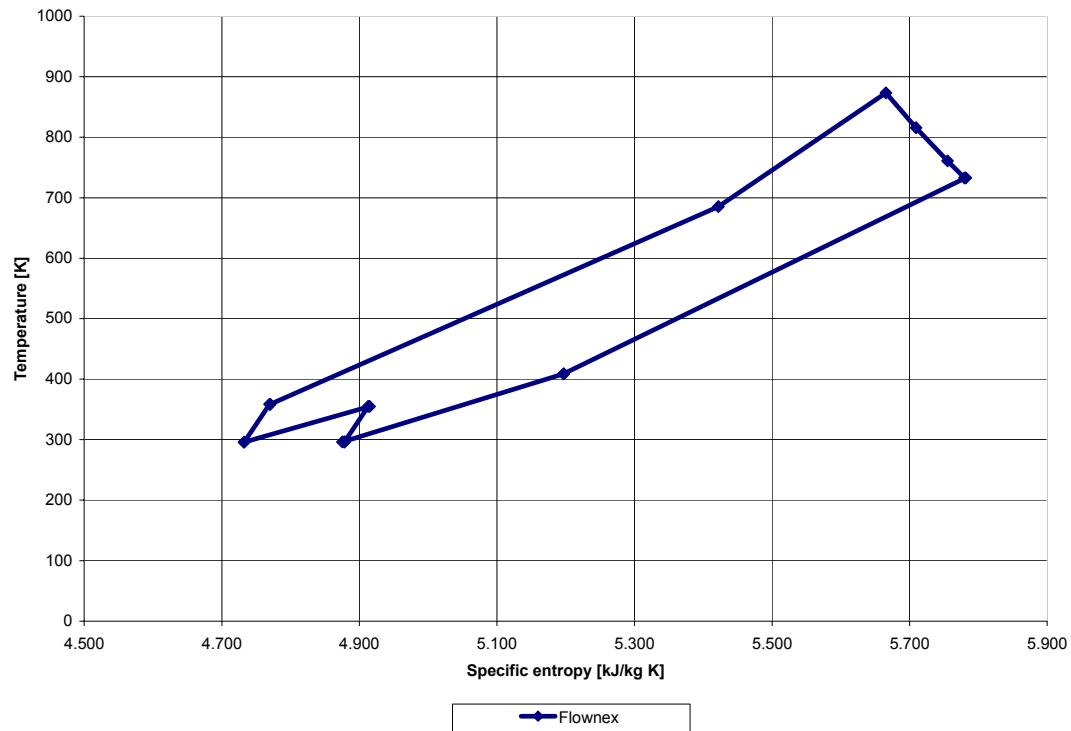


Figure 6.7: T-s graph of Flownex results of PBMM

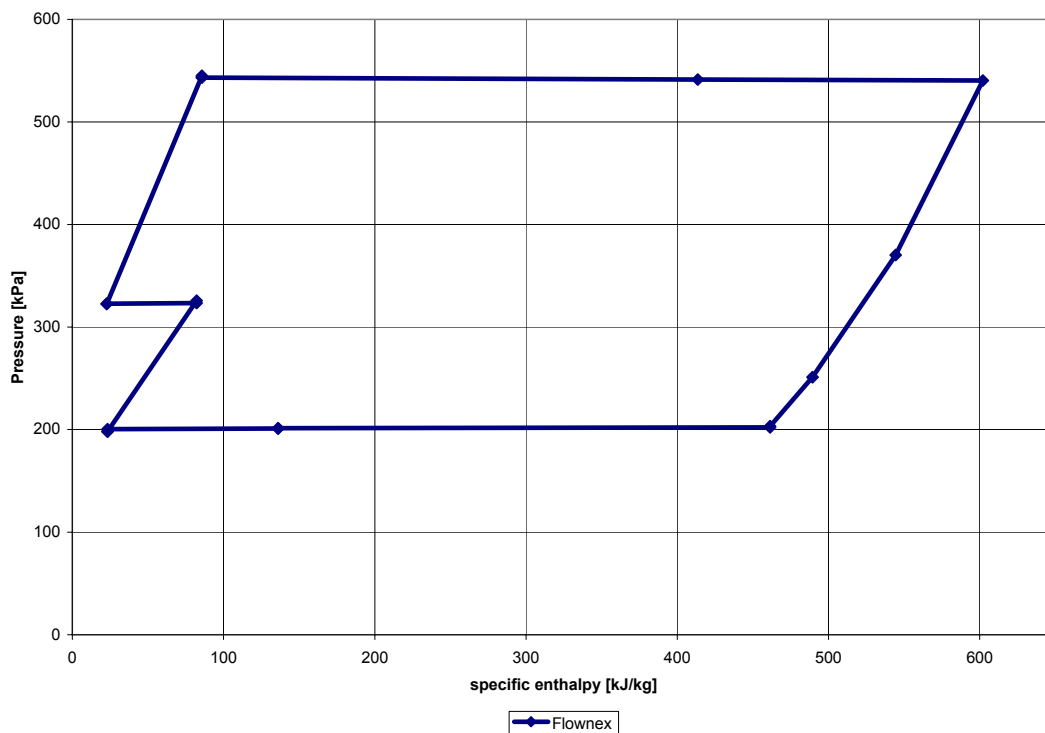


Figure 6.8: P-h graph of Flownex results of PBMM

6.4 SENSITIVITY ANALYSIS

As mentioned in Chapter 3 the presence of uncertainties is unavoidable in thermal-fluid networks and must be considered when simulating such a network. Taking into account that none of these uncertainties are present in the steady-state simulation, there must be some questions about the integrity of the results generated. This is why it is absolutely necessary to include these uncertainties in networks when simulations are done.

When conducting a sensitivity analysis it is very important to have a detail as-built network (see section 6.3) of the plant. It is pointless to do such analyses for elementary networks as the computational time is lengthy. Determining the uncertainties present in such a system is uncomplicated and is comprehensively described in Chapter 3. This is the most important aspect of the analysis as incorrectly defined uncertainties will influence the range calculated. The purpose of this analysis is to determine a realistic range for the response variables and this is only feasible if the uncertainties are correctly defined. The last step is to choose a convergence criteria. The convergence criterion that is used in this analysis is to define the number of runs to be conducted. To ensure convergence, 10 000 runs will be conducted. However, it is necessary to inspect if the criteria described in section 4.3.1 converge. Figure 6.9 shows this plot for the sensitivity analysis of the PBMM.

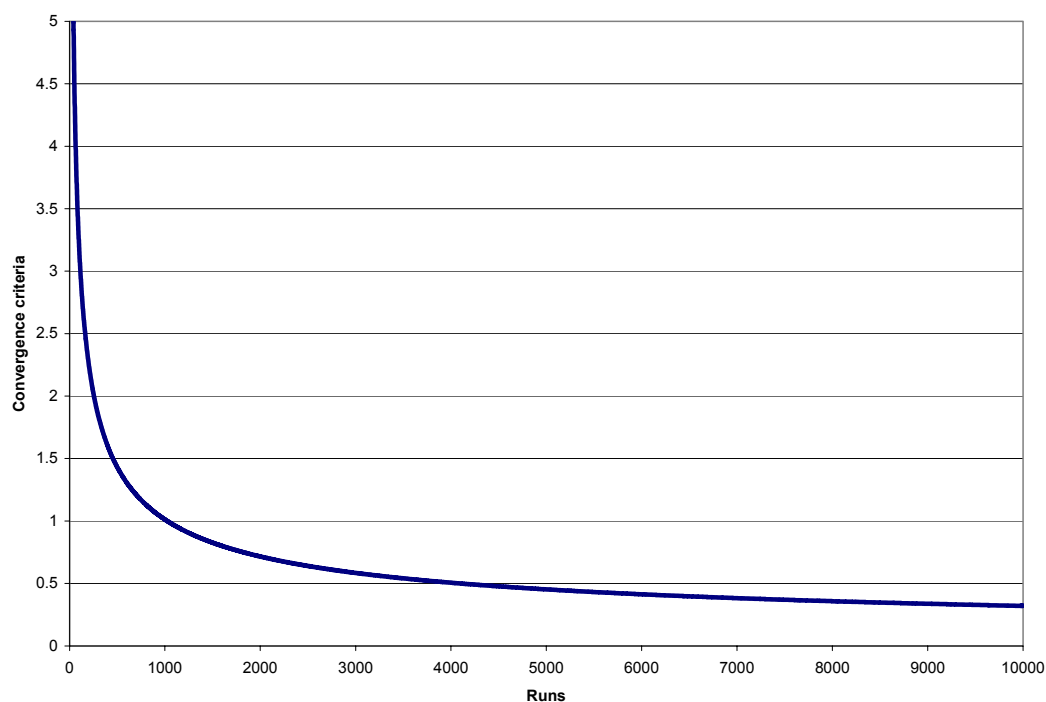


Figure 6.9: Convergence criteria plot of PBMM sensitivity analysis

It is clear that the analysis has converged and the answers obtained will be suitable and correct. The temperature and pressure before and after each major component were used to compare with the results obtained from the steady state simulation.

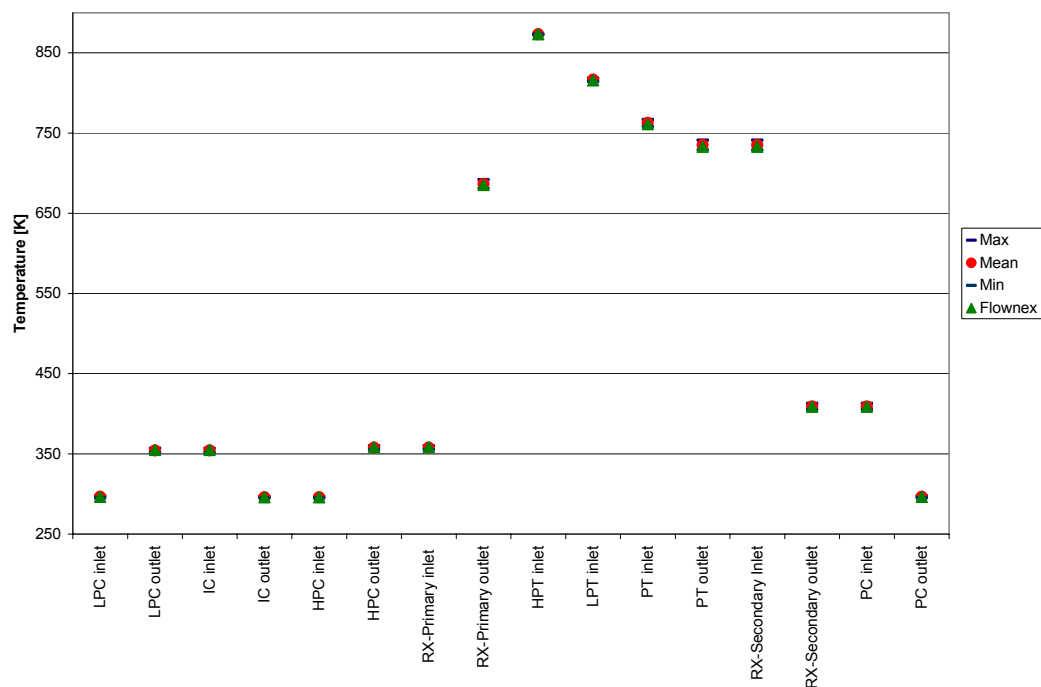


Figure 6.10: Temperature range obtained from sensitivity analysis

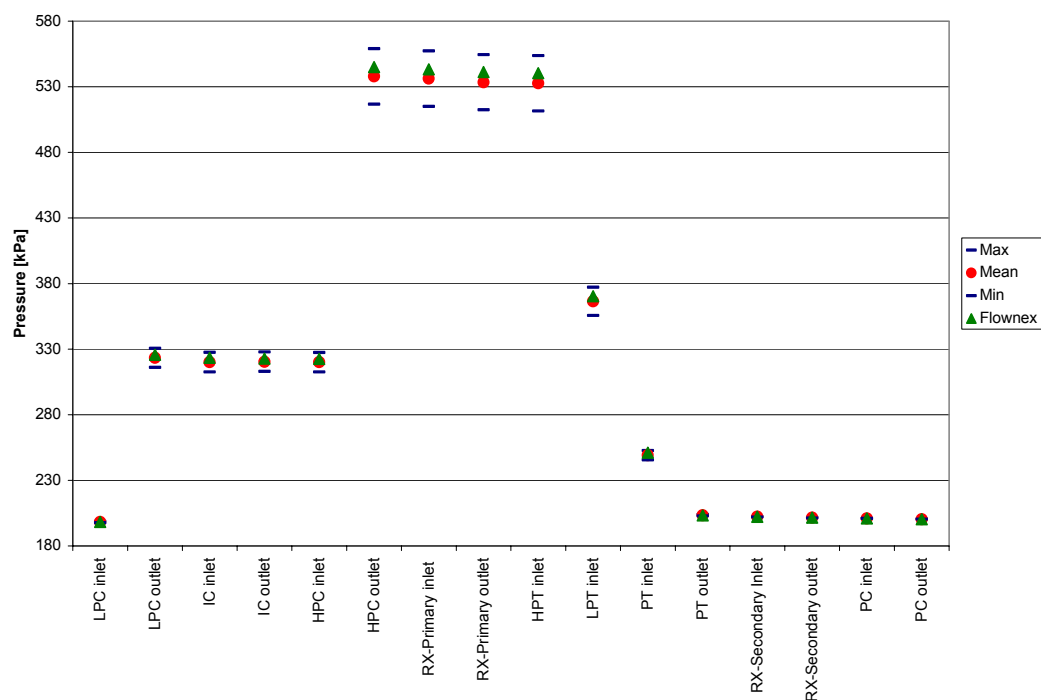


Figure 6.11: Pressure range obtained from sensitivity analysis

Figure 6.10 and Figure 6.11 show the temperature and pressure ranges obtained from the sensitivity analysis as well as the Flownex values from the steady state simulations. All of the cases showed that the values of the steady-state simulation are within the range specified by the sensitivity analysis. Figure 6.12 shows the ranges of power for the turbo units and the heat transfer for the heat exchangers. It is clear that all the steady state values are also within the specified ranges.

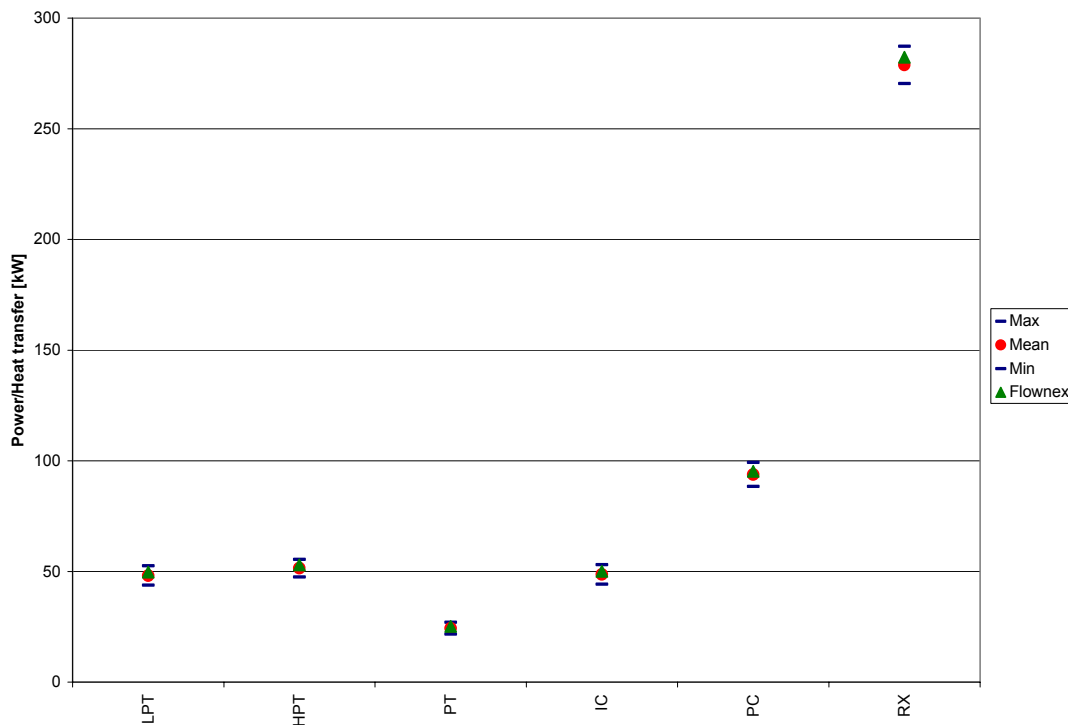


Figure 6.12: Power/Heat transfer range obtained from sensitivity analysis

6.5 CONCLUSION

The background of the system is briefly explained by firstly giving the origin of the PBMR and the operating of the three-shaft recuperative Brayton cycle. The difference and layouts of the PBMR and PBMM were also discussed in detail. It is clear that the same cycle is used by both the PBMR and PBMM. The PBMM only uses off-the-shelf components and some of the problems in the actual PBMR plant is avoided. A detailed as-built network of the PBMM was built in Flownex to do steady-state simulations. The sensitivity analysis was conducted on this as-built network and the results were compared with the steady state values.

After inspection of the convergence criteria plot it was found that the analysis reached a converged value after approximately 24 hours and 10 000 runs. Although the value of this criteria can still be minimized by conducting more runs the computational time will be extended tremendously. Flownex steady-state and sensitivity analysis results were compared by means of simple range plots. Flownex steady-state results were well within the ranges specified by the sensitivity analysis for temperatures, pressure and power of the different components.

The sensitivity analysis is a handy tool in thermal-fluid network simulations. All the uncertainties can be included to determine the sensitivity of the network due to the variation of the input parameters.

CHAPTER 7

CONCLUSION AND RECOMMENDATION

- 7.1 Summary
 - 7.2 Conclusion
 - 7.3 Recommendations for further work
-

7.1 SUMMARY

In the first chapter background was given as to why the study was regarded as important. In Chapter 2 a literature study was conducted during which it was found that little previous work had been conducted specifically on the application of Monte Carlo analysis on thermal-fluid network simulations. Literature was found on Monte Carlo models used in predicting and forecasting different aspects of engineering. Literature was also found on other, more complex, sampling techniques which can be more accurate but are much more complicated than the Monte Carlo method. The Taguchi method was also investigated but shortcomings on the number of variables that this technique could handle, prevented it from being used in the analysis. An algorithm had to be developed to conduct a sensitivity analysis on thermal fluid simulations by using the Monte Carlo approach.

Chapter 3 discussed the uncertainties involved in thermal-fluid systems as well as the physical values for these variables. These values were then used in conducting a sensitivity analysis on the PBMM in Chapter 6. In Chapter 4 the different methodologies that were considered was discussed and also the reasons why the specific method will be used. The algorithm used in conducting a sensitivity analysis was discussed in detail. Thorough validation and verification were done in Chapter 5 before the algorithm was implemented into the simulation code, Flownex. The algorithm was implemented into Excel and C++ to conduct the validation and verification. The three-shaft recuperative Brayton cycle that was used in the case study was discussed in detail in chapter 6 as well as the experimental/PBMM setup. The results obtained from the steady state and sensitivity analysis was compared to verify the integrity of the study. Certain important conclusions were drawn from these comparisons.

7.2 CONCLUSION

In this study an algorithm was developed to conduct sensitivity analysis by means of the Monte Carlo method on thermal-fluid network simulations. Given the uncertainty, the best estimate and the delta of every input variable used in a simulation, a mean and standard deviation for any response variable, will be calculated. The reliability of the values generated depends on how accurately the user chooses the values of the uncertainty of the input variables. Values for uncertainty of input variables that are far from the physical uncertainty of the variable will result in answers that will have no concrete meaning.

The Excel and C++ codes that were developed to verify and validate the algorithm are within 1 % of each other. The results of these codes were slightly different because of the different random number-generators used by Excel and C++ respectively. Despite the minor difference in results of the different codes, the algorithm was successfully verified and validated.

An experimental model of the three-shaft recuperative Brayton cycle was constructed by the Engineering Faculty at the PU for CHE. The experimental model also allowed the measuring of key variables that could be used to compare the normal steady state and sensitivity simulations results. A detailed network was simulated in Flownex that included all the components of the plant. This network was used to do steady-state simulations and the sensitivity analysis.

The results obtained from the steady-state simulations and the sensitivity analysis compared well. The Flownex steady-state results were well within the range obtained from the sensitivity analysis. The ranges showed that in all the components some uncertainties exist and that such an analysis provides valuable information of the physical plant's performance parameters.

By means of the sensitivity analysis, it is now possible to simulate a thermal fluid system while considering the uncertainties of all of the variables involved for each component. The results of the comparison obtained from the steady state, experimental and sensitivity analysis provide more confidence in the actual steady-state results.

7.3 RECOMMENDATIONS FOR FURTHER WORK

The following recommendations for further research work arose from the study:

- Changing the algorithm to handle other types of distributions like block and triangular;
- Steady-state experimental results of PBMM must be compared with Flownex steady-state and sensitivity results.

References

ANSI/ANI, 1987, Guidelines for the verification and validation of scientific and engineering computer programs for nuclear industry, PTC 10.4.

BECK, J.V.; ARNOLD, K.J. 1977. Parameter estimation in engineering and science. New York: Wiley.

BILEN, K.; SINAN, Y.; CELIK, C. 2001. A Taguchi approach for investigation of heat transfer from a surface equipped with rectangular blocks. *Energy Conversion and Management*, Vol 42 p 951-961.

BOX, G.E.P.; MULLER, E.M. 1958. A note on the generation of random normal deviates. *Statistical Techniques Research Group*, Princeton University, DA 36-034-ORD 2297.

CHEN, W.; DU, X. 2000. A Methodology for Managing the Effect of Uncertainty in Simulation-Based Design.

CHENEY, W.; KINCAID, D. 1994. Numerical Mathematics and computing, 3rd Ed, p 411 – 412, Belmont: Brooks/Cole.

CLARKE, D.D.; VASQUEZ, V.R.; WHITING, W.B.; GREINER, M. 2001. Sensitivity and uncertainty analysis of heat-exchanger designs to physical properties estimation. *Applied Thermal Engineering*, Vol 21 p 993-1017.

COHEN, H.; ROGERS, C.F.C.; SARAVANAMUTTOO, H.I.H. 1996. Gas Turbine Theory. London: Addison Wesley Longman Limited.

COLEMAN, H.W. AND STEELE, W.G. 1989. Experimentation and Uncertainty Analysis for Engineers. John Wiley, New York.

- DE LATAILLADE, A.; BLANCO, S.; CLERGENT, Y.; DUFRESNE, J.L.; EL HAFI, M.; FOURNIER, R. 2002. Monte Carlo method and sensitivity estimations. *Journal of Quantitative Spectroscopy & Radiative Transfer*, Vol 75 p 529-538.
- DU TOIT, C.G. 1991. Tracking particles through a flow field with obstructions. *Proceedings of the second national symposium on computational fluid dynamics*. Vereeniging, South Africa. p 222-235.
- FLOWNET, VERSION 6 USER MANUAL, M-TECH INDUSTRIAL, POTCHEFSTROOM, 2003.
- GREYVENSTEIN, G.P.; ROUSSEAU, P.G. 2001. Proposal for the development of a physical model of the PBMR. Faculty Engineering, Potchefstroom University.
- HAIMES, Y.Y.; BARRY, T.; LAMBERT, J.H. 1994. When and how can you specify a probability distribution if you don't know much? *Risk Analysis*, Vol 14(5) p 661-703.
- HAMMERSLEY, J.M.; HANDSCOMB, D.C. Monte Carlo methods. Methuen's monographs on applied probability and statistics, London, 1964.
- HOWELL, J.R. 1969. Applications of Monte Carlo to heat transfer problems. *Adv Heat Transfer*, Vol 5 p 1-54.
- KAYS, W.M.; LONDON, A.L. 1984. Compact Heat Exchangers. New York: McGraw-Hill.
- LABUSCHAGNE, J.T.; NIEMAND, H.J.; ROUSSEAU, P.G. 2002. PBMR Micro Model M400 Input Report. Faculty of Engineering, Potchefstroom University. 145 pages.
- LABUSCHAGNE, J.T. 2003. PBMR Micro Model Data Pack. Faculty of Engineering, Potchefstroom University. 76 pages.
- MACKEOWN, P.K. 1997. Stochastic simulation in physics. Berlin: Springer.

- PANG, W.K.; YANG, Z.H.; HOU, S.H.; LEUNG, P.K. 2002. Non-uniform random variate generation by vertical strip method. *European Journal of Operational Research*, Vol 142 p 595-609.
- PHADKE, M.S. 1989 *Quality engineering using robust design*.
- PRESS, H.W.; TEUKOLSKY, S.A.; VETTERLING, W.T.; FLANNERY, B.P. 1997. Numerical recipes in Fortran. *The art of scientific computing*. p. 684-686
- REED, M.E.; TONG, T.; WHITING, W.B. 1993. Effect of uncertainties in thermodynamic data and model parameters on calculated process performance. *Industrial Engineering Chemistry Research*, Vol 32 p 1367-1371.
- REED, M.E.; WHITING, W.B. 1993. Sensitivity and uncertainty of process design to thermodynamic model parameters: a Monte Carlo approach. *Chemical Engineering Communication*, Vol 124 p 39-48.
- ROACHE, P.J. 1997. Quantification of uncertainty in computational fluid dynamics. *Annual Review of Fluid Mechanics*, Vol 29 p 123-160.
- ROUSSEAU, P.G.; STRAUSS, J.P.; GREYVENSTEIN, G.P. 2001. Demand side management for water heating installations in South African commercial buildings. *International Journal of Energy Research*, Vol 25 p 291-317.
- ROUSSEAU, P.G. 2001. Advanced thermal-fluid systems course notes. Potchefstroom.
- ROUSSEAU, P.G. 2002. Simulation Techniques course notes. Potchefstroom.
- SEILER, F.A.; ALVAREZ, J.L. 1996. On the selection of distributions for stochastic variables. *Risk Analysis*, Vol 16(1) p 5-18.

- STEYN, H.S. 2002. Personal conversation with author. Potchefstroom.
- TAYLOR, R.P.; HODGE, B.K.; JAMES, C.A. 1999. Estimating uncertainty in thermal fluid systems and design. *Applied Thermal Engineering*, Vol 19 p 51-73.
- TOMOVIC, R. 1963. Sensitivity analysis of dynamic systems. New York: McGraw-Hill.
- VARDEMAN, S.B. 1993. Statistics for engineering problem solving. Boston: PWS.
- VASQUEZ, V.R.; WHITING, W.B. 2000. Uncertainty and sensitivity analysis of thermodynamic models using equal probability sampling (EPS). *Computers and Chemical Engineering*, Vol 23 p 1825-1838.
- WANG, S.B.; PAN, C. 1998. Two phase flow instability experiment in a natural circulation loop using the Taguchi method. *Experimental Thermal and Fluid Science*, Vol 17 p 189-201.
- WHITING, W.B.; VASQUEZ, V.R. 1998. Uncertainty of predicted process performance due to variations in thermodynamics model parameter estimation from different data sets. *Fluid Phase Equilibria*, Vol 142 p 115-130.
- WOLLER, T.A.J. 1996. Study guide for physical chemistry. *Department of Nature studies*, University of Nebraska - Lincoln. p 1-4.
- YANG, Y.G.; ZHOU, X.W.; JOHNSON, R.A.; WADLEY, H.N.G. 2001. Monte Carlo simulation of hyper thermal physical vapor deposition. *Acta mater*, Vol 49 p 3321-3332.
- ZHOU, Y.H.; SHEN, Y.J.; ZHANG, Z.M.; TSAI, B.K.; DEWITT, D.P. 2002. A Monte Carlo model for predicting the effective emissivity of the silicon wafer in rapid thermal processing furnaces. *International Journal of Heat and Mass Transfer*, Vol 45 p 1945-1949.

APPENDIX A

CORRECTION FACTORS

- A.1 Standard deviation correction
 - A.2 Maximum standard deviation correction
-

A.1 STANDARD DEVIATION CORRECTION

A correction factor for several delta values was determined by plotting the standard deviation desired versus the standard deviation obtained from the analysis for the different input variables. In each case below a simple pipe was simulated. The diameter of the pipe was then used in obtaining the correction factor for the specific delta. The calculations done in Excel for the least square fit are shown in Table A. 1. The coefficient of determination and equation of the correction are shown on the graphs that are provided after the calculations.

SD	Delta	CSD 150%	Fit 150%	Least Square	A	B			arcTAN (B x SD)	B*SD
0	1.5	0.00	0.00	0.00	71.20	0.02	a ₀	1.79	0.00	0.00
10	1.5	10.06	11.78	2.97	71.20	0.02	a ₁	9.86	0.17	0.17
20	1.5	20.06	22.95	8.35	71.20	0.02	a ₂	10.05	0.32	0.33
30	1.5	30.10	33.07	8.81	71.20	0.02	a ₃	9.48	0.46	0.50
40	1.5	40.34	41.93	2.54	71.20	0.02	b ₀	8.14	0.59	0.67
50	1.5	48.76	49.53	0.60	71.20	0.02	b ₁	13.80	0.70	0.83
60	1.5	57.15	55.99	1.35	71.20	0.02	b ₂	14.09	0.79	1.00
70	1.5	63.52	61.46	4.28	71.20	0.02	b ₃	-17.93	0.86	1.17
80	1.5	68.13	66.09	4.15	71.20	0.02			0.93	1.34
90	1.5	71.28	70.04	1.55	71.20	0.02			0.98	1.50
100	1.5	74.17	73.43	0.56	71.20	0.02			1.03	1.67
			Min	35.16						
SD	Delta	CSD 100%	Fit 100%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	1	0.00	0.00	0.00	46.20	0.03	a ₀	11.78	0.00	0.00
10	1	10.06	11.72	2.77	46.20	0.03	a ₁	11.78	0.25	0.26
20	1	20.06	22.11	4.18	46.20	0.03	a ₂	11.78	0.48	0.52
30	1	29.77	30.55	0.60	46.20	0.03	a ₃	10.87	0.66	0.78
40	1	38.21	37.13	1.16	46.20	0.03	b ₀	0.01	0.80	1.04
50	1	44.03	42.22	3.25	46.20	0.03	b ₁	0.01	0.91	1.30
60	1	47.61	46.18	2.03	46.20	0.03	b ₂	0.01	1.00	1.56
70	1	50.17	49.31	0.74	46.20	0.03	b ₃	0.01	1.07	1.82
80	1	52.42	51.82	0.35	46.20	0.03			1.12	2.07
90	1	53.02	53.87	0.74	46.20	0.03			1.17	2.33
100	1	53.40	55.57	4.70	46.20	0.03			1.20	2.59
			Min	20.52						

SD	Delta	CSD 90%	Fit 90%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.9	0.00	0.00	0.00	40.30	0.03	a ₀	11.87	0.00	0.00
10	0.9	10.06	11.86	3.24	40.30	0.03	a ₁	11.90	0.29	0.30
20	0.9	20.06	21.96	3.60	40.30	0.03	a ₂	11.93	0.54	0.61
30	0.9	29.29	29.73	0.20	40.30	0.03	a ₃	11.04	0.74	0.91
40	0.9	36.89	35.50	1.91	40.30	0.03	b ₀	-0.39	0.88	1.21
50	0.9	41.50	39.79	2.92	40.30	0.03	b ₁	0.13	0.99	1.52
60	0.9	44.53	43.04	2.24	40.30	0.03	b ₂	0.19	1.07	1.82
70	0.9	46.60	45.55	1.12	40.30	0.03	b ₃	0.20	1.13	2.12
80	0.9	47.49	47.53	0.00	40.30	0.03			1.18	2.42
90	0.9	48.09	49.14	1.10	40.30	0.03			1.22	2.73
100	0.9	48.48	50.45	3.91	40.30	0.03			1.25	3.03
			Min	20.24						
SD	Delta	CSD 80%	Fit 80%	Least Square	A	B			arcTan (B x SD)	B x SD
0	0.8	0.00	0.00	0.00	34.99	0.04	a ₀	11.99	0.00	0.00
10	0.8	10.06	12.03	3.88	34.99	0.04	a ₁	12.01	0.34	0.36
20	0.8	20.06	21.74	2.82	34.99	0.04	a ₂	12.03	0.62	0.72
30	0.8	28.94	28.73	0.04	34.99	0.04	a ₃	11.13	0.82	1.07
40	0.8	35.24	33.63	2.60	34.99	0.04	b ₀	0.06	0.96	1.43
50	0.8	38.88	37.14	3.03	34.99	0.04	b ₁	-0.33	1.06	1.79
60	0.8	41.05	39.72	1.77	34.99	0.04	b ₂	0.19	1.13	2.15
70	0.8	42.08	41.68	0.16	34.99	0.04	b ₃	0.23	1.19	2.51
80	0.8	42.77	43.21	0.20	34.99	0.04			1.23	2.86
90	0.8	43.28	44.44	1.33	34.99	0.04			1.27	3.22
100	0.8	44.04	45.43	1.95	34.99	0.04			1.30	3.58
			Min	17.78						

SD	Delta	CSD 70%	Fit 70%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.7	0.00	0.00	0.00	29.97	0.04	a ₀	11.90	0.00	0.00
10	0.7	10.06	12.08	4.08	29.97	0.04	a ₁	11.96	0.40	0.43
20	0.7	19.87	21.16	1.67	29.97	0.04	a ₂	12.01	0.71	0.85
30	0.7	28.19	27.19	1.00	29.97	0.04	a ₃	11.13	0.91	1.28
40	0.7	32.58	31.18	1.94	29.97	0.04	b ₀	1.04	1.04	1.71
50	0.7	35.44	33.93	2.27	29.97	0.04	b ₁	-3.06	1.13	2.13
60	0.7	36.86	35.91	0.91	29.97	0.04	b ₂	1.39	1.20	2.56
70	0.7	37.44	37.39	0.00	29.97	0.04	b ₃	1.37	1.25	2.98
80	0.7	37.86	38.53	0.44	29.97	0.04			1.29	3.41
90	0.7	38.60	39.43	0.70	29.97	0.04			1.32	3.84
100	0.7	38.98	40.17	1.42	29.97	0.04			1.34	4.26
			Min	14.44						
SD	Delta	CSD 60%	Fit 60%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.6	0.00	0.00	0.00	25.19	0.05	a ₀	15.98	0.00	0.00
10	0.6	10.06	12.06	4.01	25.19	0.05	a ₁	9.99	0.48	0.52
20	0.6	19.55	20.26	0.50	25.19	0.05	a ₂	6.40	0.80	1.04
30	0.6	26.46	25.19	1.60	25.19	0.05	a ₃	4.24	1.00	1.56
40	0.6	29.71	28.27	2.08	25.19	0.05	b ₀	-3.29	1.12	2.08
50	0.6	31.53	30.31	1.50	25.19	0.05	b ₁	2.88	1.20	2.60
60	0.6	32.11	31.75	0.13	25.19	0.05	b ₂	2.95	1.26	3.11
70	0.6	32.73	32.81	0.01	25.19	0.05	b ₃	2.56	1.30	3.63
80	0.6	33.26	33.62	0.13	25.19	0.05			1.33	4.15
90	0.6	33.51	34.26	0.56	25.19	0.05			1.36	4.67
100	0.6	33.56	34.78	1.50	25.19	0.05			1.38	5.19
			Min	12.01						

SD	Delta	CSD 50%	Fit 50%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.5	0.00	0.00	0.00	20.52	0.07	a ₀	13.59	0.00	0.00
10	0.5	10.06	11.99	3.75	20.52	0.07	a ₁	9.46	0.58	0.66
20	0.5	19.18	18.95	0.05	20.52	0.07	a ₂	6.52	0.92	1.32
30	0.5	23.86	22.66	1.45	20.52	0.07	a ₃	4.54	1.10	1.99
40	0.5	26.18	24.82	1.85	20.52	0.07	b ₀	-41.46	1.21	2.65
50	0.5	26.78	26.21	0.33	20.52	0.07	b ₁	49.40	1.28	3.31
60	0.5	27.38	27.17	0.05	20.52	0.07	b ₂	50.41	1.32	3.97
70	0.5	27.70	27.87	0.03	20.52	0.07	b ₃	33.80	1.36	4.63
80	0.5	28.00	28.40	0.16	20.52	0.07			1.38	5.29
90	0.5	28.18	28.82	0.41	20.52	0.07			1.40	5.96
100	0.5	28.18	29.15	0.95	20.52	0.07			1.42	6.62
			Min	9.02						
SD	Delta	CSD 40%	Fit 40%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.4	0.00	0.00	0.00	16.13	0.09	a ₀	10.88	0.00	0.00
10	0.4	10.06	11.54	2.19	16.13	0.09	a ₁	9.49	0.72	0.87
20	0.4	17.66	16.91	0.56	16.13	0.09	a ₂	7.10	1.05	1.74
30	0.4	20.56	19.43	1.28	16.13	0.09	a ₃	5.05	1.20	2.61
40	0.4	21.44	20.82	0.38	16.13	0.09	b ₀	-142.84	1.29	3.47
50	0.4	22.04	21.69	0.12	16.13	0.09	b ₁	240.33	1.34	4.34
60	0.4	22.38	22.28	0.01	16.13	0.09	b ₂	241.42	1.38	5.21
70	0.4	22.55	22.71	0.03	16.13	0.09	b ₃	127.62	1.41	6.08
80	0.4	22.55	23.04	0.24	16.13	0.09			1.43	6.95
90	0.4	22.80	23.29	0.24	16.13	0.09			1.44	7.82
100	0.4	22.91	23.49	0.34	16.13	0.09			1.46	8.68
			Min	5.39						

SD	Delta	CSD 30%	Fit 30%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.3	0.00	0.00	0.00	11.85	0.13	a ₀	7.91	0.00	0.00
10	0.3	9.82	10.62	0.65	11.85	0.13	a ₁	10.24	0.90	1.25
20	0.3	14.88	14.11	0.60	11.85	0.13	a ₂	7.98	1.19	2.50
30	0.3	16.10	15.53	0.33	11.85	0.13	a ₃	5.57	1.31	3.75
40	0.3	16.64	16.28	0.14	11.85	0.13	b ₀	-4.00	1.37	5.00
50	0.3	16.84	16.73	0.01	11.85	0.13	b ₁	10.23	1.41	6.25
60	0.3	16.92	17.04	0.01	11.85	0.13	b ₂	10.06	1.44	7.50
70	0.3	17.10	17.27	0.03	11.85	0.13	b ₃	5.74	1.46	8.75
80	0.3	17.23	17.43	0.04	11.85	0.13			1.47	10.00
90	0.3	17.25	17.56	0.10	11.85	0.13			1.48	11.25
100	0.3	17.38	17.67	0.08	11.85	0.13			1.49	12.50
			Min	1.99						
SD	Delta	CSD 20%	Fit 20%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.3	0.00	0.00	0.00	7.68	0.24	a ₀	4.11	0.00	0.00
10	0.3	8.88	9.07	0.04	7.68	0.24	a ₁	9.10	1.18	2.44
20	0.3	10.77	10.51	0.07	7.68	0.24	a ₂	7.64	1.37	4.88
30	0.3	11.24	11.02	0.05	7.68	0.24	a ₃	5.47	1.43	7.32
40	0.3	11.31	11.28	0.00	7.68	0.24	b ₀	-3.79	1.47	9.76
50	0.3	11.47	11.43	0.00	7.68	0.24	b ₁	9.98	1.49	12.20
60	0.3	11.52	11.54	0.00	7.68	0.24	b ₂	9.80	1.50	14.64
70	0.3	11.60	11.61	0.00	7.68	0.24	b ₃	5.64	1.51	17.08
80	0.3	11.57	11.67	0.01	7.68	0.24			1.52	19.52
90	0.3	11.61	11.71	0.01	7.68	0.24			1.53	21.96
100	0.3	11.63	11.75	0.01	7.68	0.24			1.53	24.39
			Min	0.19						

SD	Delta	CSD 10%	Fit 10%	Least Square	A	B			arcTAN (B x SD)	B x SD
0	0.3	0.00	0.00	0.00	3.78	0.82	a ₀	0.56	0.00	0.00
10	0.3	5.45	5.48	0.00	3.78	0.82	a ₁	8.04	1.45	8.16
20	0.3	5.72	5.71	0.00	3.78	0.82	a ₂	7.32	1.51	16.32
30	0.3	5.82	5.78	0.00	3.78	0.82	a ₃	5.37	1.53	24.48
40	0.3	5.85	5.82	0.00	3.78	0.82	b ₀	-3.00	1.54	32.64
50	0.3	5.88	5.84	0.00	3.78	0.82	b ₁	9.47	1.55	40.80
60	0.3	5.87	5.86	0.00	3.78	0.82	b ₂	9.19	1.55	48.96
70	0.3	5.87	5.87	0.00	3.78	0.82	b ₃	5.41	1.55	57.12
80	0.3	5.86	5.88	0.00	3.78	0.82			1.56	65.28
90	0.3	5.84	5.89	0.00	3.78	0.82			1.56	73.44
100	0.3	5.86	5.89	0.00	3.78	0.82			1.56	81.60
			Min	0.01						

