

**Thermal-fluid simulation of nuclear steam generator performance
using Flownex and RELAP5/mod3.4**

Charl Cilliers

Supervisor: Prof. P.G. Rousseau

Thesis submitted to the University of the North-West, Potchefstroom, in partial
fulfilment for the degree of
Master of Engineering (Nuclear Science and Engineering)

December 2012

Dedicated to the eternal pursuit of knowledge.

Abstract

The steam generator plays a primary role in the safety and performance of a pressurized water reactor nuclear power plant. The cost to utilities is in the order of millions of Rands a year as a direct result of damage to steam generators. The damage results in lower efficiency or even plant shutdown. It is necessary for the utility and for academia to have models of nuclear components by which research and analysis may be performed. It must be possible to analyse steam generator performance for both day-to-day operational analysis as well as in the case of extreme accident scenarios.

The homogeneous model for two-phase flow is simpler in its implementation than the two-fluid model, and therefore suffers in accuracy. Its advantage lies in its quick turnover time for development of models and subsequent analysis. It is often beneficial for a modeller to be able to quickly set up and analyse a model of a system, and a trade-off between accuracy and time-management is thus required.

Searches through available literature failed to provide answers to how the homogeneous model compares with the two-fluid model for operational and safety analysis. It is expected to see variations between the models, from the analysis of the mathematics, but it remains to be shown what these differences are.

The purpose of this study was to determine how the homogeneous model for two-phase flow compares with the two-fluid model when applied to a u-tube steam generator of a typical pressurized water reactor. The steam generator was modelled in both RELAP5 and in Flownex. A custom script was written for Flownex in order to implement the Chen correlation for boiling heat transfer. This was significantly less detailed than RELAP5's solution of a matrix of flow regimes and heat transfer correlations. The geometry of the models were based on technical drawings from Koeberg Nuclear Power Plant, and were simplified to a one-dimensional model. Plant data obtained from Koeberg was used to validate the models at 100%, 80% and 60% power output.

It was found that the overall heat transfer rate predicted with the RELAP5 two-fluid model was within 1.5% of the measured data from the Koeberg plant. The results generated by the homogeneous model for the overall heat transfer were within 4.5% of the measured values.

However, the differences in the detailed temperature distributions and heat transfer coefficient values were quite significant at the inlet and outlet ends of the tube bundle, at the bottom tube sheet of the steam generator. In this area the water-level was not accurately modelled by the homogeneous model, and therefore there was an under-prediction in heat transfer in that region. Large differences arose between the Flownex and RELAP5 solutions due to difference in the heat transfer correlations used. The Flownex model exclusively implemented the Chen correlation, while RELAP5 implements a flow regime map correlated to a table of heat transfer correlations.

It was concluded that the results from the homogeneous model for two-phase flow do not differ significantly when compared with the two-fluid model when applied to the u-tube steam generator at the normal operating conditions. Significant differences do, however, occur in lower regions of the boiler where the quality is lower. We conclude that the homogeneous model offers significant advantage in simplicity over the two-fluid model for normal operational analysis. This may not be the case for detailed accident analysis, which was beyond the scope of this study.

Keywords: Nuclear engineering, pressurized water reactor, U-tube steam generator, Flownex, RELAP5, thermal-fluid simulation

Acknowledgements

I would like to thank Professor Pieter Rousseau for his critical input as advisor and study leader for this project. Thanks go to the Department of Science and Technology and the National Research Foundation for financial assistance of this study. I would also like to thank Tommy Booysen and Randolph Damon from Koeberg Nuclear Power Plant (ESKOM) for dedicating time and putting in effort to provide data and support for the study. Furthermore, engineers at M-Tech Industrial who provided valuable input on the Flownex simulation, for which I am thankful for, were William Theron and Faan Oelofse. Lastly, thanks need to go to my family and friends. My parents, my uncle, my brother and the close support structure of friends that have all unknowingly contributed to this work in many ways.

Disclaimer

This work is based upon research supported by the South African Research Chairs Initiative of the Department of Science and Technology and National Research Foundation.

Any opinion, findings and conclusions or recommendations expressed in this material are those of the author(s) and therefore the NRF and DST do not accept any liability with regard thereto.

Contents

1	Introduction	1
1.1	Background	1
1.1.1	Pressurised Water Reactors	2
1.1.2	Steam Generators	2
1.1.3	Computer Modelling and Simulation of Steam Generators	4
1.2	Motivation	5
1.3	Problem Statement	6
1.4	Methodology	6
2	Overview of the Literature	8
2.1	Issues facing Steam Generator operators	8
2.1.1	Degradation of the primary side	8
2.1.2	Degradation of the secondary side	9
2.1.3	The cost effect of degradation	9
2.1.4	The effect of degradation on heat transfer and efficiency	9
2.1.5	Concluding remarks regarding issues faced in steam generator operation . .	10
2.2	Thermal-fluid models of two-phase flow	11
2.2.1	Multi-phase flow and phase transitions	11
2.2.2	Chen correlation for the nucleate boiling heat transfer coefficient	14
2.2.3	Two-fluid model	16
2.2.4	Homogeneous model	17
2.3	Simulating steam generators using thermal-hydraulic codes	18
2.3.1	Flownex	19

2.3.2	RELAP5/Mod3.4	20
2.3.3	Previous work on steam generator models	21
3	Basis for the Models	22
3.1	Data obtained from Koeberg Nuclear Power Station	22
3.1.1	Statistical analysis of the data	24
3.2	Preliminary steady-state calculations	27
3.3	Simplification of the geometry	29
3.4	Geometry and Heat Structure inputs	34
3.5	Model Development	35
3.5.1	RELAP5 - Two-Fluid	35
3.5.2	RELAP5 - Homogeneous	37
3.5.3	Flownex	38
4	Results and discussion	41
4.1	Comparison with empirical data	41
4.1.1	100% Power Output	41
4.1.2	80% Power Output	42
4.1.3	60% Power Output	42
4.2	Detailed inter-model comparisons	43
4.2.1	Primary side temperatures	43
4.2.2	Quality through the boiler	45
4.2.3	Heat transfer coefficient on the surface of the tubes	47
4.2.4	Flow velocity through the boiler region	48
4.2.5	Tube surface temperature on secondary side	51
4.2.6	Heat flux on the surface of the tubes	52
4.3	Summary of inter-model comparison	54
5	Conclusions and Recommendations	56
5.1	Conclusions	56
5.2	Improvements and Recommendations	59

CONTENTS

6	Potential for Future Work	61
6.1	Model improvements	61
6.2	Model alterations	61
6.3	Transient analysis	61
6.4	Model extensions	62
	References	63
A	Primary Conditions EES script	66
B	Two-fluid parameters EES script	68
C	Chen correlation C# script	70
D	RELAP5 Code	80
E	Inputs to the Flownex Model	96

List of Figures

1.1	Simplified diagram of a PWR connected to the power-producing side of the power plant (Kok, 2009)	3
1.2	Diagram of a typical steam generator used in a PWR (Bonavigo and de Salve, 2011) .	3
1.3	Quantitative research methodology with model development	7
2.1	Various boiling regimes that occur within a two-phase fluid (Ishii and Hibiki, 2006) .	12
2.2	Flow regime matrix for vertical flow used in RELAP5 for boiling heat transfer calculations (RELAP5, 2001c)	13
2.3	The boiling and condensing curve used by RELAP5 to calculate heat flux (RELAP5, 2001b)	14
2.4	Typical nodalization for the model of a steam generator	18
3.1	General geometry of the Koeberg SG (ESKOM)	30
3.2	Inlet plenum geometry used for the model)	31
3.3	Geometry of the boiler region	31
3.4	Geometry of the riser region	32
3.5	Geometry of the separator region	32
3.6	Geometry of the dryer region	33
3.7	Geometry of the steam dome region	33
3.8	Nodalization of the steam generator model for RELAP5	36
3.9	Nodalization of the steam generator model for Flownex	38
4.1	Primary side fluid temperatures at 100% power output	44
4.2	Primary side fluid temperatures at 80% power output	44
4.3	Primary side fluid temperatures at 60% power output	45

LIST OF FIGURES

4.4	Secondary quality through the boiler region at 100% power output	46
4.5	Secondary quality through the boiler region at 80% power output	46
4.6	Secondary quality through the boiler region at 60% power output	47
4.7	Heat transfer coefficient on the surface of the tubes at 100% power output.	48
4.8	Heat transfer coefficient on the surface of the tubes at 80% power output.	48
4.9	Heat transfer coefficient on the surface of the tubes at 60% power output.	49
4.10	Flow velocity through the boiler region at 100% power output.	49
4.11	Flow velocity through the boiler region at 80% power output.	50
4.12	Flow velocity through the boiler region at 60% power output.	50
4.13	Secondary surface temperatures on the tubes 100% power output.	51
4.14	Secondary surface temperatures on the tubes 80% power output.	51
4.15	Secondary surface temperatures on the tubes 60% power output.	52
4.16	Heat flux on the surface of the tubes at 100% power output.	53
4.17	Heat flux on the surface of the tubes at 80% power output.	53
4.18	Heat flux on the surface of the tubes at 60% power output.	54

List of Tables

2.1	Heat transfer correlations used in the various boiling regimes for RELAP5	13
2.2	Heat transfer correlations used in the various boiling regimes for Flownex	14
2.3	Advantages and Disadvantages to using Flownex and the homogeneous model. . .	20
2.4	Advantages and Disadvantages to using RELAP5 and the two-fluid model.	20
3.1	Sample of the steady-state data obtained from a single unit at Koeberg Nuclear Power Station	23
3.2	Statistical analysis of steady-state plant operating data at 100% power output.	25
3.3	Statistical analysis of steady-state plant operating data at 80% power output.	26
3.4	Statistical analysis of steady-state plant operating data at 60% power output.	27
3.5	Volumetric inputs for the steam generator model	34
3.6	Heat structure inputs for the steam generator model	35
3.7	Boundary conditions specified to RELAP5 for 100% power output.	37
3.8	Boundary conditions specified to RELAP5 at 80% power output.	37
3.9	Boundary conditions specified to RELAP5 for 60% power output.	37
3.10	Boundary conditions specified to Flownex for 100% power output.	39
3.11	Boundary conditions specified to Flownex for 80% power output.	40
3.12	Boundary conditions specified to Flownex at 60% power output.	40
4.1	Steady-state validation of the model at 100% power output	41
4.2	Steady-state validation of the model at 80% power output	42
4.3	Steady-state validation of the model at 60% power output	43

Nomenclature

Terms and Acronyms

CFD Computational Fluid Dynamics

CFD Computational Fluid Dynamics

EPRI Electric Power Research Institute

HTGR High Temperature Gas Reactor

LOCA Loss of Coolant Accident

MSLB Main Steam Line Break

NNR South African National Nuclear Regulator

nodalization A network of nodes and components connected to form a system, shown in diagram form in Figure 2.4

NPP Nuclear Power Plant

PWR Pressurised Water Reactor

SG Steam Generator

SSE Safe Shut-down in event of Earthquake

UTSG U-tube Steam Generator

Constants and Variables

$\dot{m}$ Mass flow-rate (kg/s)

A Area (m^2)

α_k The void fraction of phase k

α_{kw} Void fraction at the wall

NOMENCLATURE

Γ_k	Mass generation for phase k
μ	Viscosity ($\frac{kg}{m \cdot s}$)
ρ	Density ($\frac{kg}{m^3}$)
ρ_k	Density of phase k (kg/m ³)
Σ	Stress tensor (Navier-stokes)
Σ^T	Turbulent stress tensor
τ_{kw}	Shear stress at the wall
M_k^d	Inter-facial shear force
ζ_h	Heated perimeter (m)
C_{hk}	Distribution parameter for the k phase enthalpy
D_h	Hydraulic diameter (m)
d_i	Inner diameter of the tubes
d_o	Outer diameter (m)
h_i	Inlet enthalpy (kJ/kg)
h_o	Outlet enthalpy (kJ/kg)
k_L	Coefficient of heat conduction for the liquid
k_w	Thermal conductivity of the wall material ($\frac{W}{m^2 K}$)
p_{st}	Saturation pressure (Pa)
q''_{kw}	Heat flux at the wall (W/m^2)
R_f	Fouling factor, or resistance to heat transfer due to fouling ($\frac{m^2 K}{W}$)
Re	Reynolds number - dimensionless
v	Flow velocity ($\frac{m}{s}$)
v_k	Average velocity of phase k (m/s)
h_{tp}, h_{nb}, h_{cb}	Heat transfer coefficients for two-phase flow, nucleate boiling and convective boiling respectively
U	Over-all heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)

Introduction

1.1 Background

Nuclear power plants around the world produced 369 Gigawatts of electricity at the end of 2011 (IAEA, 2012). The types of nuclear reactors are described in various introductory texts (Lamarsh and Baratta, 2001; Lewis, 2008; Shultis and Faw, 2002). Most nuclear reactors sustain a fission chain reaction which provides heat to a flowing coolant. The coolant may either boil and drive a set of turbines directly, or it may be under pressure and transfer heat to a secondary side used for boiling and power generation. As of March 2012, there were 436 nuclear power plants (NPP) in operation around the world, of which 272 were pressurised water reactors (PWR) (IAEA, 2012). PWRs thus accounted for 67% of the installed nuclear power capacity. In addition, 51 of the 63 new reactors under construction around the world as of early 2012 are also of the PWR type (IAEA, 2012). The PWR's critical primary components include the nuclear reactor, pressurizer and steam generators (SG). The SGs transfer the primary side heat to feed-water on the secondary side, producing steam. The steam is then used to drive a set of turbines that produces electrical power.

The SGs in PWRs are designed for temperatures up to 340°C and pressures up to 18 MPa. In addition to the extreme conditions, the components are susceptible to many forms of degradation such as corrosion and mechanical wear from fluid induced vibrations. The two-phase boiling phenomenon occurs during the production of steam and is a complex process to model accurately. The information gained from an accurate thermal-fluid analysis may include predictions of local flow velocity, temperature, pressure and quality. These parameters are beneficial to the study of chemical reaction theory, solid deposition and water-hammer, all of which may impact negatively on SG performance.

A valid model of a steam generator is beneficial for predicting local flow parameters that may be used to supplement more complex studies of SG degradation or to make operational decisions.

1.1.1 Pressurised Water Reactors

Many introductory texts give a general description of a typical PWR (Lamarsh and Baratta, 2001; Lewis, 2008; Shultis and Faw, 2002). A simplified schematic diagram is given in Figure 1.1. The nuclear reactor, primary pump, pressurizer and steam generator systems are collectively referred to as the primary loop. The reactor controls a chain reaction of nuclear fission in the reactor core, while pressurized light water at approximately 15 MPa and 290°C enters the reactor vessel and flows over the fuel assemblies to ensure neutron moderation and cooling. The hot water exits the vessel at about 325°C and is directed from the reactor core to a steam generator. From there the heat is transferred to the secondary side feed-water to produce steam. The primary coolant will not boil significantly under design conditions at this pressure.

The secondary loop components receive heat from the primary loop and houses the high and low-pressure turbines, the electrical generator, condenser and re-heaters. The steam in a PWR usually comes from up to 4 SGs, and is produced at approximately 5 MPa and at saturation or super-heated temperatures (Lamarsh and Baratta, 2001). This gives the PWR a typical cycle efficiency of 32 to 33% (Lamarsh and Baratta, 2001).

The pressurizer in the PWR primary containment loop has the role of regulating and maintaining the pressure at approximately 15 MPa. Due to the incompressibility of water, a small volume change may have undesired effects on the pressure in the system, and may lead to boiling of the coolant. This could lead to exposure and burning of some fuel assemblies. When a reduction in load occurs and the primary temperature increases, the pressure necessarily rises. The rise in pressure raises the level in the pressurizer and actuates a spray nozzle that quenches the steam using water directed from the cold leg of the reactor. The quenching of the steam once again lowers the pressure, and in this way the primary coolant is maintained at a constant operating pressure.

1.1.2 Steam Generators

Steam generators may be categorized into vertical or horizontal vessels, with vertical vessels being most commonly used in PWRs (Green and Hetsroni, 1995). Of the vertical designs, the U-tube steam generator (UTSG) and once-through steam generators are most common, with the U-tube steam generator dominating in PWR designs since 1957 (Green and Hetsroni, 1995). A diagram of a typical UTSG is shown in Figure 1.2.

The UTSG was developed for the first PWR at Shippingport, U.S.A in 1957. It was developed by the Westinghouse Electric Company (Shultis and Faw, 2002). It receives hot water from the reactor and directs it through a large number of tubes oriented vertically upwards and then downwards in a U-shape. Heat is transferred to the secondary flow of water over the outside of the tubes as the primary coolant flows up and down through the interior of the tubes. The feed-water boils

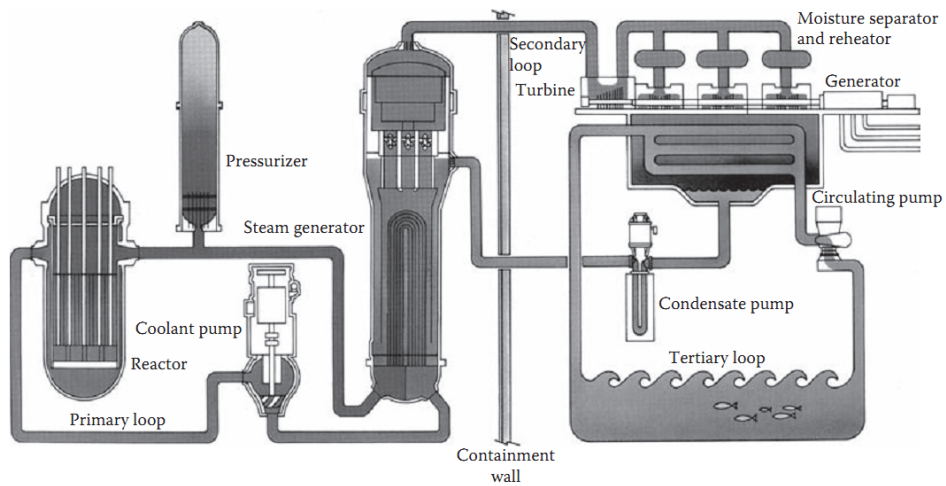


Figure 1.1: Simplified diagram of a PWR connected to the power-producing side of the power plant (Kok, 2009)

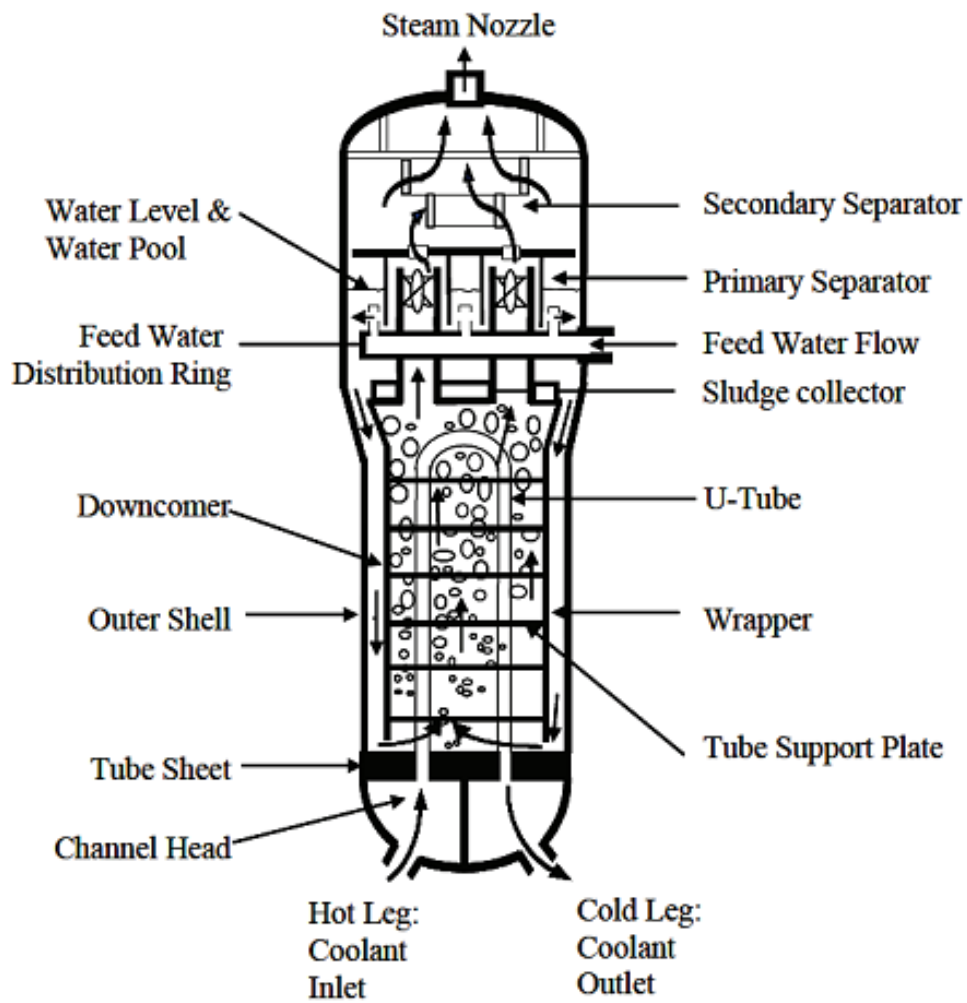


Figure 1.2: Diagram of a typical steam generator used in a PWR (Bonavigo and de Salve, 2011)

and the excess moisture is removed to produce saturated steam.

In all PWRs, the SGs provide a primary barrier from radiation between the primary side of the plant and the secondary side (Lamarsh and Baratta, 2001). The steam generators thus play a critical role in keeping radioactive materials inside the containment of the nuclear power plant. This is the primary reason why the integrity of the materials used in SGs must be ensured throughout the plant's lifetime. SG tubes are commonly manufactured from Ni-Cr-Fe alloys 600 or 690 which have been thermally treated or stress-relieved (Green and Hetsroni, 1995).

Another important parameter in the operation of the power plant is the steam pressure to the turbines (Bonavigo and de Salve, 2011). The steam temperature is governed by the outlet pressure, as the outlet steam is saturated. As high a pressure as possible is maintained, in order to maintain efficient expansion through the turbines (Kolev, 2007). Inefficiencies in steam generator operation may result in a plant operating at a lower capacity than that which it was designed for (Bonavigo and de Salve, 2011).

SGs must be designed to be able to mitigate various accident scenarios such as small steam-line breaks, loss of feed-water, turbine trips, loss of coolant accidents (LOCA), main steam-line break (MSLB) and safe shut-downs in the event of an earthquake (SSE) (Green and Hetsroni, 1995).

1.1.3 Computer Modelling and Simulation of Steam Generators

The theory governing two-phase flow extends from the fluid mechanics of single phase flow. In general, for any number of phases, the conservation field equations of mass, momentum and energy hold true and are described in some fundamental and most advanced fluid dynamics textbooks (Ishii and Hibiki, 2006; Kreith, 1999).

The homogeneous model for two-phase flow considers the case where both phases of the fluid are at the same conditions, travelling at the same velocity and have the same properties, thus can be seen as one single homogeneous fluid. This is a reasonably simple approach, as there are only three simultaneous differential equations to solve. There are a number of constituent equations such as the equation of state, reaction rate equations and shear stress equations (eg. Navier-Stokes).

The two-fluid model or the separated model for two-phase flow considers the case where two phases may be viewed as two separate fluids, each for which the conservation and constituent equations hold. Thus, we have six simultaneous differential equations to solve. This approach is, in general, more complex and comes at a cost of processing power as well as financial and time investment (Preece and Putney, 1993).

RELAP5 has been successfully used in thermal-hydraulic studies for PWRs and SGs (Hoffer et al., 2011; Jeong et al., 2000; Lin et al., 1986; Nematollahi and Zare, 2008; Preece and Putney,

1993; Woods et al., 2009), but has been found to underestimate the secondary side heat-transfer due to the use of the Chen correlation for the convective heat transfer coefficient during phase transitions. This results in a lower pressure calculated than expected. The error in the pressure calculation that is to be expected using RELAP5/mod3 is approximately 0.4 MPa, at a total pressure of about 5 MPa (Preece and Putney, 1993). Errors may also be expected in the under-prediction of the liquid inventory on the secondary side, when using RELAP5/mod2. This error has been partially eliminated with the release of mod3, however, where the introduction of new inter-phase drag models resulted in an increase in the calculated inventory at full load conditions (Preece and Putney, 1993).

RELAP5 solves the six field equations of the two-fluid model for two-phase flow, and may use any of a number of algorithms designed to solve differential equations (such as the implicit or semi-implicit algorithms).

Flownex has been developed as a systems computational fluid dynamics (CFD) network solver. It has been validated and verified for use in simulating high temperature gas reactor (HTGR) technology utilizing a direct Brayton cycle (Greyvenstein and Rousseau, 2003). It has also been successfully used in gas-turbine combustion modelling (Gouws et al., 2006), as well as many other industrial applications in two-phase and single-phase flow (Flownex, 2011a,b,c).

Flownex solves the homogeneous field equations, thus inherently being simpler to implement and achieve convergence of the solution. The graphical user interface of Flownex is also more intuitive for the end-user than conventional codes from the 1960's through 1980's (ie. RELAP5).

1.2 Motivation

Fluid mechanics text books which describe the two-fluid model and the homogeneous model of two-phase flow do often give criteria and parameters for validity of the use of these models. Unfortunately, however, the turbulent conditions and the high temperatures and pressures found in the steam generator are not conducive to accurate modelling (Green and Hetsroni, 1995). It is extremely difficult to get accurate and consistent measurements from inside the SG, and it is also very difficult to characterise the foamy emulsion that is the steam/liquid mixture flowing over the tube bundle. It is therefore not clear and there is certainly a lack of literature describing how applicable the homogeneous model for two-phase flow is in the context of the nuclear steam generator performance.

The homogeneous model has a few disadvantages. One loses much of the flow information and characteristics when reducing the field equations to three from six, or from two-fluids to one. In many cases, however, this may be acceptable when compared to the subsequent saving of time and money in the project. The two-fluid model is, on the other hand, a very specific and accurate

way of modelling the flow of two-phases. It takes into account drag between the phases as well as momentum, energy and mass transfer between the phases. Of course, with an increase in accuracy there is a drastic increase in complexity of the model. It will require increased processing power, and the software is considerably more expensive.

It would therefore certainly be advantageous to the plant or component engineer to know when it may be suitable to make use of more financially sound resources and when it would necessitate a higher expenditure in time or money. Currently, the cost of participating in the development of complex steam generator simulation programs such as ATHOS (Singhal et al., 1984) and Triton (SG software from the Electric Power Research Institute) runs upwards of R1 million a year with a five year commitment.

Flownex is developed locally, and comes at a considerably lower price than competitor software, and is also more user friendly.

There are thus clear advantages and disadvantages to using either code-base, but very little guidance for the engineer to decide which software is more suitable.

1.3 Problem Statement

Issues with steam generators result in large annual monetary losses for utility companies world-wide. There are currently large amounts of uncertainties inherent in steam generator models. The turbulent and chaotic conditions in the SG make it difficult to accurately model and predict flow parameters.

There is little literature to describe conditions under which the various models are applicable. It is clear that when the phenomenon of boiling must be considered in-depth, that the homogeneous model will not be sufficient. It remains unclear, however, under which specific conditions it is acceptable to use the homogeneous model over the two-fluid model.

This study assesses the differences in the two models within the context of nuclear steam generators. It attempts to find at which conditions certain parameters show large variance between the models. It also aims to provide direction in the selection of the model type when performing SG analysis.

1.4 Methodology

Often, in modelling two-phase flow, the problem is simplified so that important features of the flow are retained and analysis is still meaningful (Kok, 2009).

The research methodology followed in this study is quantitative, in the form of model

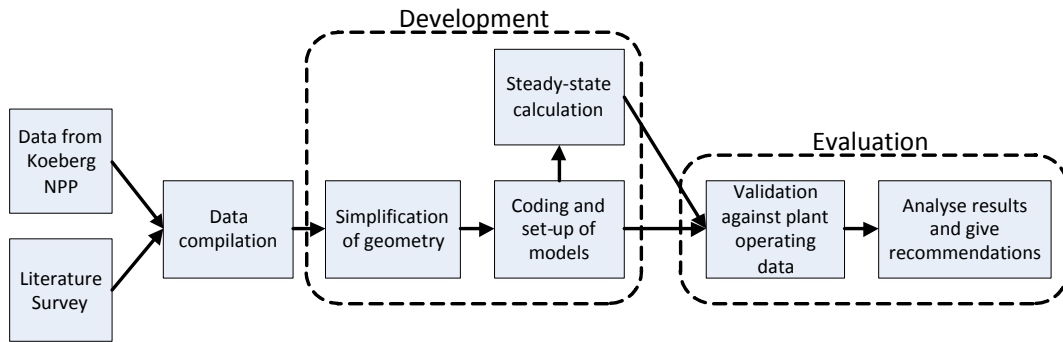


Figure 1.3: Quantitative research methodology with model development

development and evaluation.

Specifications of a PWR steam generator obtained from Koeberg Nuclear Power Plant form the basis of the models. The models are verified with a steady-state calculation in EES. The primary conditions are obtained from this calculation as there was no primary data supplied by Koeberg. The verification ensures simple mathematical consistency between the input and output conditions. It is not feasible to re-write the fluid models for verification purposes, as RELAP5 has been verified in previous studies (RELAP5, 2001d).

Validation is done against secondary side operating data supplied by Koeberg. The results from the RELAP5 and Flownex models are tabulated and the deviation from the plant data is recorded. The results form a set of comparisons in graphic form between the two models at various power levels. This provides a sound basis for making recommendations on further improvements and future extensions to the model. The research methodology is summarised in Figure 1.3.

Overview of the Literature

2.1 Issues facing Steam Generator operators

A major issue with steam generator operation is the degradation of materials used in its construction (Bonavigo and de Salve, 2011).

Uranium, trans-uranium elements and fission products may occur in the primary coolant and are caused by defects in the fuel rod cladding. They may also result from free uranium particles in the coolant also under-going fission (Bonavigo and de Salve, 2011). Corrosion products from the shell, tube and support structures may also contaminate primary or secondary water. These conditions increase the need for inspection, cleaning, maintenance and safe decommissioning of any particular SG.

For this reason, it is important to monitor and model carry-over of liquid by the SG, as damage to the turbine may have severe consequences for the plant (Bonavigo and de Salve, 2011). It is also useful to include solid accumulation and chemical reactions in the model of the SG, as the quality and chemical parameters of the water (such as pH, Boric Acid concentration, Chlorides concentration, Impurity content and dissolved Oxygen) play a large role in degradation (Bonavigo and de Salve, 2011).

2.1.1 Degradation of the primary side

Some of the degradation that has been observed in the primary side of SGs are (Diercks et al., 1999; Green and Hetsroni, 1995; Riznic, 2009; Schwarz, 2001):

- Stress corrosion cracking and inter-granular attack.
- Tube plugging.
- Tube denting.

- Flow-induced vibrations.
- Tube leakage.
- Tube support fretting.

2.1.2 Degradation of the secondary side

For the secondary side, some examples of degradation include (Bonavigo and de Salve, 2011; Schwarz, 2001) :

- Tube support degradation.
- Tube fouling (build up of magnetite on the outside of the tubes resulting in lower thermal efficiency).
- Secondary side deposits and sludge build-up.

These issues occur primarily in steam generators which formed part of the original fleet (of which Koeberg is one) where Alloy 600 MA (Ni-Cr-Fe) is used for the construction of the primary tubes. In newer steam generators, Alloy 600 TT, Alloy 690 TT and Alloy 800 (containing less Ni-Cr-Fe with small concentrations of Al and Ti) tubes have performed better. These newer materials have not mitigated the issues completely (EPRI, 2012b).

2.1.3 The cost effect of degradation

It is estimated by Electric Power Research Institute (EPRI) (EPRI, 2012b) that a tube rupture or leakage may cost the utility between R40 million and R150 million per event¹. The large variance in the number is due to the wide range of issues which may lead to component replacement and shut-down of the power plant. Integrity and performance assessments of steam generators may cost between R7 million and R14 million². Approximately 75% of steam generator outages are caused by degradation and corrosion in the tubes (Millett and Welty, 2010). Steam generator research is, therefore, extremely valuable and critical to the safe and cost effective operation of nuclear power plants.

2.1.4 The effect of degradation on heat transfer and efficiency

Chemical treatment of the primary side results in a mostly corrosion resistant environment, although degradation does occur on the primary side in small amounts. It is thus the

¹\$5-\$15 million in March 2012

²\$1-\$2 million in March 2012

feed-water/steam cycle (secondary side), which contributes largely to the degradation in heat transfer performance (Schwarz, 2001). The drop in heat transfer efficiency due to the accumulation of solids or degradation of the tubes and shell is characterized by the fouling factor (R_f). The effect of the fouling factor can be seen if we examine how the over-all heat transfer coefficient is calculated, in Equation 2.1.1.

$$\frac{1}{U} = \frac{d_o}{d_i} \frac{1}{h_i} + \frac{d_o}{2k_w} \ln \frac{d_o}{d_i} + \frac{1}{h_o} + R_f \quad (2.1.1)$$

The fouling factor is the heat transfer resistance, or inverse heat transfer coefficient, for the build up of solids found in the secondary side. Fouling factors are measured experimentally, and typical ranges are found to be (Schwarz, 2001):

$$\begin{aligned} \left(\frac{\delta R_f}{\delta T_{in}} \right) &= +0.11... + 0.13 \frac{10^{-5} m^2 K / W}{K} \\ \left(\frac{\delta R_f}{\delta T_{out}} \right) &= +0.6... + 0.6 \frac{10^{-5} m^2 K / W}{K} \\ \left(\frac{\delta R_f}{\delta p_{st}} \right) &= -0.7... - 1.2 \frac{10^{-5} m^2 K / W}{bar} \end{aligned}$$

From the above equations, we note that a typical fouling factor varies roughly $0.10 \frac{m^2 K / W}{K}$ with variation of inlet temperature. The heat transfer coefficient is inversely proportional to the heat resistance, so this creates uncertainty in the heat transfer coefficient by up to a factor of 10. If a typical heat transfer coefficient is in the order of $20\,000 \frac{W}{m^2 K}$, then it may be reported in the model as low as 18000 or as high as 22000, purely as an effect of the fouling factor alone. Of course, the degradation issue is complex and much larger discrepancies in calculated heat transfer coefficients are expected.