Table A. 1: Least square calculations for corrected standard deviation

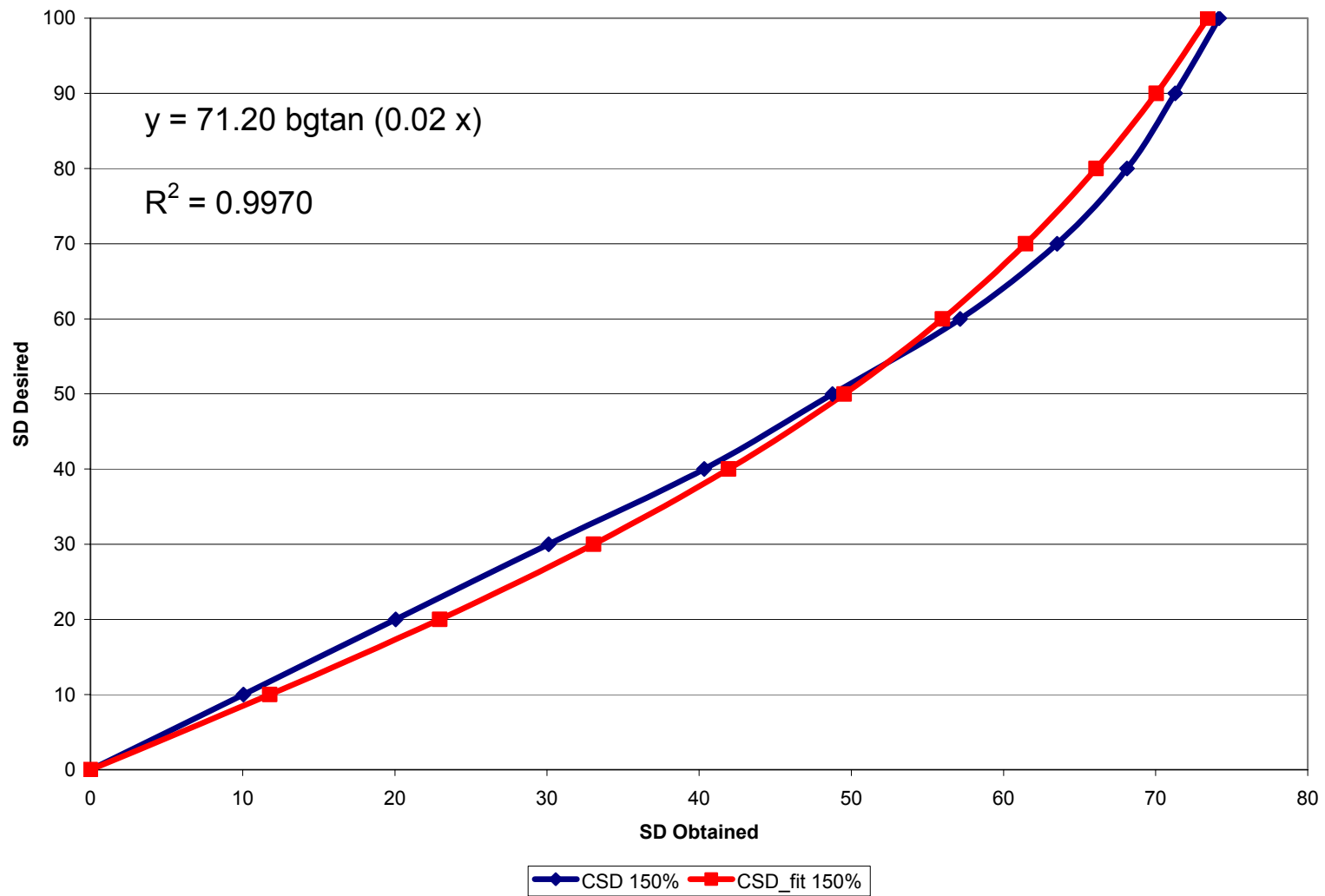


Figure A. 1: Correction factor for 150% delta

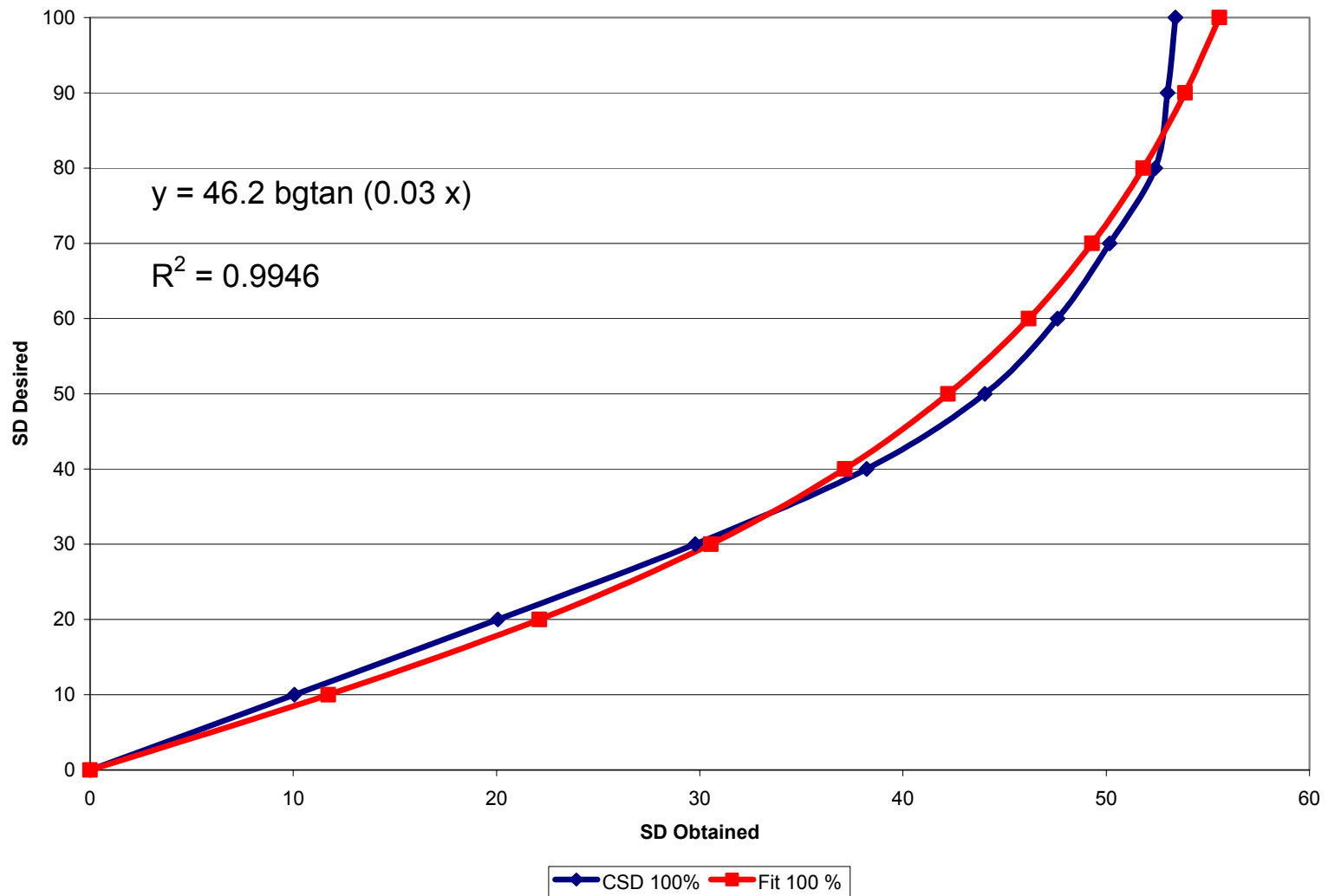


Figure A.2: Correction factor for 100% delta

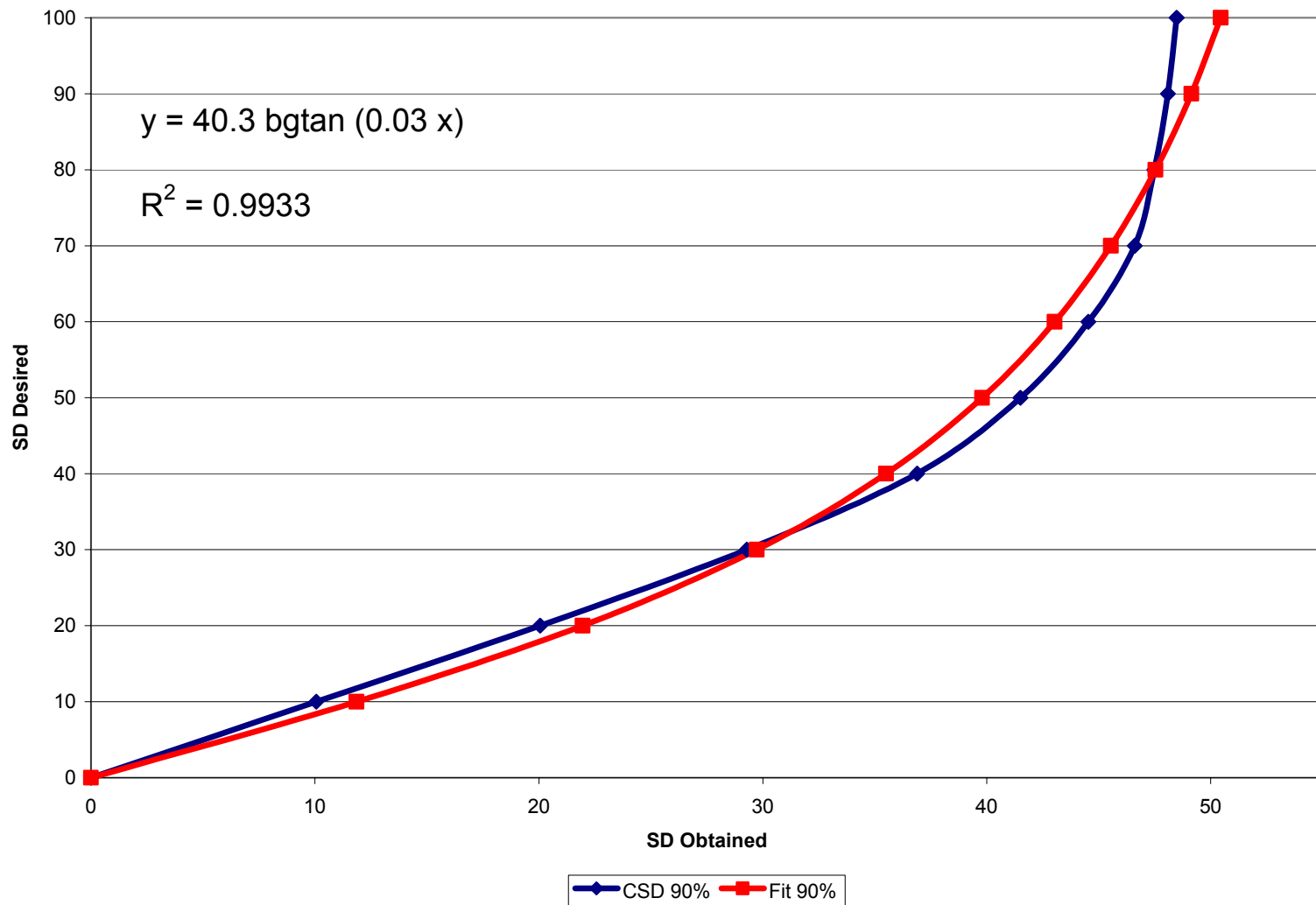
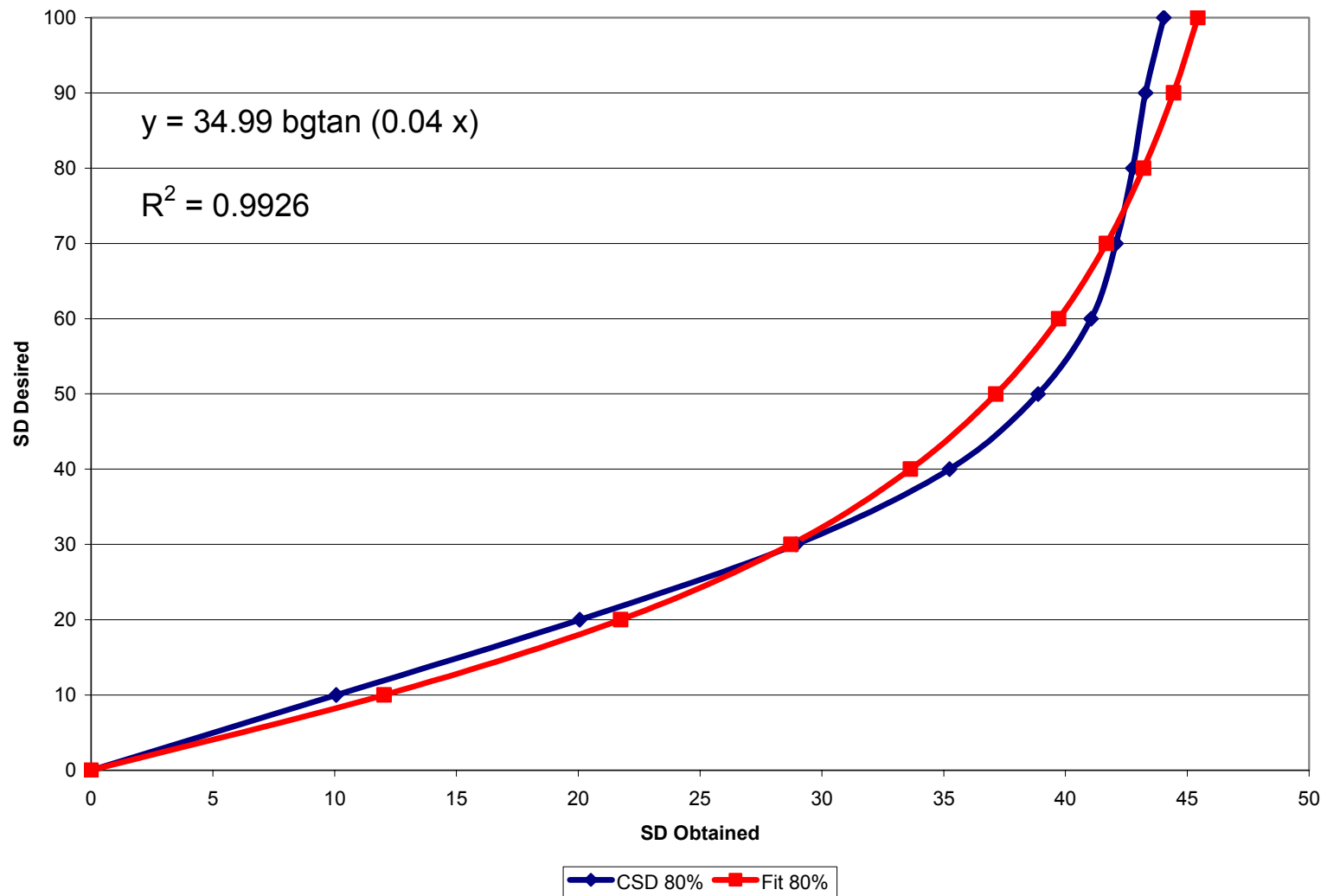


Figure A.3: Correction factor for 90% delta

**Figure A.4:** Correction factor for 80% delta

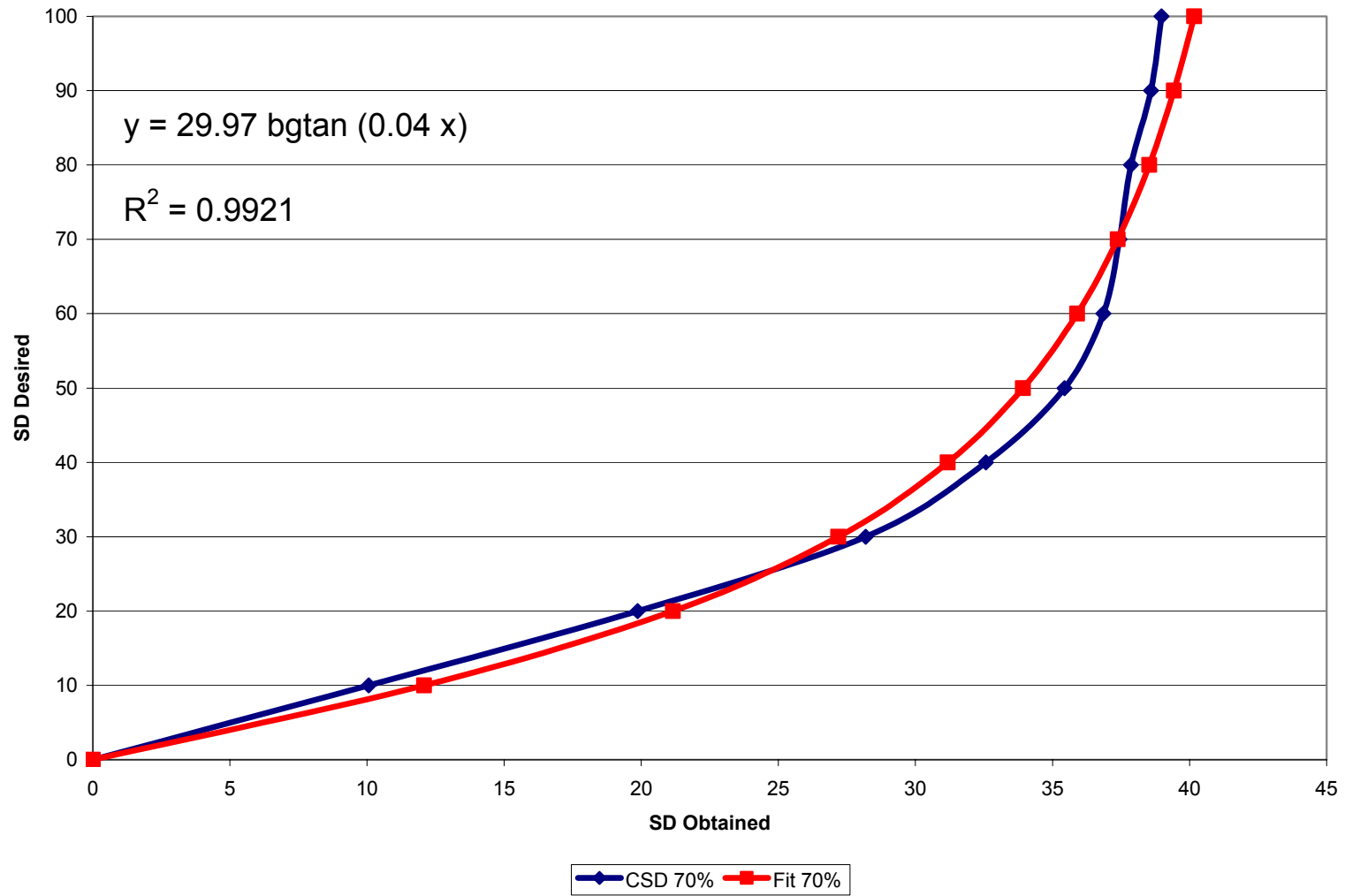


Figure A.5: Correction factor for 70% delta

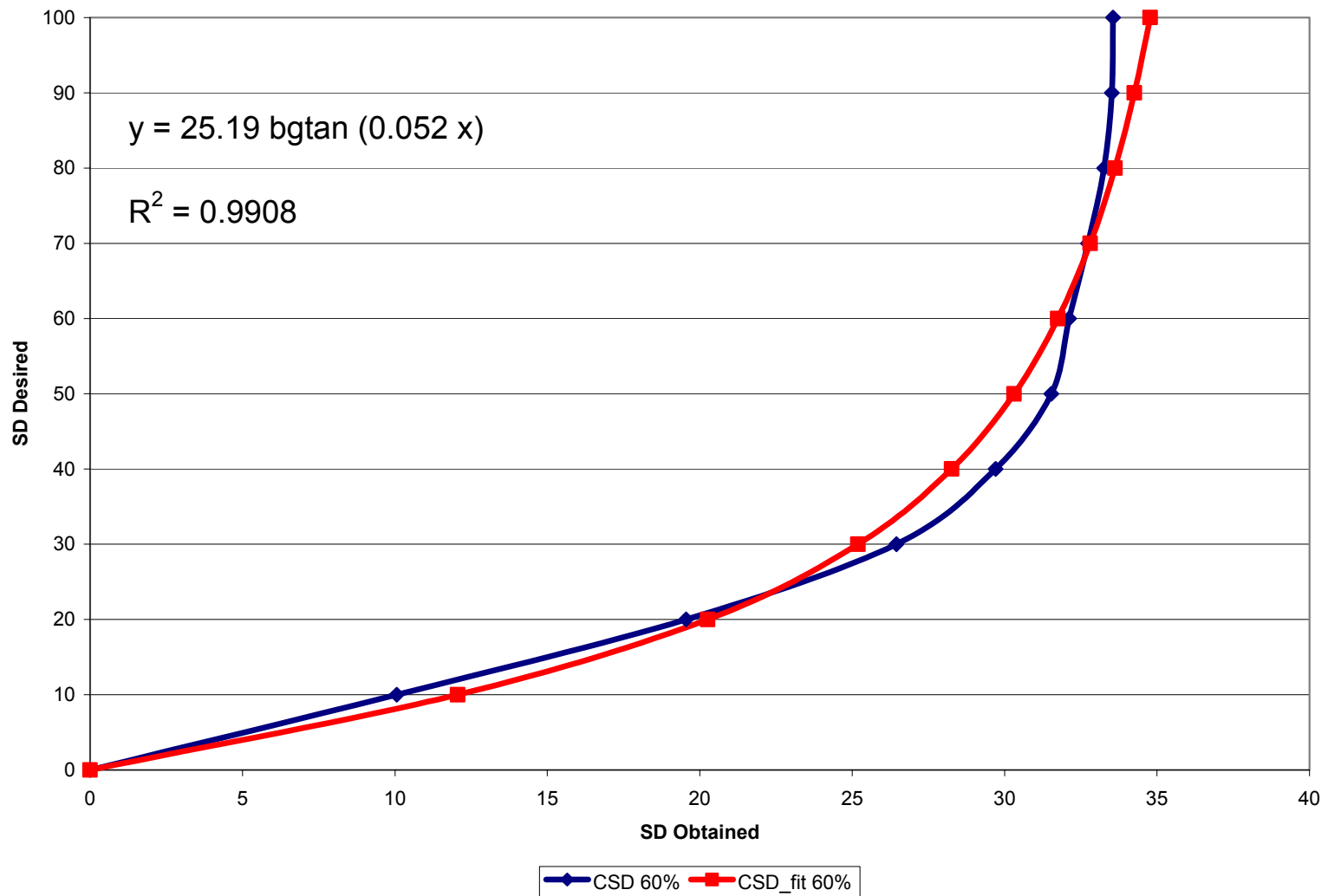


Figure A.6: Correction factor for 60% delta

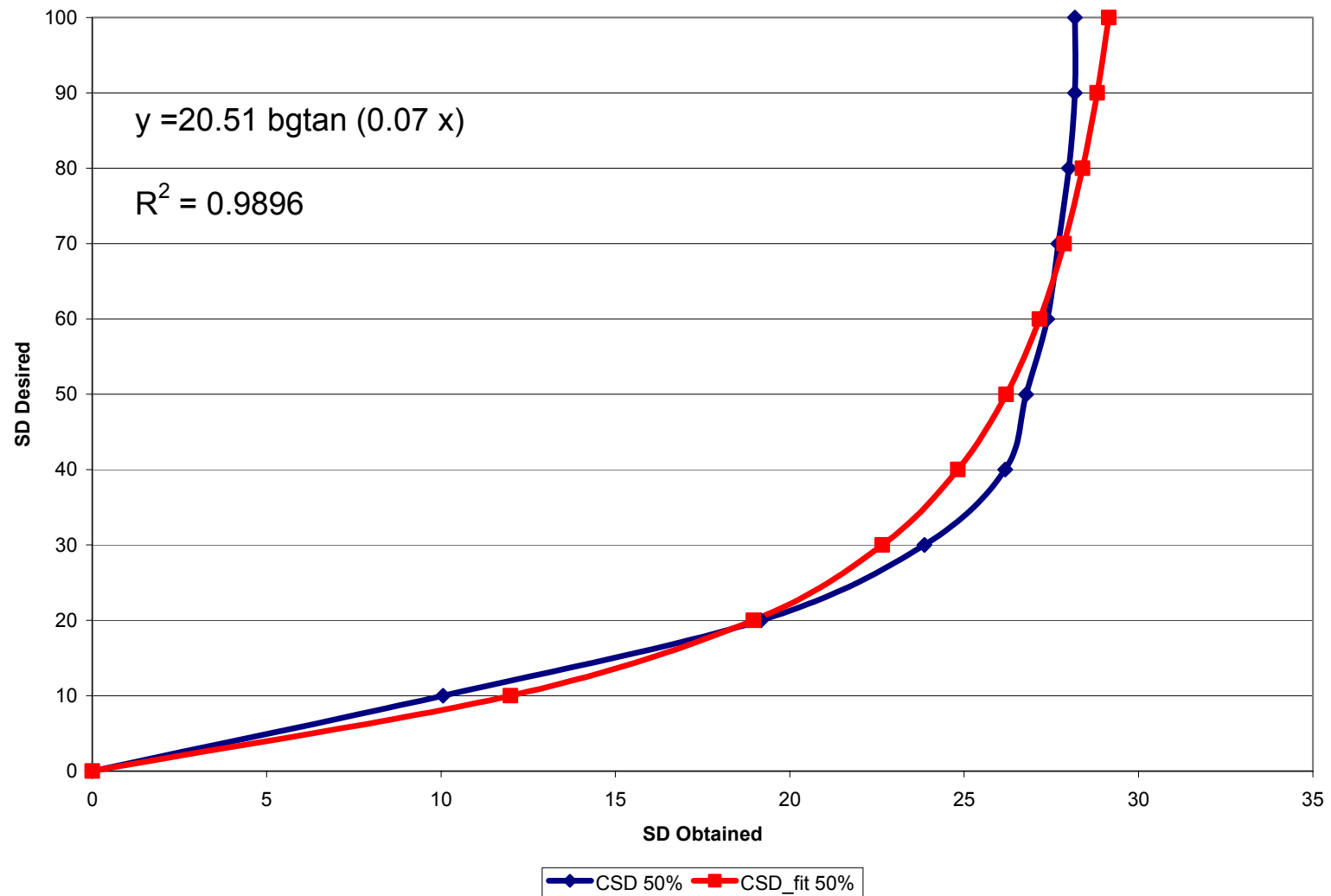


Figure A.7: Correction factor for 50% delta

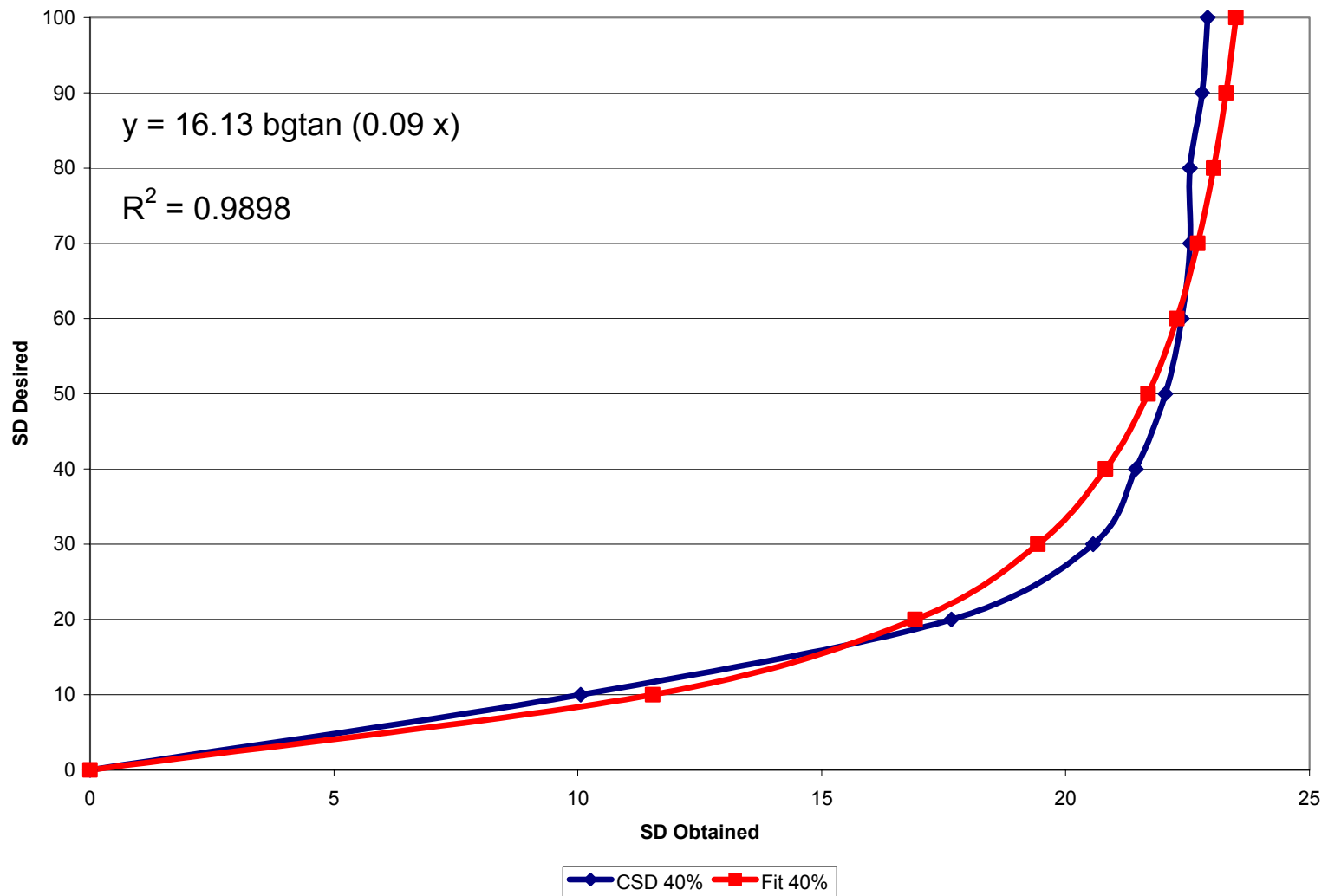


Figure A. 8: Correction factor for 40% delta

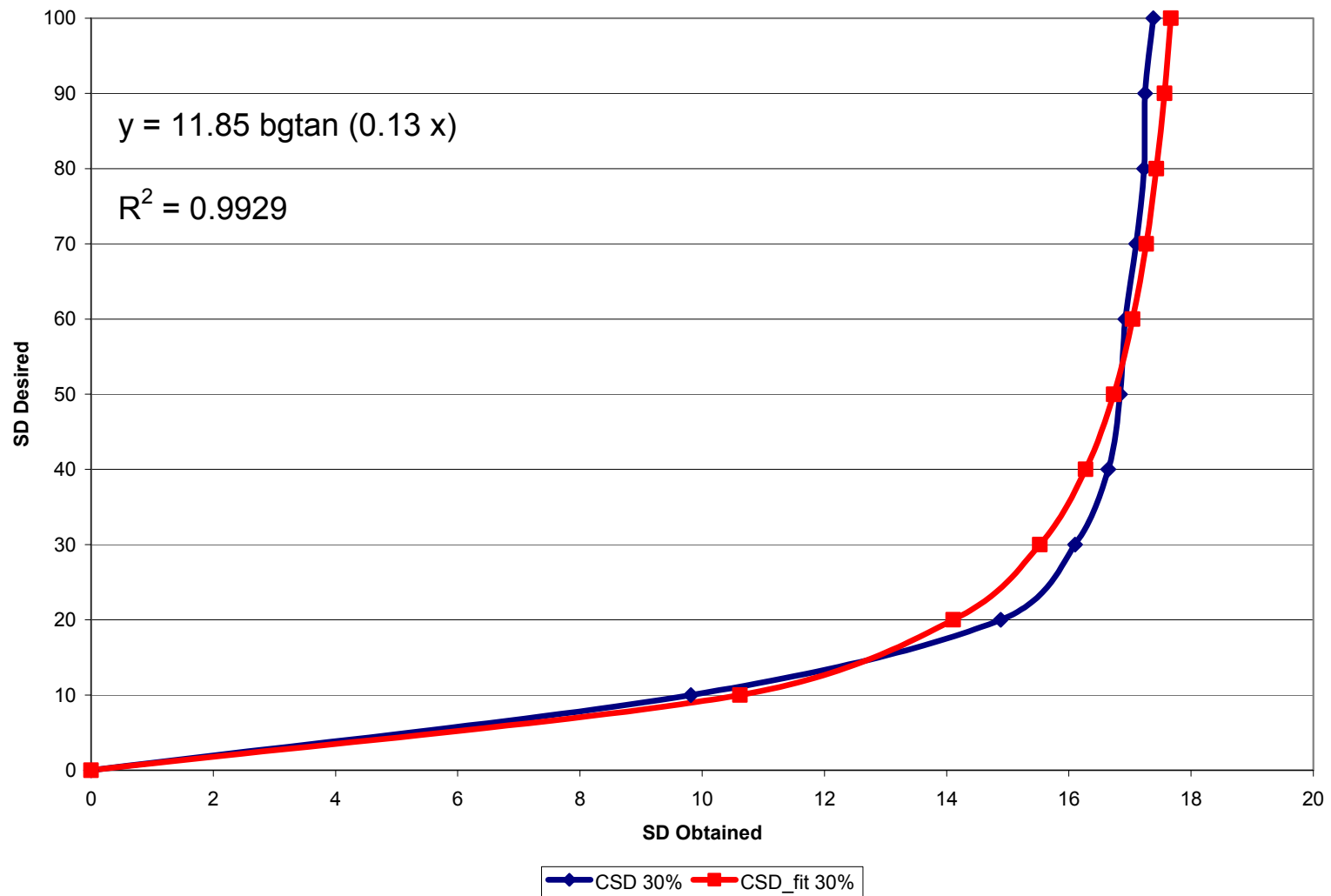


Figure A. 9: Correction factor for 30% delta

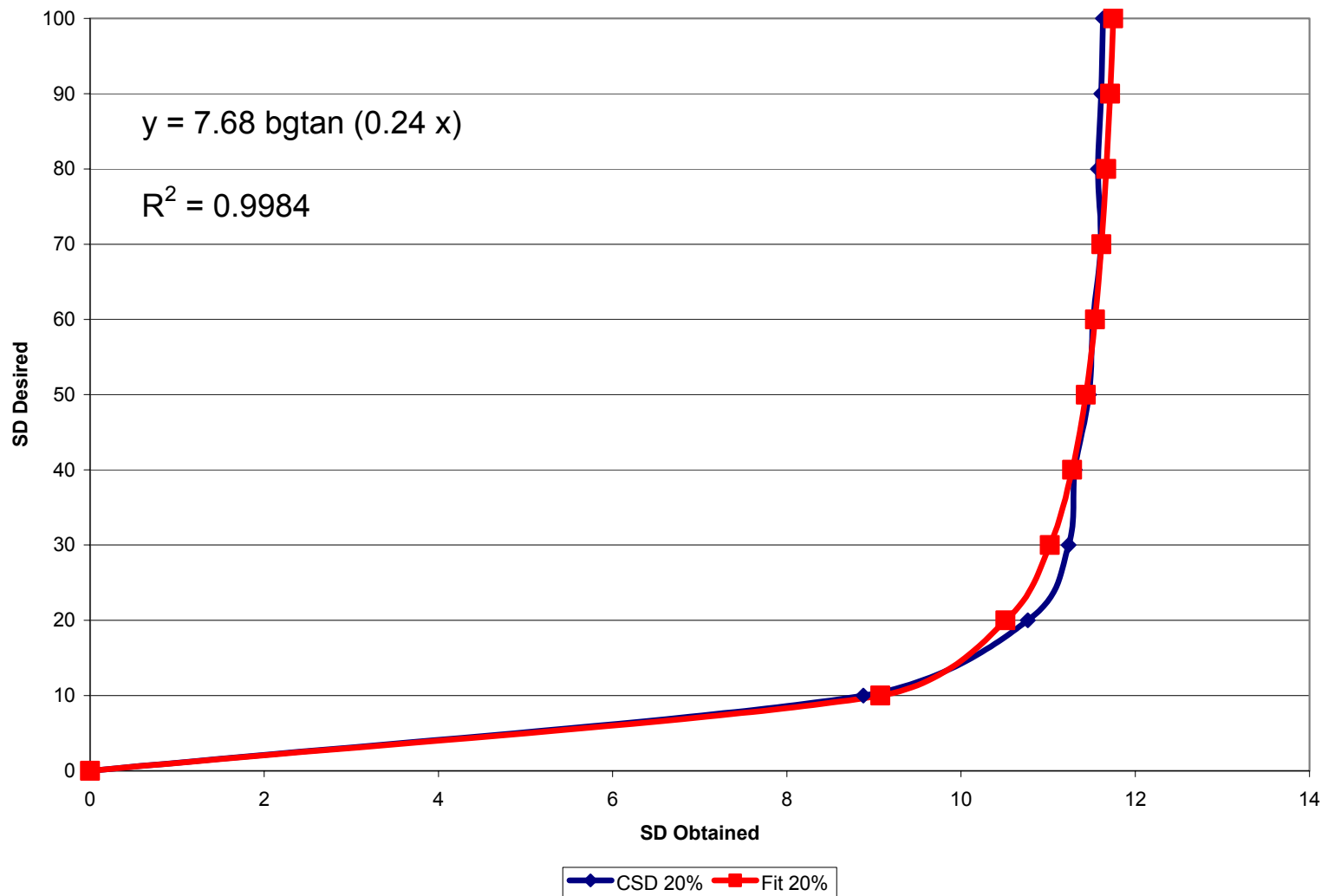


Figure A. 10: Correction factor for 20% delta

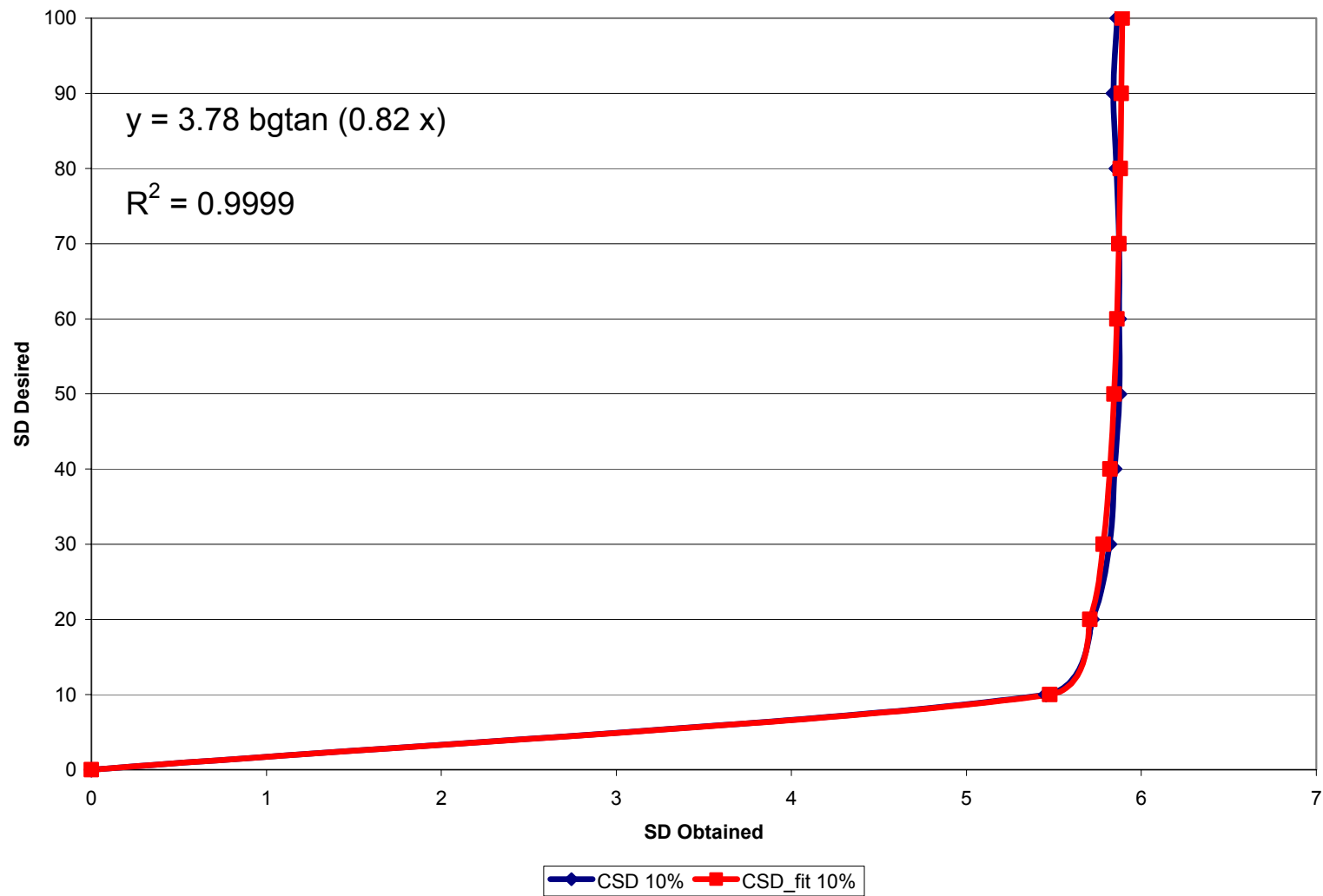


Figure A. 11: Correction factor for 10% delta

A.2 MAXIMUM STANDARD DEVIATION CORRECTION

This was done in the same way as with the SD correction. This value shows the maximum value of the SD for a certain delta.

Delta	Delta	SD Max	Max Fit	Least Square	A	B			arcTAN (B x Delta)	B x Delta
0	0.1	0.00	0.00	0.00	70.38	0.01	a_0	-331.14	0.00	0.00
10	0.1	5.86	7.16	1.69	70.38	0.01	a_1	3976.33	0.10	0.10
20	0.1	11.63	14.18	6.49	70.38	0.01	a_2	387.04	0.20	0.20
30	0.1	17.38	20.92	12.51	70.38	0.01	a_3	16.85	0.30	0.31
40	0.1	22.91	27.29	19.18	70.38	0.01	b_0	-23.08	0.39	0.41
50	0.1	28.18	33.22	25.45	70.38	0.01	b_1	209.69	0.47	0.51
60	0.1	33.56	38.68	26.31	70.38	0.01	b_2	215.17	0.55	0.61
70	0.1	38.98	43.67	22.05	70.38	0.01	b_3	-28.65	0.62	0.71
80	0.1	44.04	48.21	17.38	70.38	0.01			0.68	0.82
90	0.1	48.48	52.31	14.67	70.38	0.01			0.74	0.92
100	0.1	53.40	56.01	6.80	70.38	0.01			0.80	1.02
150	0.1	74.17	69.84	18.74	70.38	0.01			0.99	1.53
200	0.1	87.81	78.51	86.57	70.38	0.01			1.12	2.04
300	0.1	97.32	88.35	80.51	70.38	0.01			1.26	3.06
5000	0.1	525.43	520.15	27.91	-331.14	-23.08			-1.57	-115407.98
			Min	366.24						

Table A. 2: Least square calculations for maximum standard deviation

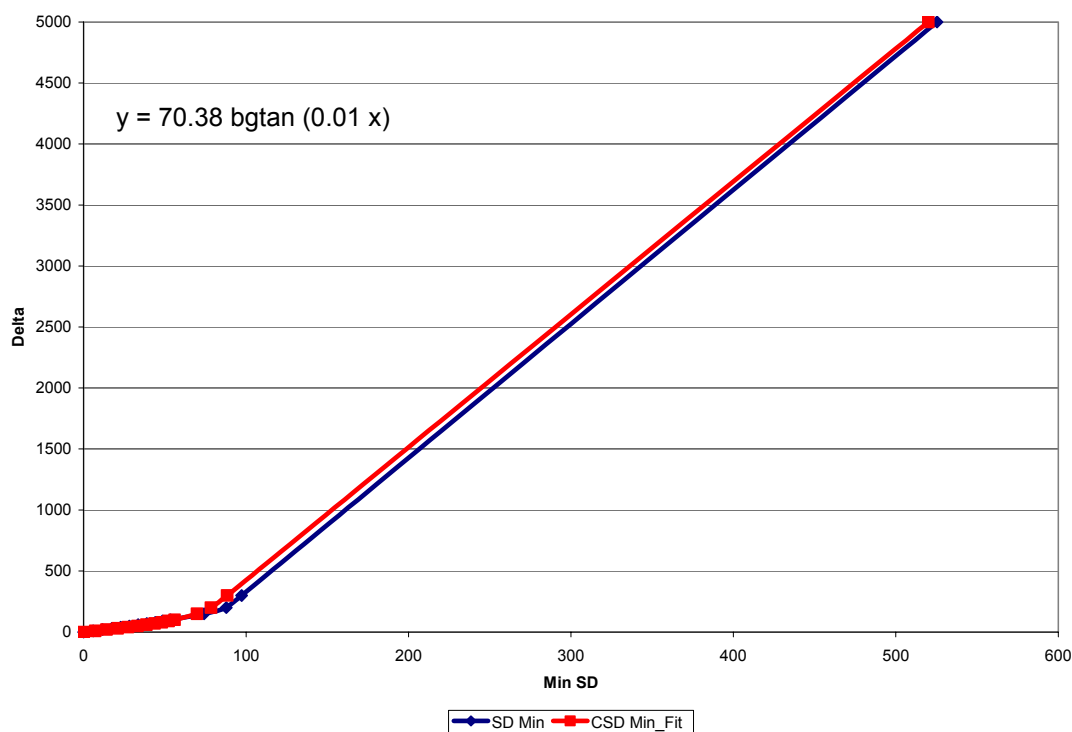


Figure A. 12: Maximum SD Correction Factor

APPENDIX B

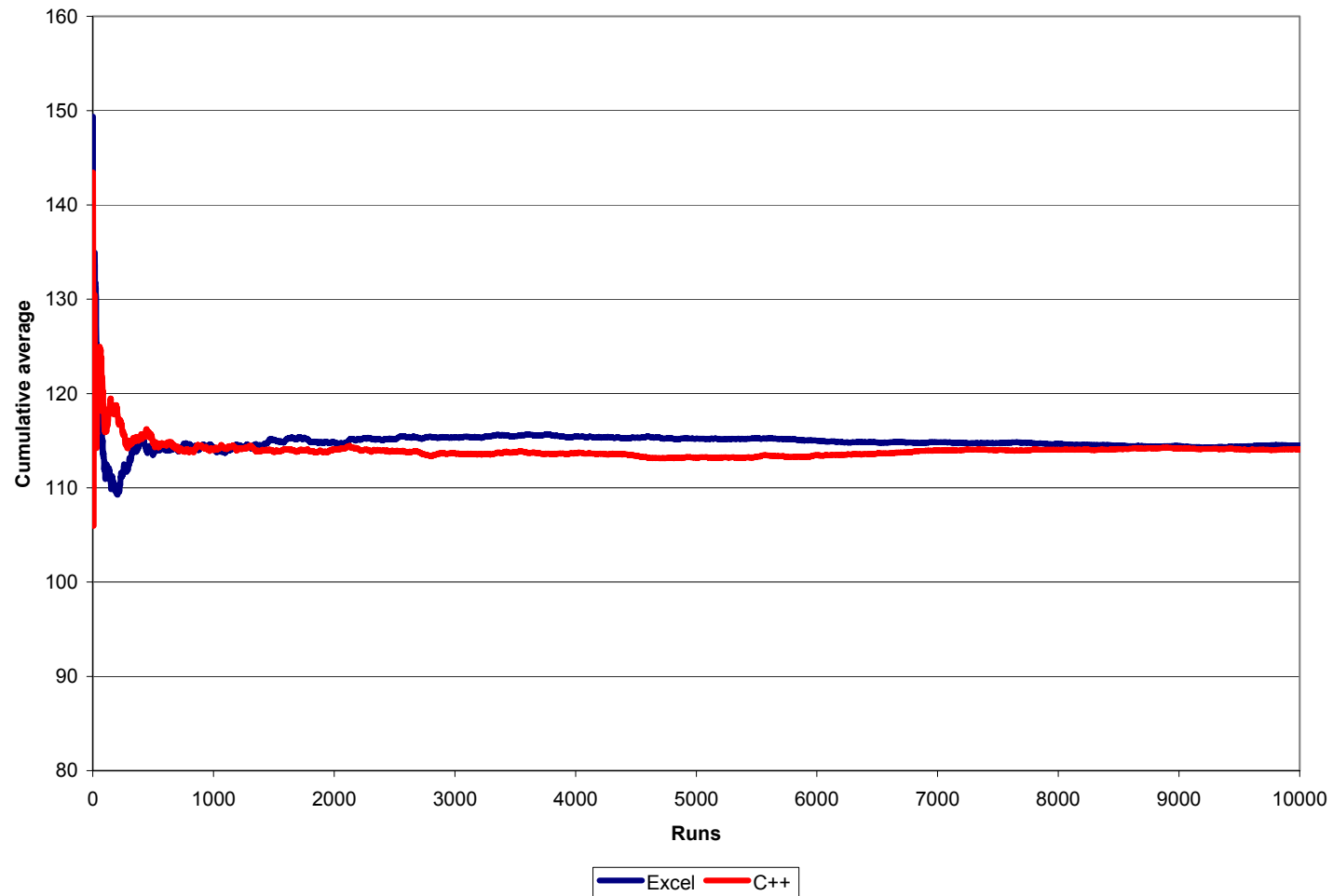
VERIFICATION AND VALIDATION RESULTS

B.1	Simulation programmes and results
B.2	Polynomial model
B.3	Chiller model
B.4	Pipe model

B.1 SIMULATION PROGRAMS AND RESULTS

The C++ as well as the Excel programmes is included on the attached CD. The following are the results of the three different models that were not shown in Chapter 4. Due to the large number of runs conducted, only plots of the data will be reflected in this appendix. All the relevant data is included in the attached CD. For each programme the following plots will be shown:

- Cumulative average plot (Figure B.1, Figure B. 5, Figure B. 6 and Figure B. 12)
- Cumulative standard deviation plot (Figure B.2, Figure B. 7, Figure B. 8 and Figure B. 14)
- Standard deviation of EPSILON plot (Figure B. 3, Figure B. 9, Figure B. 14)
- Comparison of ten sensitivity analyses (Figure B. 4, Figure B. 10, Figure B. 11 and Figure B. 15)

B.2 POLYNOMIAL MODEL**Figure B.1:** Verification plot of cumulative average for polynomial model

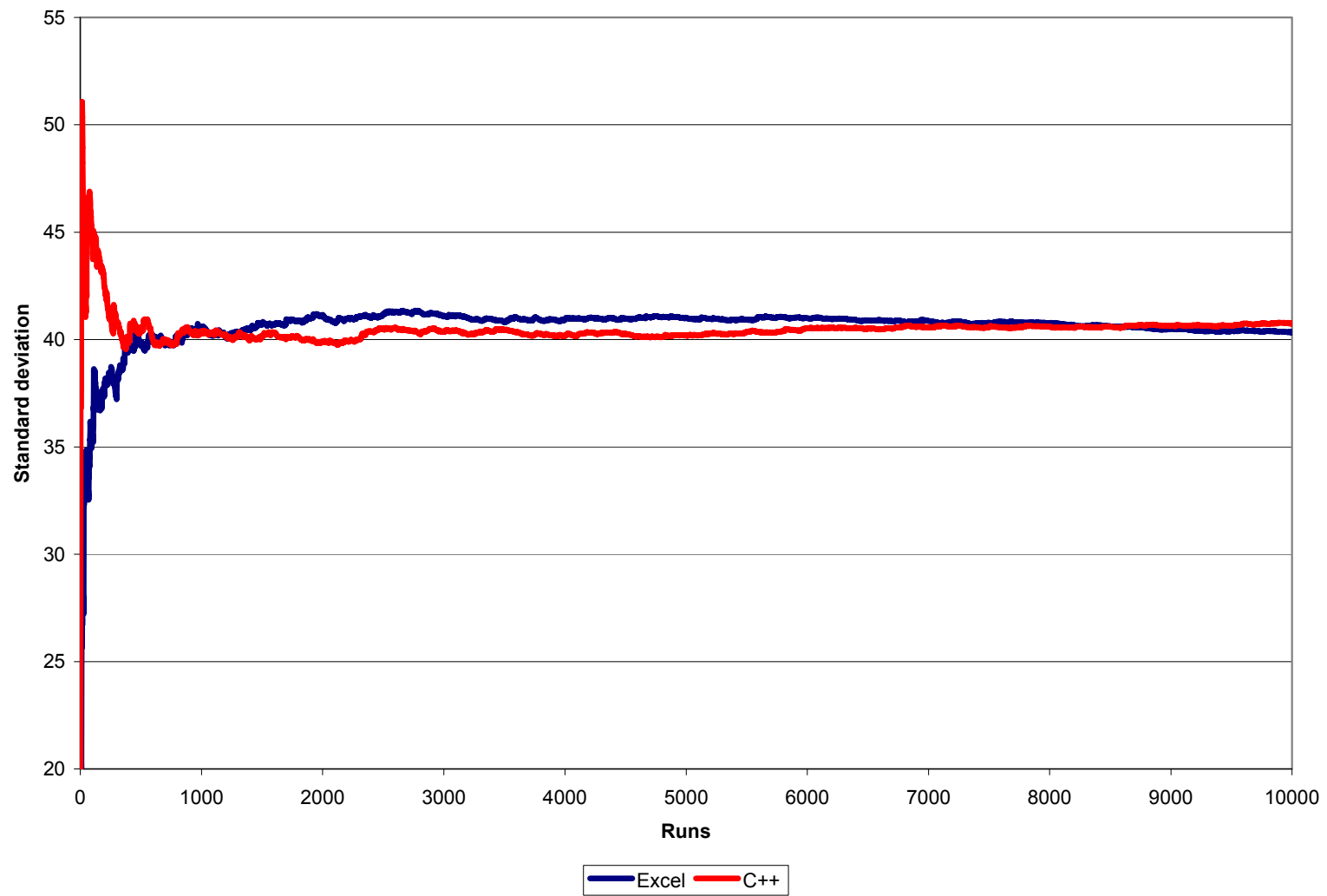


Figure B.2: Verification plot of cumulative standard deviation for polynomial model

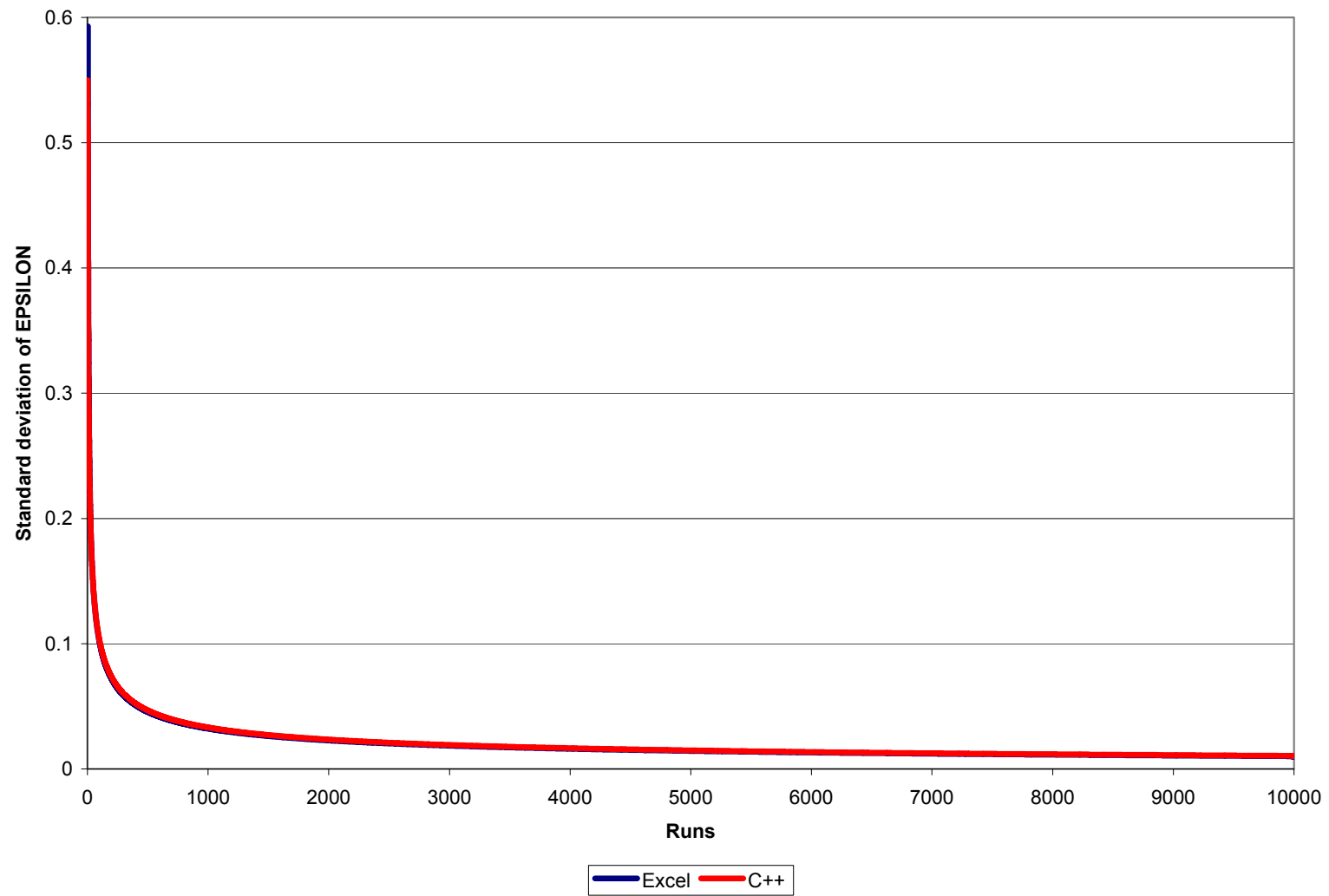


Figure B. 3: Verification plot of standard deviation of EPSILON for polynomial model

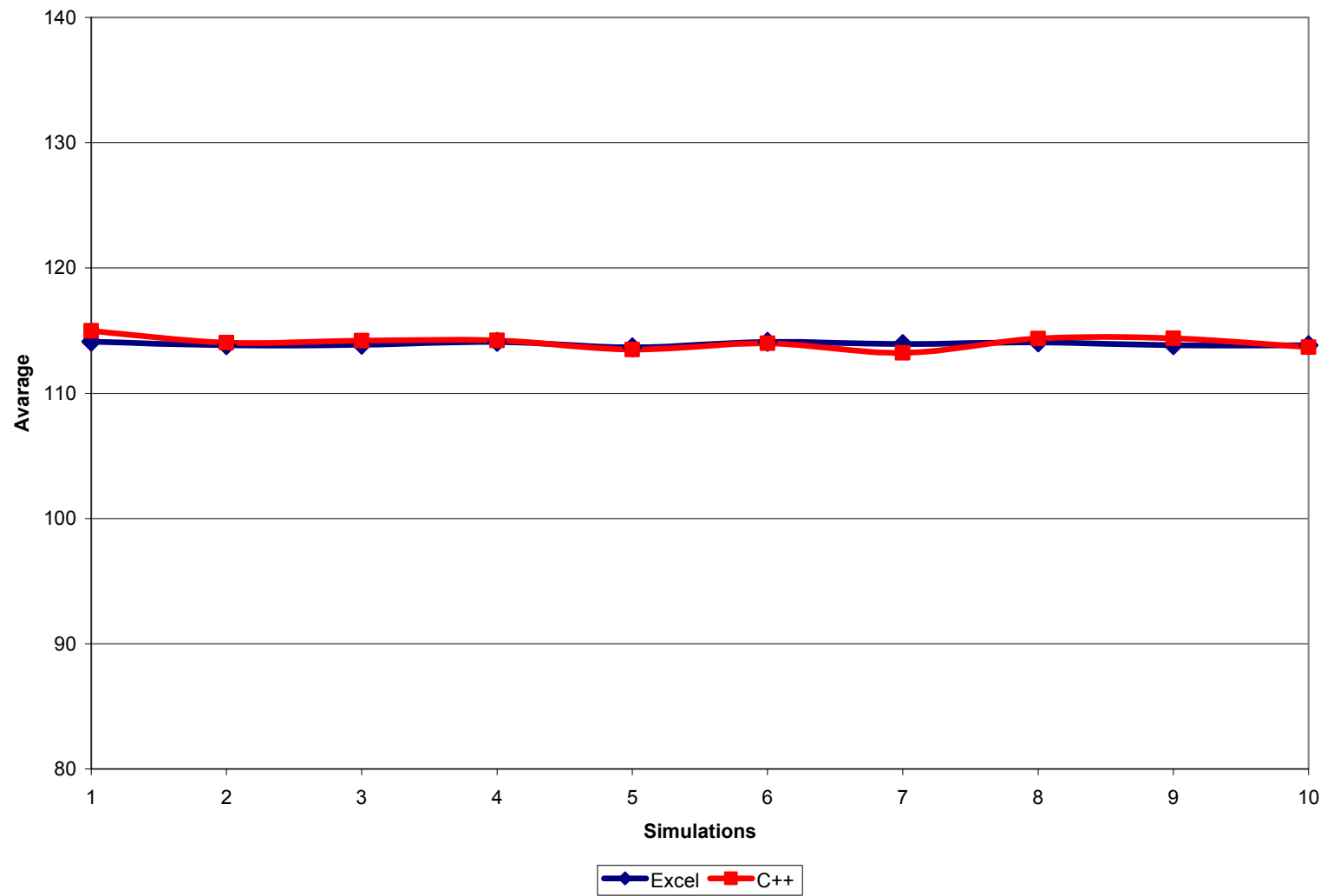


Figure B. 4: Comparison plot for 10 runs of the sensitivity analysis for the polynomial model in Excel and C++

B.3 CHILLER MODEL

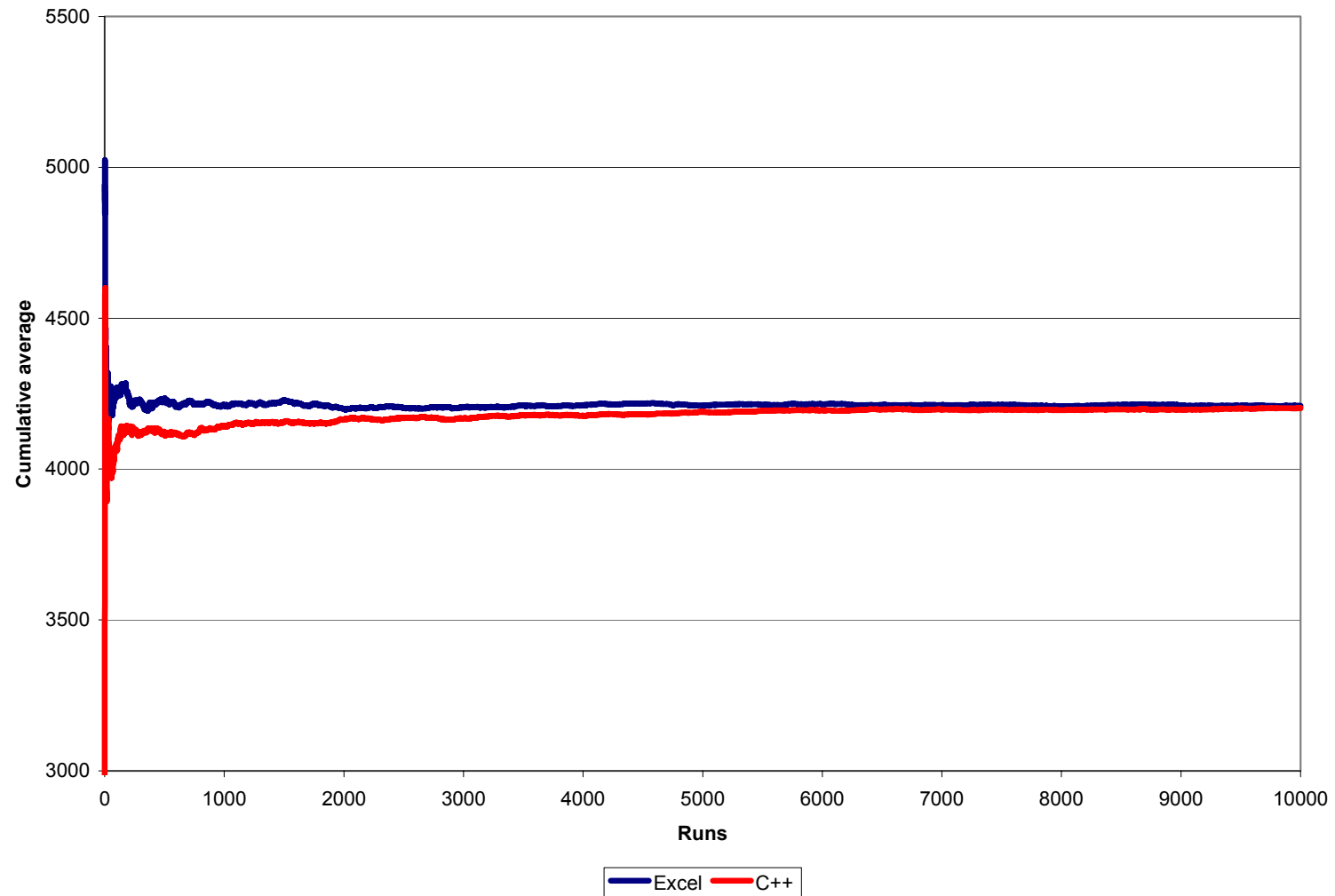


Figure B. 5: Verification plot of cumulative average of variable Q for Chiller model

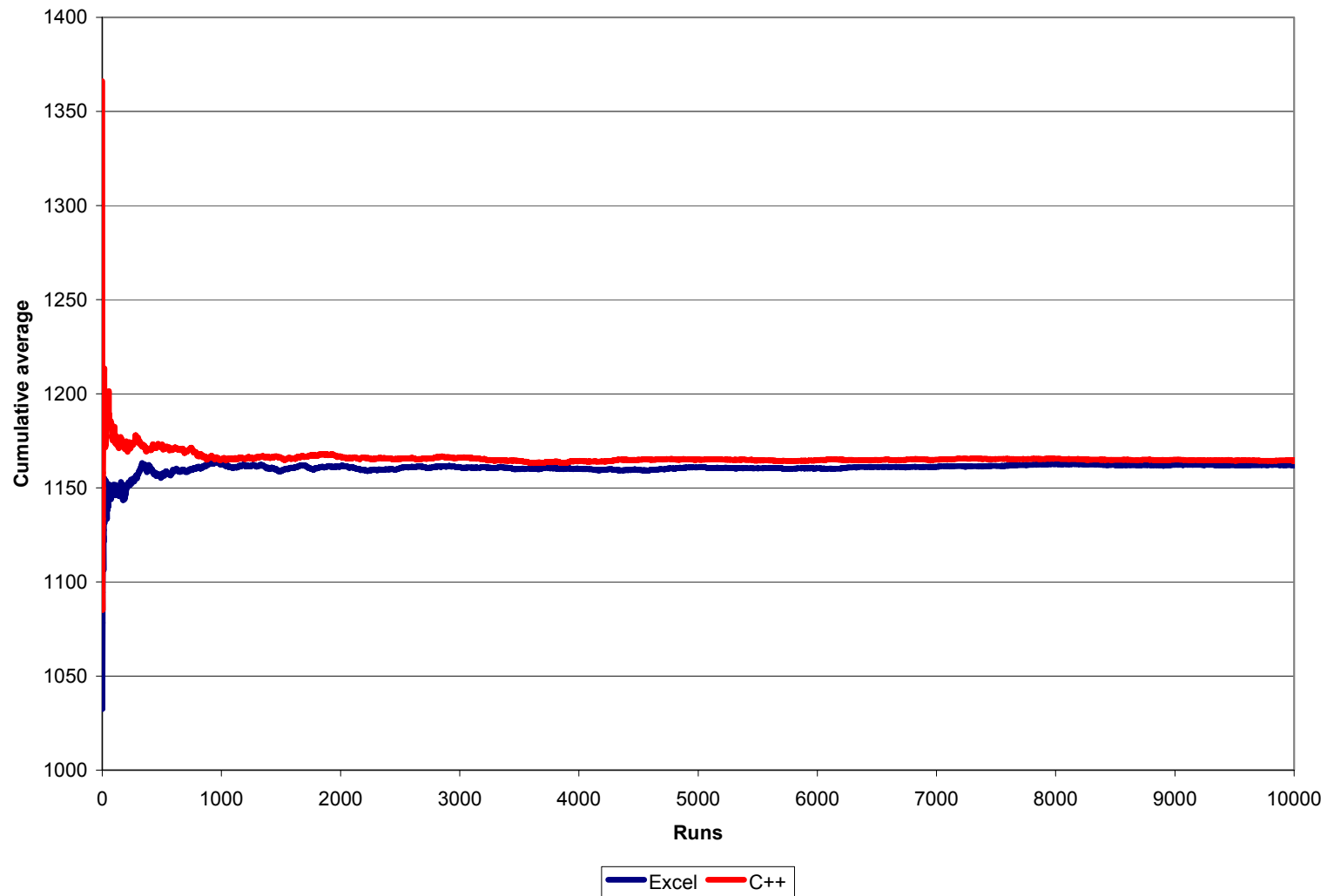


Figure B. 6: Verification plot of cumulative average of variable P for Chiller model

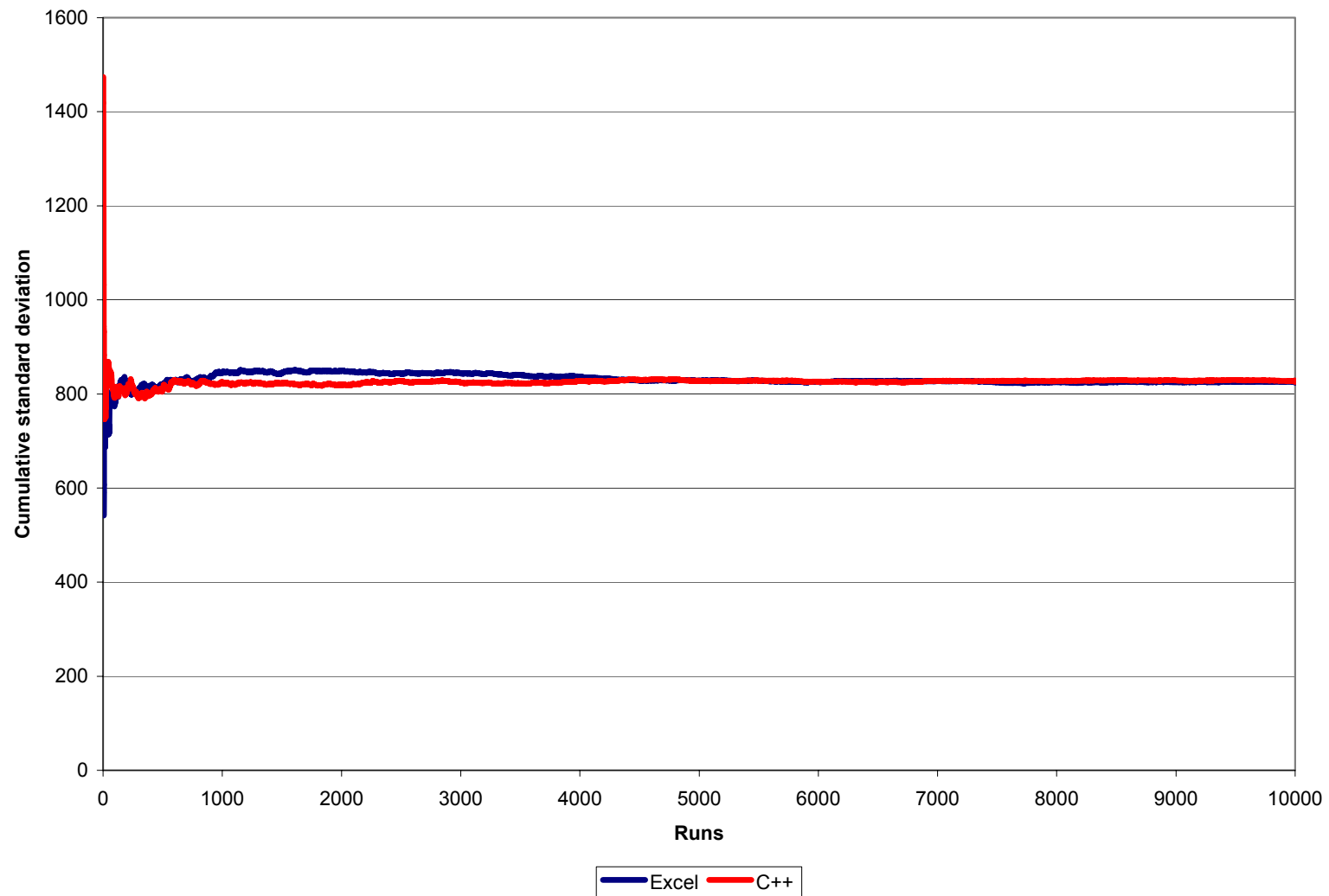


Figure B. 7: Verification plot of cumulative standard deviation of variable Q for Chiller model

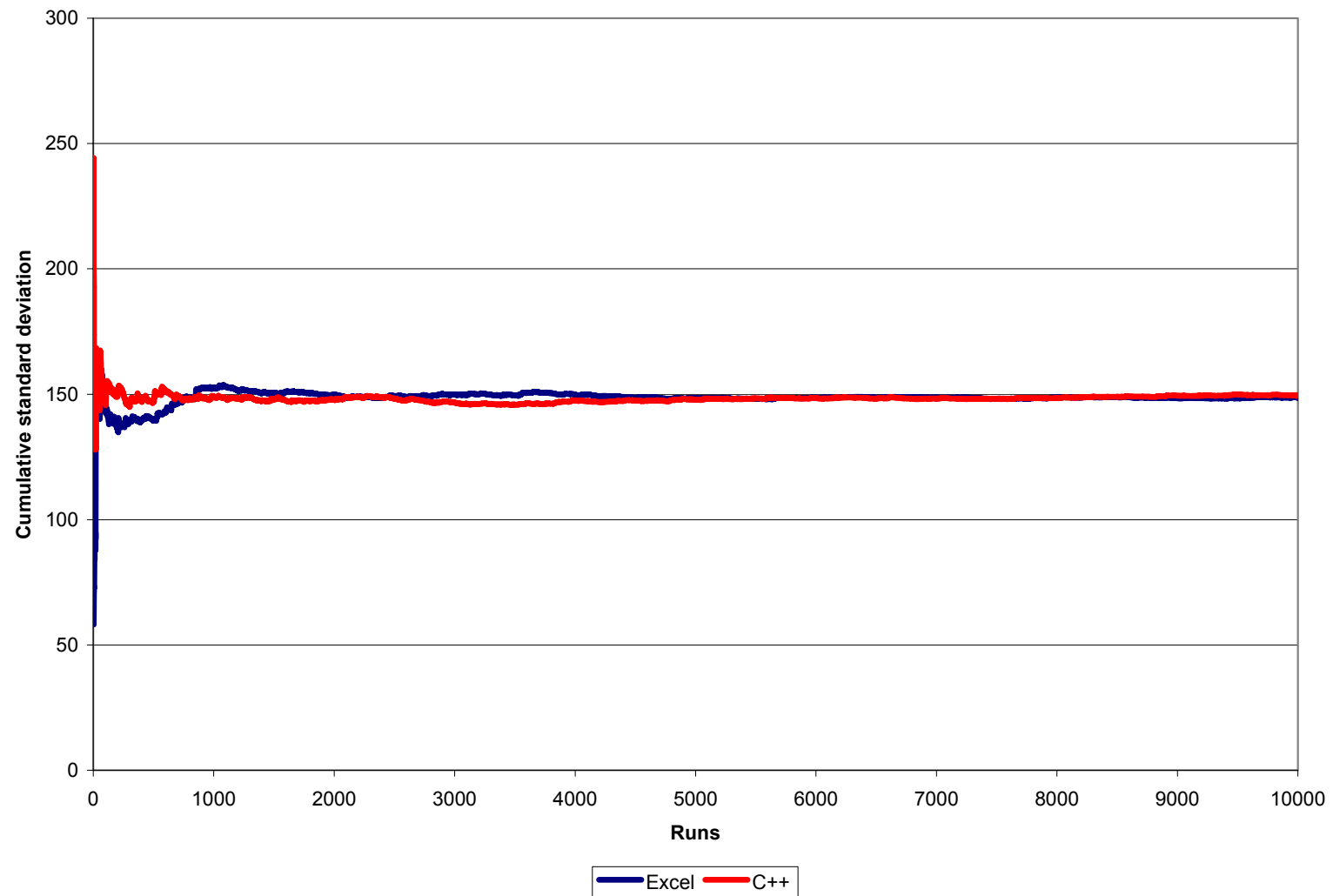


Figure B. 8: Verification plot of cumulative standard deviation of variable P for Chiller model

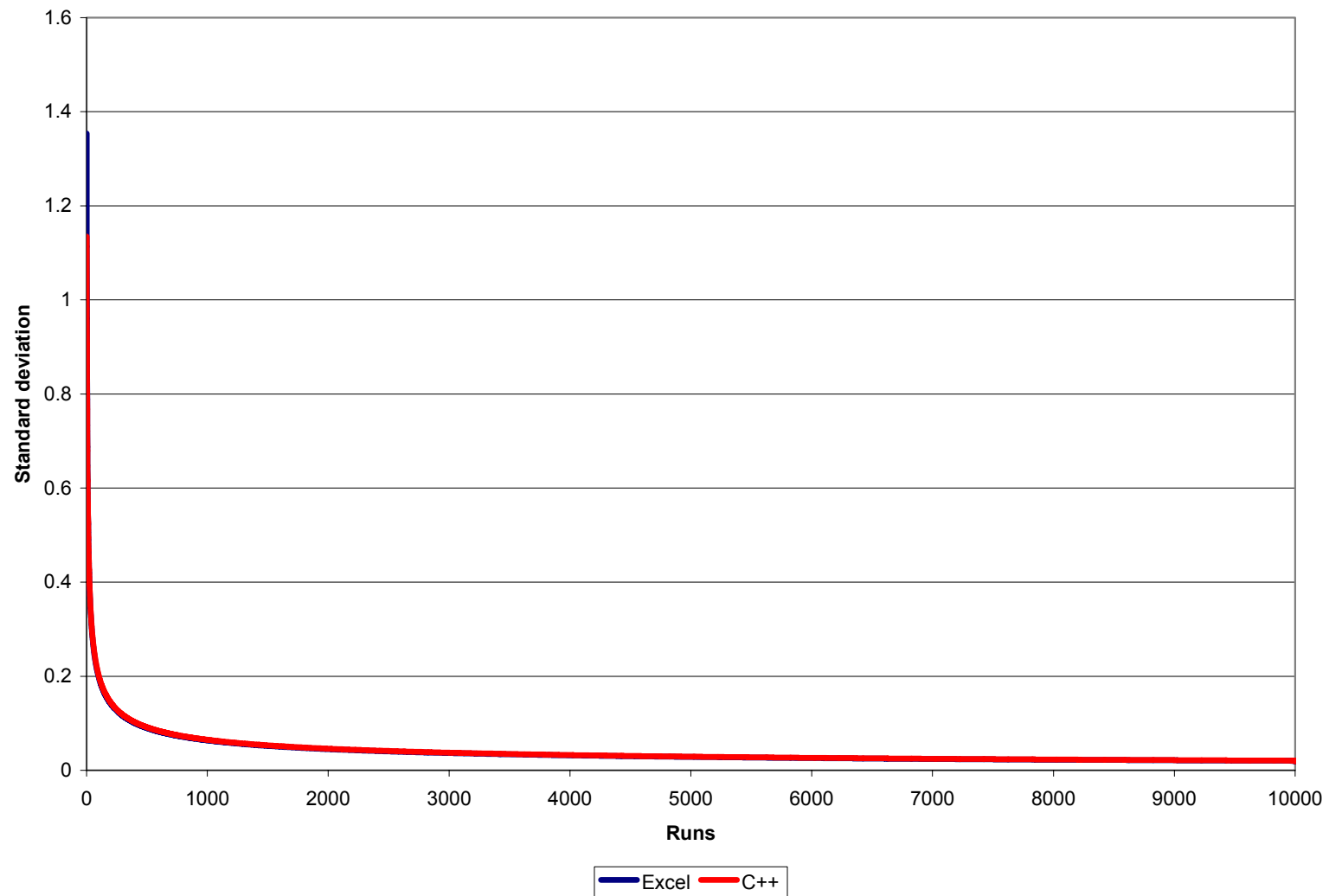


Figure B. 9: Verification plot of standard deviation of EPSILON for Chiller model

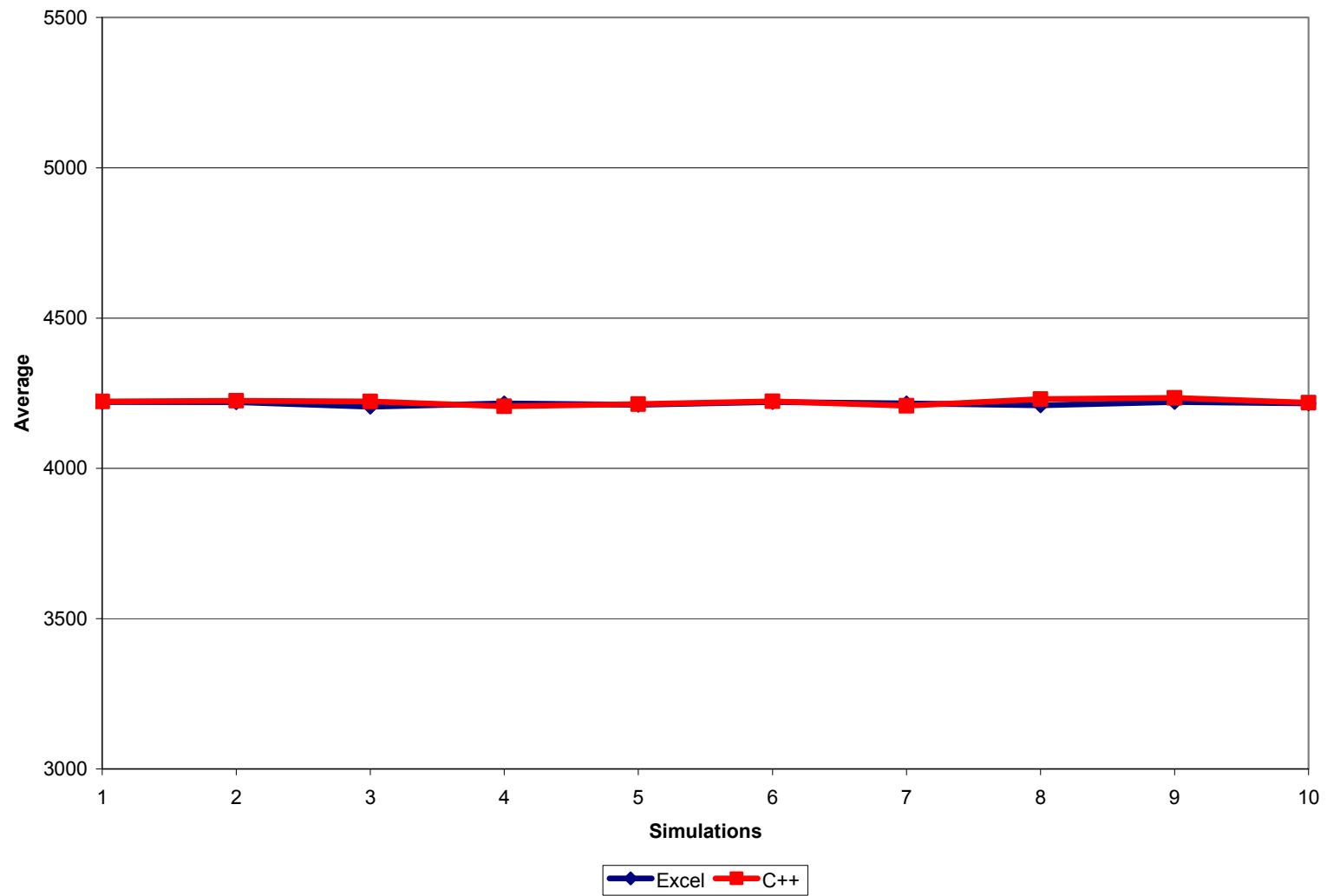


Figure B. 10: Comparison plot of variable Q for 10 runs of the sensitivity analysis for the Chiller model