2.1.5 Concluding remarks regarding issues faced in steam generator operation

From the above discussion, it is clear that there exists a need in the industry and in academia to study the effects of steam generator performance. To this end, studies focus largely on utilizing mathematical models of the two-phase flow regions of the steam generator. For many of the complex issues where interactions of particles within the fluid affect deposition and degradation of the tubes, it is necessary to employ techniques such as computational fluid dynamics (CFD) and discrete element analysis (DEM) coupled with models of chemical reactions. These techniques allow detailed analysis of the problem, and may be utilized to aid in the design of new components. They are time consuming and involve complex and expensive software, however, and are thus not always suitable for operational analysis of general plant performance conditions.

The flow solvers such as Flownex and RELAP5 (Sections 2.3.1 and 2.3.2) allow an arbitrary amount of detail in the modelling of flow paths in the form of nodes and components, but one is restricted to the components offered by the individual modelling package. RELAP5 and Flownex allow one to construct flow paths for all the components in the nuclear power plant, and a network of pipes is used to model the steam generator. This allows for a detailed operational analysis. If a fine enough nodalization is used, then a large amount of detailed flow analysis may be obtained at specific points in the steam generator.

2.2 Thermal-fluid models of two-phase flow

The subject of multiphase flow has become increasingly important since the inception of nuclear power, as it occurs in many of the primary components of the nuclear power plant. In the PWR, the primary coolant is kept sub-cooled at a high pressure and thus remains in a single phase. The secondary water on the shell-side of the steam generator is heated from sub-cooled to saturated, undergoing evaporation. A combination of forced and boiling convective conditions in the two-phase mixture results in extremely turbulent flow conditions within the shell-side. The correlations used to predict two-phase thermal-hydraulic parameters are thus less accurate and not as well understood as those for single-phase flow (Ishii and Hibiki, 2006).

For single-phase flow, the model is formulated from continuum mechanics in terms of the field equations for conservation of mass, energy and momentum. The field equations are then complemented by various constituent equations which describe thermodynamic state, energy transfer and chemical reactions.

2.2.1 Multi-phase flow and phase transitions

There are, in general, three models used to describe two-phase flow of a fluid, namely the homogeneous model, the drift-flux model and the two-fluids model (Ishii and Hibiki, 2006). They are formulated in terms of the field equations for the conservation of mass, energy and momentum; similarly to the single-phase model. Complications arise from the fact that there are two separate fluids being modelled (liquid and vapour) and they are subject to multiple, deformable and movable interfaces between the two phases. Furthermore, there exists mass and energy transfer across these interfaces. This gives rise to the various boiling flow regimes that occur in vertical pipes, shown in Figure 2.1.

The flow through the secondary side of the steam generator generally falls within the mixed flow class where the gas contains entrained liquid, and the liquid contains entrained gas. The interfaces in these regimes are rapidly changing form and size, and therefore an accurate model based on physical principals is virtually impossible (Ishii and Hibiki, 2006).

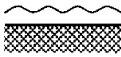
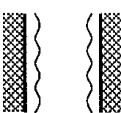
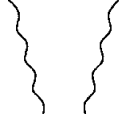
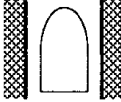
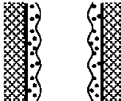
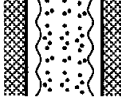
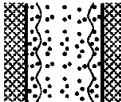
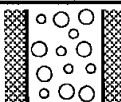
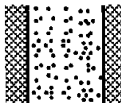
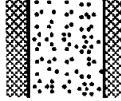
Class	Typical regimes	Geometry	Configuration	Examples
Separated flows	Film flow		Liquid film in gas Gas film in liquid	Film condensation Film boiling
	Annular flow		Liquid core and gas film Gas core and liquid film	Film boiling Boilers
	Jet flow		Liquid jet in gas Gas jet in liquid	Atomization Jet condenser
Mixed or Transitional flows	Cap, Slug or Churn-turbulent flow		Gas pocket in liquid	Sodium boiling in forced convection
	Bubbly annular flow		Gas bubbles in liquid film with gas core	Evaporators with wall nucleation
	Droplet annular flow		Gas core with droplets and liquid film	Steam generator
	Bubbly droplet annular flow		Gas core with droplets and liquid film with gas bubbles	Boiling nuclear reactor channel
Dispersed flows	Bubbly flow		Gas bubbles in liquid	Chemical reactors
	Droplet flow		Liquid droplets in gas	Spray cooling
	Particulate flow		Solid particles in gas or liquid	Transportation of powder

Figure 2.1: Various boiling regimes that occur within a two-phase fluid (Ishii and Hibiki, 2006)

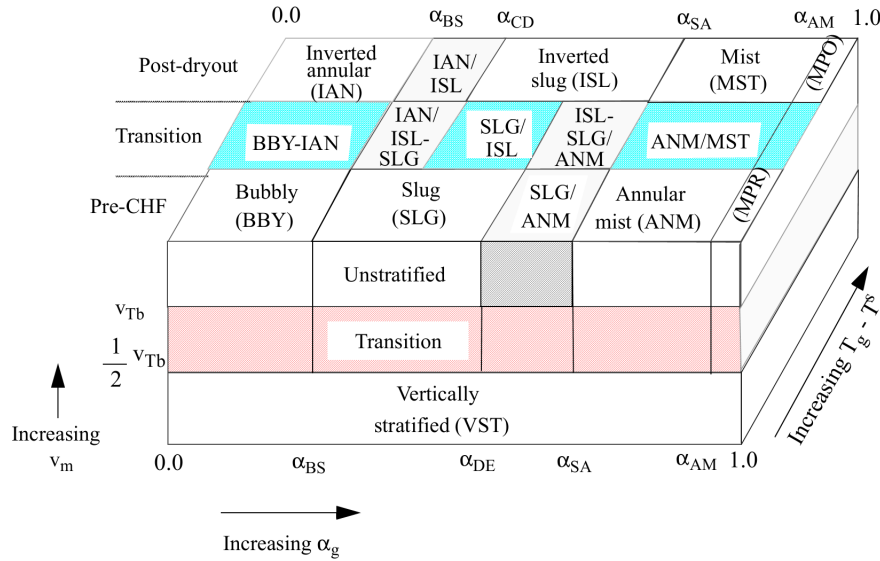


Figure 2.2: Flow regime matrix for vertical flow used in RELAP5 for boiling heat transfer calculations (RELAP5, 2001c)

Software packages such as RELAP5 have been coded with complex boiling flow regime and boiling heat transfer regime matrices. Figure 2.2 shows how RELAP5 uses the average mixture velocity (v_m) and the average void fraction (α_g) to assess which flow regime best characterizes the flow. The RELAP5 documentation (RELAP5, 2001b) describes the models and correlations in finer detail. These flow regimes dictate which correlations are used in inter-phase drag and shear, wall friction, heat transfer and inter-phase heat and mass transfer (RELAP5, 2001b).

Figure 2.3 illustrates the boiling curve employed by RELAP5 to calculate heat flux during fluid-to-wall heat transfer (RELAP5, 2001b).

As the physics change during phase transitions, so does the correlation required to calculate the heat flux. Table 2.1 shows an example of which correlations are used by RELAP5 to calculate heat flux for each boiling regime. The RELAP5 documentation (RELAP5, 2001b) expands further on each correlation. The Chen correlation is applied during nucleate boiling and transition boiling, and thus makes up the majority of the boiling regime which occurs during nominal SG operation. This is because all effort goes to operating the steam generator below or near the critical heat flux, within the nucleate or transition boiling regime (as seen in Figure 2.3).

Table 2.1: Heat transfer correlations used in the various boiling regimes for RELAP5

	Boiling regime							
	Laminar	Natural	Turbulent	Condensation	Nucleate boiling	Transition boiling	Film boiling	CHF
Heat transfer correlation	Sullars, $Nu = 4.36$	C-Chu or McAdams	Dittus-Boelter	Nusselt/Chato-Shah-Coburn-Hougen	Chen	Chen	Bromley	Table

In Flownex, the Steiner and Taborek correlation is natively used to calculate the boiling heat transfer coefficient during nucleate boiling, while the Berenson correlation is applied during transition boiling.

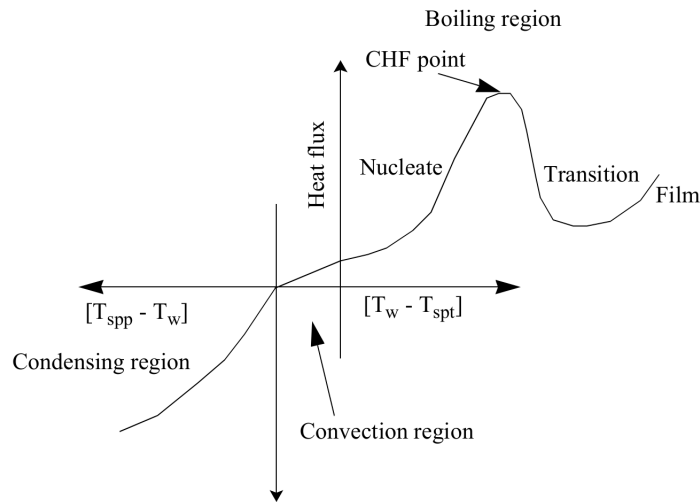


Figure 2.3: The boiling and condensing curve used by RELAP5 to calculate heat flux (RELAP5, 2001b)

Table 2.2: Heat transfer correlations used in the various boiling regimes for Flownex

	Boiling regime							
	Laminar	Natural	Turbulent	Condensation	Nucleate boiling	Transition boiling	Film boiling	CHF
Heat transfer correlation	Dittus-Boelter				Steiner and Taborek	Berenson	Zuber	Table

The mathematical details for the correlations may be found in various texts (Flownex, 2011b; Janna, 2000; RELAP5, 2001b; Rohsenow et al., 1998; Thome, 2004). None of the correlations by themselves offer an accurate solution to the boiling heat transfer problem, and it would not benefit the study to go further into each correlation. When they are combined and used in matrix form such as RELAP5 does, it increases the accuracy of the solutions substantially over using a single correlation. It is important to note the amount of effort required to perform such calculations in one's own code, and to keep the scope of the project in context.

2.2.2 Chen correlation for the nucleate boiling heat transfer coefficient

In order to directly compare the homogeneous two-phase flow model with the two-fluid model without introducing error due to different heat transfer correlations, it is necessary to perform the calculation using the same correlations in both models. The nucleate and transition boiling regions of the steam generator are much larger than the super-heated sections, and thus play the largest role in affecting the heat transfer of the system (Green and Hetsroni, 1995).

RELAP5 applies the Chen correlation to both the nucleate and transition boiling regime, and thus it will be discussed briefly. It is not possible to alter the correlations that RELAP5 uses, however, we are able to alter what Flownex uses. Therefore, it was decided to modify Flownex to use the

Chen correlation during nucleate and transition boiling, as opposed to the Steinberg and Tamorek correlation already present.

Formulation

Chen's correlation states that the local two-phase boiling coefficient is made up of two parts from the nucleate boiling regime and the convective (single-phase) regime (Thome, 2004).

$$h_{tp} = h_{nb} + h_{cb} \quad (2.2.1)$$

He further determined that the nucleate boiling coefficient and the convective coefficient could be calculated by older correlations and adjusted by a multiplying factor.

$$h_{tp} = h_{FZ} \times S + h_L \times F \quad (2.2.2)$$

The equation of Forster and Zuber is used to calculate the coefficient for nucleate boiling.

$$h_{FZ} = 0.00122 \left[\frac{k_L^{0.79} c_{pL}^{0.45} \rho_L^{0.49}}{\sigma^{0.5} \mu_L^{0.29} h_{LG}^{0.24} \rho_G^{0.24}} \right] \times \Delta T_{sat}^{0.24} \times \Delta p_{sat}^{0.75} \quad (2.2.3)$$

Where $\Delta T_{sat} = T_{wall} - T_{sat}$ and $\Delta p_{sat} = p_{wall} - p_{sat}$.

The convective heat transfer coefficient is calculated by the Dittus-Boelter correlation.

$$h_L = 0.023 Re_L^{0.8} Pr_L^{0.4} \left[\frac{k_L}{d_i} \right] \quad (2.2.4)$$

It is important to note that the Reynolds number used in the Dittus-Boelter correlation is the single-phase liquid Reynould's number.

$$Re_L = \frac{\dot{m}(1-x)d_i}{\mu_L} \quad (2.2.5)$$

Where x is the quality of the flow. Pr_L is the liquid Prandtl number.

$$Pr_L = \frac{c_{pL} \mu_L}{k_L} \quad (2.2.6)$$

The multipliers for the Chen correlation are:

$$F = \left(\frac{1}{X_{tt}} + 0.213 \right)^{0.736} \quad (2.2.7)$$

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_G}{\rho_L} \right)^{0.5} \left(\frac{\mu_L}{\mu_G} \right)^{0.1} \quad (2.2.8)$$

$$S = \frac{1}{1 + 0.00000253 Re_{tp}^{1.17}} \quad (2.2.9)$$

And finally, the two-phase Reynould's number is also calculated with a multiplier.

$$Re_{tp} = Re_L \times F^{1.25} \quad (2.2.10)$$

Application

Chen's correlation is widely applicable, including water in upward and downward flow and pressures from 0.55 to 34.8 bar. It is valid mostly between qualities of 0.01 and 0.71, but has been shown to be accurate beyond this range as well (Thome, 2004). Typically, an iterative calculation is performed between T_{wall} and p_{wall} , if the heat flux is specified. It applies only while the wall remains wet, and thus reduces in accuracy as the boiling regime shifts to film boiling.

In this study, the focus is on the steady-state operation of the steam generator at nominal conditions, and thus we assume that most of the flow will be occurring within the nucleate boiling regime as predicted by Green and Hetsroni (1995). Thus the modification of Flownex to use the Chen correlation is justified.

2.2.3 Two-fluid model

The two-fluids model is the most sophisticated model with which to analyse two-phase flow. It is formulated in terms of the mass, energy and momentum conservation equations for two fluids, resulting in six field equations to solve. For most practical purposes, the one-dimensional equations averaged over area may be used (Ishii and Hibiki, 2006). The model solves the three field equations for each phase, making a total of six field simultaneous differential equations to solve.

The continuity equation:

$$\frac{\delta \langle \alpha_k \rangle \rho_k}{\delta t} + \frac{\delta}{\delta z} \langle \alpha_k \rangle \rho_k \cdot \langle \langle v_k \rangle \rangle = \langle \Gamma_k \rangle \quad (2.2.11)$$

The momentum equation:

$$\begin{aligned} & \frac{\delta}{\delta t} \langle \alpha_k \rangle \rho_k \langle \langle v_k \rangle \rangle + \frac{\delta}{\delta z} C_{vk} \langle \alpha_k \rangle \rho_k \langle \langle v_k \rangle \rangle^2 = \\ & - \langle \alpha_k \rangle \frac{\delta}{\delta z} \langle \langle p_k \rangle \rangle + \frac{\delta}{\delta z} \langle \alpha_k \rangle \langle \langle \tau_{kzz} + \tau_{kzz}^T \rangle \rangle - \frac{4\alpha_{kw} \tau_{kw}}{D} - \langle \alpha_k \rangle \rho_k g_z \\ & + \langle \Gamma_k \rangle \langle \langle v_{ki} \rangle \rangle + \langle M_k^d \rangle + \langle (p_{ki} - p_k) \frac{\delta \alpha_k}{\delta z} \rangle \end{aligned} \quad (2.2.12)$$

The energy equation:

$$\begin{aligned} & \frac{\delta}{\delta t} \langle \alpha_k \rangle \rho_k \langle \langle h_k \rangle \rangle + \frac{\delta}{\delta z} C_{hk} \langle \alpha_k \rangle \rho_k \langle \langle h_k \rangle \rangle \langle \langle v_k \rangle \rangle = \\ & - \frac{\delta}{\delta z} \langle \alpha_k \rangle \langle \langle q_k + q_k^T \rangle \rangle + \langle \alpha_k \rangle \frac{D_k}{Dt} \langle \langle p_k \rangle \rangle + \frac{\zeta_h}{A} \alpha_{kw} q_{kw}'' + \\ & \langle \Gamma_k \rangle \langle \langle h_{ki} \rangle \rangle + \langle \alpha_i q_{ki}'' \rangle + \langle \Phi_k \rangle \end{aligned} \quad (2.2.13)$$

The constituent equations describe the distribution coefficients, drag force, inter-facial shear force, heat transfer coefficients and the equations of state. The constituent equations must be

chosen very carefully, otherwise the model will not accurately describe certain flow characteristics. Detailed information on the two-fluid model is found in many thermal-fluid texts, including Ishii and Hibiki (2006).