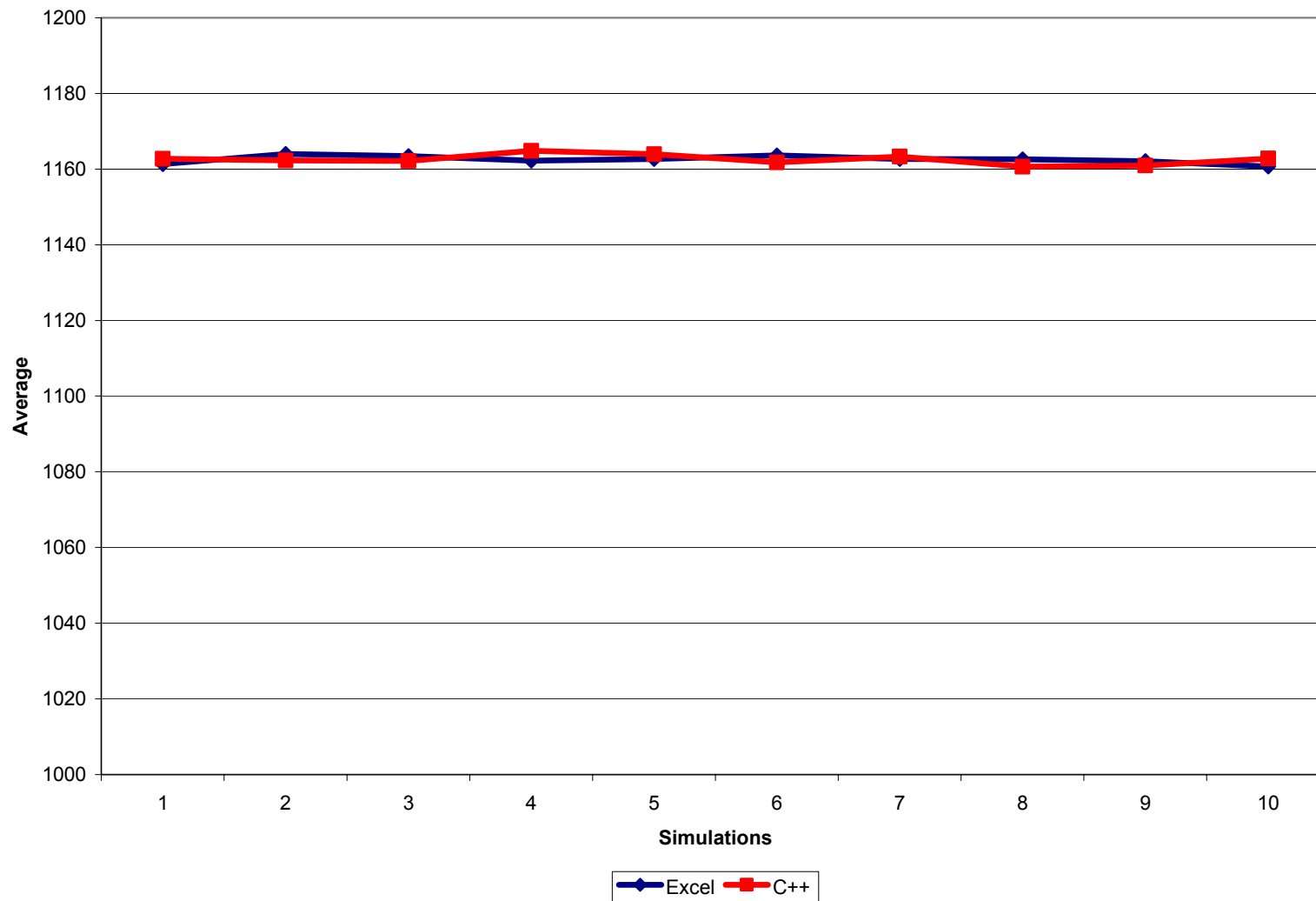


Figure B. 11: Comparison plot of variable P for 10 runs of the sensitivity analysis for the Chiller model

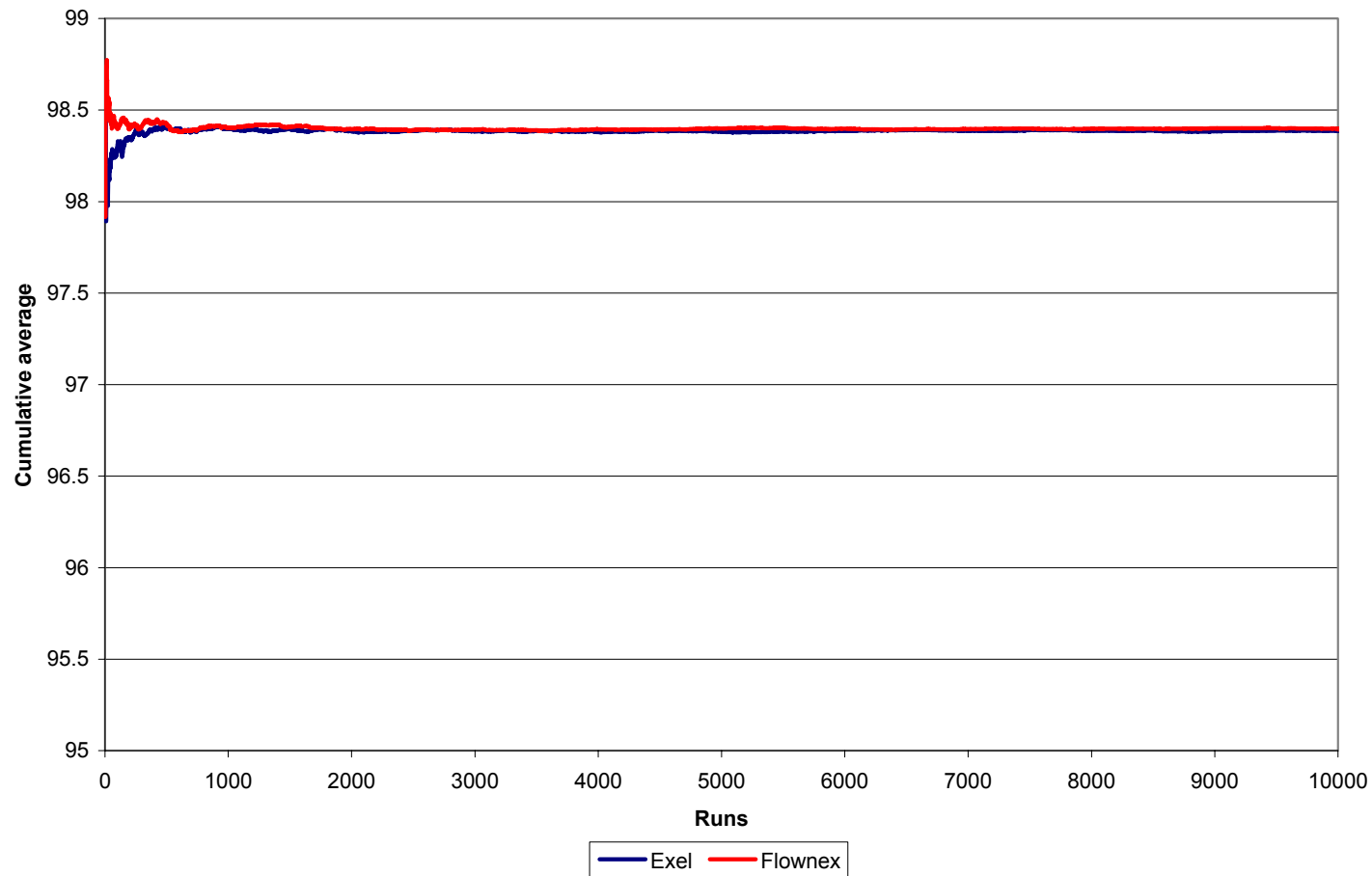
B.4 PIPE MODEL

Figure B. 12: Verification plot of cumulative average of outlet pressure for the pipe model

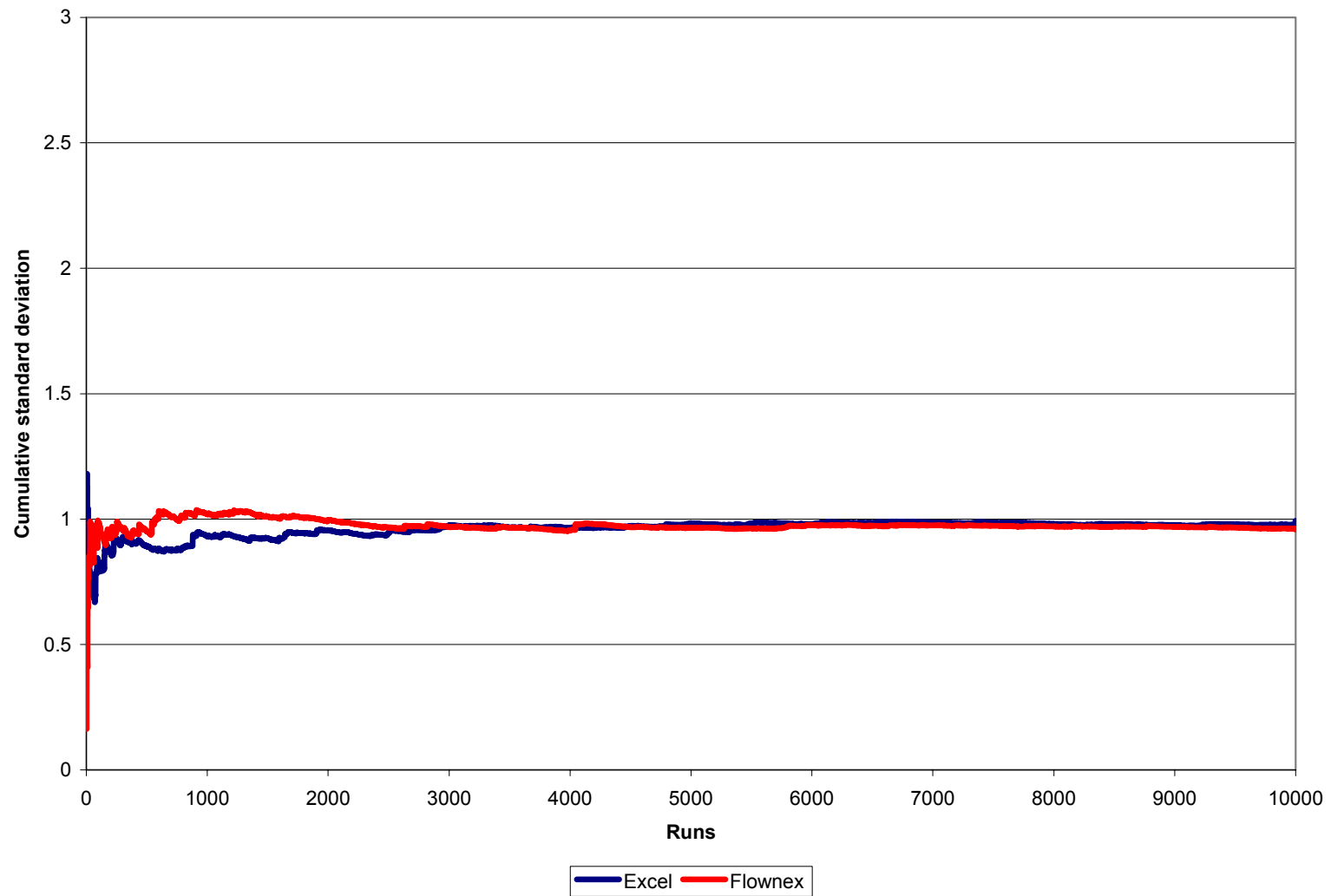


Figure B. 13: Verification plot of cumulative standard deviation of outlet pressure for the pipe model

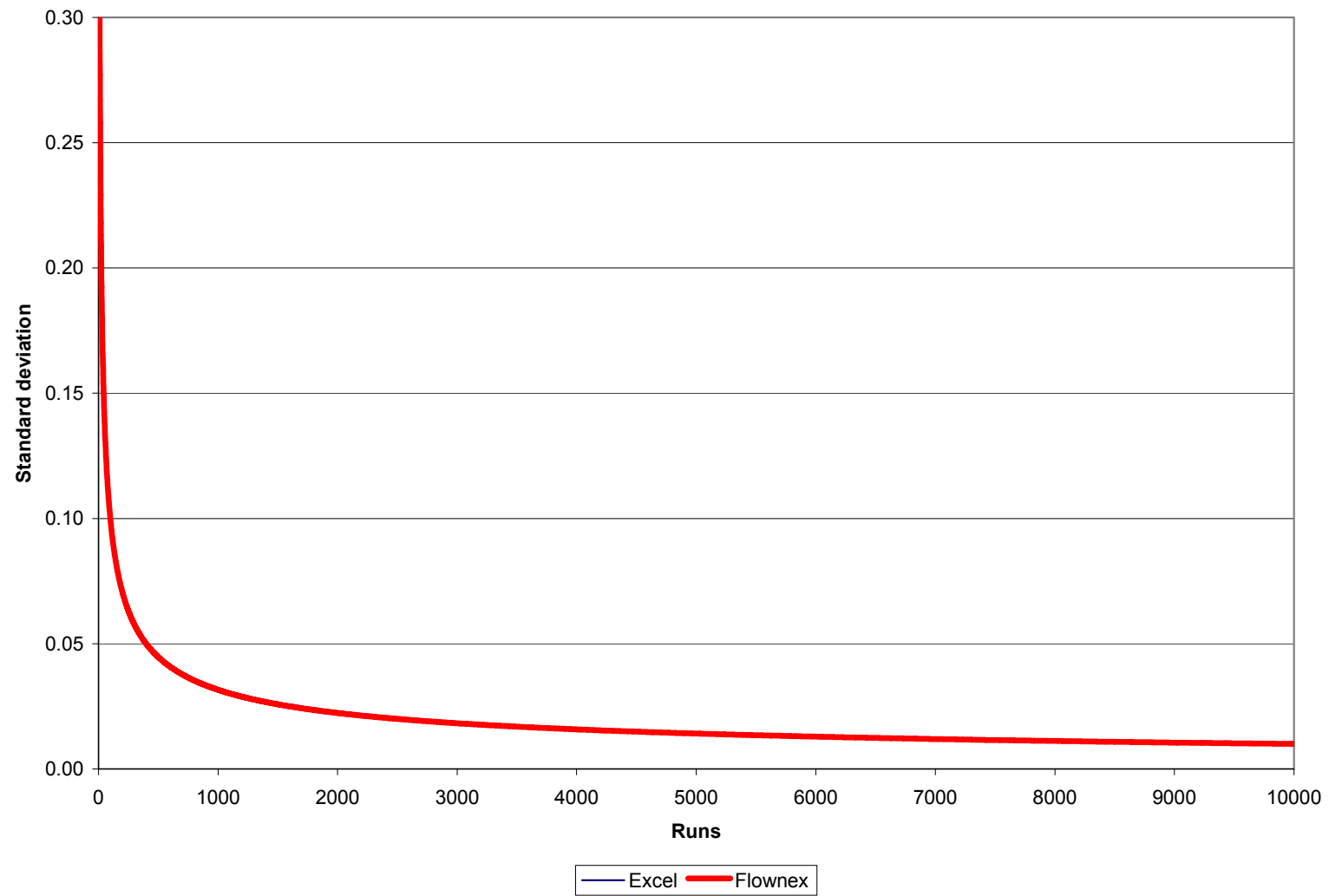


Figure B. 14: Verification plot of standard deviation of EPSILON for the pipe model

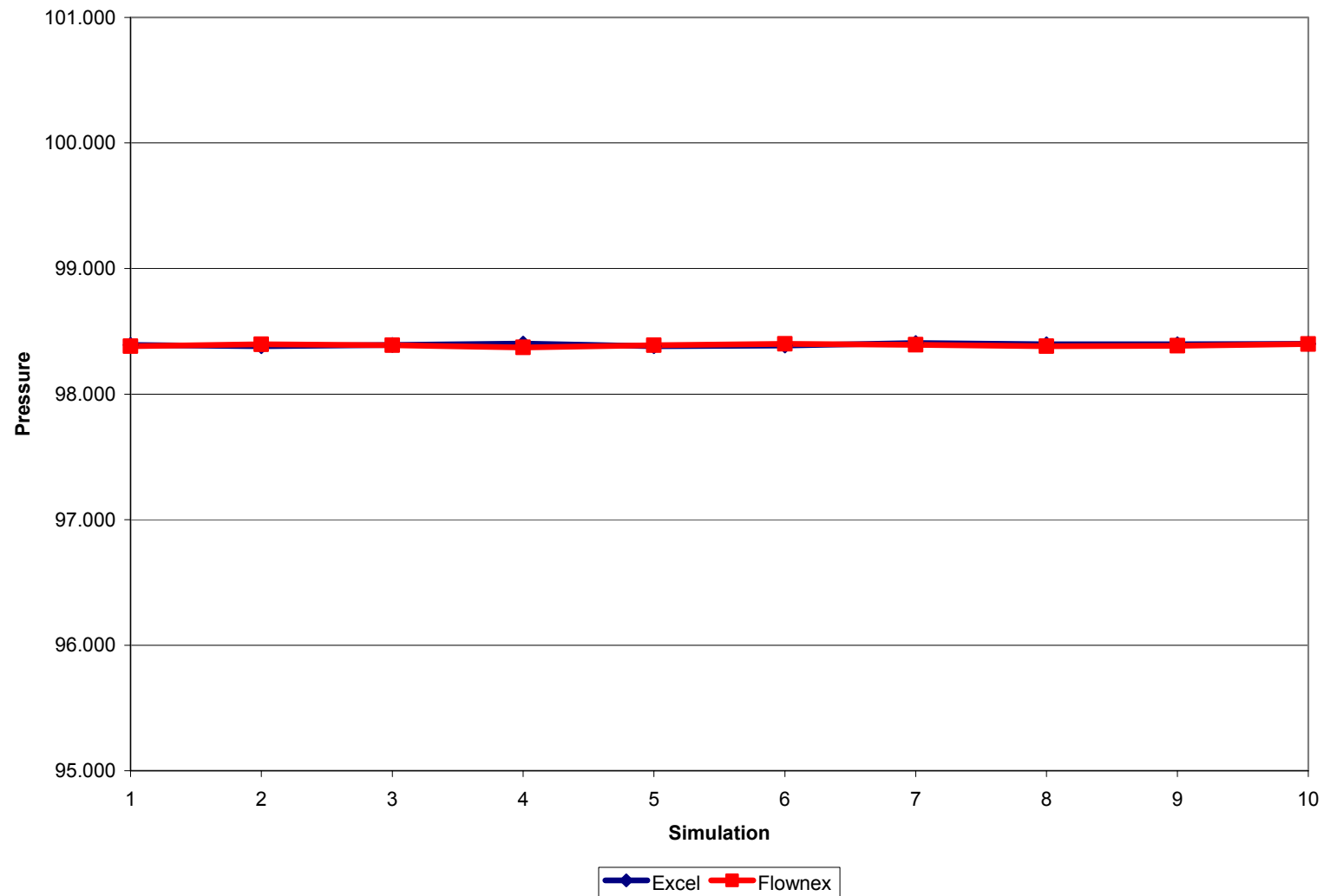


Figure B. 15: Comparison plot of outlet pressure for 10 runs of the sensitivity analysis for the pipe model in Excel and Flownex

APPENDIX C***PBMM DATA PACK***

An extract of the data pack for the PBMR micro model that consist of all the necessary data to simulate the PBMM are given in this appendix.



1. Introduction

The Pebble Bed Micro Model (PBMM) is a full functional model of the Power Conversion Unit (PCU) of the Pebble Bed Modular Reactor (PBMR), a new type of high temperature gas-cooled nuclear power plant currently under development in South Africa.

This unique type of power plant is based on the well-known Brayton power cycle (used in aircraft engines) but with the following distinguishing features.

- It uses nitrogen as the working fluid.
- The gas moves around in a closed circuit, which implies that no nitrogen is consumed in the power generation process – it merely acts as an energy carrier.
- Use of three separate shafts, one for the high pressure (HP) compressor/turbine pair, one for the low pressure (LP) compressor/turbine pair and one for the power turbine and generator. This allows the HP and LP compressor/turbine pairs to run at high speeds thereby reducing the size and therefore also the cost of the machines.
- Use of a recuperator to recover heat that would otherwise have been rejected to atmosphere. The recovered heat is transferred elsewhere in the system thereby reducing the heat required in the nuclear reactor and ultimately increasing the thermal efficiency of the plant.

2. Layout of PBMM

Description of PBMM cycle

A schematic layout of the PBMM power conversion cycle is shown in Figure 1. Starting at 10, nitrogen at a relatively low pressure and temperature is compressed by a low-pressure compressor (LPC) to an intermediate pressure (11) after which it is cooled in an intercooler to state 21. A high-pressure compressor (HPC) then compresses the nitrogen to state 31. From 40 to 41 the nitrogen is preheated in the recuperator before entering the heat source, which heats the nitrogen to state 52. After the heat source the hot high-pressure nitrogen is expanded in a high-pressure turbine (HPT) to state 61 after which it is further expanded in a low-pressure turbine (LPT) to state 71. The high-pressure turbine drives the high-pressure compressor while the low-pressure turbine drives the low-pressure compressor. After the low pressure turbine the nitrogen is further expanded in the power turbine to pressure 81. From 90 to 91 the still hot nitrogen is cooled in the recuperator after which it is further cooled in the pre-cooler to state 101. This completes the cycle. The heat rejected from 90 to 91 is equal to the heat transferred to the nitrogen from 40 to 41.

Although the system layout of the PBMM closely resembles that of the PBMR plant, it is important to highlight the following differences:

- The PBMM uses nitrogen instead of helium as the working fluid. This does not subtract from the objective of the project, which is not to address specific issues related to the use of helium as the working fluid but to develop a system that will have the same overall characteristics as that of the prototype plant.



3. Component Data

3.1 MAJOR COMPONENTS

Table 1: Major component description

Number	Symbol	Description	Section in Document
10 - 11	LPC	Low Pressure Compressor	Section 7.6
20 - 21	IC	Inter Cooler	Section 8
30 - 31	HPC	High Pressure Compressor	Section 7.7
40 - 41	RX HP	Recuperator - High pressure side	Section 8
42 - 52	HS	Heat Source	Section 9
60 - 61	HPT	High Pressure Turbine	Section 7.11
70 - 71	LPT	Low Pressure Turbine	Section 7.10
80 - 81	PT	Power Turbine	Section 7.12
90 - 91	RX LP	Recuperator - Low pressure side	Section 8
100 - 101	PC	Pre Cooler	Section 8
200 - 201	ELC	External Load compressor	Section 7.8
207 - 208	ELHX	External load heat exchanger	Section 8
600 - 601	SBS	Start-up Blower System	Section 7.9

3.2 PIPE RUNS

No lengths are given for the fittings as these lengths are included in the total pipe length. The type of fitting is given to assist the reader to calculate an appropriate loss coefficient as well as the flow path length. Also note that a smooth reducer is used where two pipes with different diameters are joined.

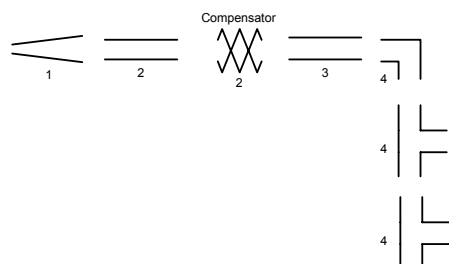


Figure 2: Schematic representation of pipe run 11 - 20

Pipe Run	#	Component	Dimensions	Value
11 - 20	1	Diffuser	Length [m] Inlet Diameter [m] Outlet diameter [m]	0.7 0.07 0.15405
	2	Pipe	Length [m] Diameter [m] Fittings	0.4782 0.15405 Compensator with L =185 mm with no inner lining.
	3	Pipe	Length [m] Diameter [m] Fittings	0.2624 0.15405 None
	4	Pipe	Length [m] Diameter [m] Fittings	1.32 0.20272 Long radius 90 ° Bend 2 x T-piece through flow

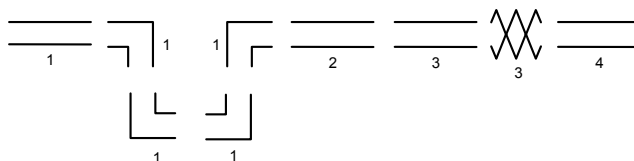


Figure 3: Schematic representation of pipe run 21 – 30

Pipe Run	#	Component	Dimensions	Value
21 - 30	1	Pipe	Length [m] Diameter [m] Fittings	8.321 0.20272 4 x Long radius 90 ° Bends
	2	Pipe	Length [m] Diameter [m] Fittings	0.4324 0.15405 None
	3	Pipe	Length [m] Diameter [m] Fittings	0.592 0.15405 Compensator with L =185 mm with no inner lining.
	4	Pipe	Length [m] Diameter [m] Fittings	1.4729 0.10676 None

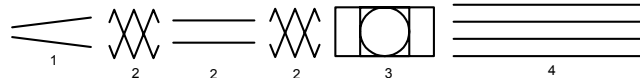


Figure 4: Schematic representation of pipe run 31- 40

Pipe Run	#	Component	Dimensions	Value
31 - 40	1	Diffuser	Length [m] Inlet Diameter [m] Outlet diameter [m]	0.37 0.069 0.15405
	2	Pipe	Length [m] Diameter [m] Fittings	0.65 0.15405 2 x Compensator with L =185 mm with no inner lining.
	3	Filter	Length [m] Diameter [m] $\Delta P = k\rho Q^2$	0.5 0.179 k = 2
	4	Annulus	Outer Diameter [m] Inner Diameter [m] Fittings	0.9 0.8 None

Note: That the annulus is the area between the recuperator and the pressure boundary. Volume 33 is given in Section 6.3.

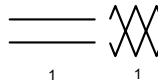


Figure 5: Schematic representation of pipe run 41 – 42

Pipe Run	#	Component	Dimensions	Value
41 - 42	1	Pipe	Length [m] Diameter [m] Fittings	0.588 0.20272 Compensator with L =185 mm with no inner lining.



Figure 6: Schematic representation of pipe run 52 – 60

Pipe Run	#	Component	Dimensions	Value
52 – 60	1	Pipe	Length [m] Diameter [m] Fittings	0.588 0.20272 Compensator with L =185 mm with no inner lining.
	2	Reducer	Length [m] Inlet Diameter [m] Outlet Diameter [m]	0.03 0.20272 0.0769

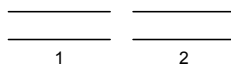


Figure 7: Schematic representation of pipe run 61 -70

Pipe Run	#	Component	Dimensions	Value
61 – 70	1	Pipe	Length [m] Diameter [m] Fittings	0.18 0.115 None
	2	Pipe	Length [m] Diameter [m] Fittings	0.01 0.0769 None

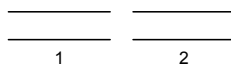


Figure 8: Schematic representation of pipe run 71 – 80

Pipe Run	#	Component	Dimensions	Value
71 – 80	1	Pipe	Length [m] Diameter [m] Fittings	0.18 0.115 None
	2	Pipe	Length [m] Diameter [m] Fittings	0.01 0.081 None

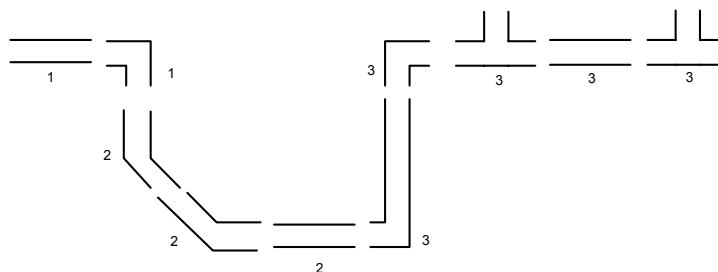


Figure 9: Schematic representation of pipe run 81 – 90

Pipe Run	#	Component	Dimensions	Value
81 – 90	1	Pipe	Length [m] Diameter [m] Fittings	1 0.15405 Long radius 90 ° Bend
	2	Pipe	Length [m] Diameter [m] Fittings	3.6312 0.20272 2 x Long radius 45° Bends
	3	Pipe	Length [m] Diameter [m] Fittings	9.013 0.20272 2 x Long radius 90 ° Bends 2 x T-piece through flow



Figure 10: Schematic representation of pipe run 91 – 100

Pipe Run	#	Component	Dimensions	Value
91 - 100	1	Pipe	Length [m] Diameter [m] Fittings	9.013 0.20272 2 x Long radius 90 ° Bends 2 x T-piece through flow

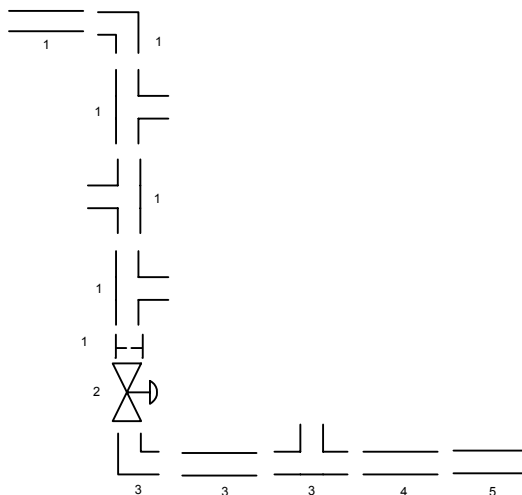


Figure 11: Schematic representation of pipe run 101 – 10

Pipe Run	#	Component	Dimensions	Value
101 – 10	1	Pipe	Length [m] Diameter [m] Fittings	8.218 0.20272 Long radius 90 ° Bend 3 x T-piece through flow Orifice with diameter ratio of 0.6114
	2	Valve (102 -103)	Diameter [m] Type	0.20272 L-series (See Section 10)
	3	Pipe	Length [m] Diameter [m] Fittings	1.578 0.20272 Long radius 90 ° Bend T-piece through flow
	4	Pipe	Length [m] Diameter [m] Fittings	0.875 0.15405 None
	5	Pipe	Length [m] Diameter [m] Fittings	0.0569 0.1313 None

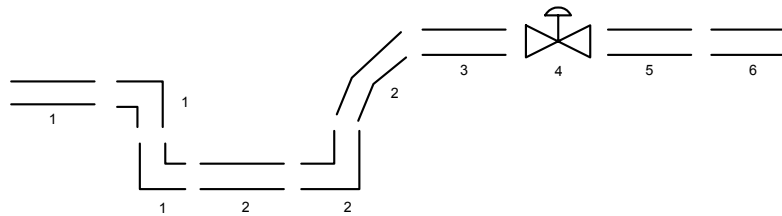


Figure 12: Schematic layout of pipe run 201- 207

Pipe Run	#	Component	Dimensions	Value
201 – 207	1	Pipe	Length [m] Diameter [m] Fittings	4.6097 0.15405 2 x Long radius 90 ° Bends
	2	Pipe	Length [m] Diameter [m] Fittings	1.2445 0.15405 Long radius 90 ° Bend Long radius 45 ° Bend
	3	Pipe	Length [m] Diameter [m] Fittings	0.28 0.07792 None
	4	Valve (204 – 205)	Diameter [m] Type	0.08 R-series (See Section 10)
	5	Pipe	Length [m] Diameter [m] Fittings	0.81 0.15405 None
	6	Pipe	Length [m] Diameter [m] Fittings	0.81 0.15405 None

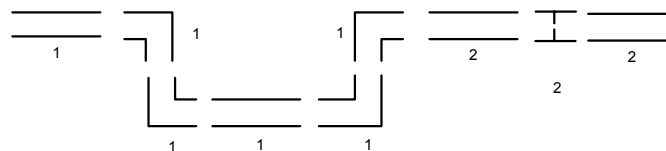


Figure 13: Schematic representation of pipe run 208 – 200

Pipe Run	#	Component	Dimensions	Value
208 - 200	1	Pipe	Length [m] Diameter [m] Fittings	9.7869 0.15405 4 x Long radius 90 ° Bends T-piece through flow
	2	Pipe	Length [m] Diameter [m] Fittings	1 0.15405 Orifice with diameter ratio of 0.52

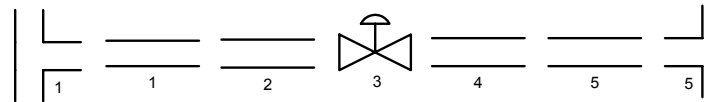


Figure 14: Schematic representations of pipe run 34 – 100 (GBP)

Pipe Run	#	Component	Dimensions	Value
34 – 100 GBP	1	Pipe	Length [m] Diameter [m] Fittings	1.255 0.10226 T-piece branch flow
	2	Pipe	Length [m] Diameter [m] Fittings	0.232 0.0779 None
	3	Valve	Diameter [m] Type	0.08 R-series (See Section 10)
	4	Pipe	Length [m] Diameter [m] Fittings	0.237 0.07792 None
	5	Pipe	Length [m] Diameter [m] Fittings	0.725 0.10226 T-piece branch flow

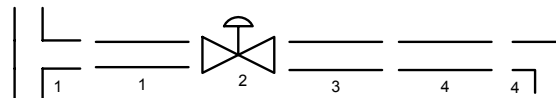


Figure 15: Schematic representation of pipe run 102 – 600

Pipe Run	#	Component	Dimensions	Value
102 - 600	1	Pipe	Length [m] Diameter [m] Fittings	0. 5 0.15405 T-piece branch flow
	2	Valve	Diameter [m] Type	0.1524 L-series (See Section 10)
	3	Pipe	Length [m] Diameter [m] Fittings	1.38 0.15405 None
	4	Pipe	Length [m] Diameter [m] Fittings	0.717 0.1282 Long radius 90 ° Bend

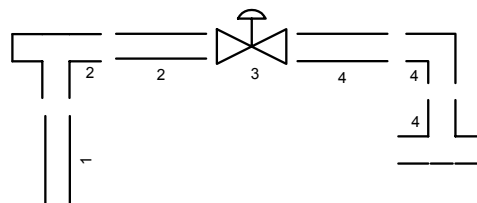


Figure 16: Schematic representation of pipe run 601 – 103



Pipe Run	#	Component	Dimensions	Value
601 - 103	1	Pipe	Length [m] Diameter [m] Fittings	0.595 0.1282 None
	2	Pipe	Length [m] Diameter [m] Fittings	0.92 0.15405 T – piece branch flow
	3	Valve	Diameter [m] Type	0.15424 L-series (See Section 10)
	4	Pipe	Length [m] Diameter [m] Fittings	1.473 0.15405 Long radius 90 ° Bend T – piece branch flow

3.3 VOLUMES

Number	Name	Description	Value
33	BV	Volume in front of filter (See Figure 36)	0.7 m ³
34	IV	Internal volume (See Figure 36)	7.1 m ³

4. Compressor and turbine data

4.1 GAS PROPERTIES

The maps are based on the following gas properties

Table 2: Gas properties

	$\gamma = c_p / c_v$	c_p [kJ/kg.K]	R [kJ/kg.K]
Compressor	1.395	1.0132	0.2870
Turbine	1.340	1.1472	0.2908

4.2 DEFINITIONS OF COMPRESSOR AND TURBINE EFFICIENCY

The compressor efficiency is the isentropic efficiency, which is defined as

$$\eta_c = \frac{T_{01} \left[\left(p_{02} / p_{01} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]}{T_{02} - T_{01}} \quad (1)$$

The turbine efficiency on a turbine map is the so-called turbine mechanical efficiency, η_{T-m} , which is defined as the product of turbine isentropic efficiency times the shaft mechanical efficiency.

Consistent with the use of total-to-static pressure ratio the turbine isentropic efficiency is defined as



$$\eta_T = \frac{T_{01} - T_{02}}{T_{01} \left[1 - (p_2 / p_{01})^{\frac{\gamma-1}{\gamma}} \right]} \quad (2)$$

The actual turbine work can be calculated as

$$W_T = \eta_T \dot{m} c_p T_{01} \left[1 - (p_2 / p_{01})^{\frac{\gamma-1}{\gamma}} \right] \quad (3)$$

The shaft mechanical efficiency is defined as

$$\eta_m = \frac{W_C}{W_T} \quad (4)$$

Combining Eqs. (3) and (4) we can write that

$$\begin{aligned} W_C &= \eta_m \eta_T \dot{m} c_p T_{01} \left[1 - (p_2 / p_{01})^{\frac{\gamma-1}{\gamma}} \right] \\ &= \eta_{T-m} \dot{m} c_p T_{01} \left[1 - (p_2 / p_{01})^{\frac{\gamma-1}{\gamma}} \right] \end{aligned} \quad (5)$$

where

$$\eta_{T-m} = \eta_T \eta_m \quad (6)$$

4.3 INERTIAS

The inertias of the compressor and turbine wheels are as follows:

Table 3: Inertias of compressor and turbine wheels

Wheel	Inertia [lb-in-s ²]
HPC	0.0008840
HPT	0.0014310
LPC	0.0014700
LPT	0.0040739
ELC	0.0075818
PT	0.0151744

Note: The turbine inertia values include the shaft inertias.

4.4 TURBINE OUTLET AREAS

The turbine pressure ratio in the turbine maps is defined as total inlet pressure divided by outlet static pressure. In order to calculate total outlet pressure one needs to know the outlet areas of the turbines at which the static pressures were measured.

These diameters are as follows:

HPT: 104.8 mm
LPT: 130.2 mm
PT: 158.8 mm



4.5 UNITS OF CORECTED MASSFLOW AND ROTATIONAL SPEED

The following definition for compressor corrected mass flow and corrected speed:

Compressor corrected mass flow [lb/min]:

$$W^* = \frac{W \sqrt{T_{1C} / 545}}{P_{1C} / 28.4} \quad (7)$$

Compressor corrected speed [RPM]:

$$N_C = \frac{N}{\sqrt{T_{1C} / 545}} \quad (8)$$

where

W	=	mass flow in [lb/min]
T _{1C}	=	total inlet temperature [R]
P _{1C}	=	total inlet pressure [inch Hg]
N	=	rotational speed [RPM]

Turbine corrected mass flow [lb/min]:

$$W^* = \frac{W \sqrt{T_{1T} / 519}}{P_{1T} / 29.92}$$

Compressor corrected speed [RPM]:

$$N_T = \frac{N}{\sqrt{T_{1T} / 519}}$$

where

W	=	mass flow in [lb/min]
T _{1T}	=	total inlet temperature [R]
P _{1T}	=	total inlet pressure [inch Hg]
N	=	rotational speed [RPM]



4.6 LOW PRESSURE COMPRESSOR (LPC)

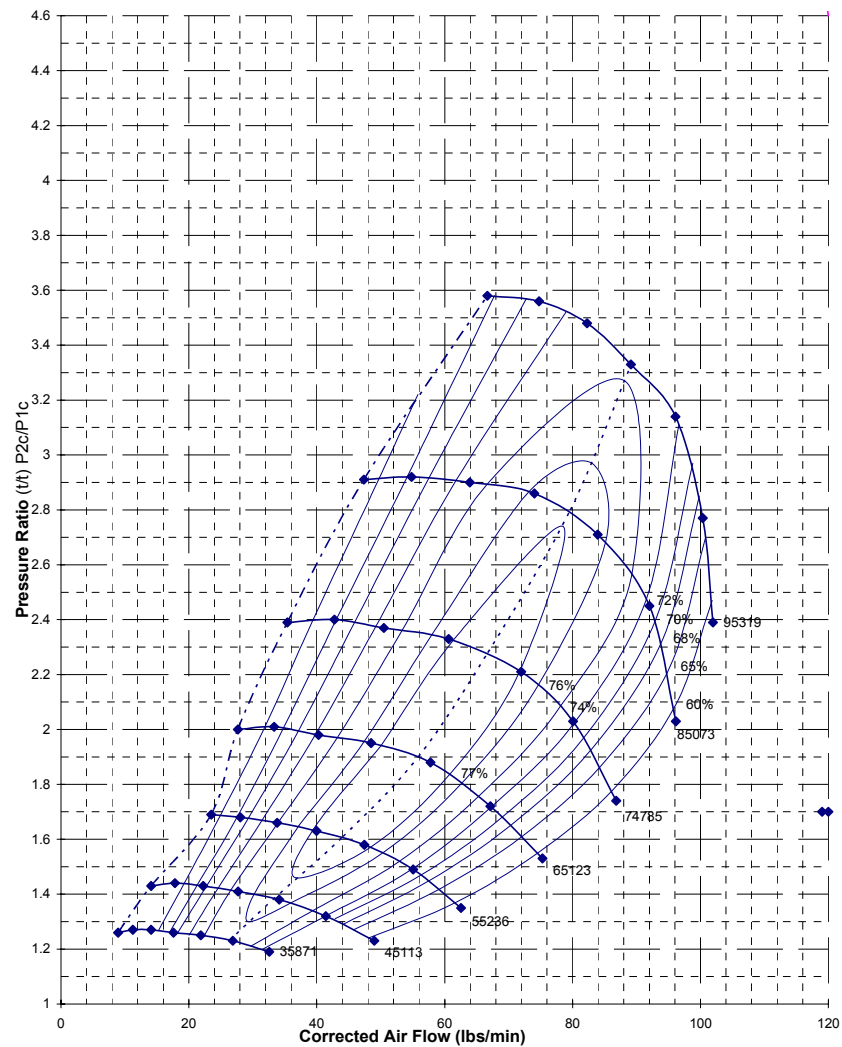


Figure 17: Performance map of LPC

Table 4: Performance map data for LPC

Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Speed 1			68%	16.96	1.26
35871	8.94	1.26		21.24	1.43
	11.24	1.27		27.53	1.68
	14.12	1.27		34.91	2.01
	17.61	1.26		43.04	2.40
	21.86	1.25		54.13	2.92
	26.86	1.23		67.77	3.58
	32.57	1.19			



Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Speed 2				99.82	2.85
45113	14.10	1.43		94.12	2.33
	17.83	1.44		83.03	1.93
	22.27	1.43		70.31	1.65
	27.70	1.41		57.63	1.45
	34.14	1.38		44.13	1.29
	41.42	1.32			
	48.99	1.23			
Speed 3			70%	18.28	1.26
55236	23.50	1.69		22.76	1.43
	28.04	1.68		29.38	1.68
	33.80	1.66		37.26	2.00
	39.97	1.63		45.91	2.39
	47.45	1.58		57.63	2.92
	55.09	1.49		72.78	3.57
	62.55	1.35			
Speed 4				98.78	2.97
65123	27.68	2.00		93.01	2.40
	33.34	2.01		81.75	1.97
	40.27	1.98		68.95	1.68
	48.50	1.95		56.32	1.47
	57.80	1.88		42.87	1.31
	67.15	1.72			
	75.31	1.53			
Speed 5			72%	20.03	1.25
74785	35.41	2.39		24.53	1.42
	42.76	2.40		31.47	1.67
	50.50	2.37		40.00	1.99
	60.63	2.33		49.35	2.38
	71.94	2.21		61.87	2.91
	80.07	2.03		78.93	3.52
	86.84	1.74			
Speed 6				96.64	3.11
85073	47.39	2.91		91.47	2.47
	54.83	2.92		80.14	2.02
	63.94	2.90		67.39	1.72
	74.02	2.86		54.79	1.49
	83.94	2.71		41.36	1.32
	92.02	2.45		31.55	1.20
	96.16	2.03			
Speed 7			74%	22.46	1.25
95319	66.66	3.58		26.72	1.42
	74.77	3.56		33.95	1.66
	82.26	3.48		43.21	1.97
	89.12	3.33		53.34	2.36
	96.09	3.14		66.90	2.90
	100.34	2.77		88.13	3.27
				89.21	2.56
		77.96	2.08		



Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Max ETAC	101.94	2.39	76%	65.50	1.76
	26.33	1.23		52.91	1.52
	33.14	1.38		39.39	1.34
	44.12	1.61		29.66	1.21
	55.89	1.90			
	66.76	2.28		37.21	1.65
	79.65	2.80		47.26	1.95
	89.18	3.33		58.14	2.35
Surge Line	8.94	1.26		73.33	2.87
	14.10	1.43		83.04	2.97
	23.50	1.69		85.13	2.68
	27.68	2.00		74.59	2.16
	35.41	2.39		62.91	1.81
	47.39	2.91		50.32	1.55
	66.66	3.58		36.06	1.37
50%	10.81	1.33	77%	29.25	1.30
55%				30.21	1.40
	14.55	1.45		37.21	1.65
	19.28	1.57			
	31.88	2.23		50.03	1.94
60%	27.87	2.01		61.52	2.33
				78.48	2.74
	101.82	2.47		71.71	2.21
	96.11	2.09		60.92	1.84
	86.30	1.78		48.35	1.57
	74.57	1.55		36.60	1.46
65%	61.73	1.37		39.56	1.64
	48.08	1.24		50.03	1.94
	15.33	1.27			
	19.28	1.44			
	25.00	1.69			
	31.90	2.01			
	39.46	2.40			
	49.66	2.91			
	55.82	3.22			
	100.79	2.70			
	95.25	2.23			
	84.54	1.87			
	72.09	1.61			
	59.33	1.42			
	45.76	1.27			



4.7 HIGH PRESSURE COMPRESSOR (HPC)

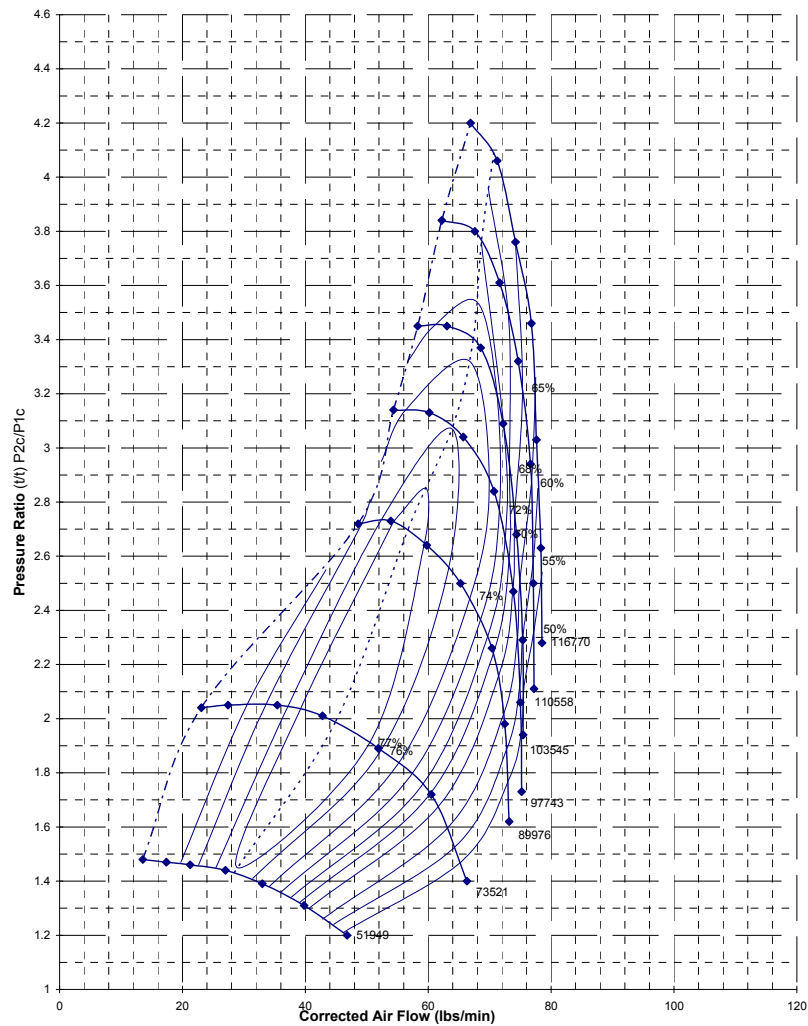


Figure 18: Performance map of HPC

Table 5: Performance map data for HPC

Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Speed 1			60%	77.49	3.26
51949	13.55	1.48		76.80	2.87
	17.38	1.47		74.93	2.51
	21.27	1.46		74.46	2.29
	26.99	1.44		72.31	2.02
	33.00	1.39		63.71	1.61
	39.79	1.31		42.81	1.26
	46.79	1.20			



Compressor Map Data						
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)	
Speed 2			65%	23.10	2.04	
73521	23.07	2.04				
	27.43	2.05		74.17	3.77	
	35.44	2.05		75.34	3.22	
	42.78	2.01		74.08	2.75	
	51.88	1.89		73.80	2.48	
	60.49	1.72		71.47	2.16	
	66.30	1.40		61.82	1.68	
Speed 3				40.64	1.30	
89976	48.61	2.72		31.92	2.27	
	53.93	2.73	63.17	3.93		
	59.76	2.64				
	65.24	2.50	68%	69.75	3.96	
	70.37	2.26		73.09	3.48	
	72.46	1.98		73.22	2.92	
	73.16	1.62		73.19	2.60	
Speed 4			70.60	2.24		
97743	54.34	3.14	70%	60.22	1.72	
	60.17	3.13		39.01	1.32	
	65.70	3.04		37.57	2.41	
	70.70	2.84		60.04	3.62	
	73.85	2.47				
	75.00	2.06		68.63	3.76	
	75.21	1.73		72.40	3.05	
Speed 5				72.56	2.68	
103545	58.29	3.45		72%	69.75	2.31
	63.04	3.45			58.86	1.75
	68.55	3.37	37.70		1.34	
	72.19	3.09				
	74.37	2.68	19.74		1.47	
	75.39	2.29	30.70		2.06	
	75.44	1.94	43.37		2.55	
Speed 6						
110558	62.20	3.84	74%		56.66	3.32
	67.58	3.80			60.93	3.45
	71.62	3.61		67.89	3.54	
	74.62	3.32		71.06	3.23	
	76.63	2.94		71.60	2.77	
	77.10	2.50		68.59	2.37	
	77.23	2.11		57.16	1.79	
Speed 7				36.11	1.36	
116770	66.89	4.20		74%	22.64	1.46
	71.22	4.06			33.74	2.06
	74.21	3.76			49.19	2.72
	76.79	3.46			50.56	2.81
	77.63	3.03				
	78.35	2.63			52.36	2.95



Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Max ETAC	78.50	2.28	76%	56.32	3.14
				66.74	3.32
	28.40	1.43		69.92	2.88
	44.95	1.99		66.86	2.45
	56.77	2.70		55.02	1.83
	64.03	3.08		34.13	1.38
	67.31	3.40			
	68.69	3.77		25.46	1.45
Surge Line	70.66	4.09	78%	37.27	2.05
	13.55	1.48		52.29	2.73
	23.07	2.04		63.86	3.07
	48.61	2.72		63.26	2.55
	54.34	3.14		52.23	1.88
	58.29	3.45		31.46	1.41
	62.20	3.84			
	66.89	4.20		52.95	2.46
Efficiency Contour Data					
50%	78.55	2.54	77%	54.41	2.73
	77.25	2.33		59.69	2.85
	75.62	2.12		59.41	2.65
	75.20	1.96		50.44	1.91
	73.20	1.78		28.93	1.45
	65.77	1.48		39.31	2.04
	46.21	1.21		54.41	2.73
55%	77.84	2.85			
	77.07	2.58			
	75.37	2.30			
	74.88	2.12			
	72.84	1.89			
	64.96	1.54			
	44.62	1.24			



4.8 EXTERNAL LOAD COMPRESSOR (ELC)

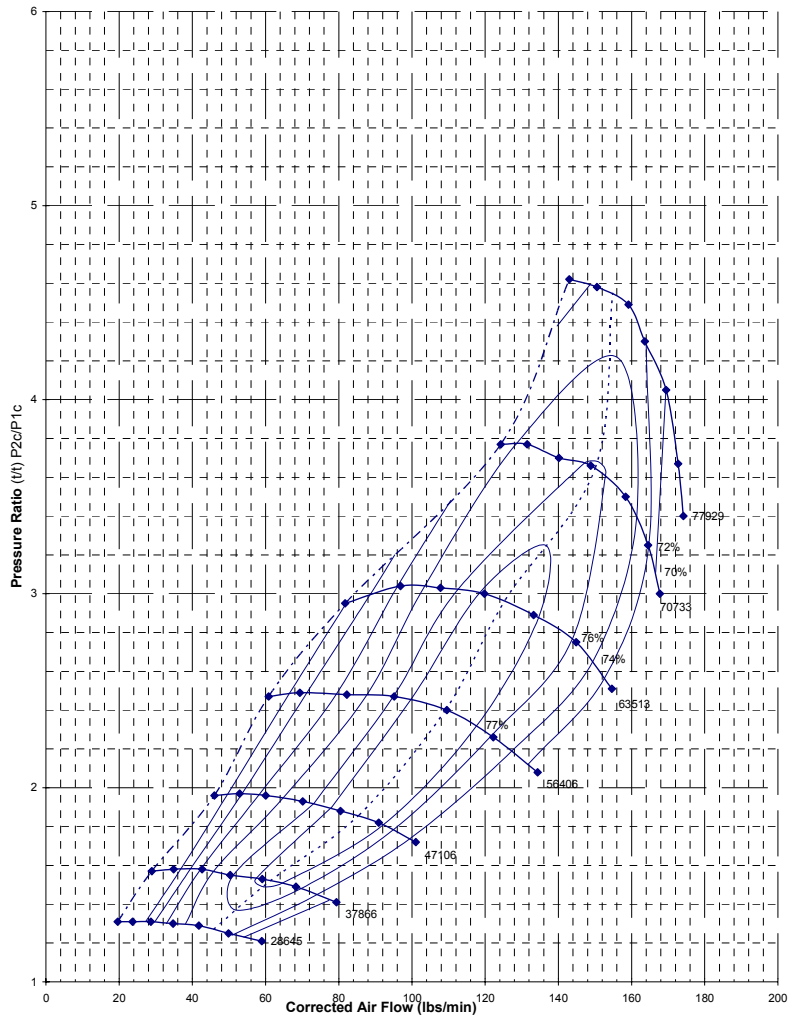


Figure 19: Performance map of ELC

Table 6: Performance map data of ELC

Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Speed 1			70%	29.74	1.31
28645	19.59	1.31		39.41	1.58
	23.69	1.31		53.57	1.97
	28.65	1.31		71.29	2.49
	34.72	1.30		88.75	3.00
	41.76	1.29		95.30	3.20
	49.89	1.25		169.41	4.05
	58.98	1.21		166.59	3.11



Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
Speed 2			72%	56.45	1.22
37866	28.92	1.57			
	34.89	1.58		32.92	1.30
	42.67	1.58		42.30	1.58
	50.35	1.55		58.05	1.96
	59.10	1.53		79.26	2.48
	68.31	1.49		95.82	3.03
	79.33	1.41		110.58	3.48
Speed 3					
47106	46.01	1.96		139.67	4.38
	52.91	1.97		148.52	4.59
	60.03	1.96			
	70.15	1.93		164.00	4.28
	80.50	1.88		164.66	3.24
	90.93	1.82		152.80	2.57
	101.04	1.72		131.65	2.12
Speed 4					
56406	60.82	2.47	77.33	1.42	
	69.38	2.49	54.03	1.23	
	82.20	2.48			
	95.16	2.47	74%	38.17	1.30
	109.56	2.40		45.84	1.57
	122.22	2.26		64.40	1.94
	134.34	2.08		87.38	2.47
Speed 5				103.49	3.04
63513	81.76	2.95		128.40	3.77
	96.88	3.04		155.99	4.22
	107.82	3.03	161.41	3.40	
	119.78	3.00	149.68	2.66	
	133.27	2.89	127.37	2.19	
	144.90	2.75	99.57	1.74	
	154.65	2.51	74.11	1.45	
Speed 6			50.75	1.24	
70733	124.25	3.77	76%		
	131.46	3.77		73.27	1.92
	140.13	3.70		94.91	2.47
	148.87	3.66		112.48	3.02
	158.40	3.50		146.95	3.67
	164.53	3.25		150.90	3.68
	167.74	3.00		152.93	3.62
Speed 7			143.91	2.77	
77929	142.99	4.62	121.78	2.27	
	150.57	4.58	95.34	1.79	
	159.18	4.49	69.60	1.48	
	163.62	4.30	51.77	1.37	
	169.43	4.05	51.17	1.55	
	172.72	3.67	73.27	1.92	



Compressor Map Data					
Label	X (lb/min)	Y (PRC)	Label	X (lb/min)	Y (PRC)
	174.17	3.40			
Max ETAC	45.81	1.27	77%	78.02	1.90
	61.27	1.52		99.86	2.46
	85.59	1.86		118.71	3.01
	109.16	2.40		136.48	3.25
	125.57	2.97		134.66	2.88
	150.11	3.65		117.71	2.32
	154.88	4.55		92.20	1.81
Surge Line	19.59	1.31		64.71	1.51
	28.92	1.57		59.50	1.49
	46.01	1.96		57.30	1.53
	60.82	2.47		78.02	1.90
	81.76	2.95			
	124.25	3.77			
	142.99	4.62			
Efficiency Contour Data					
60%	24.09	1.44			
65%	41.51	1.85			
68%	27.21	1.31			
	36.80	1.58			
	49.75	1.97			
	66.30	2.48			
	82.03	2.95			
	82.26	2.96			

4.9 START UP BLOWER SYSTEMS'S (SBS) BLOWER

Table 7: Performance data of SBS blower

SBS Blower Map Data					
Corrected Speed	X	Y	Corrected Speed	X	Y
	Corrected Mass Flow	Pressure ratio		Corrected Mass Flow	Pressure ratio
1.75	4.52	1.49	1.95	5.16	1.49
	4.74	1.35		5.3	1.35
	4.95	1.2		5.58	1.2
	5.09	1.1		5.79	1.1
2.14	5.79	1.49	2.34	6.43	1.49
	5.94	1.35		6.57	1.35
	6.15	1.2		6.78	1.2
	6.36	1.1		7	1.1
2.53	7	1.49	2.73	7.63	1.49



SBS Blower Map Data					
Corrected Speed	X	Y	Corrected Speed	X	Y
	Corrected Mass Flow	Pressure ratio		Corrected Mass Flow	Pressure ratio
	7.21	1.35		7.85	1.35
	7.42	1.2		8.06	1.2
	7.63	1.1		8.2	1.1
1.75	4.52	69	1.95	5.16	71
	4.74	75		5.3	76
	4.95	78		5.58	82
	5.09	81		5.79	83
2.14	5.79	73	2.34	6.43	74
	5.94	76		6.57	78
	6.15	81		6.78	80
	6.36	79		7	83
2.53	7	74	2.73	7.63	75
	7.21	79		7.85	79
	7.42	82		8.06	82
	7.63	81		8.2	81

With:

- Corrected Speed in $[\text{rev/s}]/\sqrt{K}$
- Corrected mass flow in $[\text{kg/s}]*\sqrt{K}/\text{Bar}$
- Efficiency in %
- 0.00147 Inertia



4.10 LOW PRESSURE TURBINE (LPT)

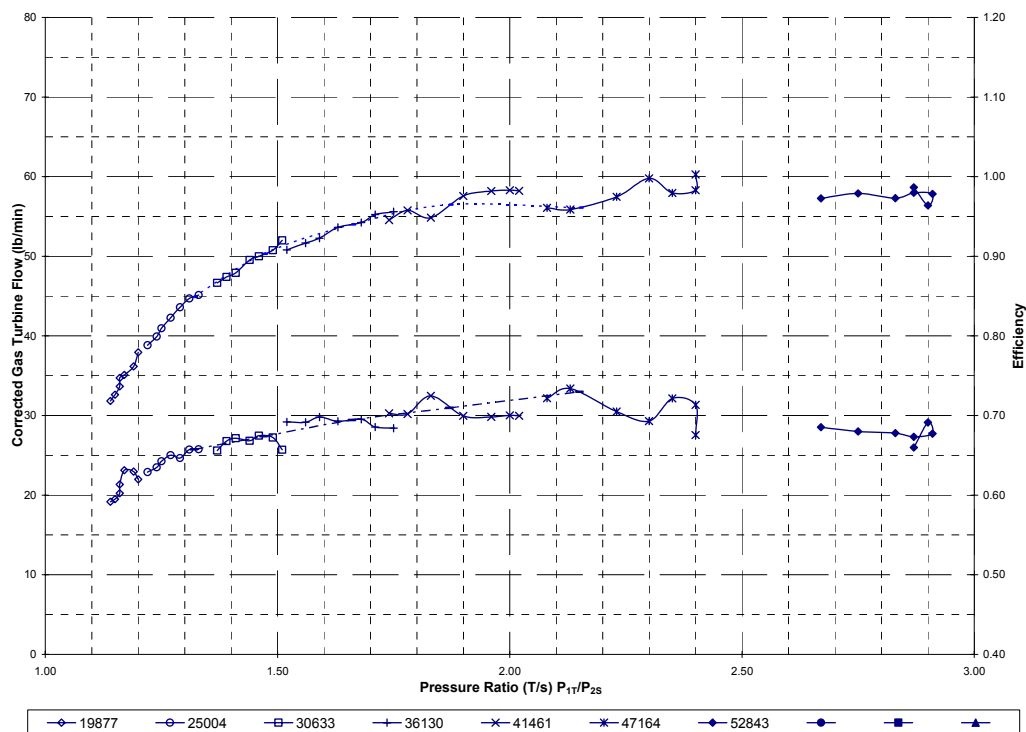


Figure 20: Performance map of LPT

Table 8: Performance map data of LPT

Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 1			
19877	1.14	31.82	0.59
	1.15	32.62	0.59
	1.16	33.66	0.60
	1.16	34.72	0.61
	1.17	35.10	0.63
	1.19	36.16	0.63
	1.20	37.94	0.62
Speed 2			
25004	1.22	38.84	0.63
	1.24	39.91	0.63
	1.25	40.96	0.64
	1.27	42.28	0.65
	1.29	43.60	0.65
	1.31	44.71	0.66
	1.33	45.12	0.66



Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 3			
30633	1.37	46.65	0.66
	1.39	47.41	0.67
	1.41	47.92	0.67
	1.44	49.53	0.67
	1.46	50.01	0.67
	1.49	50.77	0.67
	1.51	51.99	0.66
Speed 4			
36130	1.52	50.81	0.69
	1.56	51.67	0.69
	1.59	52.27	0.70
	1.63	53.64	0.69
	1.68	54.23	0.70
	1.71	55.24	0.69
	1.75	55.60	0.68
Speed 5			
41461	1.74	54.56	0.70
	1.78	55.76	0.70
	1.83	54.86	0.72
	1.90	57.58	0.70
	1.96	58.20	0.70
	2.00	58.30	0.70
	2.02	58.21	0.70
Speed 6			
47164	2.08	56.09	0.72
	2.13	55.87	0.73
	2.23	57.47	0.71
	2.30	59.79	0.69
	2.35	57.96	0.72
	2.40	58.30	0.71
	2.40	60.27	0.68
Speed 7			
52843	2.67	57.27	0.69
	2.75	57.90	0.68
	2.83	57.30	0.68
	2.87	57.98	0.67
	2.91	57.82	0.68
	2.90	56.39	0.69
	2.87	58.66	0.66



4.11 HIGH PRESSURE TURBINE (HPT)

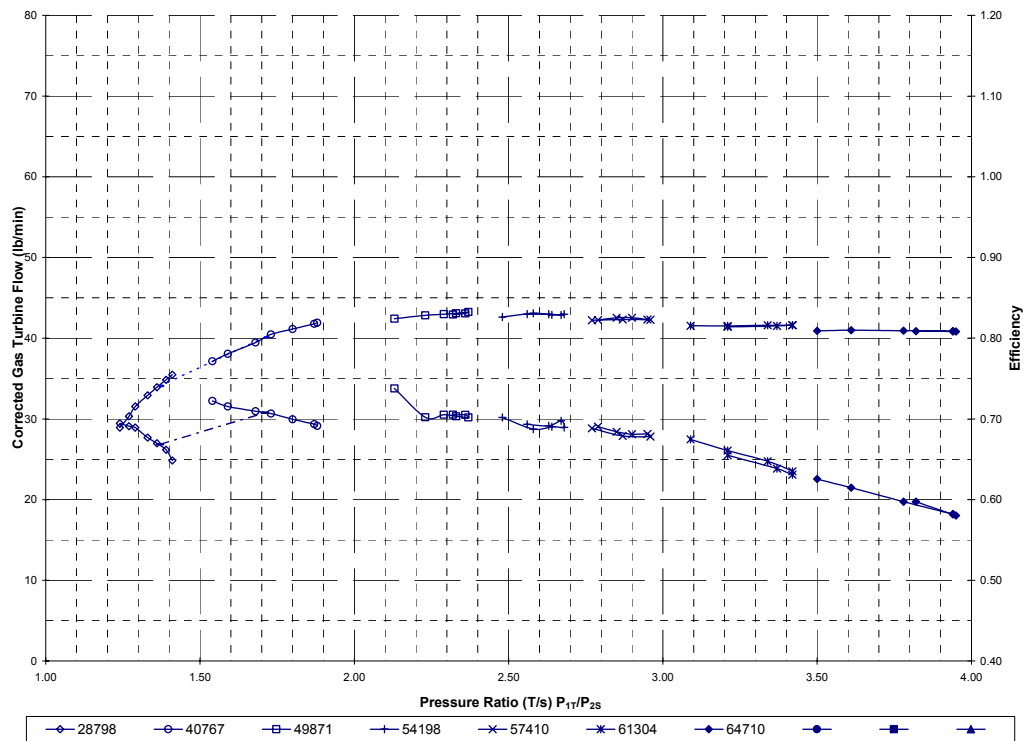


Figure 21: Performance map of HPT

Table 9: Performance data for HPT

Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 1			
28798	1.24	28.92	0.69
	1.27	30.32	0.69
	1.29	31.53	0.69
	1.33	32.92	0.68
	1.36	33.93	0.67
	1.39	34.85	0.66
	1.41	35.48	0.65
Speed 2			
40767	1.54	37.14	0.72
	1.59	38.07	0.72
	1.68	39.46	0.71
	1.73	40.48	0.71
	1.80	41.14	0.70
	1.87	41.78	0.69
	1.88	41.92	0.69



Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 3			
49871	2.13	42.41	0.74
	2.23	42.84	0.70
	2.29	42.98	0.71
	2.33	43.09	0.70
	2.37	43.26	0.70
	2.36	43.07	0.71
	2.32	42.94	0.71
Speed 4			
54198	2.48	42.62	0.70
	2.58	43.09	0.69
	2.64	42.89	0.69
	2.68	42.99	0.69
	2.67	42.88	0.70
	2.63	42.98	0.69
	2.56	42.99	0.69
Speed 5			
57410	2.77	42.22	0.69
	2.87	42.32	0.68
	2.96	42.29	0.68
	2.95	42.32	0.68
	2.90	42.54	0.68
	2.85	42.54	0.68
	2.79	42.24	0.69
Speed 6			
61304	3.21	41.42	0.66
	3.37	41.51	0.64
	3.42	41.62	0.63
	3.42	41.59	0.64
	3.34	41.60	0.65
	3.21	41.52	0.66
	3.09	41.53	0.67
Speed 7			
64710	3.82	40.87	0.60
	3.95	40.82	0.58
	3.94	40.83	0.58
	3.94	40.88	0.58
	3.78	40.94	0.60
	3.61	41.00	0.61
	3.50	40.91	0.63



4.12 POWER TURBINE (PT)

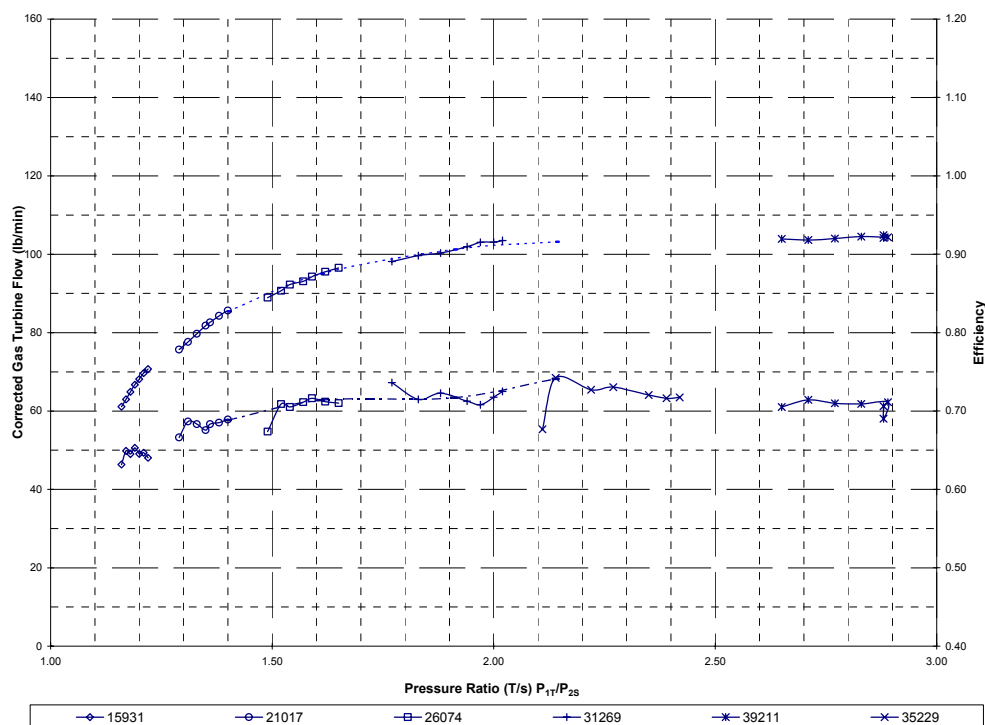


Figure 22: Performance map of PT

Table 10: Performance map data for PT

Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 1			
15931	1.16	61.09	0.63
	1.17	62.96	0.65
	1.18	64.87	0.65
	1.19	66.71	0.65
	1.20	68.12	0.65
	1.21	69.64	0.65
	1.22	70.69	0.64
Speed 2			
21017	1.29	75.68	0.67
	1.31	77.65	0.69
	1.33	79.70	0.68
	1.35	81.79	0.68
	1.36	82.62	0.68
	1.38	84.28	0.69
	1.40	85.64	0.69



Turbine Map Data			
Label	PRT	WT (lbs/min)	ETATM
Speed 3			
26074	1.49	88.93	0.67
	1.52	90.66	0.71
	1.54	92.27	0.71
	1.57	93.10	0.71
	1.59	94.27	0.72
	1.62	95.53	0.71
	1.65	96.55	0.71
Speed 4			
31269	1.77	98.14	0.74
	1.83	99.66	0.71
	1.88	100.30	0.72
	1.94	101.94	0.71
	1.97	103.05	0.71
	2.00	103.10	0.72
	2.02	103.52	0.73
Speed 5			
35229	2.11	102.84	0.68
	2.14	103.12	0.74
	2.22	103.90	0.73
	2.27	104.79	0.73
	2.35	105.36	0.72
	2.39	105.75	0.72
	2.42	105.59	0.72
Speed 6			
39211	2.65	103.91	0.71
	2.71	103.65	0.71
	2.77	104.02	0.71
	2.83	104.51	0.71
	2.89	104.36	0.71
	2.88	104.89	0.69
	2.88	104.16	0.71

5. Heat Exchangers

Note that the baffles in all of the shell-and-tube heat exchangers discussed below are equally spaced through out the shell. The height of the baffles is as follows:

- RX = 465 mm
- PC = 307 mm
- IC = 268.5 mm
- ELC = 268.5 mm

5.1 PRE-COOLER (PC)

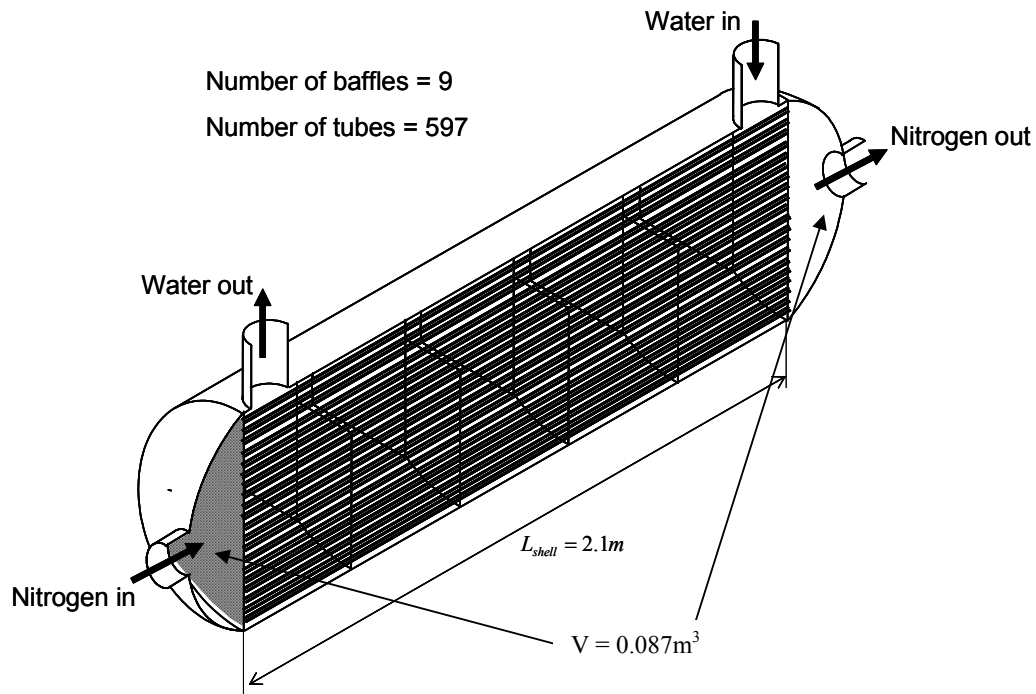


Figure 23: PC general arrangement

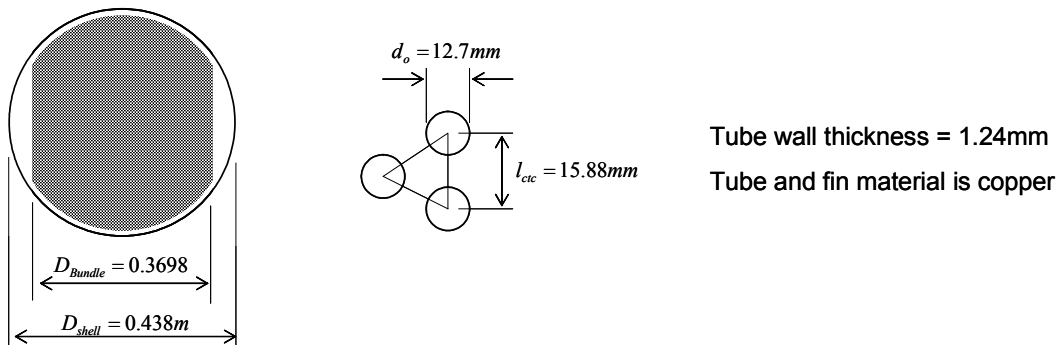


Figure 24: PC detail

5.2 INTER-COOLER (IC)

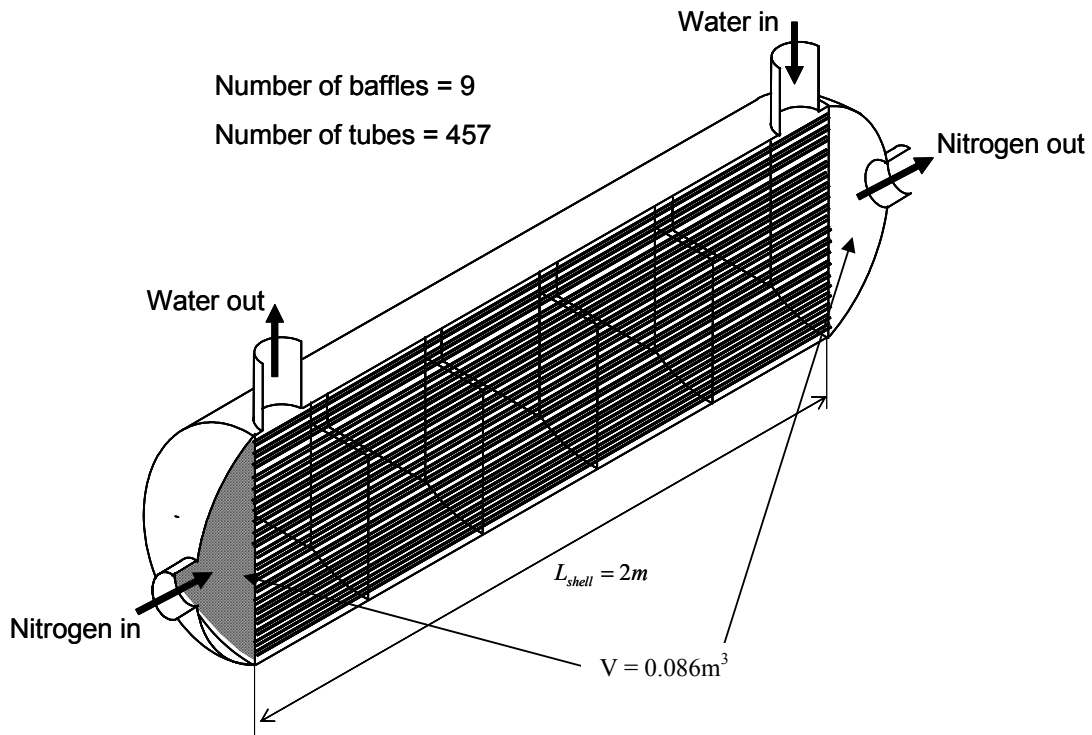


Figure 25: IC general arrangement

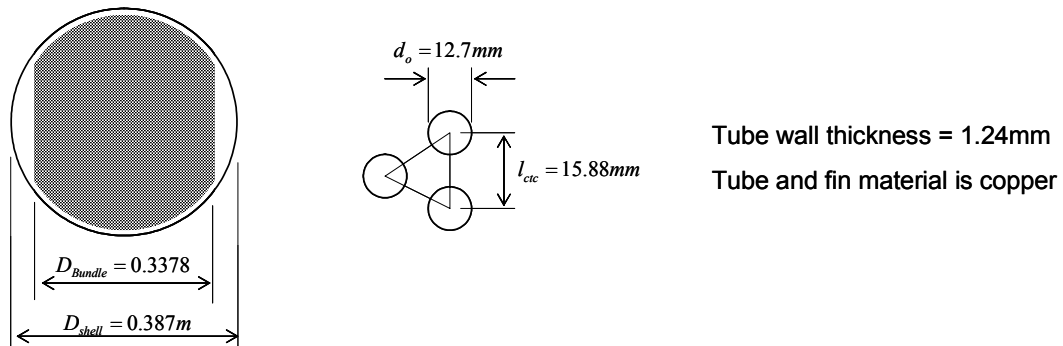


Figure 26: IC detail

5.3 EXTERNALLOAD HEAT EXCHANGER (ELHX)

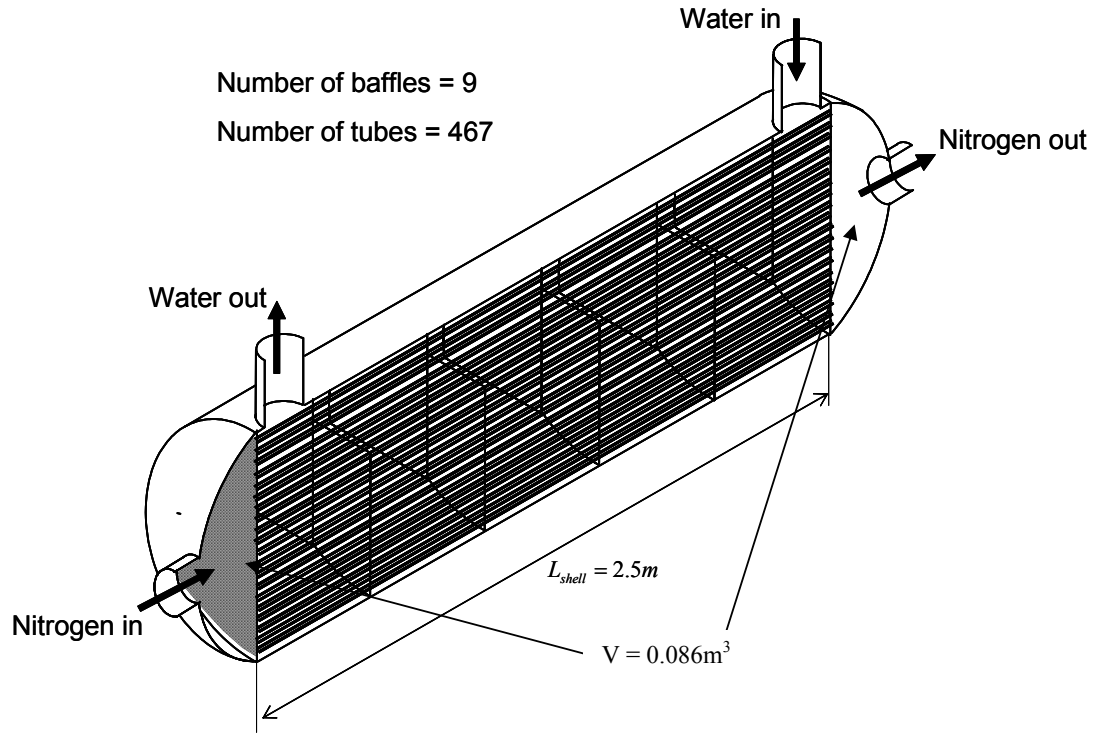


Figure 27: ELHX general arrangement

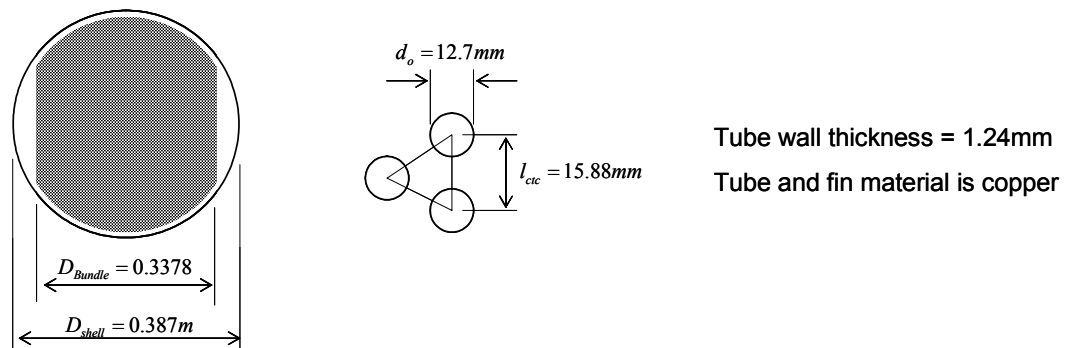


Figure 28: ELHX detail

5.4 RECUPERATOR (RX)

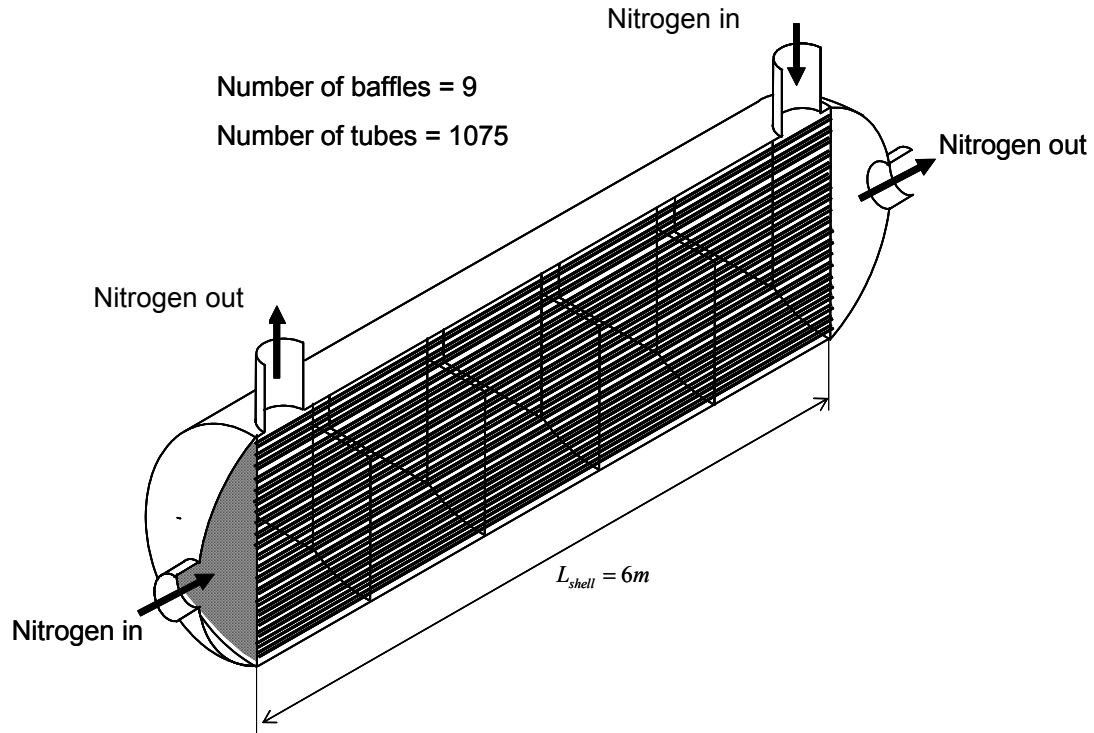


Figure 29: RX general arrangement

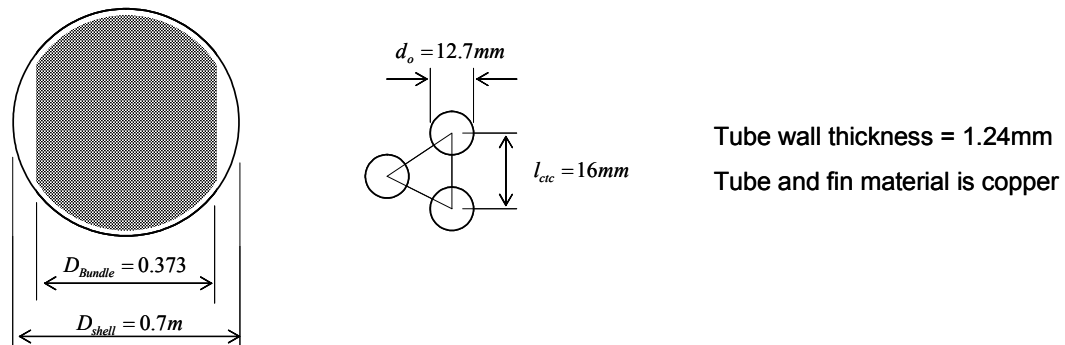


Figure 30: RX detail

Note that the figure of the recuperator only a schematic representation is and that the coned shaped volumes not applicable are in this case.