2.2.4 Homogeneous model

A rather simplified way of analysing two-phase flow arises with the homogeneous flow model. In this model, the inter-facial energy and momentum transfer as well as the inter-phase velocities are neglected. The six field equations from Section 2.2 can be reduced to four field equations. The mass, energy and momentum equations are written in terms of a homogeneous mixture of the two phases, while the mass equation for the gas phase is still included as to take into account thermal non-equilibrium between the two phases (Ishii and Hibiki, 2006).

The mixture mass equation:

$$\frac{\rho_m}{t} + \frac{\delta}{\delta z}(\rho_m v_m) = 0 \quad (2.2.14)$$

The vapour phase concentration (mass) equation:

$$\frac{\delta \alpha_2 \bar{\rho}_2}{\delta t} + \frac{\delta}{\delta z}(\alpha_2 \bar{\rho}_2 v_m) = \Gamma_k \quad (2.2.15)$$

The momentum equation:

$$\frac{\delta \rho_m v_m}{\delta t} + \frac{\delta}{\delta z}(\rho_m v_m v_m) = -\frac{\delta p_m}{\delta z} + \frac{\delta}{\delta z}(\bar{\Sigma} + \Sigma^T) + \rho_m g_m + M_m \quad (2.2.16)$$

The energy equation:

$$\frac{\rho_m i_m}{\delta t} + \frac{\delta}{\delta z}(\rho_m i_m v_m) = -\frac{\delta}{\delta z}(\bar{q} + q^T) + \frac{D p_m}{D t} + \Phi_m^\mu + \Phi_m^\sigma \quad (2.2.17)$$

The constituent equations are used to solve for stress tensors and heat flux, among other parameters.

By assuming a homogeneous mixture, we are assuming that the relative velocity between the two phases is zero. The stress tensors are written in terms of the viscosity of the fluids, and the heat fluxes are written in terms of the heat transfer coefficients. There are thus fewer equations to solve and fewer constituent equations to append to the model.

The homogeneous model is typically reserved for simple problems where accuracy of the SG interior is not of prime importance. Instead, focus is on the causal relationships between input and output variables (Green and Hetsroni, 1995). The model is generally not applicable when the flow is drag-dominated under the effect of gravity. An example is in vapour bubbles rising through liquid water, where the body forces (gravity and buoyancy) balances against the inter-phase drag (EPRI, 2012a). This may be applicable to a steam generator under low power conditions.

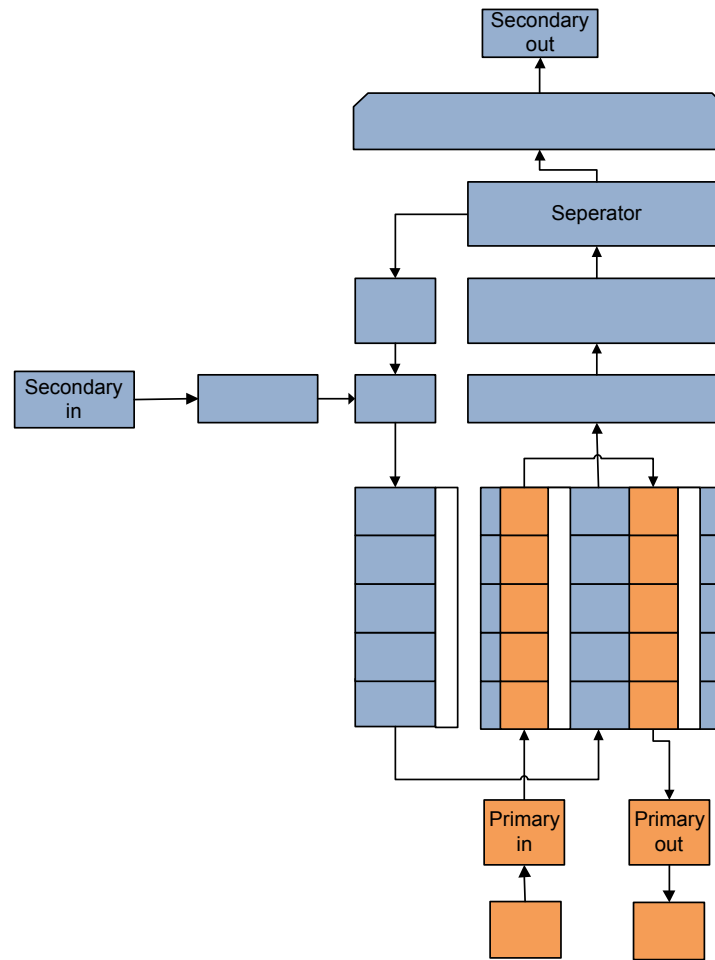


Figure 2.4: Typical nodalization for the model of a steam generator

2.3 Simulating steam generators using thermal-hydraulic codes

Thermal-hydraulic codes generally provide input in the form of component models. Pipes, reservoirs, accumulators, fluid volumes, annuli, valves, moisture separators, pumps and turbines all are types of components that may be specified as part of the model. General geometrical properties such as hydraulic diameter, length, volume, flow area and changes in height may be specified for each component. Furthermore, heat transfer elements may also be specified to simulate the heat transfer between the primary and secondary side models. Boundary conditions such as temperature and pressure of feed-water and primary coolant as well as mass flows should also be specified (Green and Hetsroni, 1995).

Important parameters for a typical thermal-hydraulic model of a steam generator can be expressed with the components as shown in Figure 2.4. This type of diagram is referred to as the nodalization of the model.

For steady-state calculations, the following boundary conditions may be specified (Singhal et al., 1984):

- Mass flow-rate of primary coolant through the SG, $\dot{m}_p$.
- Mass flow-rate of feed-water added into the down-comer, $\dot{m}_{fd}$.
- Inlet temperature of the feed-water, T_{fd} .
- Mass quality of steam leaving the dome, x_s .
- Mass fraction of steam entrained in the recirculating water flowing from the dome to the down-comer, x_w .
- Pressure in steam dome, p_d .
- Height of the water level in the down-comer, h_{WL} .
- Fraction of the down-comer feed-water added to the hot side, f_{dh} (this implies that the fraction $[1 - f_{dh}]$ is added on the cold side).

The resulting parameters should show local flow conditions such as temperature, pressure, velocity, quality and void fraction of both phases as well as the following global parameters (Singhal et al., 1984) :

- Circulation ratio, defined as $\frac{\text{Total mass flow-rate through the boiler region}}{\text{Mass flow-rate of liquid recirculated from the steam separators}}$.
- Liquid inventory in the tube bundle and riser section.
- Liquid inventory in the down-comer.
- Temperature of the down-comer water at the entry to the tube bundle region.
- In transient calculations, the primary inlet temperature is generally described as a function of time, and the primary outlet temperature and heat load are calculated as a function of time.

2.3.1 Flownex

Flownex software research began in 1986 and was initially designed to solve air distribution networks. It was subsequently expanded by M-Tech Industrial Pty (Ltd) and in 1999, M-Tech was contracted to perform studies on the pebble-bed modular reactor (PBMR) using Flownex. In 2007, the National Nuclear Regulator (NNR) reviewed the Flownex verification and validation status and found it to be acceptable for use in the support and design of safety issues in the PBMR. Flownex was expanded and integrated into the Simulation Environment (Flownex SE) in 2008. From this they formed a package for comprehensive plant simulation, analysis and optimization (Flownex, 2011c). This is the form it is used in today, and it allows one to model any

network of pipes, pumps and heaters. This is shown in the nodalization for the SG in Figure 2.4. Flownex solves the field equations using an Implicit Pressure Correction Method (IPCM) (Flownex, 2011b). The software has various advantages and disadvantages, described in Table 2.3.

Table 2.3: Advantages and Disadvantages to using Flownex and the homogeneous model.

Advantages	Disadvantages
Simple formulation Simple computability Quick model development process Inexpensive, local software Stable Approved by NNR for use in PBMR studies Real-time solving of transients	Not useful for accurate modelling of internal flow parameters Software not widely used in nuclear industry Homogeneous assumption limitations

2.3.2 RELAP5/Mod3.4

The RELAP5 code was developed for best-estimate steady-state and transient simulation of light water reactor coolant systems during normal operation as well as accident scenarios (RELAP5, 2001a). It was developed for the NRC in conjunction with many other countries and research organisations, and most of the development took place at Idaho National Engineering Laboratory. The code is based on the non-homogeneous, non-equilibrium model for two-phase flow and includes many component models from which systems can be built. It is able to model pumps, valves, pipes, heat structures, reactor point kinetics, special fluid process models (such as jet pumps and choking), turbines and separators. It makes use of a partially implicit numerical solving scheme which is fast to solve, however only accurately predicts first-order effects (RELAP5, 2001a). As with Flownex, small time steps must be used to preserve accuracy but the solution is generally stable over most conditions (Preece and Putney, 1993).

Table 2.4: Advantages and Disadvantages to using RELAP5 and the two-fluid model.

Advantages	Disadvantages
Supported by the US NRC Accurately model internal flow paths Improved accuracy Large body of knowledge and experience Stable	Expensive, proprietary software Complicated model development Longer solving time

2.3.3 Previous work on steam generator models

A comparison between steam generator models using the homogeneous model and the two-fluid model was done in 1980 (Singhal et al., 1980). They used a finite difference method to solve the field equations, and the results concluded that there were significant differences both in local and global flow parameters predicted by the two models. There was, however, no experimental or operational data to compare either model to. The computational advances since 1980 mean that the results of this study may not be applicable any more, but it does offer an indication that there will be significant differences in the parameters predicted by the two models.

RELAP5 and the two-fluid model has been used successfully in many simulations of PWRs and their components (Colorado et al., 2011; Hoffer et al., 2011; Jeong et al., 2000). The RELAP5 models were, in all cases, using the two-fluid model. From these studies, it is found that it is not necessary to have more than five increments in the down-comer and riser component models for a simple model. Five increments have been shown to be sufficient to model all important flow parameters in the riser and down-comer regions (RELAP5, 2001c). It is also shown that it is necessary to model the recirculation from the moisture separation, as it has a large impact on the natural circulation through the system (Green and Hetsroni, 1995; Jeong et al., 2000). It also becomes apparent that the choice of the convective heat transfer coefficient correlation affects the calculated heat transfer greatly. RELAP5/Mod3.4 uses the Chen correlation described in detail in Thome (2004). It relates the total convective heat transfer coefficient to a weighted linear summation of the single-phase convective heat transfer coefficient and the coefficient for nucleate boiling. The coefficients are weighted by a nucleate boiling suppression factor and a two-phase multiplier. It must be noted that the Chen correlation is, in general, only valid for plain vertical tubes. Due to its simplicity, however, it is still commonly used in many simulation models (Colorado et al., 2011; Hoffer et al., 2011; Jeong et al., 2000; Lin et al., 1986).

The use of the Chen correlation in RELAP5 results in an under-prediction of SG heat transfer for the majority of load conditions ranging from 36% to 100% (Preece and Putney, 1993). The exiting steam is saturated, therefore, the error in heat-transfer relates directly to the error in the outlet steam pressure. The error reported was lower at low power, but at full load is approximately 0.4 MPa. The under-prediction of the heat transfer results in a lower steam pressure than expected. The inter-phase drag force is also over-predicted with RELAP5/Mod3 and can contain an error of up to 25% (Preece and Putney, 1993).

The homogeneous model is commonly used when comparing codes that do not include the two-fluid model, such as older versions of ATHOS and computational fluid dynamics (CFD) packages. CFD analysis of homogeneous mixture flow is still useful, as velocity profiles and temperature distributions may still be determined (EPRI, 2012a). The homogeneous model is also applicable at low power loads such as hot shut-downs, when the reactor is shut down but still operating under decay heat (EPRI, 2012a).

Basis for the Models

One of the goals of the project was to develop a steady-state thermodynamic model for the u-tube steam generator. The software that was chosen for the model development was RELAP5 and Flownex in order to facilitate a direct comparison between the two-fluid and homogeneous model.

RELAP5 was chosen to perform two-fluid analysis due to it being widely used in the nuclear industry, well supported, well documented, and already licensed for use at the North-West University.

Flownex was chosen to perform additional homogeneous analysis due to it being widely used in South Africa in the power generation and fluid modelling industries. It is also well supported and licensed at the North-West University.

The steam generator that was modelled was a Westinghouse Type 51B u-tube steam generator. Data from Koeberg NPP was used to validate the models; this is discussed in the next section.

3.1 Data obtained from Koeberg Nuclear Power Station

The steady-state data was obtained from Koeberg NPP, and a sample is shown in Table 3.1. The data consists of tables of values for the primary inlet and outlet temperatures, the pressure in the steam drum, the feed-water pressure and temperature, the feed-water and steam flow-rate and the active power produced by the generator. These variables make up the typical boundary conditions of the steam generator model. As there was no detailed data of the internal flow of the steam generator, the model was validated against these boundary conditions.

The data was taken from selected points throughout the plant, and was requested once a day at midday. In total, there was roughly 10 years of steady-state data. There are null and erroneous values scattered throughout, as well as weeks when the reactor was being ramped up or ramped down. It was thus difficult to obtain enough data points at various steady-state conditions. It

Table 3.1: Sample of the steady-state data obtained from a single unit at Koeberg Nuclear Power Station

Date	$T_{hot}(^{\circ}\text{C})$	$T_{cold}(^{\circ}\text{C})$	SG drum pressure (kPa)	Feed-water pressure (kPa)	Feed-water temperature ($^{\circ}\text{C}$)	Feed-water flow-rate (kg/s)	Steam flow-rate (kg/s)	Generator active power (MW)
2000/01/01 12:00	303.034	280.299	5495.419	5714.844	198.848	1094.096	1142.277	600.365
2000/01/02 12:00	302.714	280.256	5492.824	5717.285	198.699	1095.571	1139.469	602.197
2000/01/03 12:00	302.927	280.449	5508.393	5729.492	198.692	1097.045	1144.384	605.860
2000/01/04 12:00	312.778	278.654	4916.817	(null)	220.048	1775.541	1851.374	953.479
2000/01/05 12:00	312.201	278.547	4911.628	(null)	220.109	1785.064	1845.757	948.717
2000/01/06 12:00	(null)	(null)	(null)	(null)	(null)	(null)	(null)	(null)
2000/01/07 12:00	312.329	278.568	4919.412	5307.129	220.222	1816.892	1855.586	952.013
2000/01/08 12:00	312.885	278.632	4919.412	(null)	220.251	1787.326	1856.990	952.380
2000/01/09 12:00	312.692	278.825	4937.574	(null)	220.263	1793.637	1856.990	951.647
2000/01/10 12:00	312.756	278.675	4924.602	(null)	220.251	1780.536	1856.288	948.350
2000/01/11 12:00	312.628	278.483	4909.033	5314.453	220.299	1791.385	1853.480	947.618
2000/01/12 12:00	312.414	278.654	4919.412	(null)	220.041	1811.553	1856.288	948.717
2000/01/13 12:00	312.692	278.675	4924.602	(null)	220.219	1799.480	1854.884	950.915
2000/01/14 12:00	312.329	278.333	4898.655	5294.922	220.183	1803.066	1847.161	950.182
2000/01/15 12:00	312.863	278.782	4924.602	5321.777	220.183	1811.553	1847.863	952.380
2000/01/16 12:00	312.607	278.590	4919.412	5314.453	220.195	1798.131	1853.480	949.449
2000/01/17 12:00	312.350	278.611	4911.628	(null)	220.183	1790.933	1845.757	954.944
2000/01/18 12:00	312.543	278.697	4911.628	(null)	220.255	1794.989	1851.374	952.380
2000/01/19 12:00	312.628	278.504	4903.845	(null)	220.315	1803.512	1856.288	951.281

was for this reason that only power outputs of 100%, 80% and 60% were evaluated in this project. There were not enough reliable data points at low power conditions for a reliable analysis.

The data was sorted by power from the generator as to group data points with similar values. The data entries with null values were discarded from the set. All data points that corresponded to 100%, 80% and 60% respectively were separated and made up in new datasets for each power level. The Statistical Analysis Tool in Microsoft Excel was then used to analyse the datasets. The results are discussed in the next section.

3.1.1 Statistical analysis of the data

The results of the statistical analysis for the data at 100%, 80% and 60% power output are given in Table 3.2, Table 3.3 and Table 3.4 respectively. The important parameters to note are the mean and the confidence level at 95%. The confidence level may be understood by Equation 3.1.1. For example, with a mean of 270.342 reported and a confidence level (at 95%) of 4.756, the mean is read as in the example below.

$$\mu = 270.342 \pm 4.756 \quad (3.1.1)$$

Equation 3.1.1 means that 95% of the data points in our analysis fall within the stated interval.

Kurtosis refers to the peak of a probability distribution when compared with a normal distribution. A higher kurtosis indicates a higher peak, with more of the data concentrated around the mean than the shoulders of the distribution (Dodge, 2003).