6. Heat Source

The heater (HS in Figure 1) of the PBMR Micro Model has a power rating of 420kW and is contained inside the Heater Section of the Pressure Vessel. Its purpose is to raise the temperature of circulated nitrogen gas flowing from the recuperator inside the pressure vessel, from about 400°C to a maximum of 700°C at 100% MCR before it reaches the High Pressure Turbine (HPT) in the Compressor/Turbine Section of the vessel.

The heater is composed of three sub assemblies or subsystems (Figure 31) consisting of:

1. three heater cassettes (HCs) within a gas-tight cover or sheath,
2. an aft duct subassembly (AftDuct), and
3. a forward duct subassembly (FwdDuct).

The FwdDuct is connected to the exit flange of the recuperator with the aid of a NPS 10" compensatory pipe allowing for thermal linear expansion of the recuperator. The AftDuct of the Heater is coupled to the HPT on the Compressor/Turbine Plate through a NPS 6" flanged pipe that is also compensated to allow for thermal heat expansion of the Heater assembly. Subassemblies are appropriately insulated to restrict heat loss to the enclosing pressure boundary atmosphere to ensure that the metal surface temperature of the pressure boundary remains below the allowed design temperature upper limit of 120°C. Detailed drawings of the heater and sub-assemblies are provided in Appendix A.

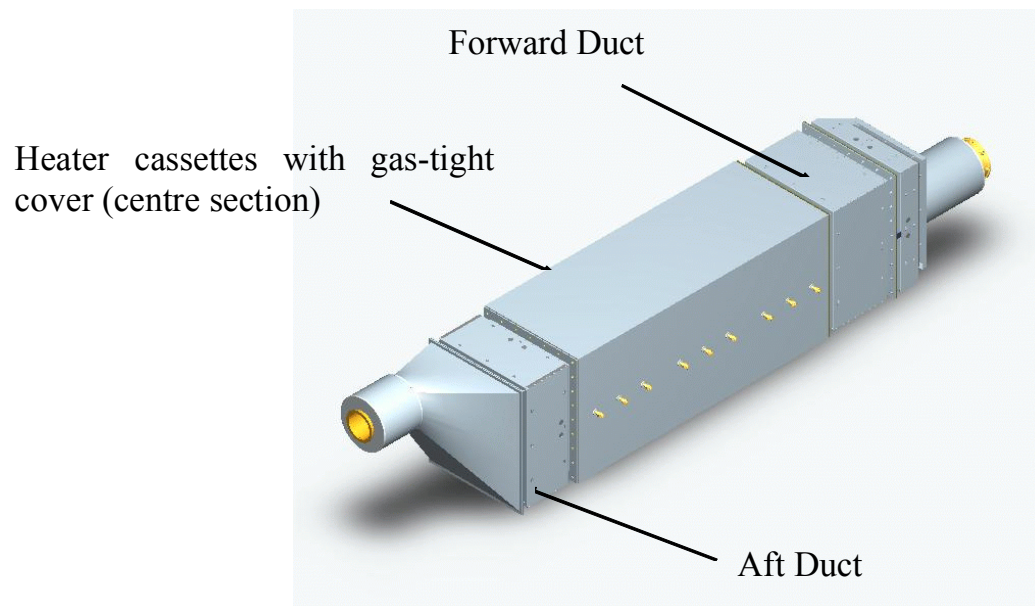


Figure 31: 3D-view of the Heater showing heater assembly (Three Heater Cassettes are contained in the gas-tight centre cover)



6.1 HEATER CASSETS

6.1.1 Heater Sub-Assembly

The three longitudinally coupled cassettes of the Heater are rated at 140 kW each. Each cassette is floating star connected to a 380V 3-phase electrical supply. Cassettes have effective inside dimensions of 500 mm x 600 mm and are 600 mm long, housing a total of 48 heating elements each. The heater elements are connected 4 in series x 4 in parallel per phase. All series and parallel connections are made on the insides of the cassettes and these connections are linked to out-side, side terminals, to facilitate connection to the external power supply (Figure 31). Appropriately positioned alumina tubes are employed to electrically insulate parallel connections.

Cassettes are manufactured from SA312 TP304L stainless steel sheet and angle. A 600 mm x 560 mm x 600 mm long sub-frame welded from 30 mm x 30 mm x 6 mm angles forms the base of each cassette (). Small rectangular stainless steel blocks, welded to the open-end sides of opposing sub-frame vertical angles, function as restrains to two opposing 640 mm x 572 mm side plates allowing for thermal expansion of these plates in three directions. These plates are provided with 48 tapped holes that are equally spaced in 8 horizontal rows with 6 holes in a row, staggered in a zigzag fashion between rows. The side plates are provided with 45 mm long M10, stainless steel bolts (SA 312 TP 316) and with spring washers of the same, acting as central suspension anchor stubs to ceramic insulation tubes hung on the insides of the cassette sub-frames. Electrical insulation between protruding electrodes and side plates are provided by 6 x 24 mm "T"-type (hole diameter 16.5 mm) alumina insulators on each cassette.

The insulation tubes form the bases to spirally wound heating elements giving rise to a 7-point star when viewed head-on. The sub-frame of each cassette is welded to two opposing 60 mm x 60 mm x 6 mm thick stainless angles orientated in such a manner as to provide flanged open-ends to each cassette. The flange angles are provided with 28 x 14-mm diameter holes to allow for longitudinal stacking and bolting of cassettes.

The top and bottom sides of cassette sub-frames consist of latched profiled covers with inside dimensions of 588 mm x 556 mm produced from 1.5 mm-thick steel sheets, which fit between cassette flange angles. Twenty-five millimetres wide ninety-degree bends limit further side-ways displacement of these covers after assembly.

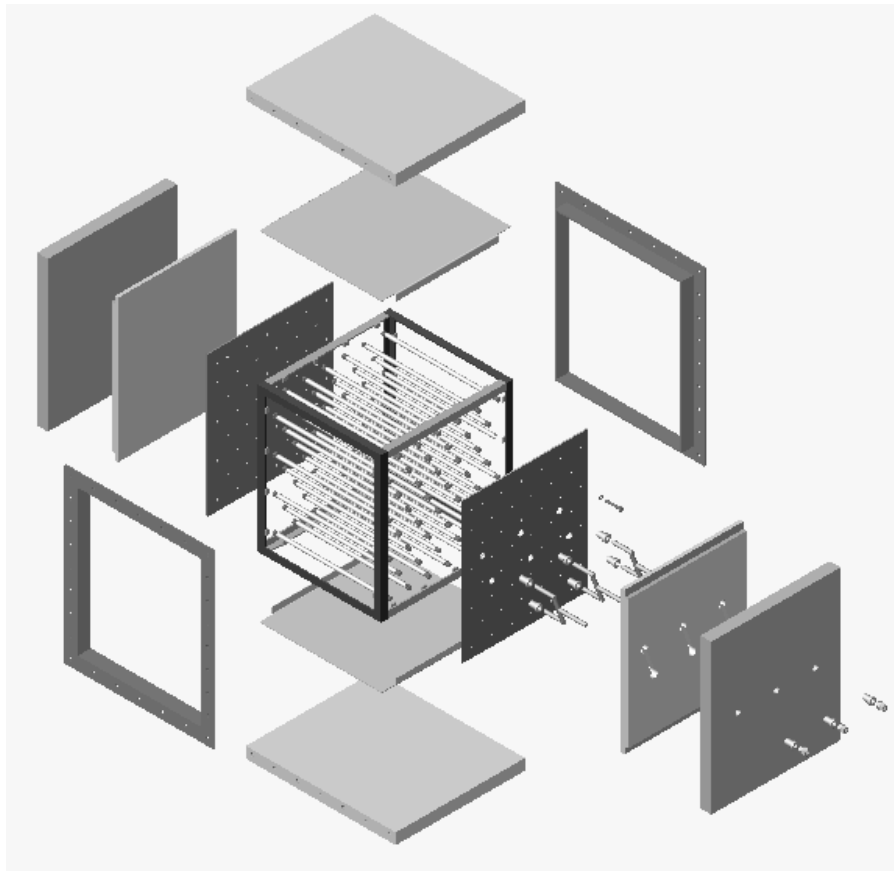


Figure 32: Exploded view 3D-model of a Heater Cassette showing the sub-frame with heater element insulation tubes and other assembly parts. Spirally wound heater elements are not shown. (See text and attached drawings for detail)

Longitudinally stacked cassettes are bolted to each other and are covered with an appropriately bent sheath produced from 1.5-mm thick stainless steel sheet. One side of the sheet used to produce the sheath is provided with 9 x 24.2-mm holes to allow for cassette electrode protrusion. The sheath is welded length-wise and to the flanged angles of the aft and forward cassettes.

4.2 HEATER ELEMENTS AND TUBES

The heater element insulation tubes are 4 mm thick and about 495 mm long with an outside diameter of 17 mm.

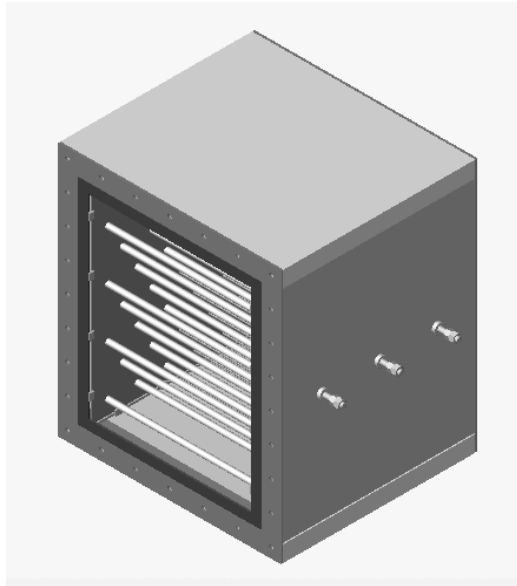


Figure 33 : *Orientated PBMM Heater Cassette assembly illustrating e.g., external electrical connectors and heater element insulation tubes. Spirally wound heater elements are not shown.*

The spirally wound element wire has been insulated from sub-frame side plates through the use of alumina rings that fit over the insulation tubes and are held in place against the sub-frame side plates by the wound element wire.

4.3 HEATER CASSETTE THERMAL INSULATION

Heater cassette thermal insulation is provided by Type Kerform KVS 141 alumina-silica fibreboard with a continuous application rating of 1300°C. The mean specific heat capacity of the Type 141 board is 0.96 kJ/kg K for the temperature range 20°C to 400°C, and 1.06 kJ/kg K for the temperature range between 400°C and 1200°C. Thermal conductivity in the temperature range 200°C to 800°C varies between 0.09 – 0.19 W/mK (0.15 W/mK at 600°C).

6.2 AFT AND FORWARD DUCTS

6.2.1 General

The Aft and Forward Ducts are bolted to the heater cassette assembly via the flanged angles provided. Graphite gaskets produced to fit the flanged angles were originally used to seal the contact surfaces. The use of graphite as gasket material was later replaced by 0.25 mm stainless steel foil², as a precaution to eliminating carbon soot build-up on element insulator

² The material utilised, and the design of the flange angles, require revisiting in order to eliminate slow persistent gas-leakage that was observed during preliminary pressurisation test runs of the



tubes which gave rise to electric short circuiting of the Heater during preliminary test runs of the model.

Three staggered stainless steel sieves having sieve sizes of 9, 16 and 64 mesh which are welded to stainless angle sub-frames, are bolted to the inside of the Forward Duct assembly. The sieve with the smallest sieve size (64 mesh) separates the other sieves in the sieve assembly from the first heater cassette. The aim of the sieves is to ensure uniform flow through the heater in order to prevent the formation of jot spots. The Aft Duct assembly similarly, houses a sieve (64 mesh) in order to finally restrict the transmission of weld met particles or other unwanted material to the High Pressure Turbine (HPT) in the Compressor/Turbine Section of the Model.

The Forward Duct assembly is provided with a NPS 10" compensated pipe which couples to the recuperator with the aid of two stainless steel half-section clamps. The flange end of the pipe boasts 8 equally spaced 20 mm sockets welded to the circumference of the pipe. Sockets at 12, 3 and 9 o'clock provide for 3/8" pressure measuring fittings. Four sockets equally spaced between the above sockets (2, 5, 7, and 11 o'clock) provide for 1/4" temperature fittings (See tags on drawing model). 5 holes were drilled through both the sockets and the pipe to accommodate e.g., the measuring thermocouples.

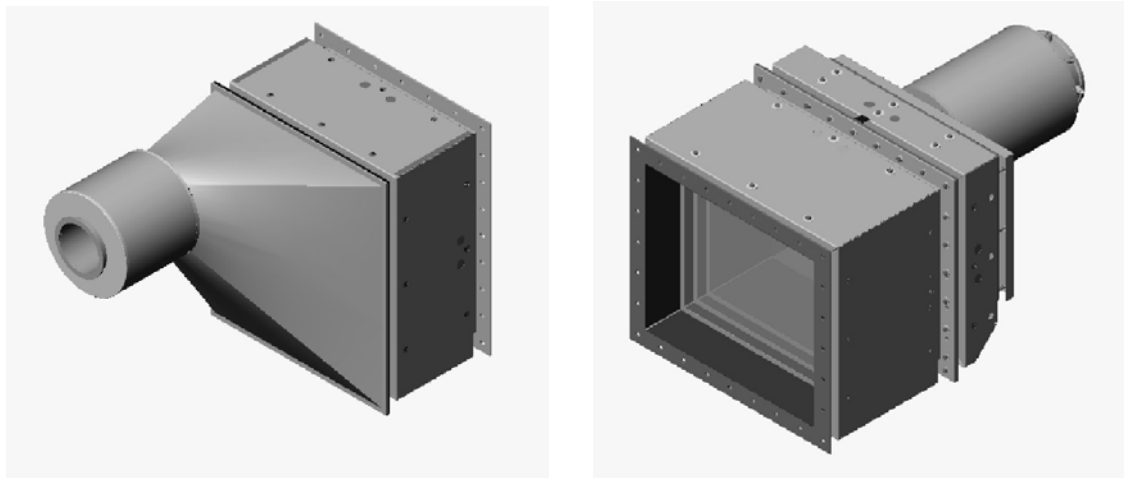


Figure 34 : Aft (Left) and Forward (Right) Duct Assemblies showing the insulated connecting pipes with pressure and temperature sockets on the welded flanged end of the Forward Duct Assembly compensated connecting pipe. The attached set of three sieves inside the Forward Duct Assembly is also shown.

Heater. It is suggested that use be made of annealed copper as gasket material or that graphite be reconsidered.



6.2.2 Aft and Forward Duct Pipe Insulation

Both Forward and Aft duct pipe couplings are insulated with 75 mm thick refractory fibre blankets (Thermal Ceramics type Fiberfrax Durablanket) wrapped around each pipe. The blankets are enclosed by 0.5 mm thick Grade 420 2B stainless steel sheet metal cladding and end-pieces. The alumina-silica containing refractory blanket has a continuous operation rating of 1260°C, a mean thermal conductivity of 0.4 W/mK at 760°C and a packing density of 192 kg/m³ for the material employed. This would result in a hot face pipe temperature of about 650°C being reduced to 72°C for 75 mm thick material. A hot face temperature of 760°C would be reduced to 86°C, based on a surface emissive factor of 0.9 at 27°C.

6.2.3 Aft and Forward Duct Insulation

Insulation blankets of similar type and thickness as described in Section 5 were sandwiched between the outer and inner cowlings within both the Forward and Aft duct assemblies. The blanket material however, was enclosed in woven refractory matt stitched with stainless steel wire. This design was adopted to be able to place the blanket inside the contoured ducts of the Aft assembly with relative ease and to further eliminate the possibility of blanket fibre escape through cowl joint thereby contaminating nitrogen gas-flow and negatively influencing HPT operation.

7. Control Valve

All the control valves in the PBMM are ANSI control valves. All the definitions and equations that were used are according to the ANSI/ISA-75.01 – 1985 (R1995) standard.

Table 11: R-series control valve data

Size	Relative opening									
	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1	0.52	1.13	2.23	3.83	5.95	8.58	11.7	16.2	24.1	45
1.5	1.3	3.3	6.4	11.1	17.2	24.8	33.9	46.5	69.3	110
2	2	5	10	17.2	26.6	38.4	52.5	72.4	108	180
2.5	3.3	8	15.9	27.3	42.3	61	83.4	114	170	280
3	5	12	23	39	61	88	121	165	246	420
4	8	19	37	63	98	141	193	264	393	620
6	14	34	67	115	178	258	352	484	719	1260
8	23	55	109	187	290	418	571	784	1164	2030

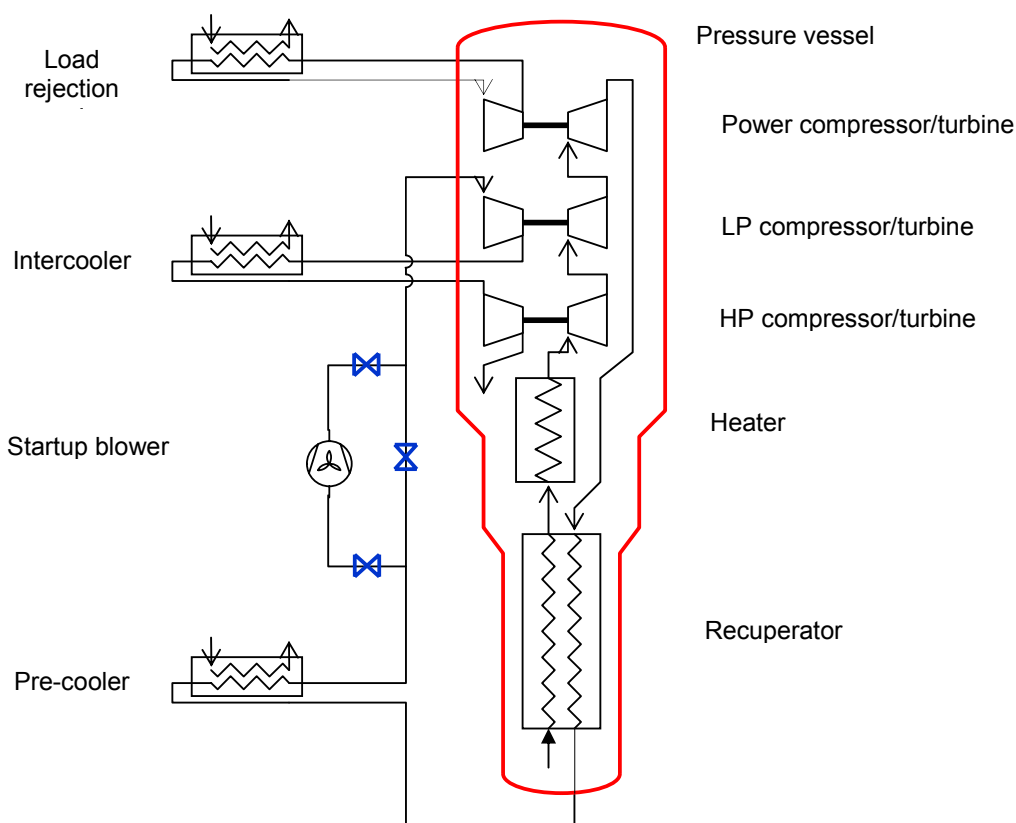
Cv/d2	0.59	1.45	2.86	4.93	7.64	11	15.07	20.67	30.8	48.9
F1	0.94	0.93	0.92	0.88	0.85	0.81	0.78	0.72	0.61	0.42
xT	0.64	0.64	0.63	0.62	0.59	0.54	0.49	0.4	0.32	0.16
z	0.44	0.43	0.41	0.38	0.35	0.31	0.28	0.25	0.2	0.16

**Table 12:** L-series control valve data

Size	Relative opening									
INCH	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
3	12.5	31.3	51	75	103	137	174	208	238	245
4	17	40.4	73	108	152	198	225	321	413	450
6	38	82.6	139	212	306	430	596	820	1116	1500
8	77	168	283	432	622	874	1212	1668	2268	3050

Cv/d2	1.38	3.02	5.09	7.76	11.17	15.69	21.77	29.96	40.72	54.75
F1	0.87	0.85	0.83	0.81	0.77	0.73	0.67	0.6	0.49	0.36
xT	0.53	0.53	0.53	0.52	0.47	0.41	0.35	0.27	0.19	0.11
z	0.38	0.34	0.31	0.28	0.25	0.23	0.2	0.17	0.14	0.11

8. Pressure Boundary

**Figure 35:** Physical layout of PBMM

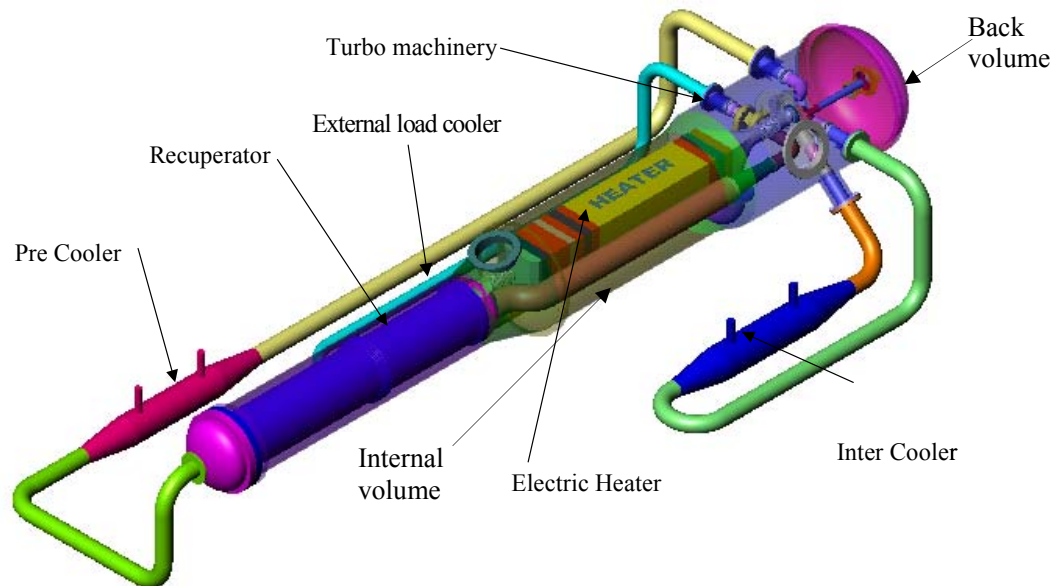


Figure 36: Solid model of the PBMM

9. Benchmarks

9.1 STEADY-STATE

Two steady-state options are identified:

1. Supply pressure from the NICS tanks (Point 100 in Figure 1) are 100 kPa and the exit temperature (Point 50 in) of the heater is 700 °C
2. Supply pressure from the NICS tanks (Point 100 in Figure 1) are 250 kPa and the exit temperature (Point 50 in) of the heater is 700 °C

The secondary sides of the heat exchangers are as follows:

- For the PC and IC:
 - Inlet Temperature of 20 °C
 - Mass flow rate of 5 kg/s
- For the ELHX:
 - Inlet Temperature of 20 °C
 - Mass flow rate of 2 kg/s

9.2 TRANSIENTS

Four different transient simulations are identified and the events for each transient are given below:



9.2.1 Load rejection

Use the steady-state model as described in Point 2 of Section 11.1 and apply the following transient events:

Transient events:

Nr	Start time	Event
1	0s	Open the GBP valve to 7% relative opening.

Plot the following results from $t = 0\text{ s}$ to $t = 81\text{ s}$

- Mass flows of the:
 - LPC
 - HPT
 - ELC
- The rotational speed of the three Turbines (HPT, LPT and PT).
- The power of the three compressors and turbines.
- The pressures and temperatures before and after each major component, this is:
 - LPC
 - IC
 - HPC
 - RX_HP
 - HS
 - HPT
 - LPT
 - PT
 - RX_LP
 - PC
 - ELC
 - ELHX

9.2.2 Mass injection at high pressure point

Use the steady-state model as described in Point 2 of Section 11.1 and apply the following transient events:

Transient events:

Nr	Start time	Event
1	0s	Inject mass at the extraction point at the rate of 1 kg/s.
2	40s	Stop injecting
3	60s	Extract mass at the extraction point at the rate of -1 kg/s.
4	100s	Stop extracting

Plot the following results from $t = 0\text{ s}$ to $t = 243\text{ s}$

- Mass flows of the:
 - LPC
 - HPT



- ELC
- The rotational speed of the three Turbines (HPT, LPT and PT).
- The power of the three compressors and turbines.
- The pressures and temperatures before and after each major component, this is:
 - LPC
 - IC
 - HPC
 - RX_HP
 - HS
 - HPT
 - LPT
 - PT
 - RX_LP
 - PC
 - ELC
 - ELHX

9.2.3 Mass injection at low pressure point

Use the steady-state model as described in Point 2 of Section 11.1 and apply the following transient events:

Transient events:

Nr	Start time	Event
1	0s	Inject mass at the injection point at the rate of 0.1 kg/s.
2	399s	Stop injecting
3	499s	Extract mass at the injection point at the rate of -0.1 kg/s.
4	900s	Stop extracting

Plot the following results from $t = 0\text{s}$ to $t = 1000\text{ s}$

- Mass flows of the:
 - LPC
 - HPT
 - ELC
- The rotational speed of the three Turbines (HPT, LPT and PT).
- The power of the three compressors and turbines.
- The pressures and temperatures before and after each major component, this is:
 - LPC
 - IC
 - HPC
 - RX_HP
 - HS
 - HPT
 - LPT
 - PT
 - RX_LP



- PC
- ELC
- ELHX

9.2.4 Start-up

Use the steady-state model as described in Point 1 of Section 11.1, with the following changes in boundary values:

- NICS injection pressure at 160 kPa
- Heater outlet temperature 200 °C

and apply the following transient events:

Transient events:

Nr	Start time	Event
2	0s	Ramp the heater outlet pressure with the following equation: $y = 200 + 40t$
3	12.5s	Switch of the ramping of the temperature and solve the flow in the heater element
4	15.04s	Open the SBSIV to fully open
5	15.06s	Shut down the SBS blower

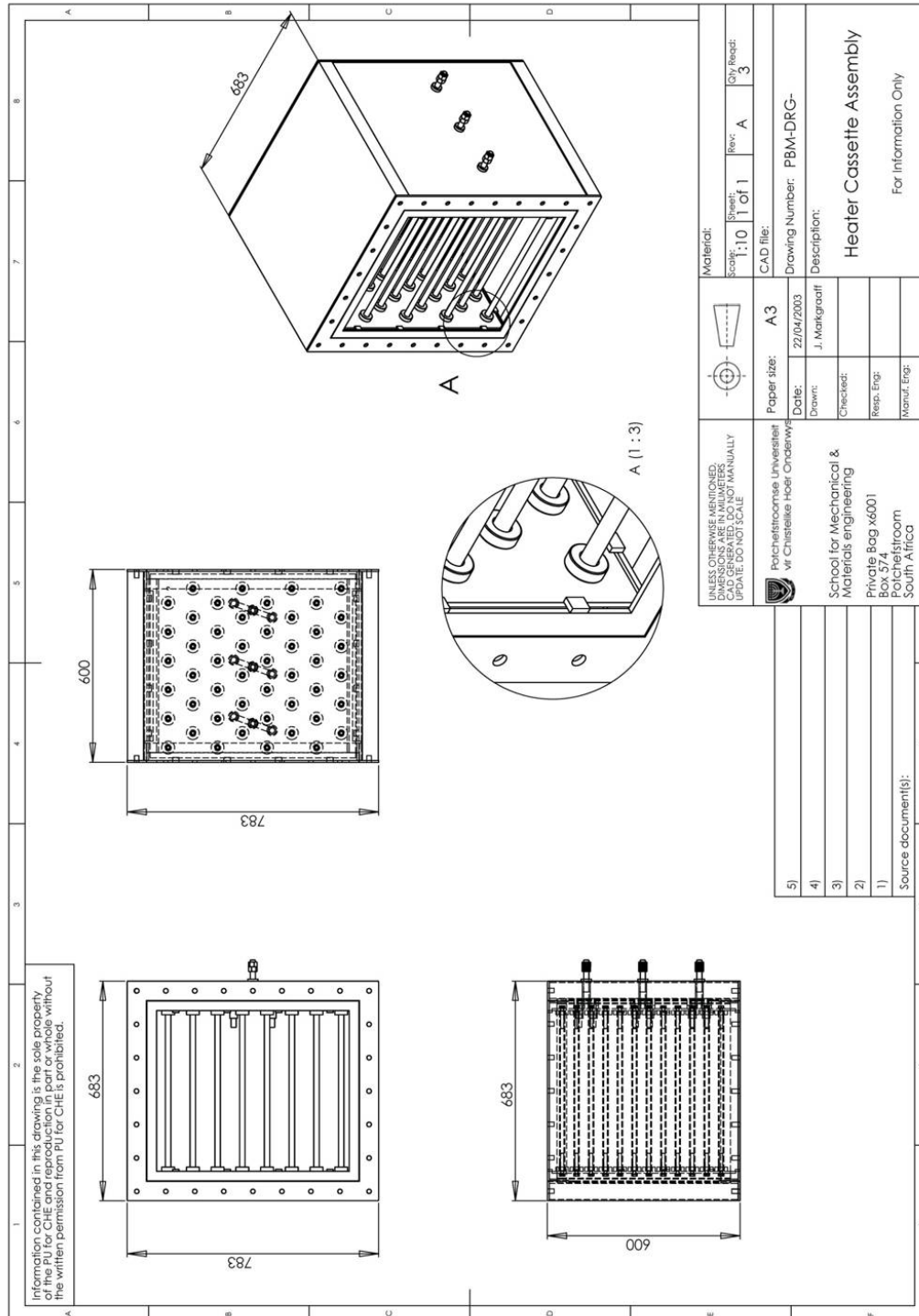
Plot the following results from $t = 0s$ to $t = 178s$

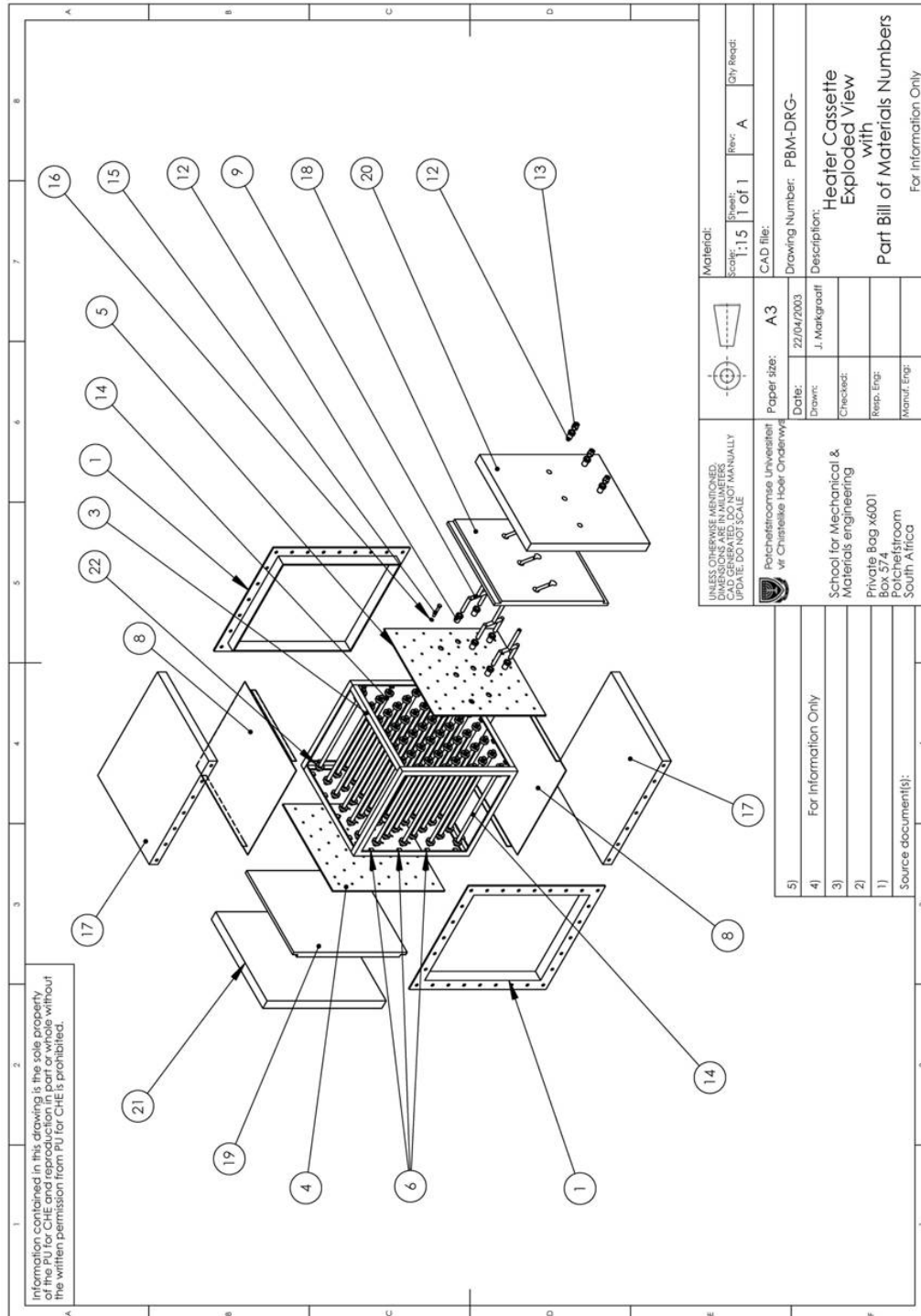
- Mass flows of the:
 - LPC
 - HPT
 - ELC
- The rotational speed of the three Turbines (HPT, LPT and PT).
- The power of the three compressors and turbines.
- The pressures and temperatures before and after each major component, this is:
 - LPC
 - IC
 - HPC
 - RX_HP
 - HS
 - HPT
 - LPT
 - PT
 - RX_LP
 - PC
 - ELC
 - ELHX

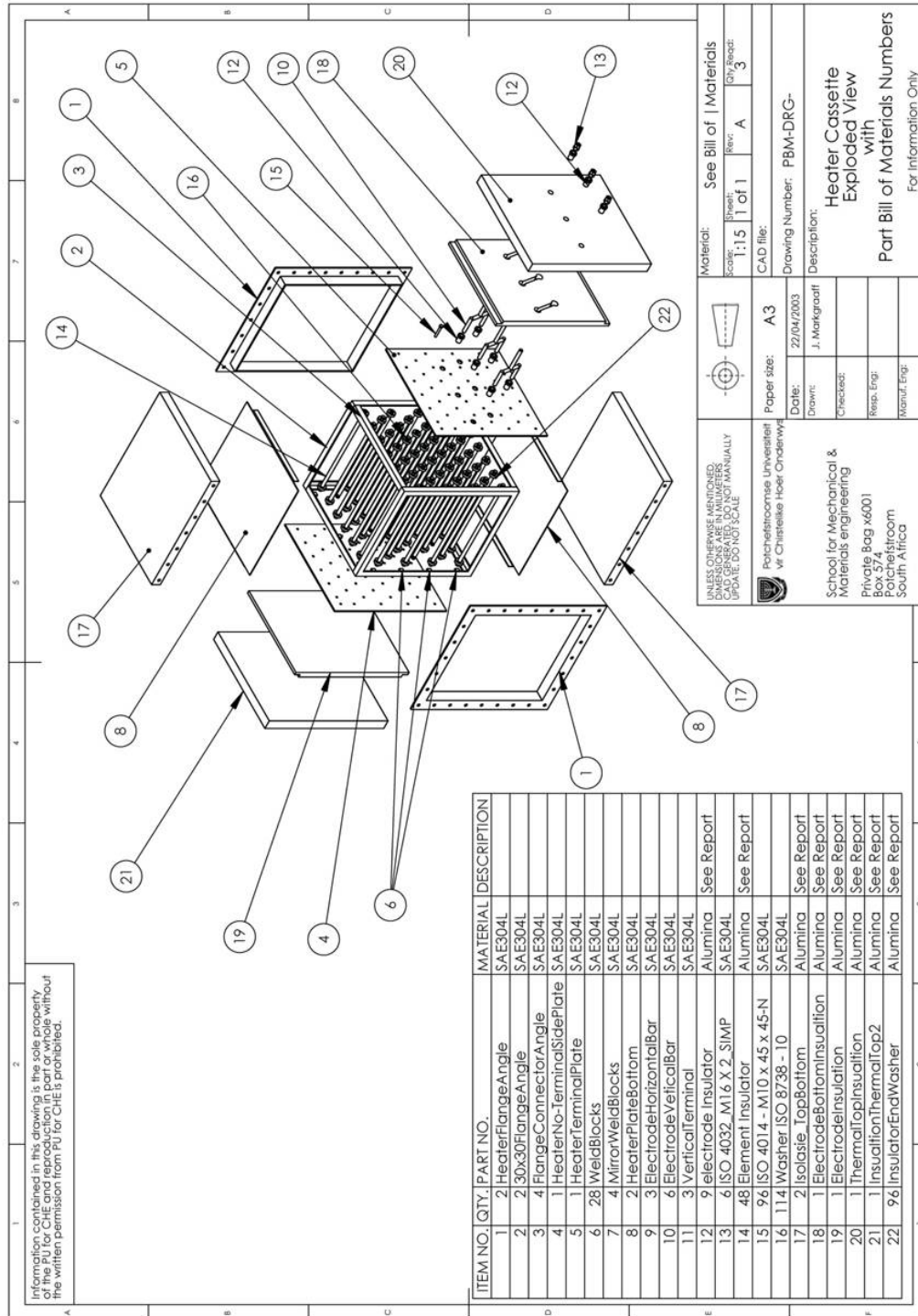


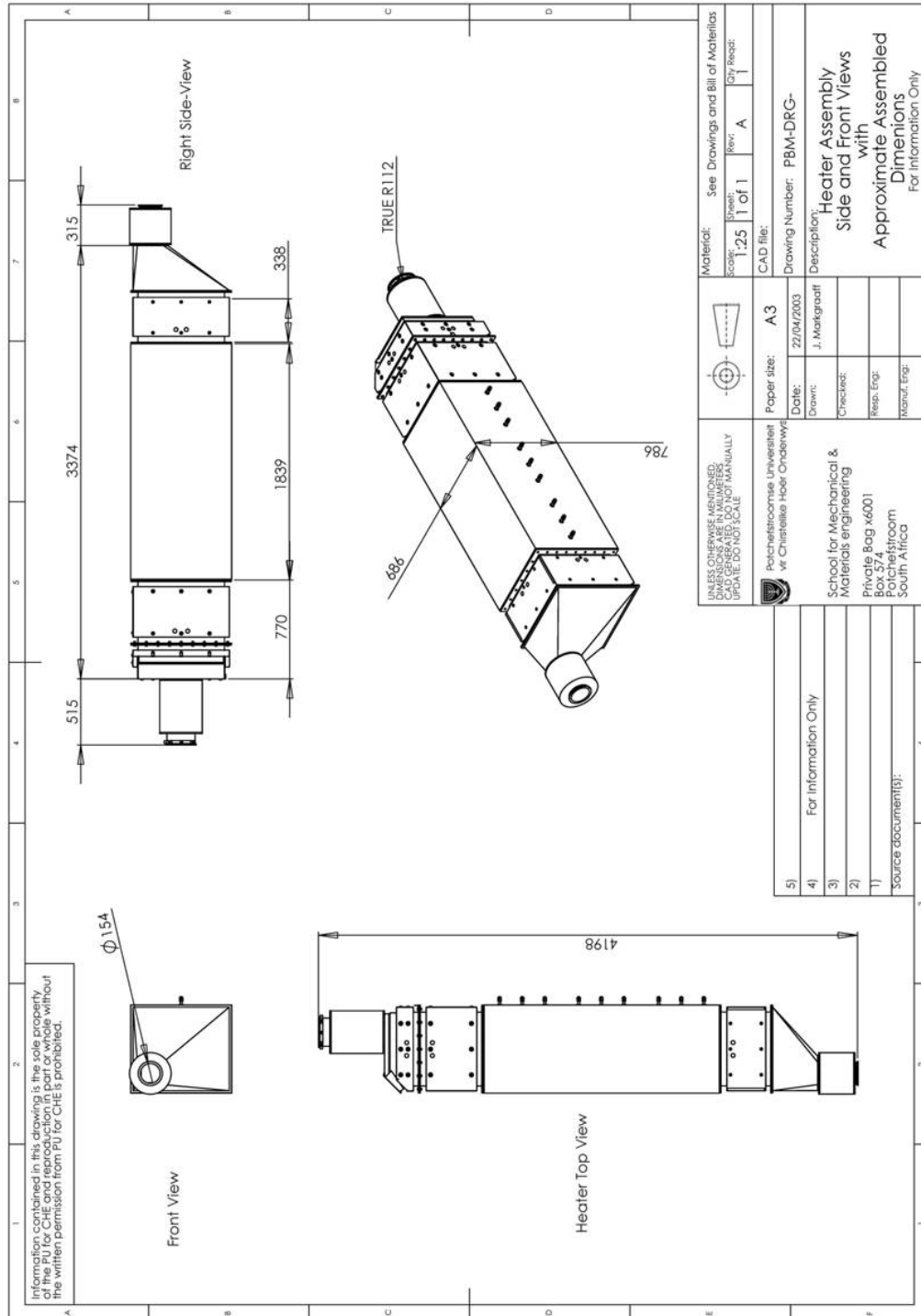
Appendix A

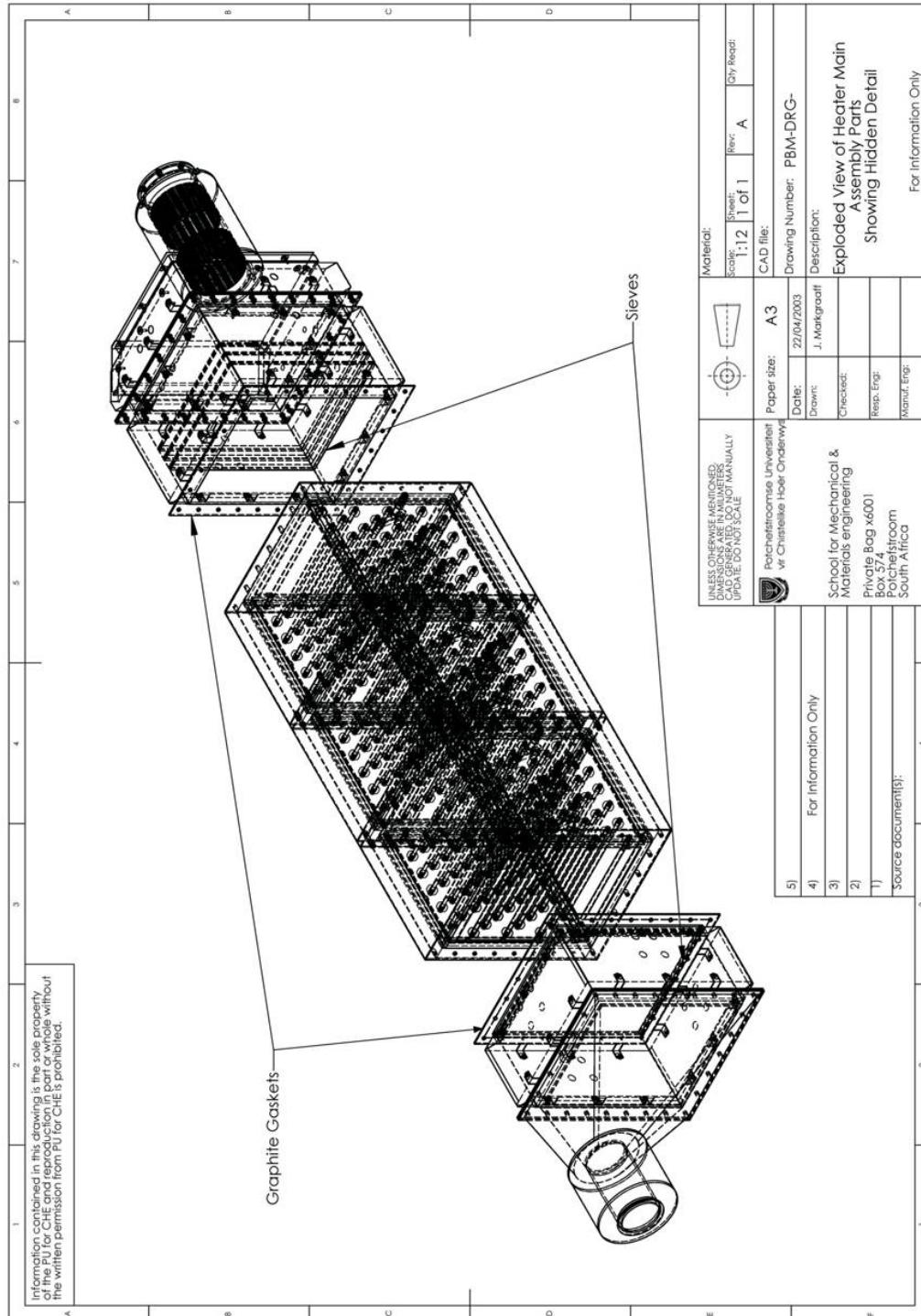
Heater Drawings

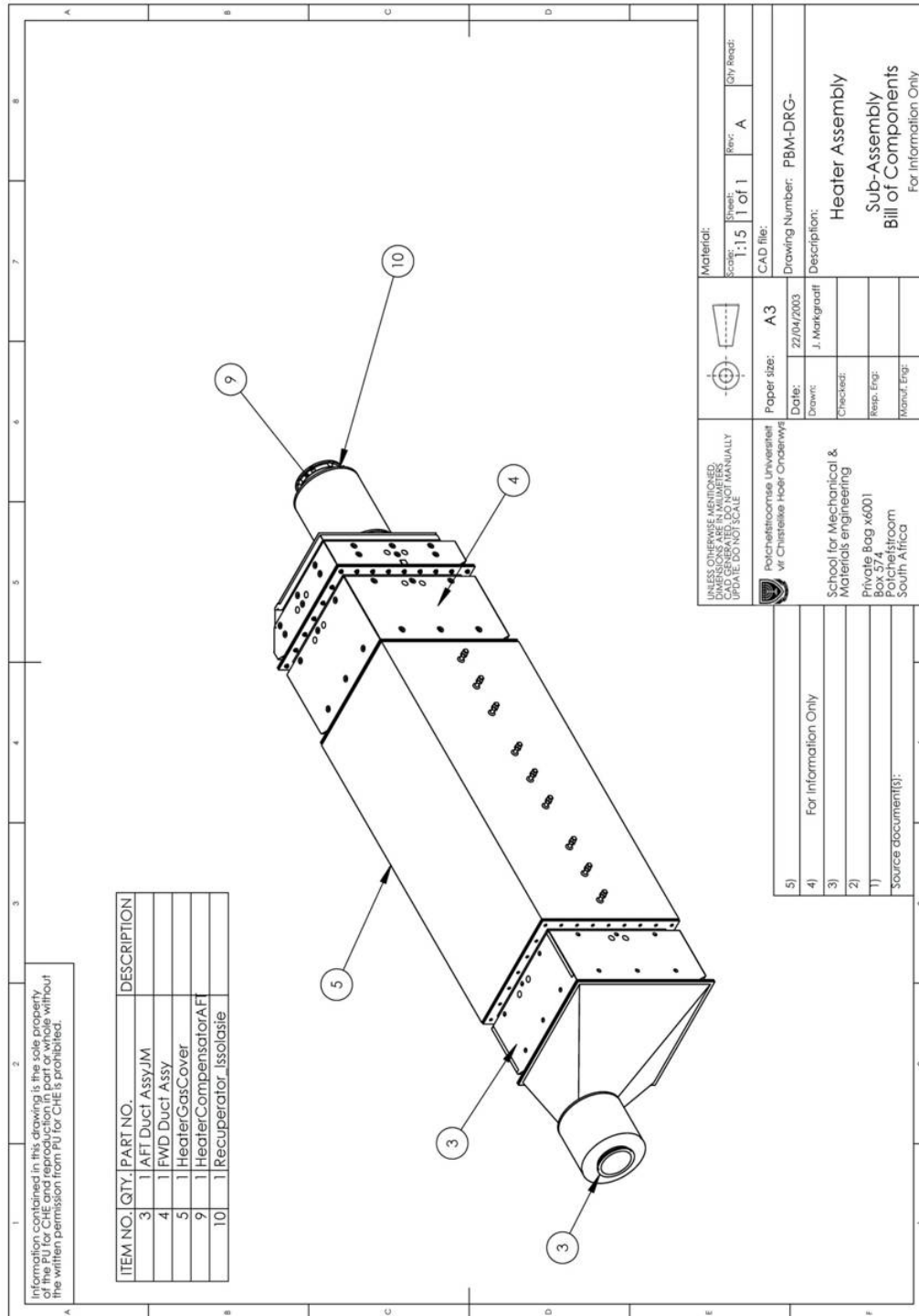


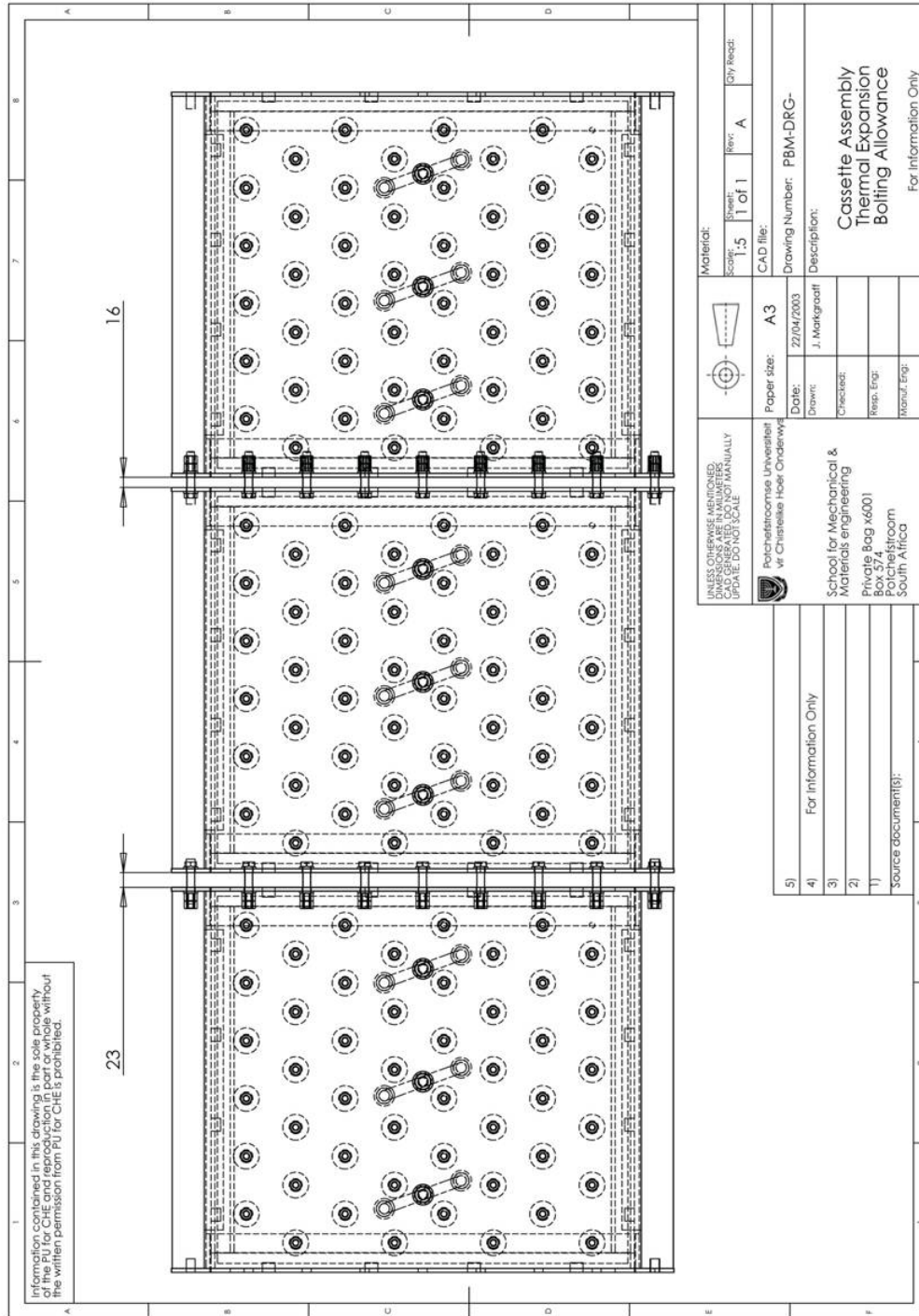


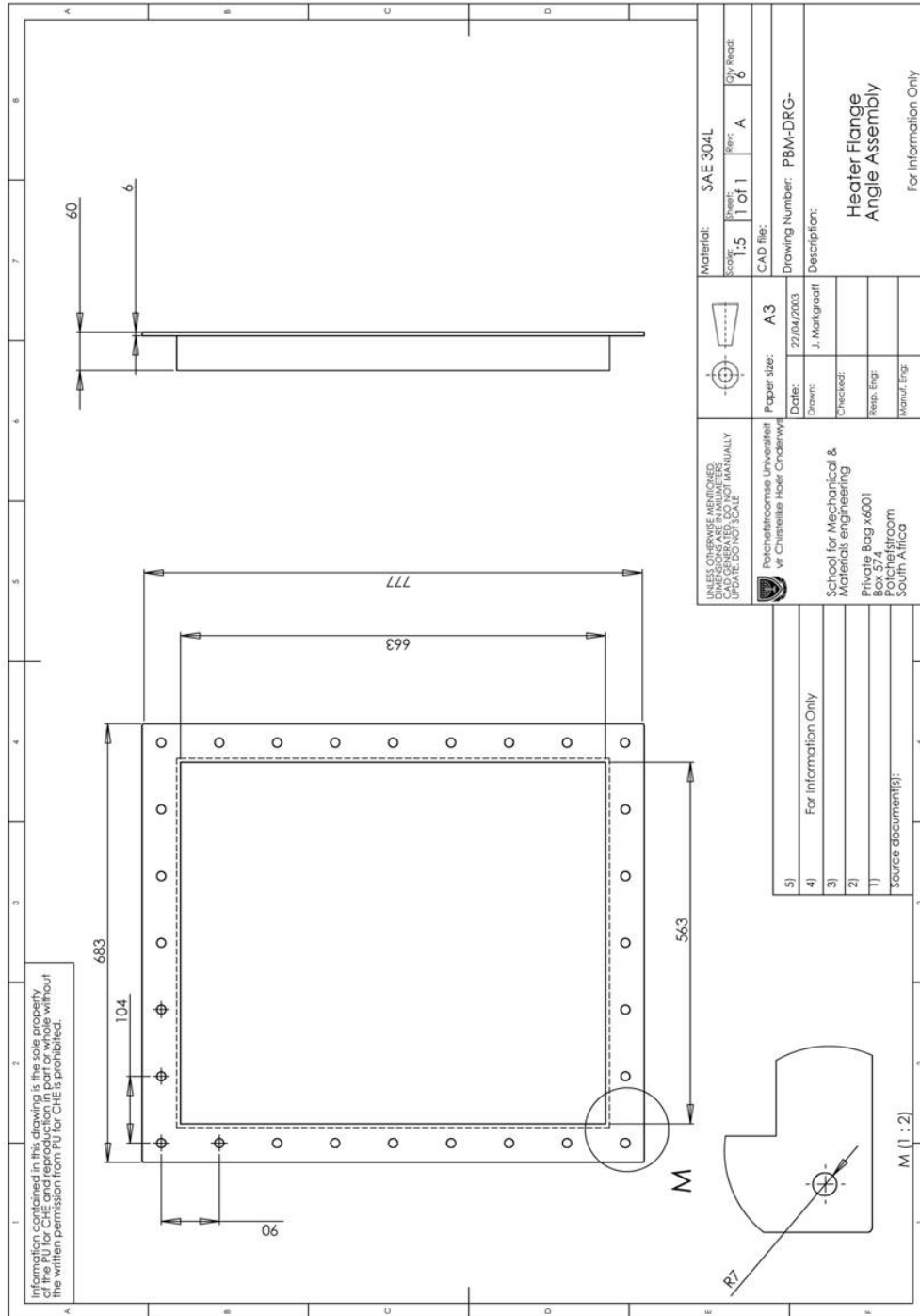














ITEM NO.	QTY.	PART NO.	MATERIAL	DESCRIPTION
1	2	HeaterFlangeAngle	SAE 304L	
2	2	30x30FlangeAngle	SAE 304L	
3	4	FlangeConnectorAngle	SAE 304L	
4	1	HeaterNo-TerminalSidePlate	SAE 304L	
5	1	HeaterTerminalPlate	SAE 304L	
6	28	WeldBlocks	SAE 304L	
7	4	MirrorWeldBlocks	SAE 304L	
8	2	HeaterPlateBottom	SAE 304L	
9	3	ElectrodeHorizontalBar	SAE 316	
10	6	ElectrodeVerticalBar	SAE 316	
11	3	VerticalTerminal	SAE 316	
12	9	Electrode Insulator	Alumina	
13	6	ISO 4032 - M16 X 2 - SIM P	SAE316	
14	48	Element Insulator	Alumina	
15	96	ISO 4014 - M10 x 45 x 45-N	SAE316	
16	114	Washer ISO 8738 - 10	SAE316	
17	2	Isolasie TopBottom	Alumina	See Report
18	1	ElectrodeBottom Insualtion	Alumina	See Report
19	1	ElectrodeInsulation	Alumina	See Report
20	1	ThermalTopInsualtion	Alumina	See Report
21	1	InsualtionThermalTop2	Alumina	See Report
22	96	InsulatorEndWasher	Alumina	See Report

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5) Source document(s):

4)

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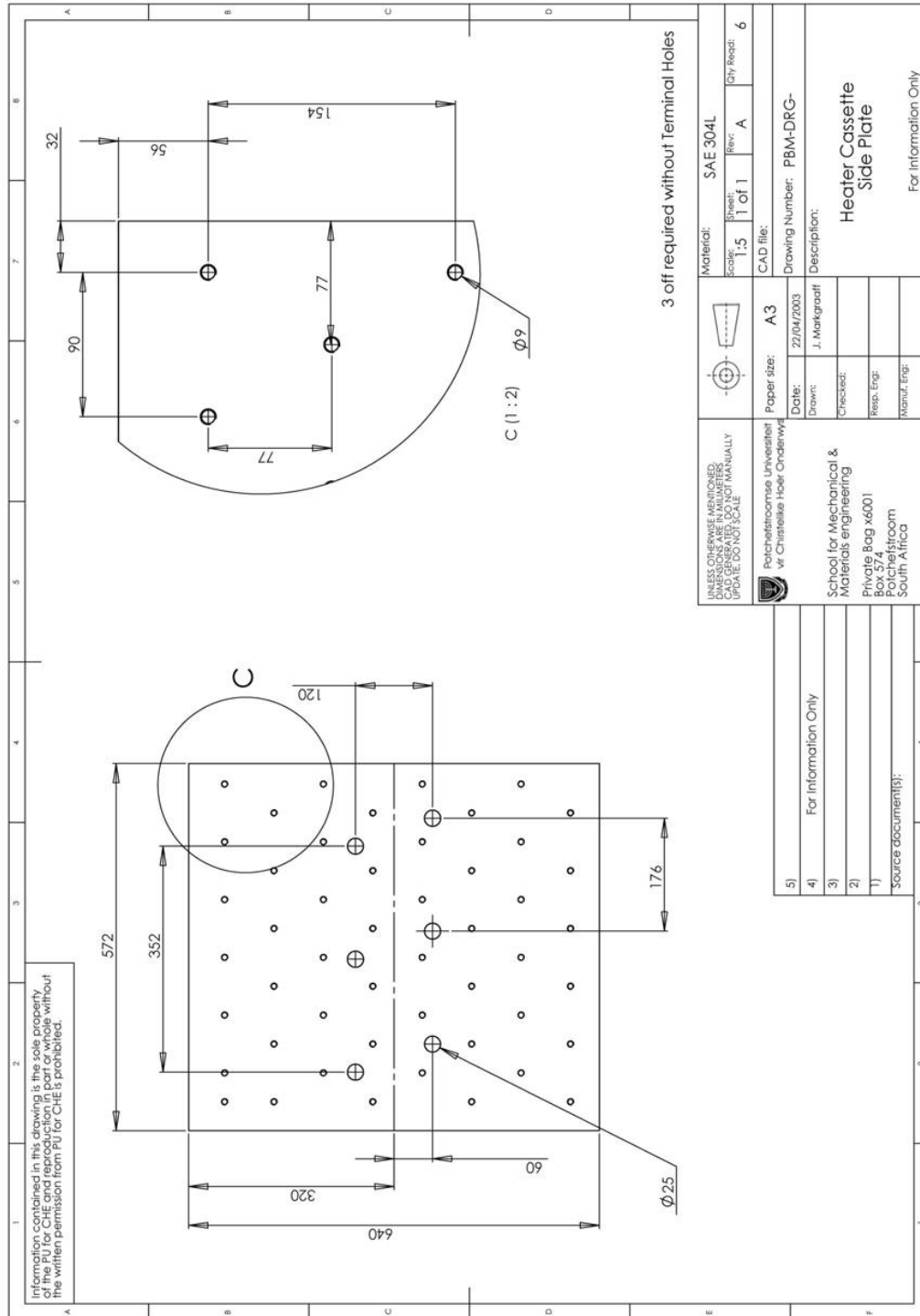
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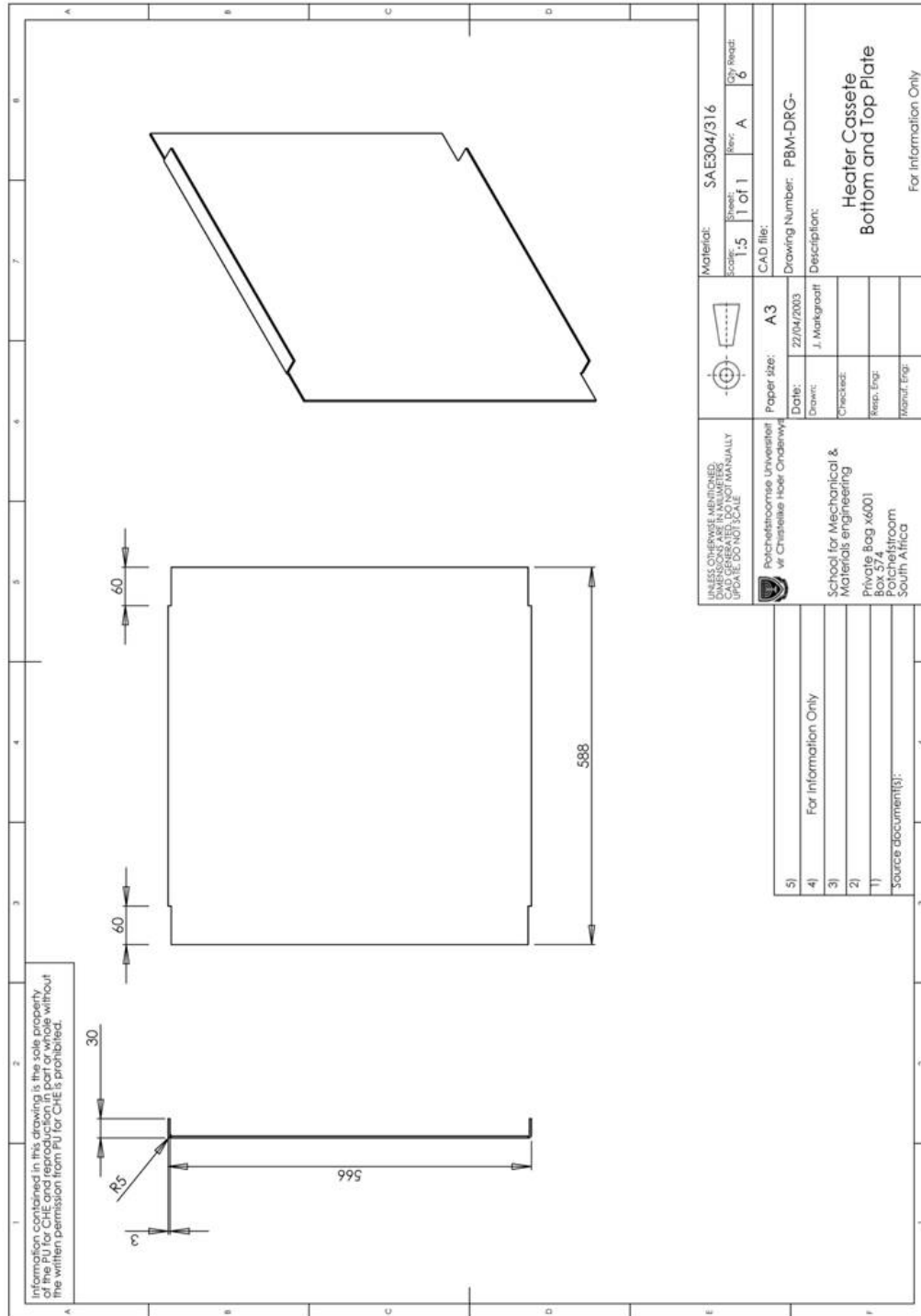
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Private Bag x6001
Potchefstroom
South Africa

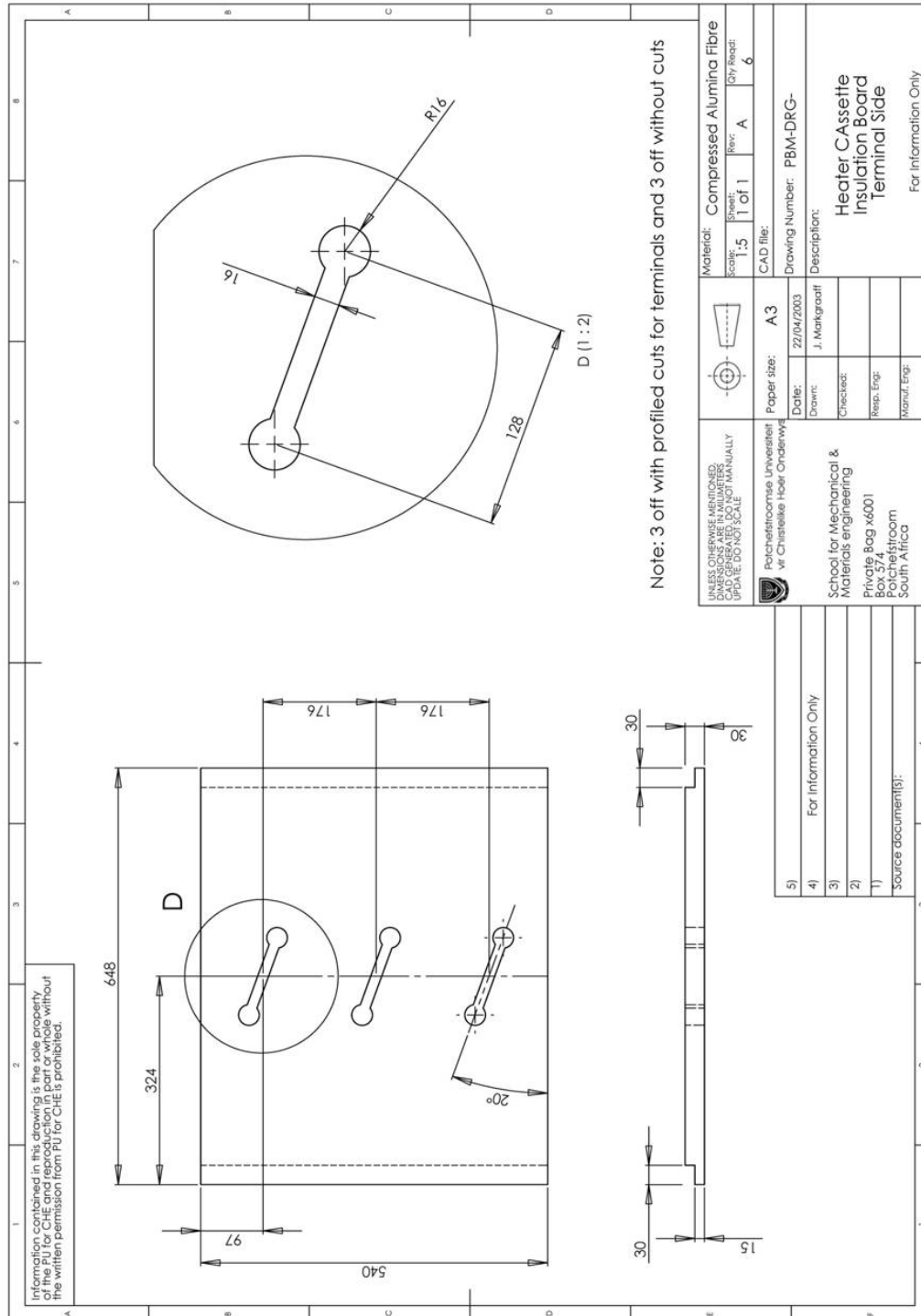
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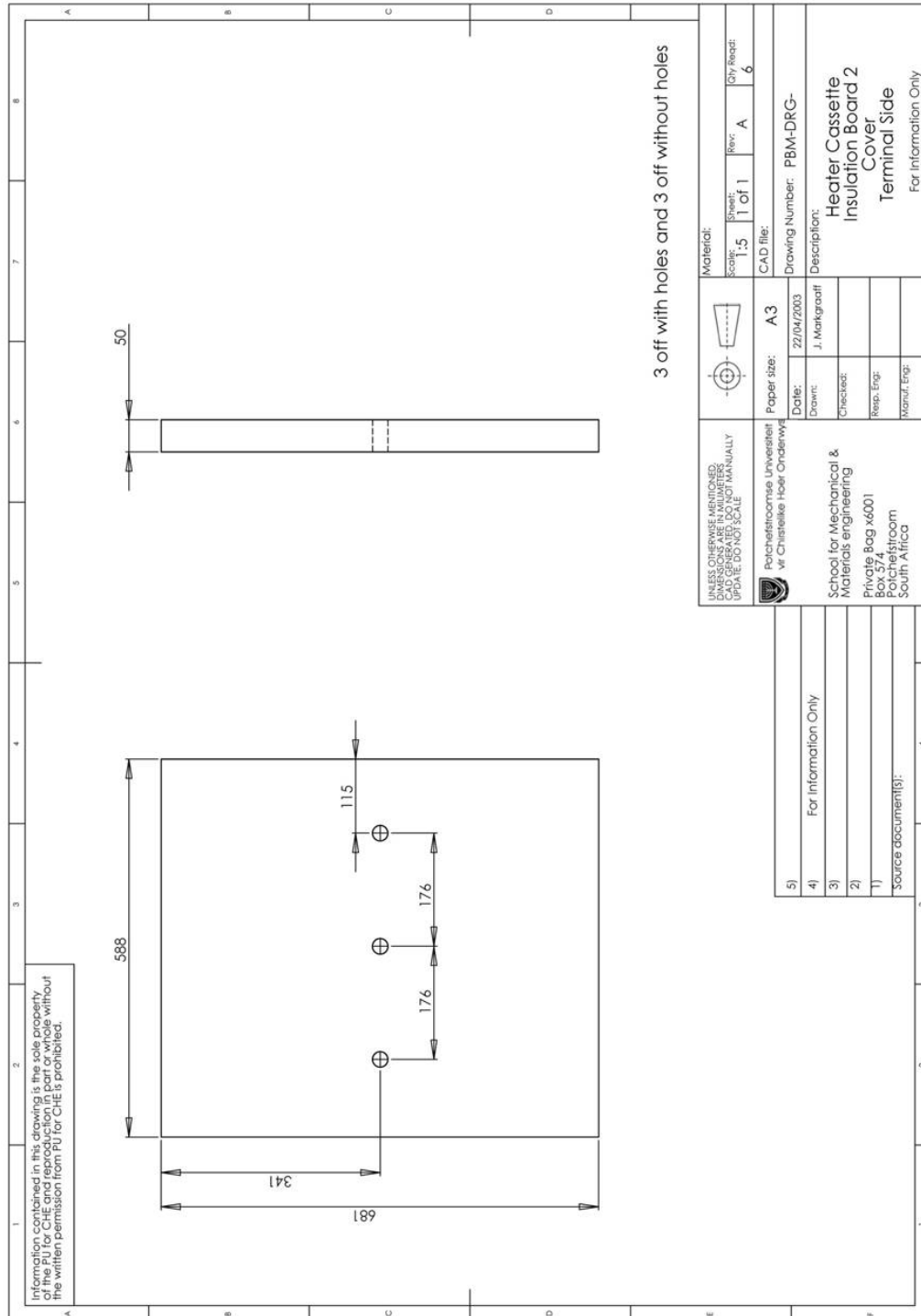
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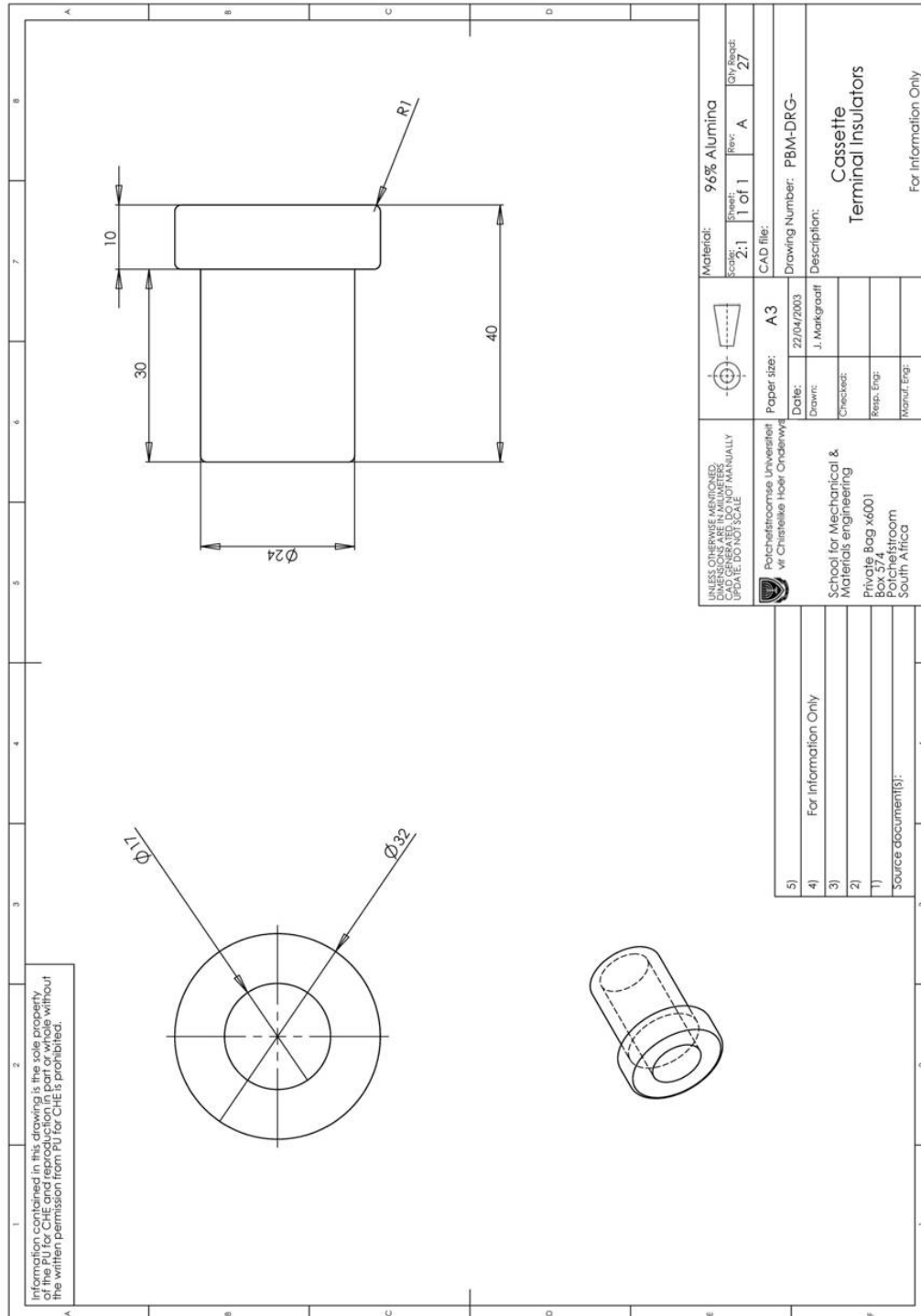
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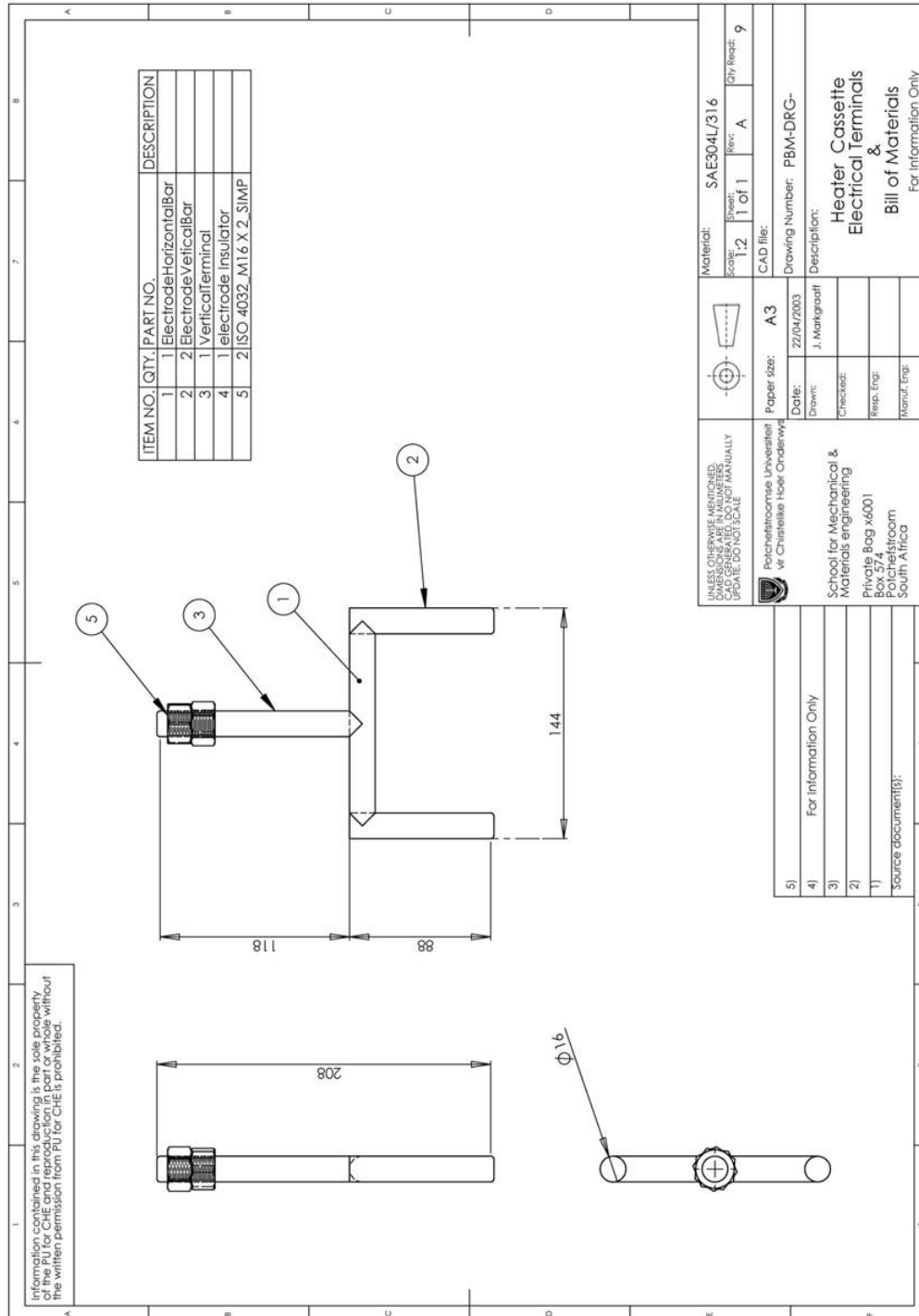