The skewness of a distribution refers to where the majority of data points are concentrated. A negative skewness means that more of the data points are found to the right of the mean, while a positive skewness means the opposite. The skewness could indicate whether there are a number of outliers in the data. A large negative skewness might also indicate that the mean is underestimated, as most of the data points lie to the right of the mean.

Other parameters of importance are the minimum value, range and maximum value. These will indicate whether some errors may be attributed to incorrectly sampled data.

100% Power Output

Table 3.2 shows the results of the analysis for 763 data points at approximately 100% power output. The maximum uncertainty in the confidence level (95%) was noted for the steam flow-rate, at 0.25% of the mean. We also noted the large range for the steam flow-rate, which means that the data is populated with one or more extreme outliers.

The interval at 95% confidence level was similar or lower for all the other variables.

Kurtosis and skewness was relatively small for all variables, with the exception of steam flow-rate and feed-water flow-rate. The negative skewness would indicate that there is a chance that our mean was under-estimated, as most of the data points actually occur at higher values than the mean. The high kurtosis also indicates that a large number of the data points were centered on the mean, and less along the edges of the distribution.

Table 3.2: Statistical analysis of steady-state plant operating data at 100% power output.

Thot (narrow) loop 1		Tcold (narrow) loop 1		SG drum pressure		Feed-water (pressure)	
Mean	312.3747	Mean	278.6679	Mean	4911.1929	Mean	5277.3901
Standard Error	0.0091	Standard Error	0.0078	Standard Error	1.2394	Standard Error	0.8257
Median	312.3718	Median	278.6538	Median	4919.4121	Median	5277.2539
Mode	312.3290	Mode	278.6752	Mode	4924.6016	Mode	5281.3936
Standard Deviation	0.2515	Standard Deviation	0.2150	Standard Deviation	34.2354	Standard Deviation	22.8088
Sample Variance	0.0633	Sample Variance	0.0462	Sample Variance	1172.0609	Sample Variance	520.2415
Kurtosis	1.1565	Kurtosis	0.6255	Kurtosis	-0.0854	Kurtosis	0.0976
Skewness	-0.2584	Skewness	0.5976	Skewness	-0.7380	Skewness	-0.3850
Range	2.0513	Range	1.3676	Range	155.6768	Range	115.8174
Minimum	310.9828	Minimum	277.9914	Minimum	4826.0059	Minimum	5215.0752
Maximum	313.0341	Maximum	279.3589	Maximum	4981.6826	Maximum	5330.8926
Sum	238341.9	Sum	212623.6	Sum	3747240.2	Sum	4026648.6
Count	763	Count	763	Count	763	Count	763
Largest(1)	313.0341	Largest(1)	279.3589	Largest(1)	4981.6826	Largest(1)	5330.8926
Smallest(1)	310.9828	Smallest(1)	277.9914	Smallest(1)	4826.0059	Smallest(1)	5215.0752
Confidence Level(95.0%)	0.0179	Confidence Level(95.0%)	0.0153	Confidence Level(95.0%)	2.4331	Confidence Level(95.0%)	1.6210

Feed-water (temperature)		Feed-water (flow-rate)		Steam (flow-rate)		Generator active power	
Mean	219.7379	Mean	1780.1998	Mean	1852.8929	Mean	1143.0000
Standard Error	0.0153	Standard Error	1.3216	Standard Error	2.3857	Standard Error	0.2181
Median	219.7990	Median	1782.3469	Median	1842.9487	Median	936.2639
Mode	219.9115	Mode	1783.7048	Mode	1918.7729	Mode	932.6008
Standard Deviation	0.4213	Standard Deviation	36.5045	Standard Deviation	65.8977	Standard Deviation	6.0239
Sample Variance	0.1775	Sample Variance	1332.5771	Sample Variance	4342.5101	Sample Variance	36.2868
Kurtosis	0.0306	Kurtosis	116.3417	Kurtosis	131.9850	Kurtosis	2.7248
Skewness	-0.4735	Skewness	-6.7591	Skewness	-7.3765	Skewness	0.3554
Range	2.7617	Range	714.5876	Range	1251.0989	Range	65.9326
Minimum	217.8149	Minimum	1148.8127	Minimum	676.0989	Minimum	902.9304
Maximum	220.5766	Maximum	1863.4004	Maximum	1927.1978	Maximum	968.8630
Sum	167660.0	Sum	1358292.4	Sum	1413757.3	Sum	715092.9
Count	763	Count	763	Count	763	Count	763
Largest(1)	220.5766	Largest(1)	1863.4004	Largest(1)	1927.1978	Largest(1)	968.8630
Smallest(1)	217.8149	Smallest(1)	1148.8127	Smallest(1)	676.0989	Smallest(1)	902.9304
Confidence Level(95.0%)	0.0299	Confidence Level(95.0%)	2.5943	Confidence Level(95.0%)	4.6832	Confidence Level(95.0%)	0.4281

80% Power Output

Table 3.3 shows the results for the 126 data points at approximately 80% power output. The maximum uncertainty in the mean at 95% confidence level was for the feed-water pressure, at 2.8%.

Kurtosis and skewness was relatively low for most variables, with the exception of the feed-water pressure. For feed-water pressure we also noted a more negative skewness. This might indicate some errors in the data set, and a look at the range will tell us that some erroneous data points were

included, where the feed-water pressure was low. Slightly negative skewness for all variables indicate that the mean may be slightly under-estimated.

Table 3.3: Statistical analysis of steady-state plant operating data at 80% power output.

Thot (narrow) loop 1		Tcold (narrow) loop 1		SG drum pressure		Feed-water (pressure)	
Mean	306.3308	Mean	277.9975	Mean	5022.8882	Mean	5221.3574
Standard Error	0.3038	Standard Error	0.2610	Standard Error	19.6049	Standard Error	74.3506
Median	307.7563	Median	279.1453	Median	5082.8740	Median	5430.6104
Mode	307.8419	Mode	279.1453	Mode	5085.4678	Mode	5430.6104
Standard Deviation	3.4101	Standard Deviation	2.9292	Standard Deviation	220.0647	Standard Deviation	834.5836
Sample Variance	11.6285	Sample Variance	8.5804	Sample Variance	48428.4528	Sample Variance	696529.7883
Kurtosis	2.8302	Kurtosis	1.9669	Kurtosis	1.3065	Kurtosis	32.6823
Skewness	-2.0922	Skewness	-1.9324	Skewness	-1.5260	Skewness	-5.6393
Range	12.5427	Range	10.7906	Range	879.5791	Range	5471.4571
Minimum	295.5769	Minimum	269.5513	Minimum	4426.4326	Minimum	98.3603
Maximum	308.1196	Maximum	280.3419	Maximum	5306.0117	Maximum	5569.8174
Sum	38598	Sum	35028	Sum	632884	Sum	657891
Count	126	Count	126	Count	126	Count	126
Largest(1)	308.1196	Largest(1)	280.3419	Largest(1)	5306.0117	Largest(1)	5569.8174
Smallest(1)	295.5769	Smallest(1)	269.5513	Smallest(1)	4426.4326	Smallest(1)	98.3603
Confidence Level(95.0%)	0.6012	Confidence Level(95.0%)	0.5165	Confidence Level(95.0%)	38.8006	Confidence Level(95.0%)	147.1491

Feed-water (temperature)		Feed-water (flow-rate)		Steam (flow-rate)		Generator active power	
Mean	209.8552	Mean	1436.0134	Mean	1451.0902	Mean	908.2000
Standard Error	0.1506	Standard Error	3.9582	Standard Error	3.6675	Standard Error	2.5025
Median	210.7045	Median	1447.9231	Median	1458.9133	Median	790.8413
Mode	210.7021	Mode	1459.5857	Mode	1458.9133	Mode	793.0391
Standard Deviation	1.6907	Standard Deviation	44.4312	Standard Deviation	41.1679	Standard Deviation	28.0908
Sample Variance	2.8585	Sample Variance	1974.1280	Sample Variance	1694.7963	Sample Variance	789.0946
Kurtosis	4.0215	Kurtosis	5.8446	Kurtosis	7.0683	Kurtosis	2.5394
Skewness	-2.0401	Skewness	-2.1673	Skewness	-1.8770	Skewness	-1.8169
Range	8.0613	Range	267.7117	Range	274.5115	Range	126.7399
Minimum	202.8404	Minimum	1226.3174	Minimum	1257.4177	Minimum	668.4972
Maximum	210.9017	Maximum	1494.0291	Maximum	1531.9292	Maximum	795.2371
Sum	26442	Sum	180938	Sum	182837	Sum	97837
Count	126	Count	126	Count	126	Count	126
Largest(1)	210.9017	Largest(1)	1494.0291	Largest(1)	1531.9292	Largest(1)	795.2371
Smallest(1)	202.8404	Smallest(1)	1226.3174	Smallest(1)	1257.4177	Smallest(1)	668.4972
Confidence Level(95.0%)	0.2981	Confidence Level(95.0%)	7.8339	Confidence Level(95.0%)	7.2585	Confidence Level(95.0%)	4.9528

60% Power Output

Table 3.4 shows results for the 97 data points at approximately 60% power output. The maximum uncertainty again fell on the feed-water pressure. The confidence level at 95% was calculated as 2.8% of the mean.

The kurtosis and skewness of the variables remained relatively low, indicating a nearly uniform distribution. The exception was feed-water pressure with a slightly elevated kurtosis. The skewness of all data was close to zero with the exception of feed-water pressure, which was slightly negatively skewed. The range for the feed-water flow-rate and the steam flow-rate was large, as was the range for the steam drum pressure and the feed-water pressure. This indicates towards a number of outliers in this data set, and illustrates why further data at lower powers

were not included.

Table 3.4: Statistical analysis of steady-state plant operating data at 60% power output.

Thot (narrow) loop 1		Tcold (narrow) loop 1		SG drum pressure		Feedwater (pressure)	
Mean	294.4966	Mean	272.9632	Mean	4889.1592	Mean	5054.5517
Standard Error	0.5062	Standard Error	0.5418	Standard Error	49.6826	Standard Error	71.0407
Median	292.4999	Median	270.2350	Median	4636.5977	Median	4873.4805
Mode	290.8120	Mode	270.9615	Mode	4558.7588	Mode	4879.1221
Standard Deviation	4.9851	Standard Deviation	5.3356	Standard Deviation	489.3164	Standard Deviation	699.6701
Sample Variance	24.8517	Sample Variance	28.4689	Sample Variance	239430.5181	Sample Variance	489538.2821
Kurtosis	-0.8792	Kurtosis	-1.0424	Kurtosis	-0.7333	Kurtosis	27.6735
Skewness	0.6545	Skewness	0.8911	Skewness	1.0138	Skewness	-3.6057
Range	18.1624	Range	15.4915	Range	1442.6123	Range	6012.1163
Minimum	286.6025	Minimum	266.8803	Minimum	4405.6758	Minimum	0.0947
Maximum	304.7649	Maximum	282.3718	Maximum	5848.2881	Maximum	6012.2109
Sum	28566.2	Sum	26477.4	Sum	474248.4	Sum	490291.5
Count	97	Count	97	Count	97	Count	97
Largest(1)	304.7649	Largest(1)	282.3718	Largest(1)	5848.2881	Largest(1)	6012.2109
Smallest(1)	286.6025	Smallest(1)	266.8803	Smallest(1)	4405.6758	Smallest(1)	0.0947
Confidence Level(95.0%)	1.0047	Confidence Level(95.0%)	1.0754	Confidence Level(95.0%)	98.6191	Confidence Level(95.0%)	141.0147

Feed-water (temperature)		Feed-water (flow-rate)		Steam (flow-rate)		Generator active power	
Mean	194.7248	Mean	1023.4041	Mean	1083.4404	Mean	670.1000
Standard Error	0.5771	Standard Error	14.1036	Standard Error	14.6660	Standard Error	5.9112
Median	195.6016	Median	1023.9580	Median	1069.9634	Median	562.6365
Mode	#N/A	Mode	1102.9160	Mode	1126.1294	Mode	427.4718
Standard Deviation	5.6838	Standard Deviation	138.9048	Standard Deviation	144.4435	Standard Deviation	58.2184
Sample Variance	32.3056	Sample Variance	19294.5463	Sample Variance	20863.9244	Sample Variance	3389.3867
Kurtosis	0.6149	Kurtosis	2.3748	Kurtosis	3.2206	Kurtosis	-1.1387
Skewness	0.4119	Skewness	0.9159	Skewness	1.1238	Skewness	-0.2896
Range	26.2863	Range	740.6776	Range	795.4517	Range	213.1866
Minimum	185.3304	Minimum	776.4083	Minimum	805.9829	Minimum	426.7391
Maximum	211.6167	Maximum	1517.0859	Maximum	1601.4346	Maximum	639.9258
Sum	18888.3	Sum	99270.2	Sum	105093.7	Sum	53393.7
Count	97	Count	97	Count	97	Count	97
Largest(1)	211.6167	Largest(1)	1517.0859	Largest(1)	1601.4346	Largest(1)	639.9258
Smallest(1)	185.3304	Smallest(1)	776.4083	Smallest(1)	805.9829	Smallest(1)	426.7391
Confidence Level(95.0%)	1.1455	Confidence Level(95.0%)	27.9955	Confidence Level(95.0%)	29.1118	Confidence Level(95.0%)	11.7336

The mean for each plant parameter thus collectively form a set of plant data values.

At 60% power output, in Table 3.4, it can be seen that the largest interval for the 95% confidence level is for the feed-water pressure at 2.7% . The uncertainty gets larger as there were less data points, but still meaningful analysis could be done at both 80% and 60% power outputs.

3.2 Preliminary steady-state calculations

A preliminary calculation was performed using EES (Engineering Equation Solver) to determine the relevant primary side conditions for the model. This was done as the primary side data was not directly available in the form required for inputs to the simulation model. The steady-state also serve as a verification of the input and output parameters of the model. More in-depth mathematical verification of both software packages has been performed in previous studies (RELAP5, 2001d; van der Merwe et al., 2006).

The mass flow-rate of the primary side was not directly accessible from the data provided by Koeberg. It was, therefore, necessary to first calculate the primary side conditions of the steam generator before running simulations.

This was done by assuming the steady-state operation of the SG. With the secondary conditions known, it was possible to calculate the total heat transferred from the inlet and outlet enthalpies. As the SG is assumed to be at steady-state, the heat transferred to the secondary side is equal to the heat transferred from the primary side. With this information, we could calculate the primary mass flow with Equation 3.2.1.

$$\dot{Q} = \dot{m}_s \cdot (h_{so} - h_{si}) = \dot{m}_p \cdot (h_{po} - h_{pi}) \quad (3.2.1)$$

In order to directly calculate the primary mass flow-rate, however, it is necessary to know the inlet and outlet enthalpies of the primary side. This was calculated from the temperature and pressure conditions at the inlet and the outlet. The inlet conditions were obtained from the Safety Analysis Report from Koeberg (ESKOM, 2004). The primary outlet conditions were calculated from a pressure drop calculation described below.

Pressure drop

The Reynolds number is a common dimensionless number used in fluid analysis, and was calculated here for the primary fluid in the tubes. It gives us an indication of whether the flow is in the laminar or turbulent regime. We expect all flow in the steam generator to be turbulent, with a high Reynolds number.

$$Re_p = \frac{\rho_p \cdot v_p \cdot D_{h,p}}{\mu_p} \quad (3.2.2)$$

The velocity in the primary circuit was calculated from the density and the average flow area. The mass flow-rate is used here when calculated from Equation 3.2.1.

$$v_p = \frac{\dot{m}_p}{\rho_p \cdot A_p} \quad (3.2.3)$$

The friction factor was then calculated using the Haaland correlation (Thome, 2004). The roughness of stainless steel was used here, approximately $\epsilon = 30\mu m$ (Flownex, 2011a).

$$f = \left(\frac{1}{-1.8 \cdot \log_{10} \left[\left(\frac{\epsilon/D_{h,p}}{3.7} \right)^{1.11} + \frac{6.9}{Re_p} \right]} \right)^2 \quad (3.2.4)$$

The head-loss associated with the friction factor was then calculated for the lengths of the tubes.

$$h_l = f \cdot \left(\frac{L_p}{D_{h,p}} \right) \cdot \left(\frac{v_p^2}{2 \cdot g} \right) \quad (3.2.5)$$

The pressure drop across the primary side was calculated from the head loss.

$$\Delta P_p = \rho_p \cdot g \cdot h_l \quad (3.2.6)$$

Implicit mass flow-rate

In Equation 3.2.1 we can see that the primary side mass flow-rate can only be calculated if the primary inlet and outlet conditions are known. The outlet conditions, however, are a function of the pressure drop, which in turn is a function of the mass flow-rate. This can be seen in Equations 3.2.2 through 3.2.6. The friction factor, and thus also the pressure drop, is a function of the Reynolds number which in turn is a function of the flow velocity or mass flow-rate.

The primary outlet conditions are, therefore, initially guessed. New outlet conditions are calculated from the resulting pressure drop, and the calculation is iterated until guessed conditions converge with the calculated conditions.