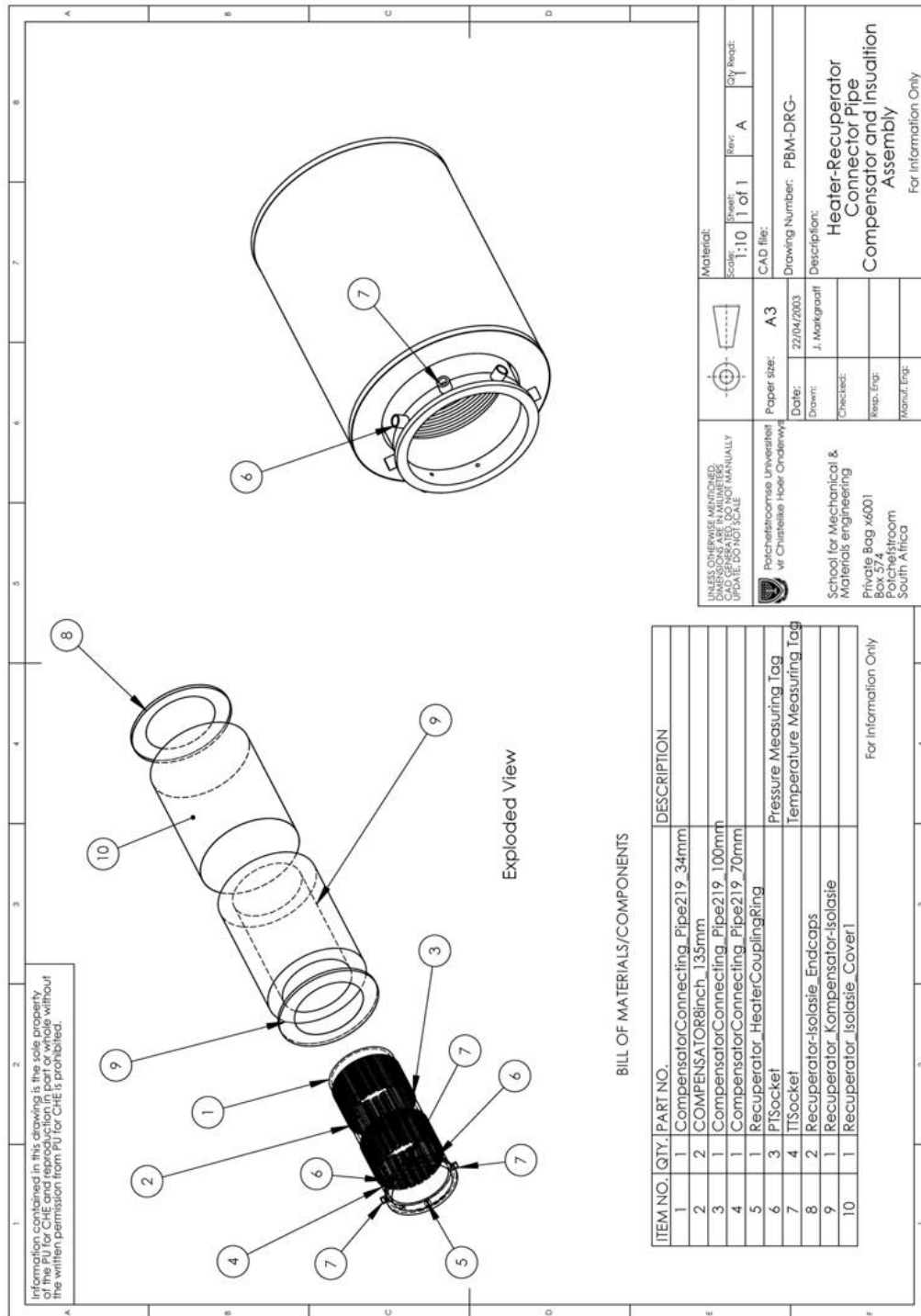


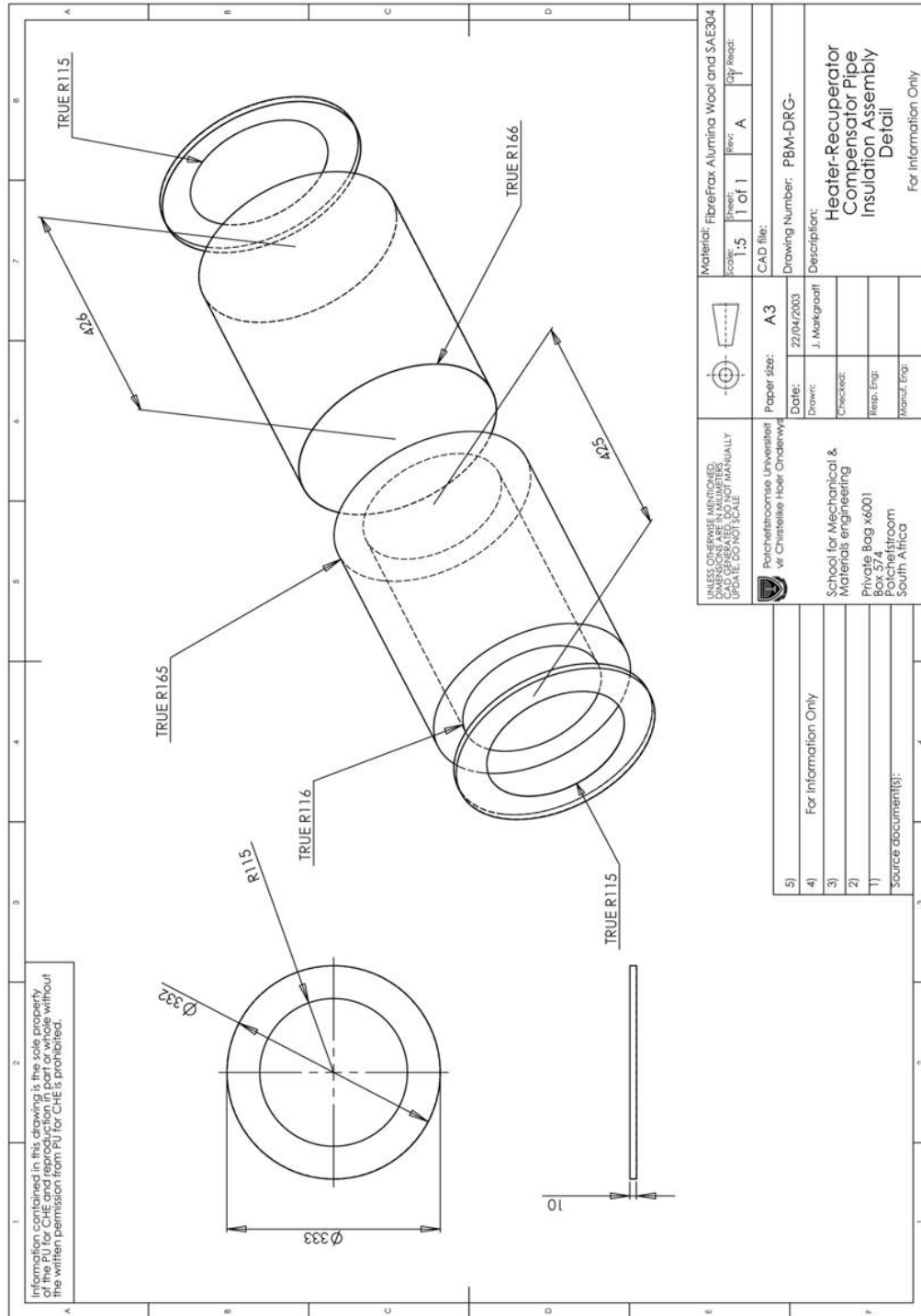




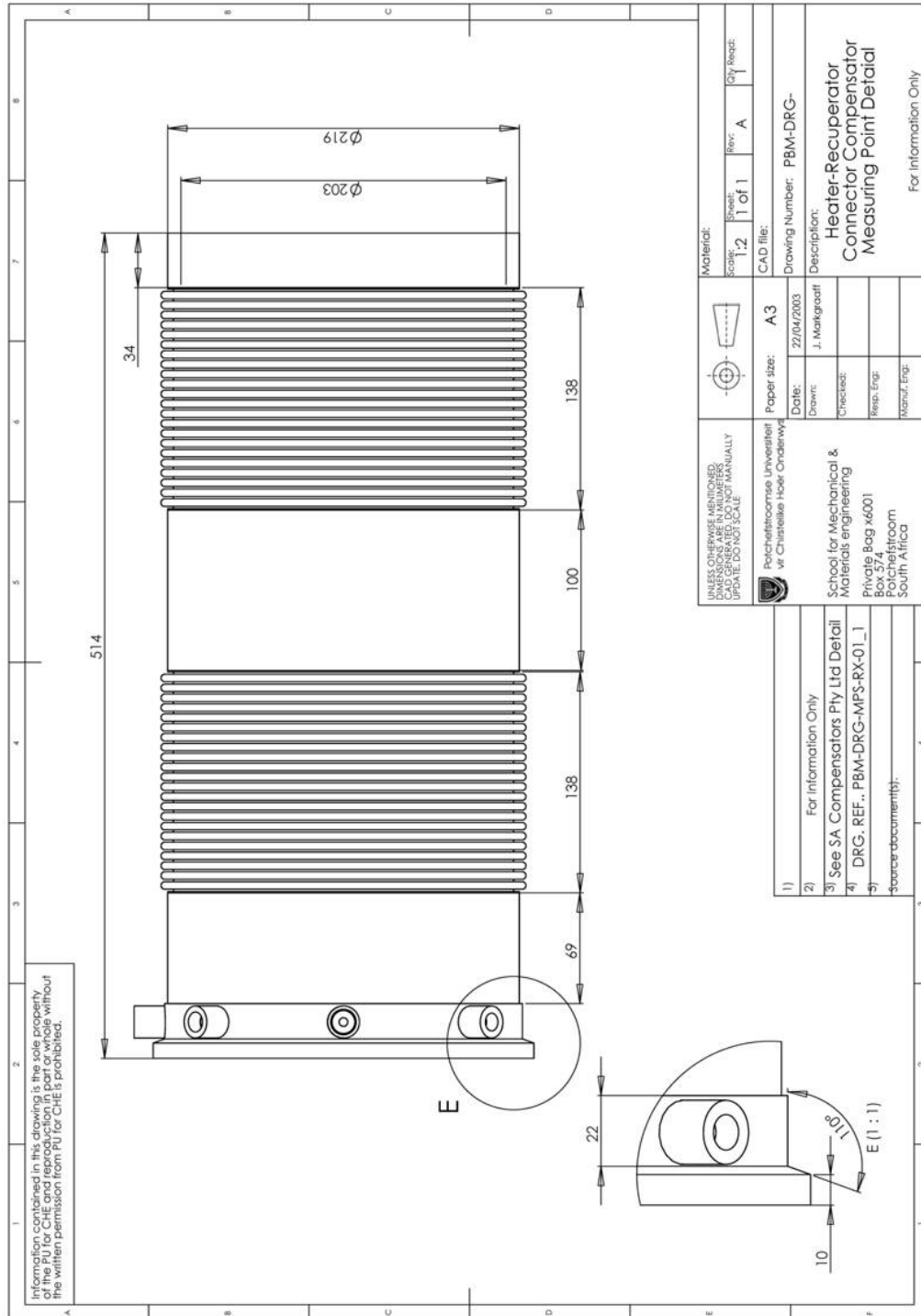


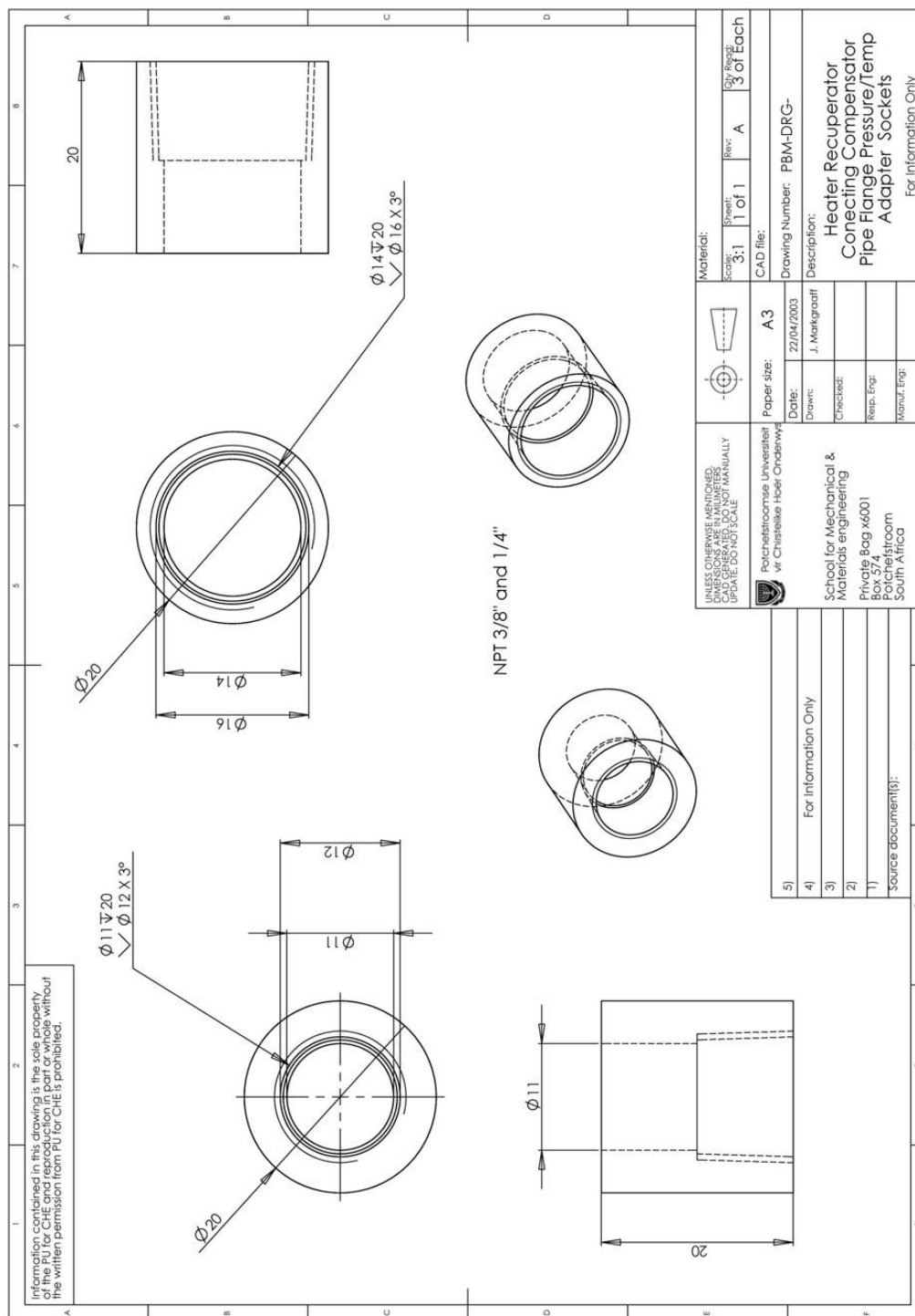


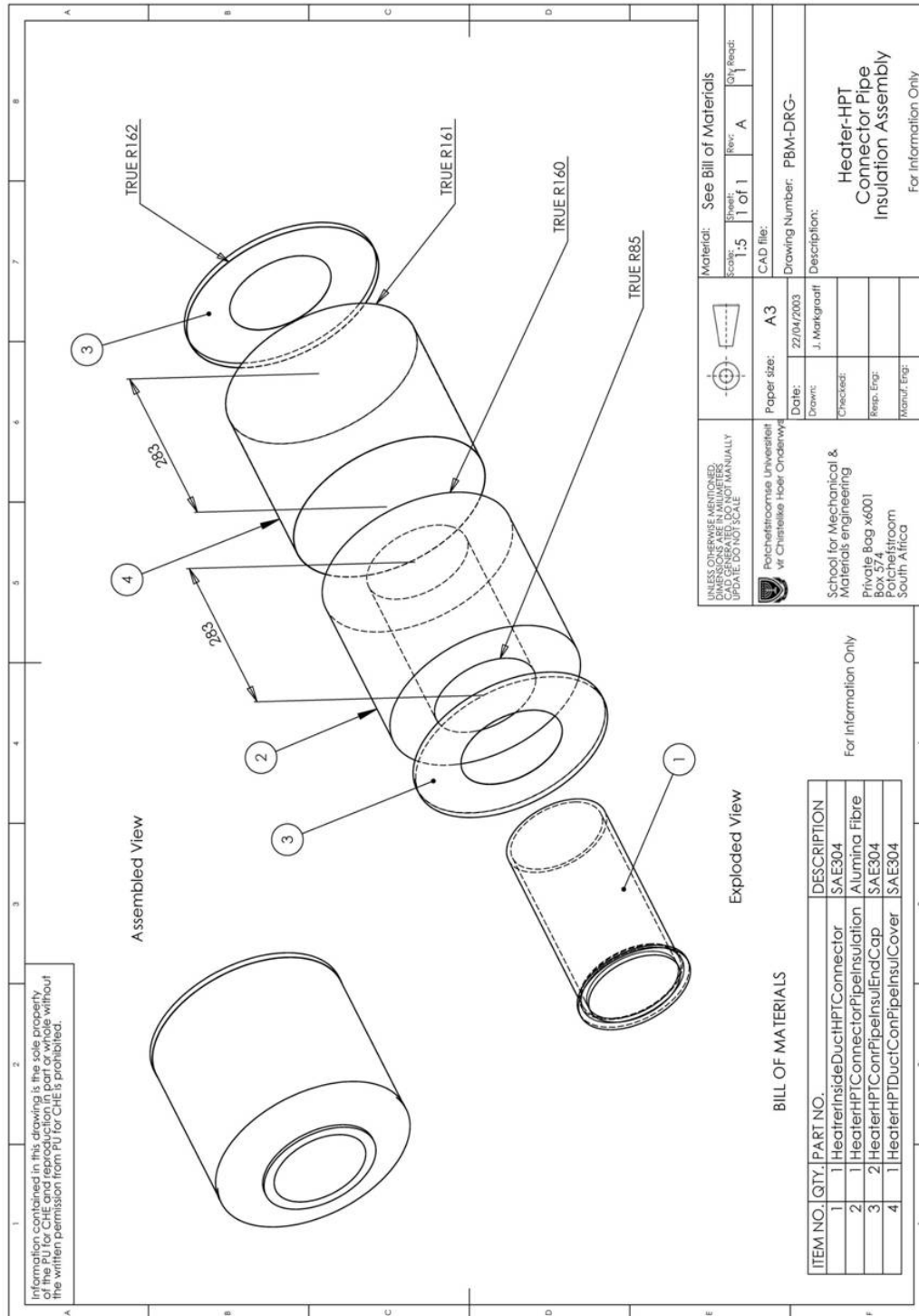


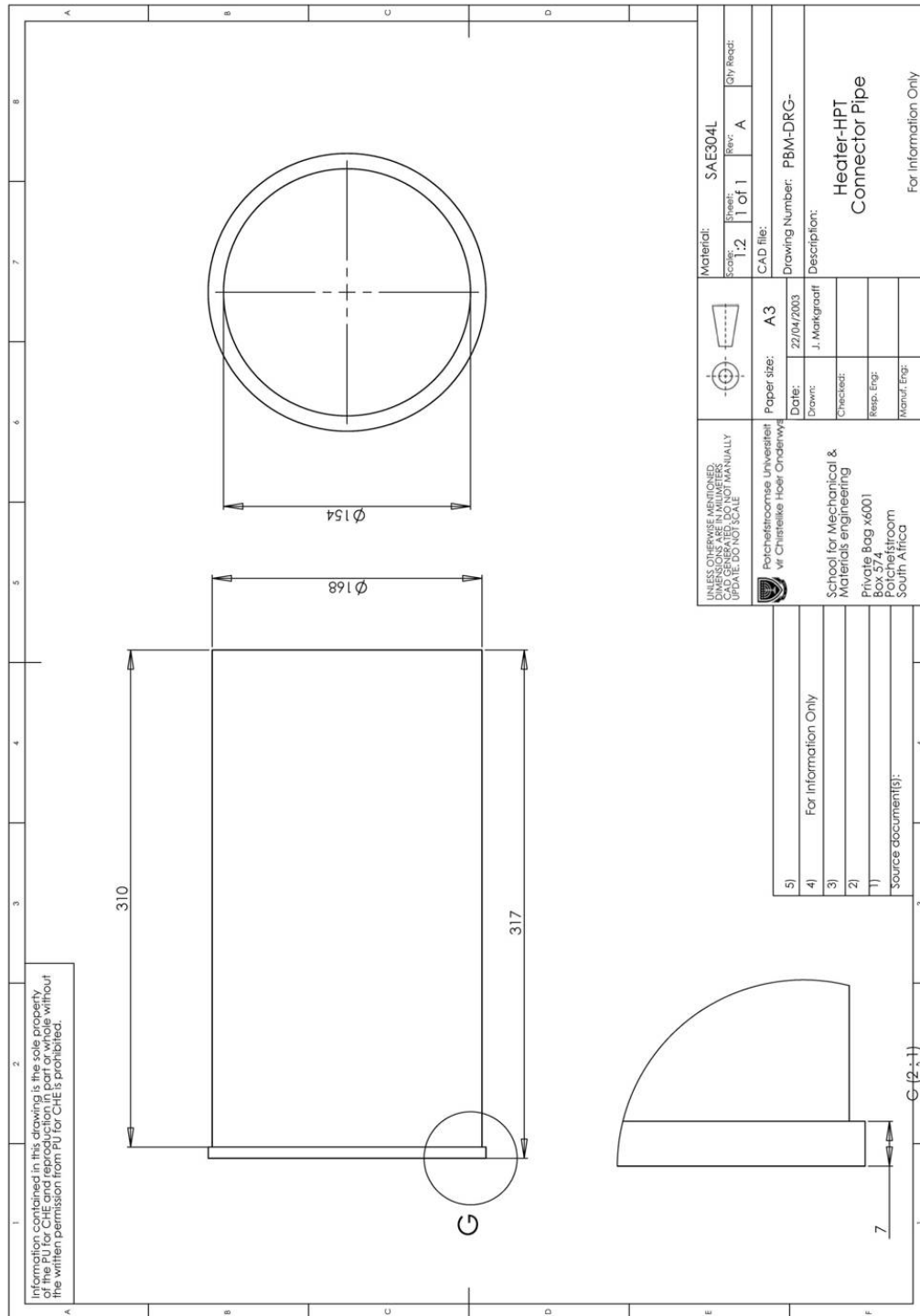


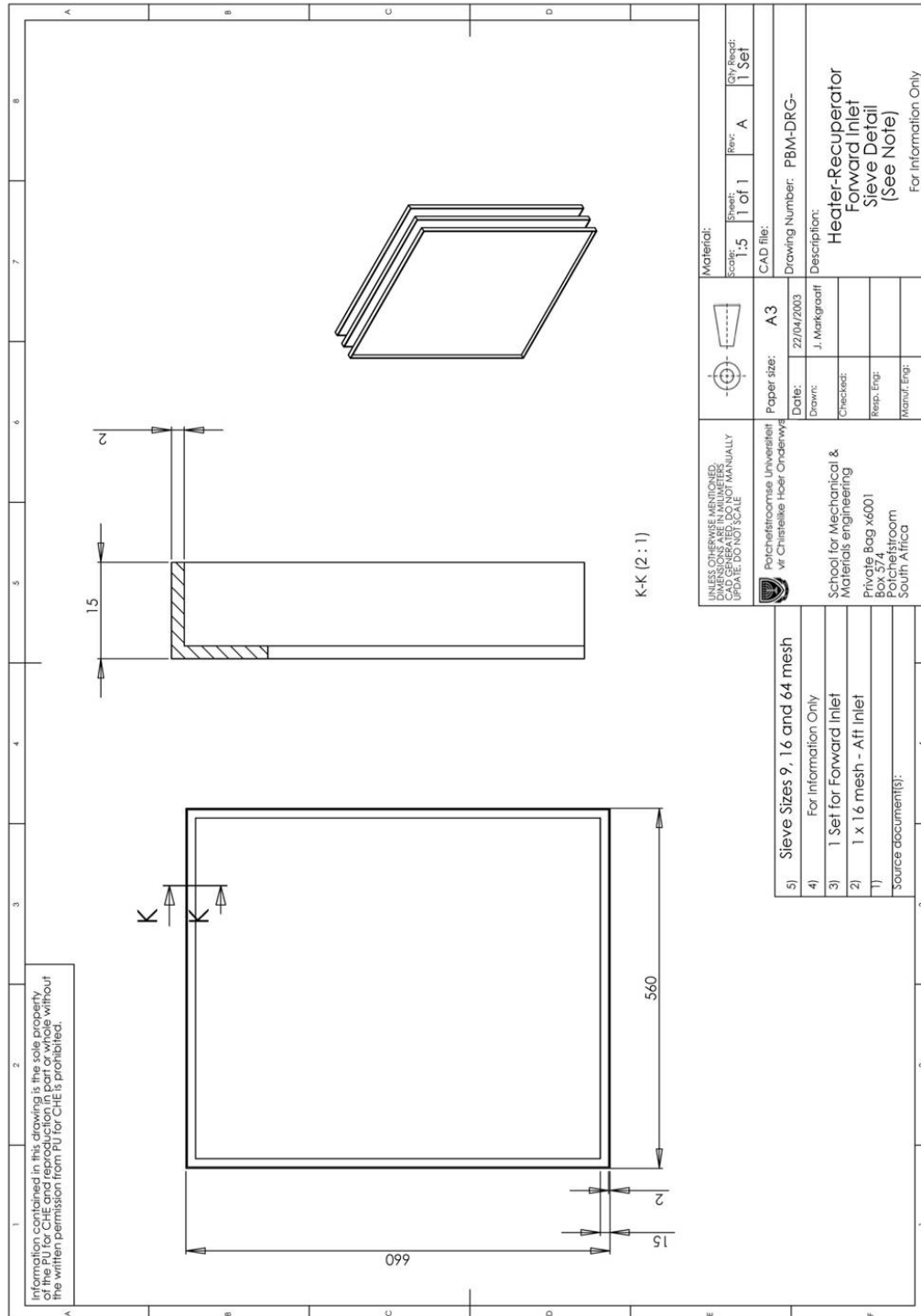
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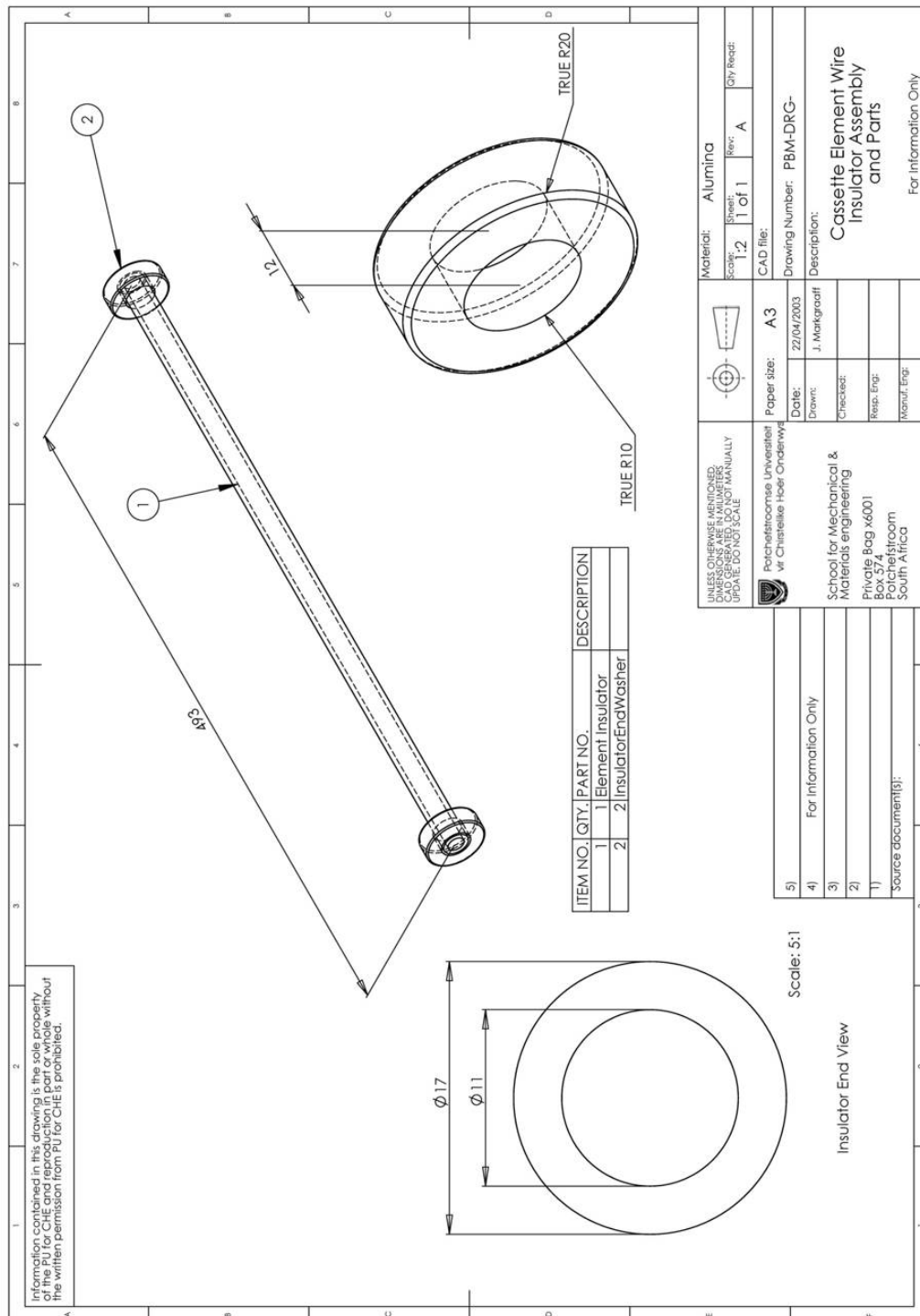


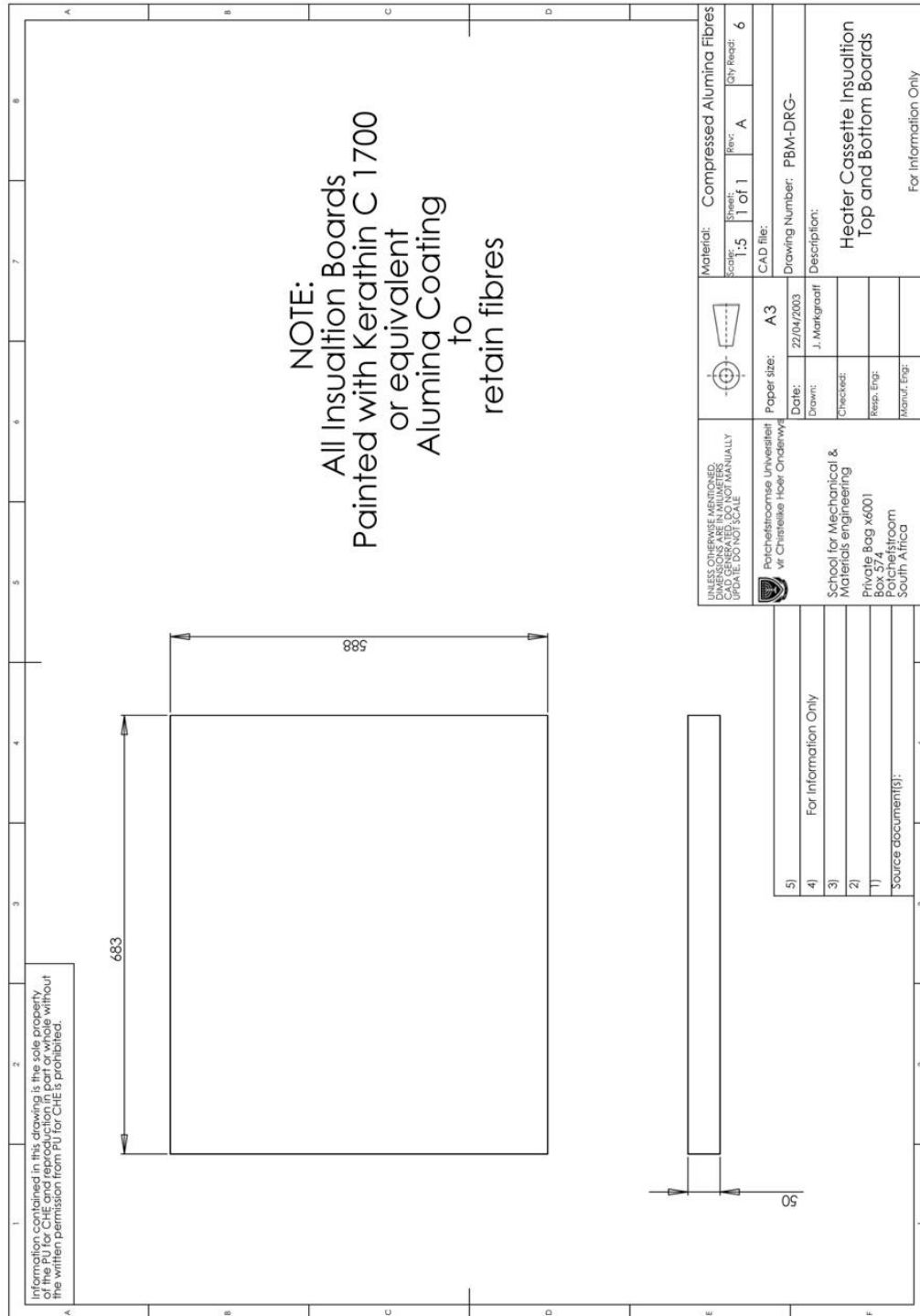


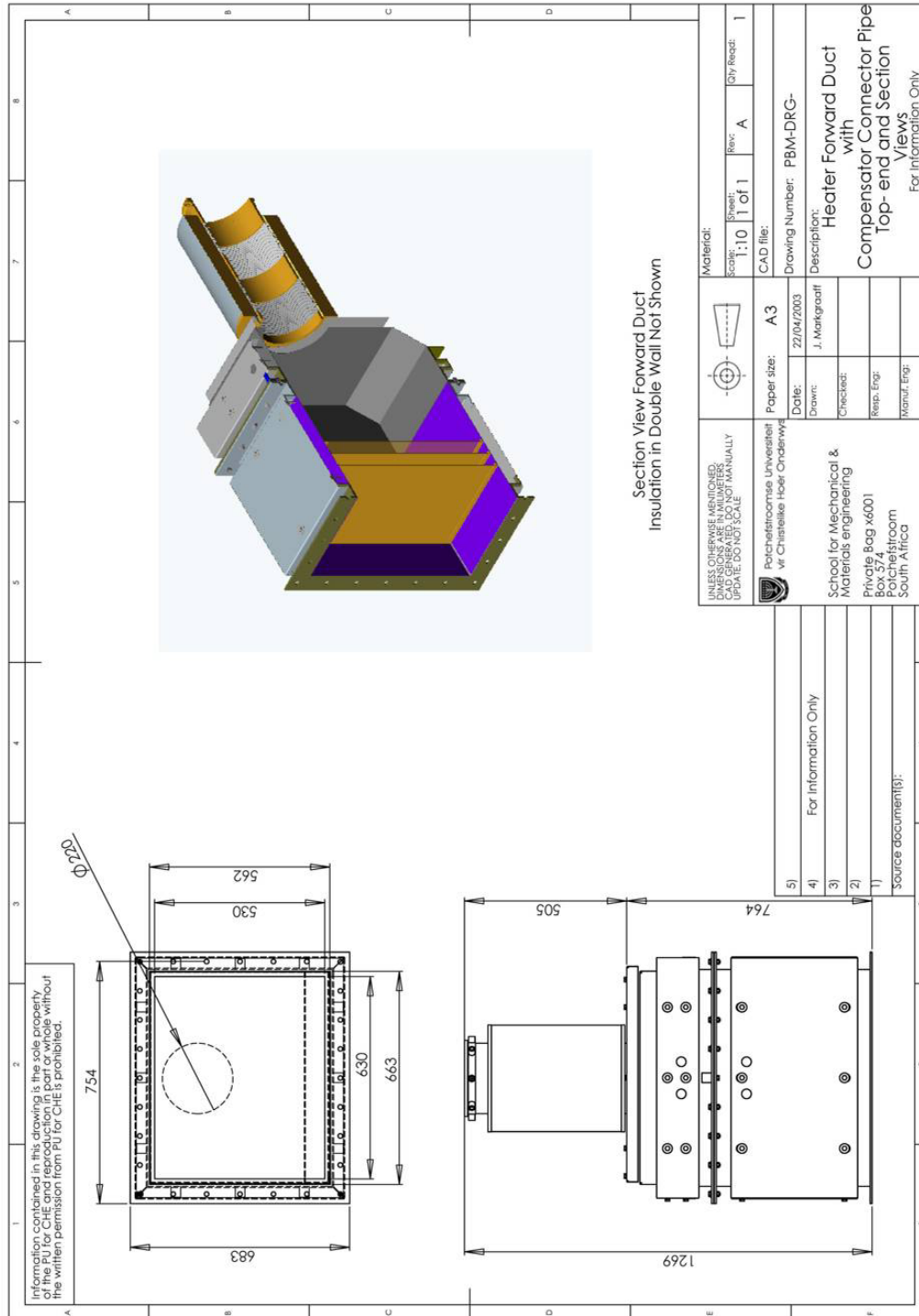


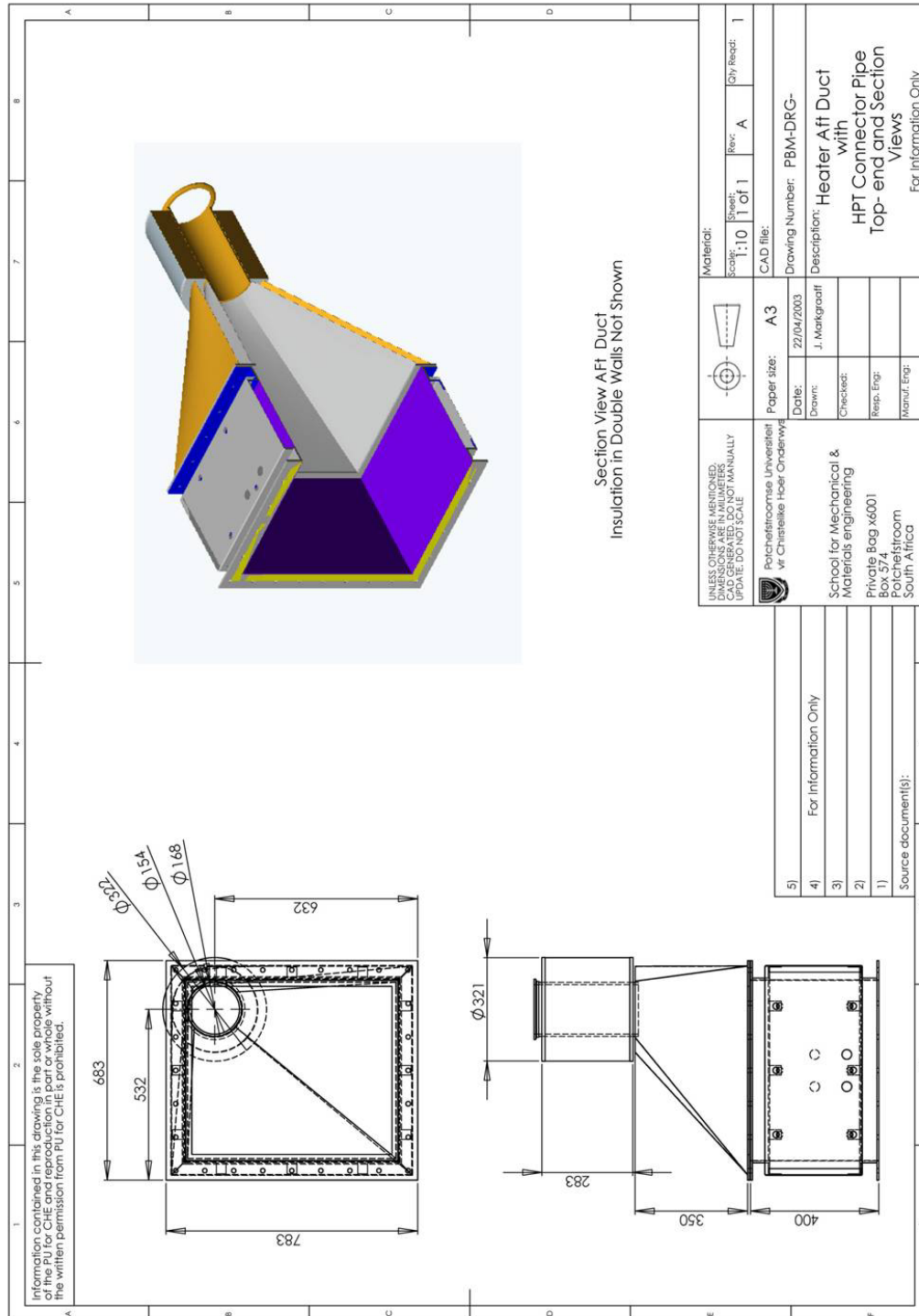












APPENDIX D

ACCOMPANYING CD-ROM

The attached CD-ROM contains the following files:

1. Dissertation JT Labuschagne 2003.pdf – This dissertation in electronic format.
2. Case Study.zip – Compressed file containing the Flownet network.
3. Case Study.sao – The Monte Carlo Analysis results file of the case study.
4. Monte Carlo C++.zip – Compressed file containing the C++ program of the Monte Carlo Analysis.
5. Chiller Comparison.xls - Comparison between Excel and C++ for the Chiller.
6. Linear Comparison.xls - Comparison between Excel and C++ for the linear model.
7. Polynomial Comparison.xls - Comparison between Excel and C++ for the polynomial model.
8. SD Correlation.xls – Correlation of the standard deviation.

All the files were created with Microsoft Office XP, Flownet and C++.