3.3 Simplification of the geometry

Figure 3.1 shows the general geometry of the original steam generators installed at Koeberg NPP. It specifies the upper internals, including the geometry for the dryers and separators. It also specifies the geometry for the primary tubes. Some important geometrical aspects are the number and diameter of the separator and dryer stages. The flow paths for these components should be modelled separately (RELAP5, 2001c). The details for the tube bundle are also important. The heat transfer surface area of $4\,699\text{m}^2$ is used for a total of 3 330 tubes. The inner and outer diameters were given, as well as the square pitch. Also from the drawing, we are able to get the length of the SG, the spherical radius of the inlet plenums and the outside diameters of the lower and upper SG shell.

The final dimensions are shown in Figures 3.2 to 3.7.

The geometry for the flow areas was simplified to suit the scope of the project. The geometry from the technical documents were condensed to a set of one dimensional geometries suitable for the application of the one-dimensional model.

The simplified cross-section of the primary inlet plenum is shown in Figure 3.2. It was modelled as a cylinder, of the same radius as the spherical radius specified in the documents.

The boiler region consists of the primary tubes and the channels between the tubes for secondary flow. Dimensions for the down-comer were also included. A schematic is shown in Figure 3.3.

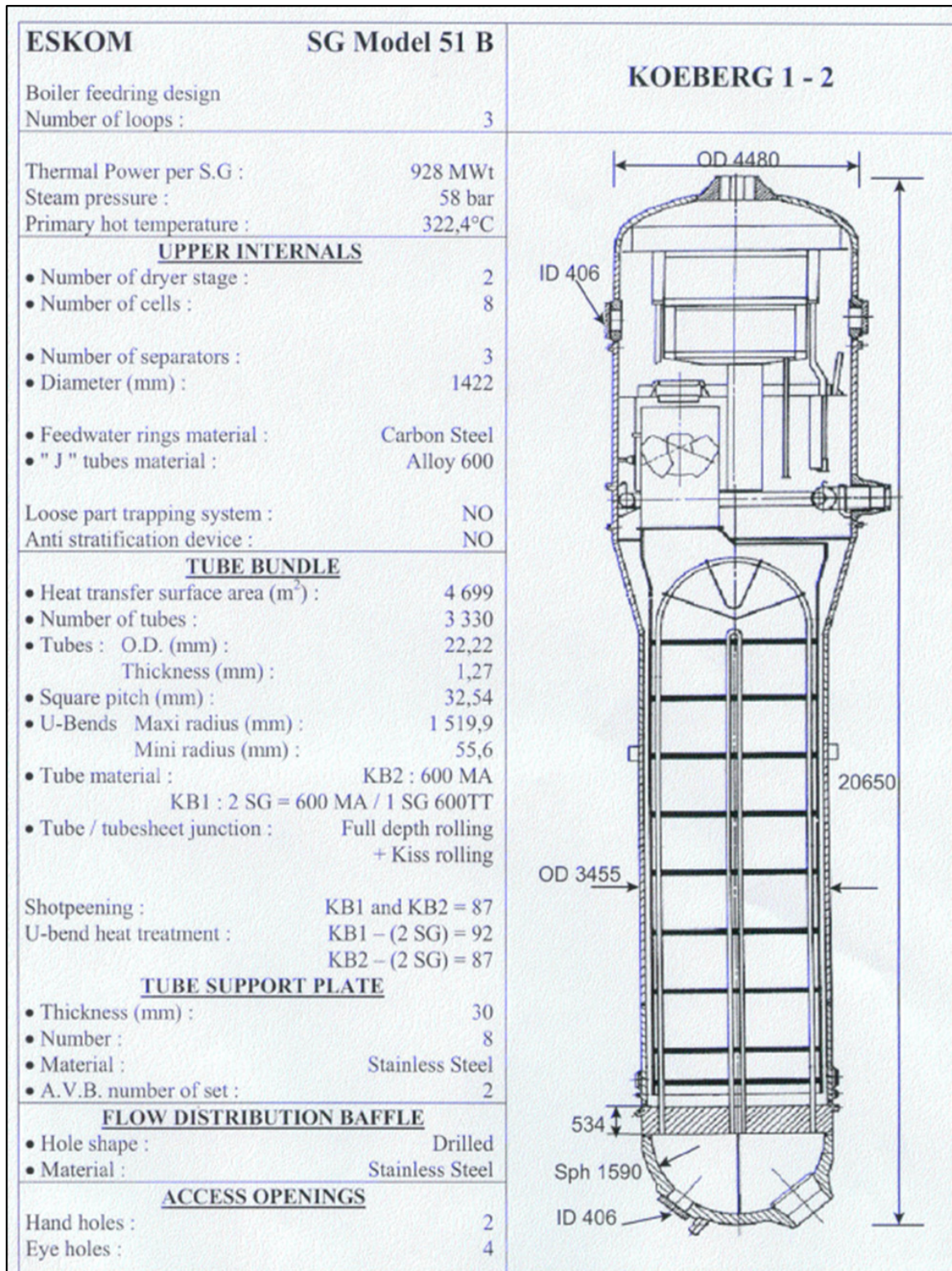


Figure 3.1: General geometry of the Koeberg SG (ESKOM)

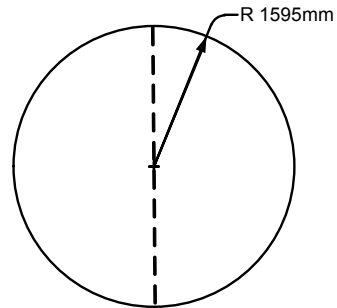


Figure 3.2: Inlet plenum geometry used for the model)

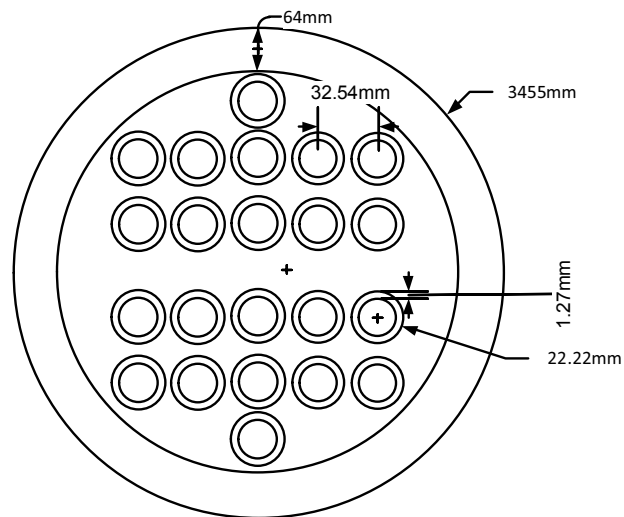


Figure 3.3: Geometry of the boiler region

The geometry of the riser consists mostly of the down-comer region that allows for recirculating flow. It is shown in Figure 3.4.

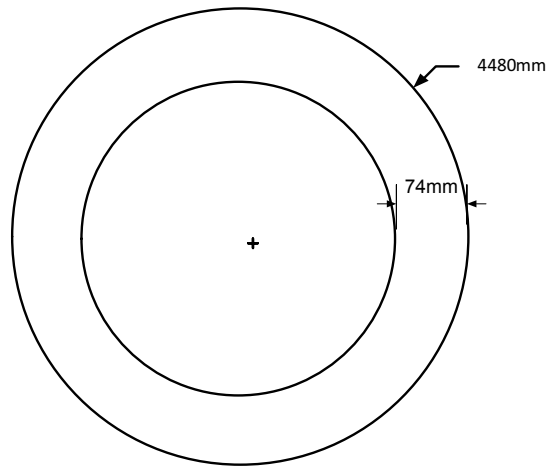


Figure 3.4: Geometry of the riser region

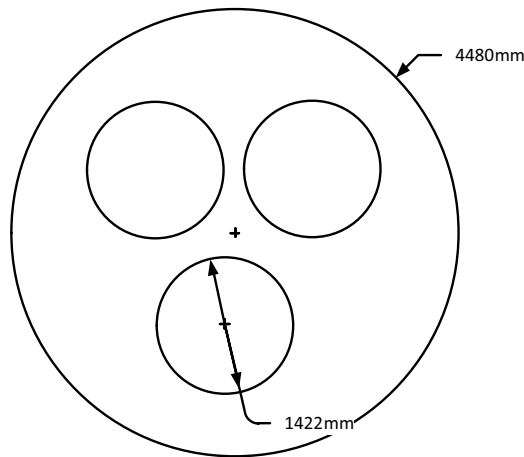


Figure 3.5: Geometry of the separator region

The geometry for the separators and the dryer stages is shown in Figure 3.5 and 3.6. The flow areas for the separator stage consist of the three centrifugal separator cylinders. The cylinders are shown in the figures as 3 circles, as they move vertically up through the upper shell of the SG.

The dryer stage is shown for clarity, but they were not modelled as custom flow resistances were added to the separator components to increase stability of the solution (RELAP5, 2001c). The dashed lines indicate where the dryer's would be situated in an actual model, but they do not significantly obstruct the flow so they were omitted to simplify the separation calculation.

The geometry of the steam dome was modelled as a simple cylindrical pipe. The outlet was linked to a time dependent volume, or boundary conditions simulating the turbine.

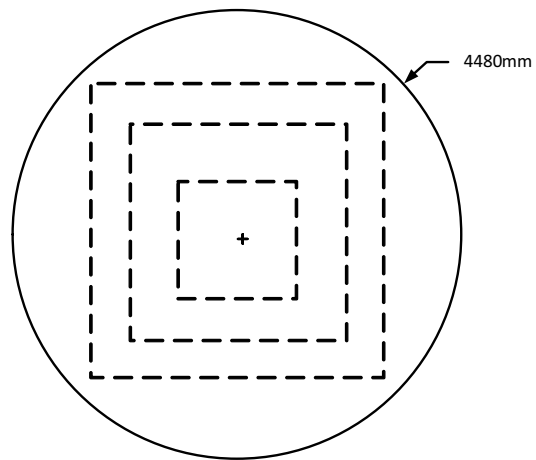


Figure 3.6: Geometry of the dryer region

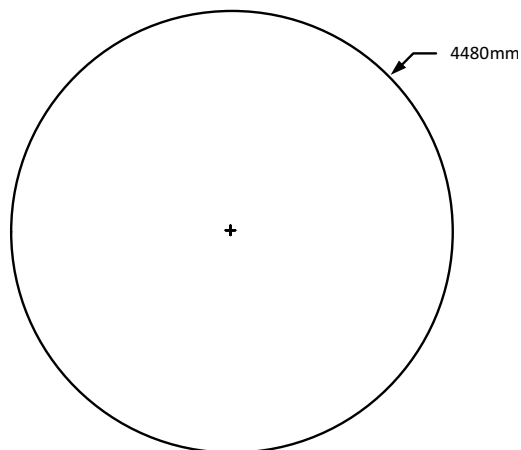


Figure 3.7: Geometry of the steam dome region

3.4 Geometry and Heat Structure inputs

The volumetric inputs for the model are shown in Table 3.5. These are the flow areas, volume lengths, hydraulic diameter, circumference and flow volume used for each of the components of the model.

Table 3.5: Volumetric inputs for the steam generator model

Primary Side Components									
Component	Flownex	RELAP5	No. of vol.	L (m)	D_h (m)	Circum. (m)	FA (m2)	V (m3)	Inc. (°)
Primary Inlet Volume	P-101	tmpdvol 101	1	-			0.518	-	90
Primary Inlet Header/Plenum	P-103	snglvol 103	1	1.063			3.996	4.249	90
U-Tube-1	P-110-1	pipe 110	10	11.412	0.01968		1.013	11.560	90
U-Tube-2	P-110-2								90
U-Tube-3	P-110-3								90
U-Tube-4	P-110-4								90
U-Tube-5	P-110-5								90
U-Tube-6	P-110-6								-90
U-Tube-7	P-110-7								-90
U-Tube-8	P-110-8								-90
U-Tube-9	P-110-9								-90
U-Tube-10	P-110-10								-90
Primary Outlet Header/Plenum	P-106	snglvol 106	1	1.063			3.996	4.249	-90
Primary Outlet Volume	P-108	tmdpvvol 108	1	-			0.7850	-	-90
Secondary Side Components									
Component	Flownex	RELAP5	No. of vol.	L (m)	D_h (m)	Circum. (m)	FA (m2)	V (m3)	Inc. (°)
Feed-water Inlet Volume	S-201	tmdpvvol 201	1	-			-	-	0
Feed-water Inlet Pipe	S-203	snglvol 203	1	3.000			0.518	1.554	0
Feed-water Branch	S-225	branch 225	1						-90
Down-comer Annulus	S-214	annulus 214	5	11.412			0.682	7.781	-90
Heated Riser Region 1	S-215-1	pipe 215	5	11.412	0.0385	815.956	7.402	84.473	90
Heated Riser Region 2	S-215-2								
Heated Riser Region 3	S-215-3								
Heated Riser Region 4	S-215-4								
Heated Riser Region 5	S-215-5								
Unheated Riser Region	S-216	snglvol 216	1	0.833			14.739	12.280	90
Separator Riser	S-221	snglvol 221	1	2.058			4.764	9.803	90
Dryers Riser	S-222	separatr 222	1	2.058			15.763	32.433	90
Reflux Down-comers	S-224	annulus 224	1	2.058			10.999	22.630	-90
Steam Dome	S-250	separatr 250	1	1.627			15.763	25.647	90
Steam Outlet Volume	S-260	tmdpvvol 260	1	-			-	-	90

The heat structure inputs for both RELAP5 and Flownex are shown in Table 3.6. The geometry of the heat structure was taken from the primary tube geometry. The heat structure models the tube material, and in both RELAP5 and Flownex, the material was chosen to be stainless steel.

Table 3.6: Heat structure inputs for the steam generator model

Heat Structures								
Component	From	To	Left SA (m ²)	Right SA (m ²)	Length (m)	Mesh Points	dx (m)	Thickness (m)
Tubing	P-110	S-215	4699	5305	22.8	5	0.0003175	0.00127

3.5 Model Development

The codes and inputs developed for the model are given in Appendix E and D for Flownex and RELAP5 respectively. The geometry and nodalization for both models were the same, as discussed in the previous section. The following subsections discuss the subtle differences in the setups.

3.5.1 RELAP5 - Two-Fluid

The nodalization used for RELAP5 is shown in Figure 3.8. The boundary conditions were represented by time-dependent volumes.

Due to the complicated nature of the SG internals, it was necessary to add custom flow losses to some of the junctions in order to simulate the correct re-circulation ratio (RELAP5, 2001c). The flow losses were adjusted in junction 206 (the junction entering the boiler region) so that a re-circulation ratio of 3.8 was achieved at 100% power output. The value of 3.8 was taken from Desfontaines-Leromain (2004), and is a standard design reference. The actual recirculation within the steam generator may vary from design due to a tube plugging, leakage or many of the other issues discussed in the previous chapter.

Further flow losses were added to the separator junctions to increase stability of the solution, in accordance with RELAP5 (2001c). When flow-losses were added to the separator, they were subtracted from the flow losses added to junction 206. This was done to maintain the re-circulation ratio, while still maintaining stability of the outlet quality.

The flow losses added to the separator were justified because RELAP5 models the separator components as a black box. The void fraction of the outlet steam and the return liquid is a function of the calculated void fraction within the steam separator component at any given time step. More detailed models of the steam separator components were available, but data to support the models were not.

The steam generator inputs were then left unchanged when run at 80% and 60% conditions.

Boundary conditions

The boundary conditions specified to RELAP5 for 100%, 80% and 60% power output conditions are shown in Table 3.7, Table 3.8 and Table 3.9.

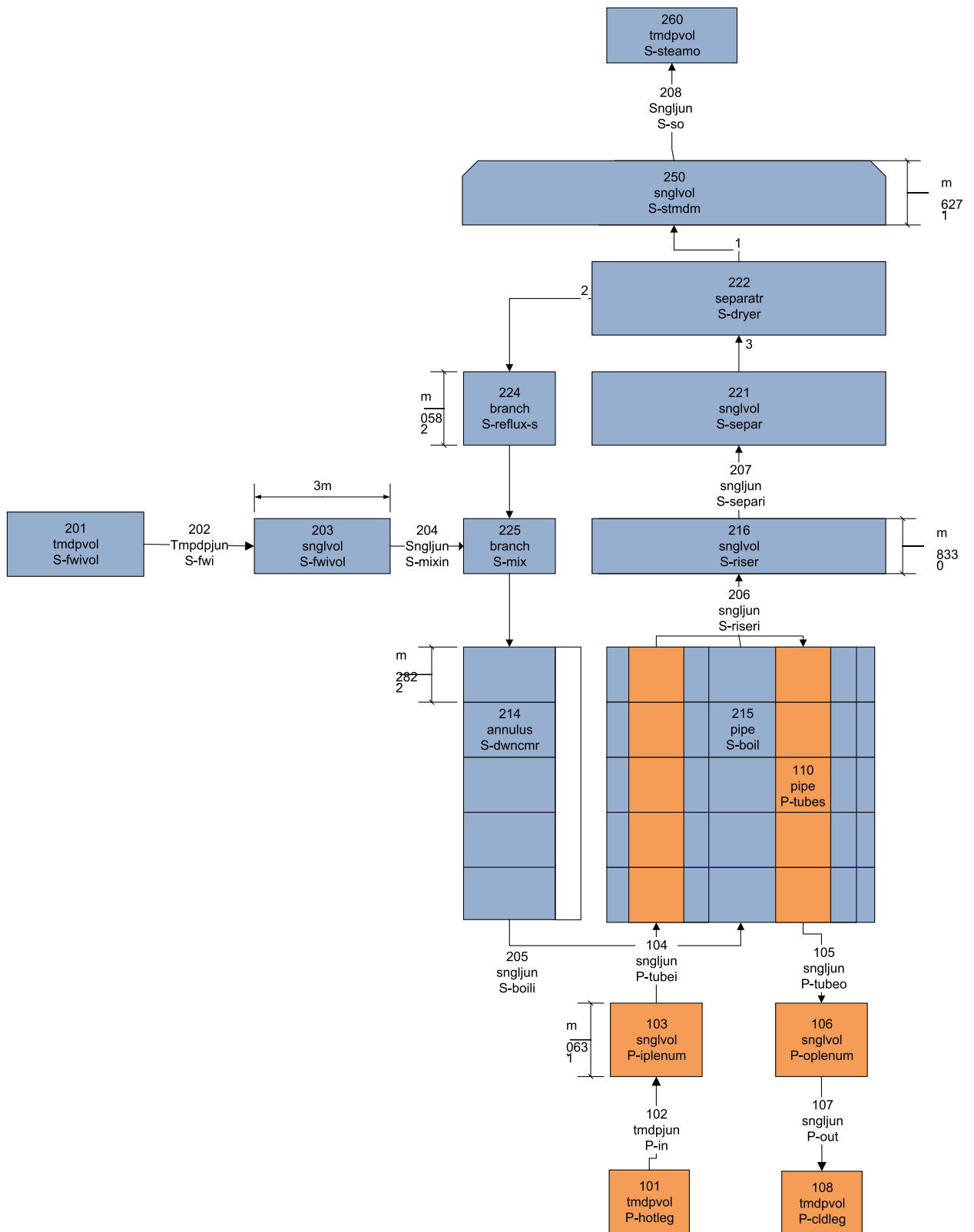


Figure 3.8: Nodalization of the steam generator model for RELAP5

The primary mass flow-rate and the primary outlet pressure were calculated in Section 3.2 of this report. The inlet mass flow-rate and inlet temperature were then specified to the primary and secondary circuit. The pressure and quality were specified for the outlet volumes of the primary and the secondary circuit.

The inlet pressure specified for the time-dependent volume is irrelevant to the calculation, as the time-dependent junction forces the mass-flow to the specified value (RELAP5, 2001c). The pressure of the time-dependent volume was therefore not used in the pressure calculation of the rest of the system.

Table 3.7: Boundary conditions specified to RELAP5 for 100% power output.

	m_dot (kg/s)	T (°C) or Quality	P (MPa)
Primary Inlet BC	6316	312	
Primary Outlet BC		0.0	14.825
Secondary Inlet BC	618	219	
Secondary Outlet BC		1.0	4.911

Table 3.8: Boundary conditions specified to RELAP5 at 80% power output.

	m_dot (kg/s)	T (°C) or Quality	P (MPa)
Primary Inlet BC	6051	306	
Primary Outlet BC		0.0	14.886
Secondary Inlet BC	479	220	
Secondary Outlet BC		1.0	5.023

Table 3.9: Boundary conditions specified to RELAP5 for 60% power output.

	m_dot (kg/s)	T (°C) or Quality	P (MPa)
Primary Inlet BC	6057	294	
Primary Outlet BC		0.0	14.897
Secondary Inlet BC	341	195	
Secondary Outlet BC		1.0	4.889

3.5.2 RELAP5 - Homogeneous

The development of the homogeneous RELAP5 model followed the same procedure as with the two-fluid model. The nodalization from Figure 3.8 was used. The difference lies in the fact that the homogeneous model was chosen for the solution of all the components except for the separator.

The two-fluid model is needed for the separator volume so that steam and liquid separation may take place in the component. The remainder of the model, including the boiler region, used the homogeneous solution. In RELAP5, this was achieved by setting the homogeneous switch on for each component except for the separator.

The custom flow losses were again added to junction 206 so that the re-circulation ratio was approximately 3.8.

Additional flow losses were added to the separator junctions to increase stability of the solution. To monitor stability, the outlet steam quality was monitored. It was found to oscillate wildly when unstable, and settle to a steady-state when brought to stability.

3.5.3 Flownex

The nodalization of the model used in Flownex is shown in Figure 3.9. The volumes mostly consist of pipe volumes and heat structure components. The separator was modelled with a two-phase tank. The separator component (or two-phase tank) behaves ideally, removing all steam and returning all liquid in the entering stream. The inputs set for the model may be found on the CD-ROM attached with this report.

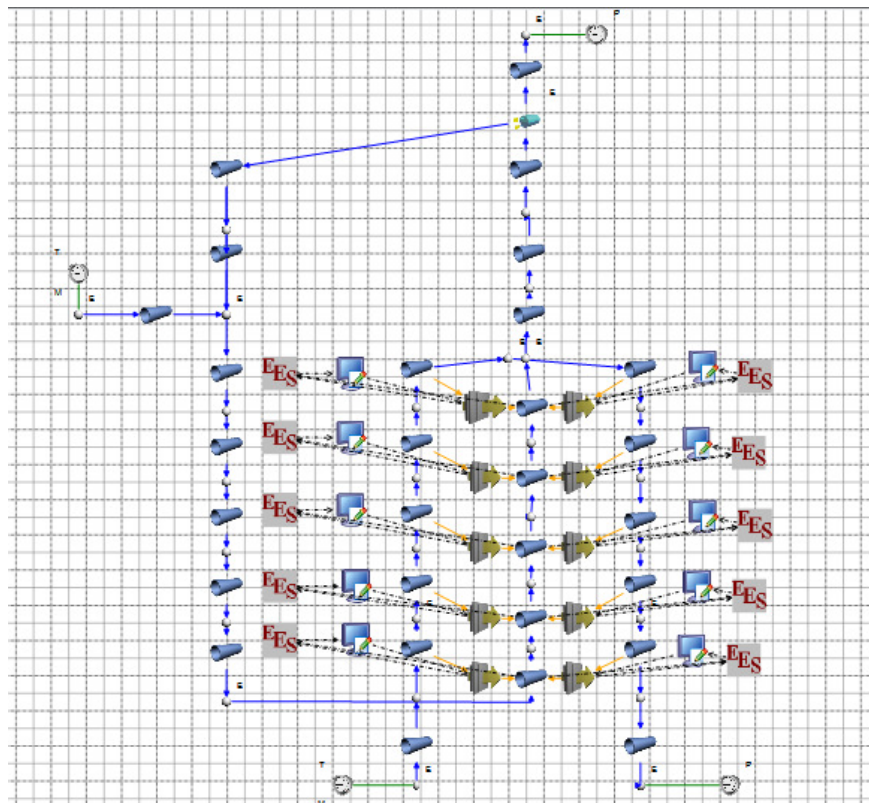


Figure 3.9: Nodalization of the steam generator model for Flownex

Heat transfer correlation script

The heat transfer correlation was custom written, as Flownex only provides a built in correlation for single-phase heat transfer using the Dittus-Boelter correlation. The boiling phenomenon is complicated, and the heat transfer more so. There are many flow and boiling regimes applicable over the steam generator (Green and Hetsroni, 1995), and it is thus difficult to model accurately. It was simplified by assuming that the Chen correlation can describe the heat transfer through the entire range of the boiler.

Flownex provides functionality to include EES scripts in the model. The flow parameters were calculated and sent to the EES script (see Appendix B) where two-phase parameters were calculated that weren't available in Flownex. The EES script then sent the parameters to the custom C# script included in Flownex. The Chen correlation was implemented with a C# script, utilizing the parameters received from the EES script. The C# script then calculated the heat transfer coefficient, and sent it to the heat transfer component.

The process is therefore iterative, and the steady-state was calculated until the heat transfer coefficient converged. The code for the Chen correlation script may be found in Appendix C. The EES script for calculating the two-phase parameters may be found in Appendix B.

Boundary conditions

The boundary conditions specified to the model in Flownex for 100%, 80% and 60% power conditions are shown in Table 3.10, Table 3.11 and Table 3.12 respectively.

The mass flow-rate and temperature were specified for the inlets of both the primary and secondary circuits. The outlet pressure was specified for the primary and secondary circuits.

Table 3.10: Boundary conditions specified to Flownex for 100% power output.

	$\dot{m}$ (kg/s)	T (°C)	P (MPa)
Primary Inlet BC	6316	312	
Primary Outlet BC			14.825
Secondary Inlet BC	618	219	
Secondary Outlet BC			4.911

Table 3.11: Boundary conditions specified to Flownex for 80% power output.

	m_dot (kg/s)	T (°C)	P (MPa)
Primary Inlet BC	6051	306	
Primary Outlet BC			14.886
Secondary Inlet BC	479	220	
Secondary Outlet BC			5.023

Table 3.12: Boundary conditions specified to Flownex at 60% power output.

	m_dot (kg/s)	T (°C)	P (MPa)
Primary Inlet BC	6057	294	
Primary Outlet BC			14.897
Secondary Inlet BC	341	195	
Secondary Outlet BC			4.889

Results and discussion

4.1 Comparison with empirical data

The models were validated against the plant operating data obtained from Koeberg NPP, as was discussed in Section 3.1 of this report. The arithmetic mean from the plant parameters were used as a single value describing each condition of 100%, 80% and 60% power output. In Table 4.1, Table 4.2 and Table 4.3 the results from the RELAP5 and Flownex models are tabulated against these values. The error is reported for each variable for each model.

4.1.1 100% Power Output

Table 4.1 shows the Koeberg data describing the 100% power level tabulated against the results from RELAP5 and Flownex.

Table 4.1: Steady-state validation of the model at 100% power output

		T_pi (°C)	T_po (°C)	P_so (kPa)	P_si (kPa)	T_si (°C)	x_so	m_dot_s (kg/s)	Q_boiler (MW)	R_circ
100% Power	Koeberg	312	279	4911	5277	220	1.000	618	1143	3.80
	RELAP5 - Two-Fluid	312	279	4912	4942	220	1.000	610	1131	3.81
	Error %	-0.1	0.0	0.0	-6.4	0.1	0.0	-1.3	-1.0	0.2
	RELAP5 - Homogeneous	312	279	4911	4924	220	1.000	604	1121	3.81
	Error %	-0.1	0.1	0.0	-6.7	0.1	0.0	-2.2	-1.9	0.3
	Flownex - Homogeneous	312	280	4911	4951	220	1.000	618	1092	3.80
	Error %	-0.1	0.4	0.0	-6.2	0.1	0.0	0.1	-4.4	-0.1

The largest errors were -6.4%, -6.7% and -6.2% for the secondary inlet pressure calculated by the RELAP5 two-fluid, homogeneous and Flownex models respectively.

The errors for the heat transferred in the boiler for the RELAP5 two-fluid, homogeneous and Flownex models were -1.0%, -1.9% and -4.4% respectively. The slight underestimation by RELAP5 was attributed to the fact that the heat transfer correlations slightly under-estimate the actual heat-transfer which occurs (RELAP5, 2001b). In Flownex, where we exclusively used the Chen correlation, we saw an even larger under-estimation in heat transfer.

The flow-rate of steam was under-estimated by 1.3% and 2.2% by the RELAP5 two-fluid and homogeneous models, respectively. The mass flow-rate reported in the results corresponds to the outlet steam flow-rate. While the feed-water flow-rate is kept constant, as described in Chapter 3, there are instabilities brought in by the steam separator component (RELAP5, 2001c). These instabilities result in oscillations of the steam flow-rate exiting the separator. By adding flow losses to the separator component, as described in the previous section, these oscillations may be reduced (RELAP5, 2001c).

4.1.2 80% Power Output

The models were developed specifically to achieve a re-circulation ratio of 3.8 at 100% power output. This was done by adjusting flow losses through the boiler region as well as the separator component. The subsequent calculations at lower power levels such as 80% and 60% were done without adjusting flow losses further. In this way, we were able to see how the model reacts to various power levels.

Table 4.2 shows the Koeberg data values tabulated against the values calculated by RELAP5 and Flownex.

Table 4.2: Steady-state validation of the model at 80% power output

		T _{pi} (°C)	T _{po} (°C)	P _{so} (kPa)	P _{si} (kPa)	T _{si} (°C)	x _{so}	m _{dot_s} (kg/s)	Q _{boiler} (MW)	R _{circ}
80% Power	Koeberg	306	278	5023	5221	210	1.000	479	908	5.00
	RELAP5 - Two-Fluid	306	277	5026	5057	210	1.000	483	916	4.89
	Error %	-0.1	-0.2	0.1	-3.1	0.1	0.0	0.9	0.9	-2.1
	RELAP5 - Homogeneous	306	277	5023	5051	210	1.000	485	919	5.81
	Error %	-0.1	-0.3	0.0	-3.3	0.1	0.0	1.4	1.2	16.2
	Flownex - Homogeneous	306	278	5023	5049	210	1.000	479	892	4.84
	Error %	-0.1	0.0	0.0	-3.3	0.1	0.0	0.1	-1.8	-3.1

The largest errors were again the inlet pressure calculated for the secondary circuit. The RELAP5 two-fluid model calculates an error of -3.1%, while the RELAP5 homogeneous model and Flownex both calculated an error of -3.3%.

The error in heat transfer calculated by the RELAP5 two-fluid model, the RELAP5 homogeneous model and Flownex were 0.9%, 1.2% and -1.8% respectively.

The error in the steam flow-rate was 0.9% and 1.4% for the RELAP5 two-fluid and homogeneous models, respectively.

4.1.3 60% Power Output

Table 4.3 shows the Koeberg data tabulated against the results calculated from RELAP5 and Flownex.

Table 4.3: Steady-state validation of the model at 60% power output

		T _{pi} (°C)	T _{po} (°C)	P _{so} (kPa)	P _{si} (kPa)	T _{si} (°C)	x _{so}	m _{dot_s} (kg/s)	Q _{boiler} (MW)	R _{circ}
60% Power	Koeberg	294	273	4889	5055	195	1.000	341	670	7.00
	RELAP5 - Two-Fluid	294	273	4892	4892	195	0.982	341	660	6.37
	Error %	-0.2	-0.1	0.1	-3.2	0.1	-1.8	0.0	-1.5	-9.1
	RELAP5 - Homogeneous	294	273	4889	4916	195	0.987	341	663	7.66
	Error %	-0.2	-0.1	0.0	-2.7	0.1	-1.3	0.0	-1.0	9.4
	Flownex - Homogeneous	294	273	4889	4919	195	1.000	341	666	6.63
	Error %	-0.2	-0.2	0.0	-2.7	0.1	0.0	0.0	-0.6	-5.2

The error in the pressure calculation was -3.2%, -2.7% and -2.7% for the RELAP5 two-fluid, homogeneous and Flownex models respectively.

The error in heat transfer was -1.5%, -1.0% and -0.6% for the RELAP5 two-fluid, homogeneous and Flownex models respectively.

The quality of the exit steam was calculated to have a larger error at lower power levels. The RELAP5 two-fluid and homogeneous solution calculated an error of -1.8% and -1.3% respectively.

4.2 Detailed inter-model comparisons

The results from RELAP5 showed that the flow regime through the first 3 vertical volumes of the boiling region (corresponding to the first 6.85m in height) was in the sub-cooled nucleate boiling regime, in which the Chen correlation and the Bergles-Rohsenow correlation is used to calculate the heat transfer. The upper height of the shell side (the remaining 4.56m) was in the saturated nucleate boiling regime, applying the Chen correlation as well as the Araki correlation to the solution (discussed in Section 2.2.1). The reason the Chen correlation is not used exclusively is because the correlation used within RELAP5 also varies with the surface and geometry type specified. The results show, however, that the assumption of the boiling regime is correct, and that the Chen correlation does indeed apply in the boiler region.

This was true at 100%, 80% and 60% power, and shows that the initial assumption that the Chen correlation will dominate heat transfer effect was accurate.

It was not possible to analyze the micro- and macro-scopic parts of the Chen correlation from RELAP5, and due to this inability, was omitted from the results in Flownex as well.

4.2.1 Primary side temperatures

The primary side temperatures calculated for the models at 100%, 80% and 60% power output are shown in Figure 4.1, Figure 4.2 and Figure 4.3 respectively. The middle of the graph at 11m represents the top of the tube bundle. The left half of the graph below 11m represents the upwards portion of the tube bundle, while the right side represents the downward section.

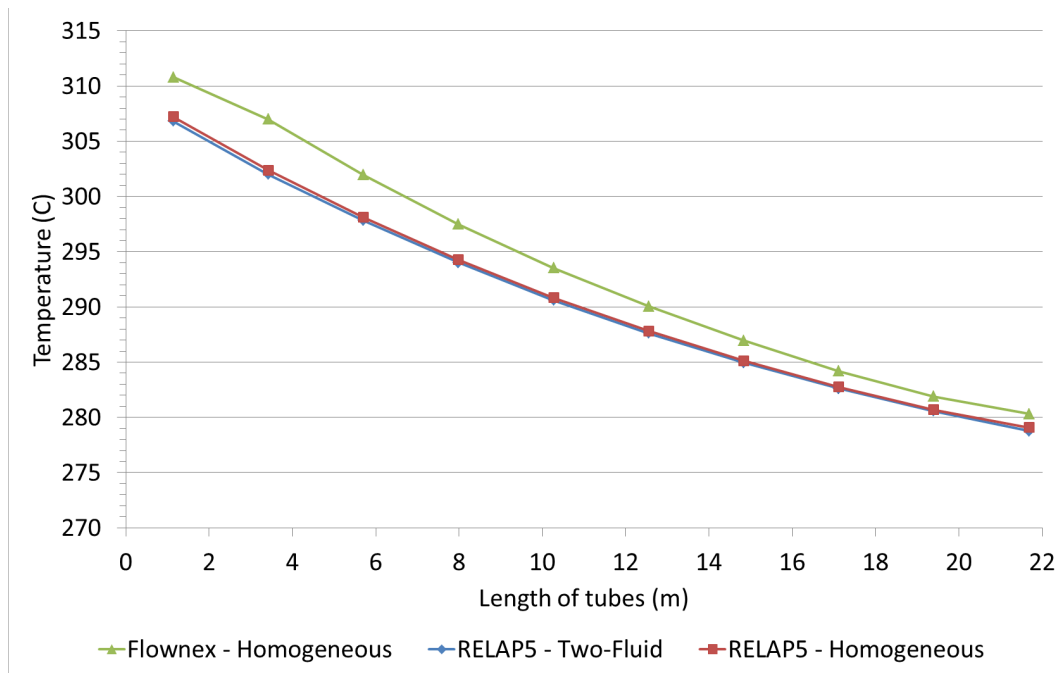


Figure 4.1: Primary side fluid temperatures at 100% power output

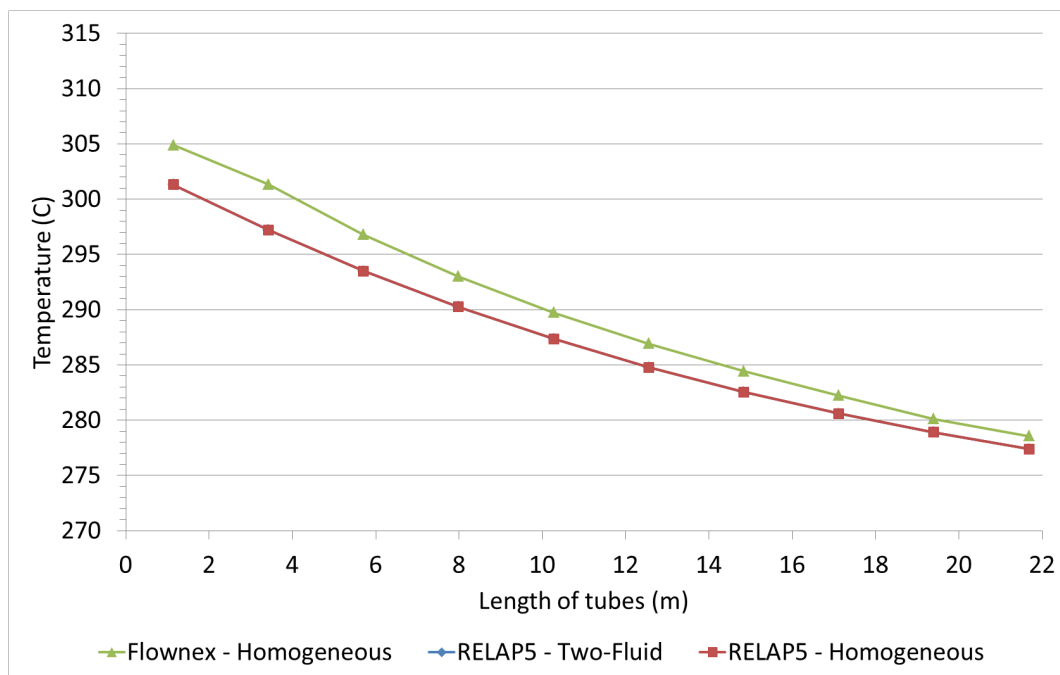


Figure 4.2: Primary side fluid temperatures at 80% power output

There was no noticeable difference between the RELAP5 two-fluid and homogeneous solution at any power level. The Flownex solution approached the RELAP5 solution at higher qualities, indicating that the heat transfer correlation in Flownex might be the cause of the error, and not the homogeneous assumption.

The Flownex solution differed by as much as 5°C from the RELAP5 solution in the first half of the

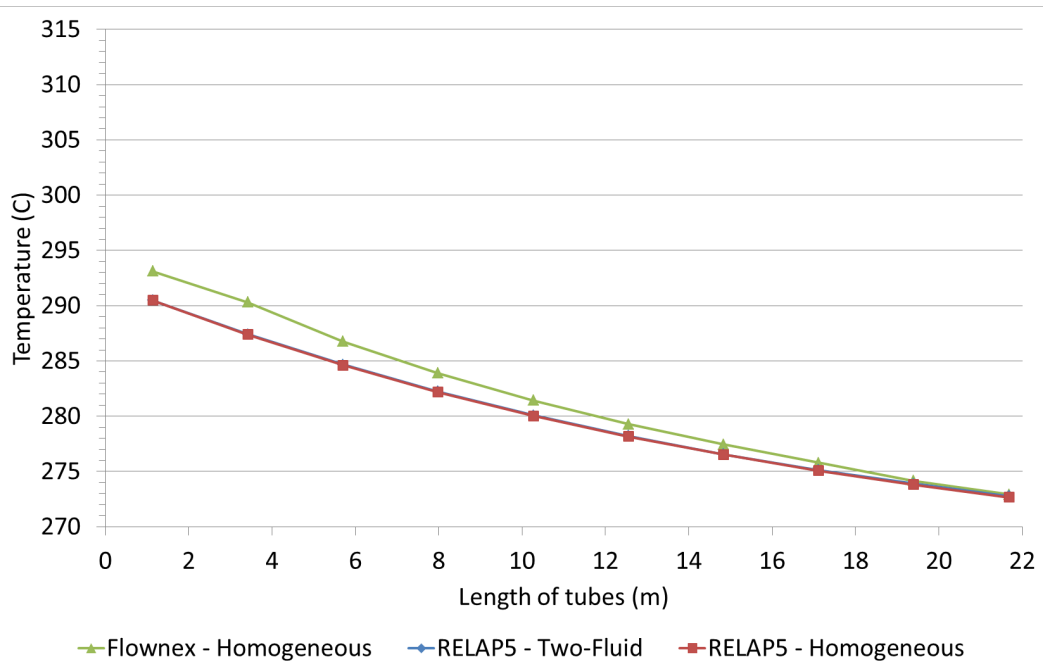


Figure 4.3: Primary side fluid temperatures at 60% power output

tubes. The difference decreased with decreasing power levels. The difference was attributed to the use of the Chen correlation in Flownex over the entire range of the boiler.

4.2.2 Quality through the boiler

The quality of the secondary fluid flowing through the boiler region was calculated and is shown in Figure 4.4, Figure 4.5 and Figure 4.6 respectively.

At 100% power output there was little difference between the homogeneous and two-fluid solutions from RELAP5. At lower powers, there was a marked difference between the two solutions. At 80% and 60% power output, the quality calculated by the homogeneous model was up to 4% less than calculated by the two-fluid model. The difference between the quality calculated by the two models increased linearly as the quality and elevation above the tube-sheet increases.

The Flownex model predicted a lower quality than the RELAP5 model by up to 0.05 throughout the range of the boiler region. At 100%, where the difference between the homogeneous solution and the two-fluid solution was small, the error was largely attributed to the heat transfer correlation used in Flownex. At 80% and 60% power levels, the RELAP5 homogeneous solution approached the Flownex solution at higher qualities.

In the RELAP5 model, boiling starts at close to 0m above the tube-sheet, as there is already significant quality increase in the first volume. In the Flownex model, boiling starts in the second volume. This may be attributed to the inability of the homogeneous model to accurately calculate

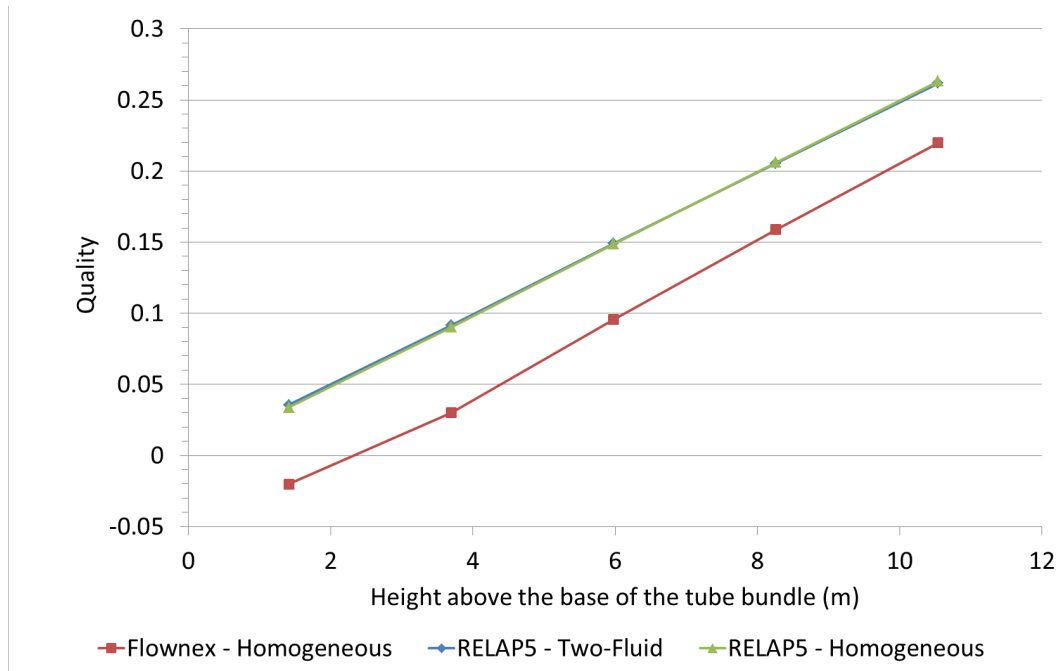


Figure 4.4: Secondary quality through the boiler region at 100% power output

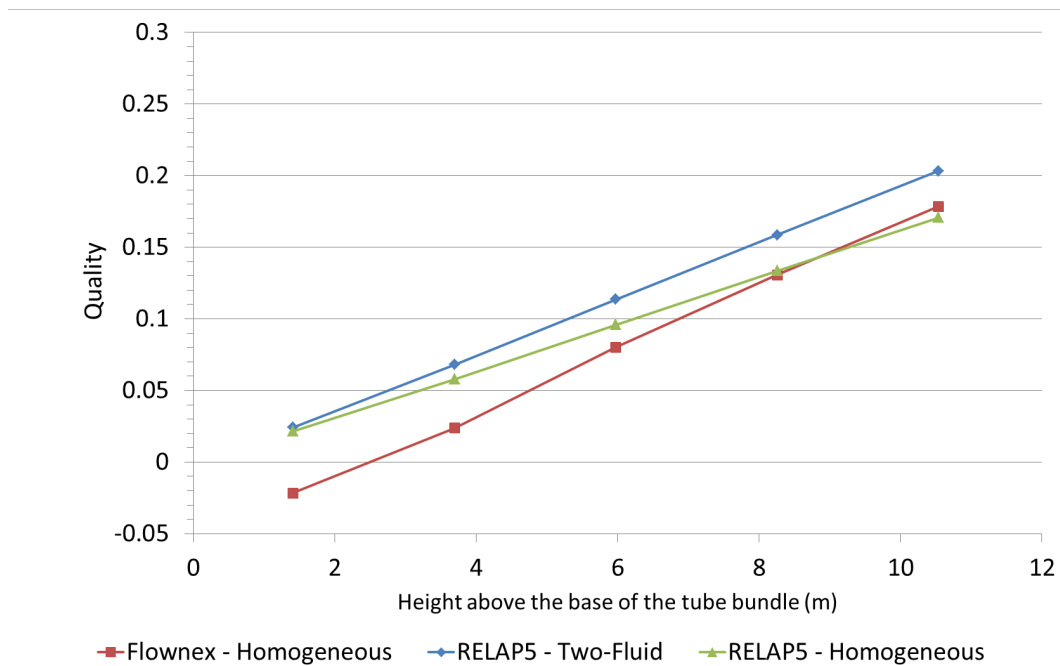


Figure 4.5: Secondary quality through the boiler region at 80% power output

the water level in the two-phase solution. In reality, the flow at the bottom of the tube bundle is chaotic and frothy, and no true water line exists. In the Flownex model, the bottom volume still consists only of water, and so the heat transfer coefficient is reduced and boiling starts a short while later than the RELAP5 model.

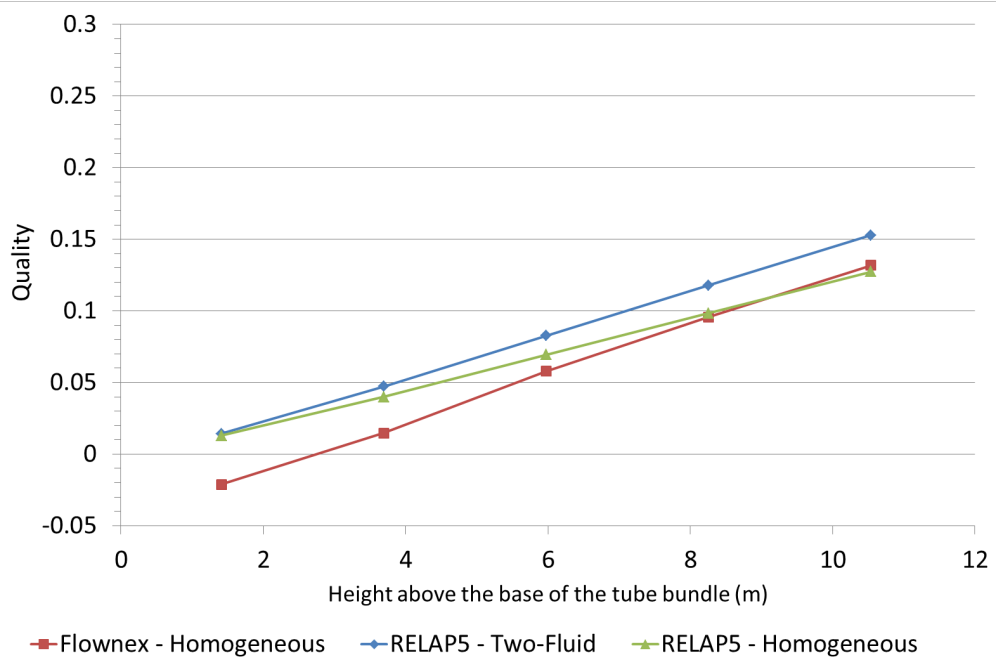


Figure 4.6: Secondary quality through the boiler region at 60% power output

4.2.3 Heat transfer coefficient on the surface of the tubes

The heat transfer coefficient in Flownex was calculated by the custom C# script described in the previous chapter. The heat transfer coefficient in RELAP5 was calculated by using the matrix of correlations described in Chapter 2. The comparison of the results are shown in Figure 4.7, Figure 4.8 and Figure 4.9 for 100%, 80% and 60% power output respectively.

A large difference between the homogeneous solution and the two-fluid solution occurred at the inlet and outlet ends of the tubes near the tube-sheet. A difference of approximately $11\,000 \frac{W}{m^2 \cdot K}$ was calculated at both ends. There was little to no difference between the RELAP5 homogeneous and the two-fluid model over the remainder of the tubes. The small difference was attributed to the water-level in the boiler region existing within the first and lowest volume. The homogeneous model cannot account for the water-level, and thus uses a single-phase heat transfer correlation in the lower regions. At lower power levels there was little difference between the two models.

The heat transfer coefficient calculated by the custom Flownex script was lower than RELAP5 by up to $12\,000 \frac{W}{m^2 \cdot K}$ across the range of the boiler. The discrepancy was expected in the lower regions of the boiler. However, the large difference across the rest of the boiler would indicate that the Chen correlation should not be used exclusively for boiling heat transfer.

The large difference in the calculated heat transfer coefficients was attributed to the fact that Flownex uses the Chen correlation exclusively over the range of conditions through throughout the boiler region. RELAP5 uses a matrix of correlations, as described in Chapter 2, which results in a more accurate prediction than we get with our rudimentary script.

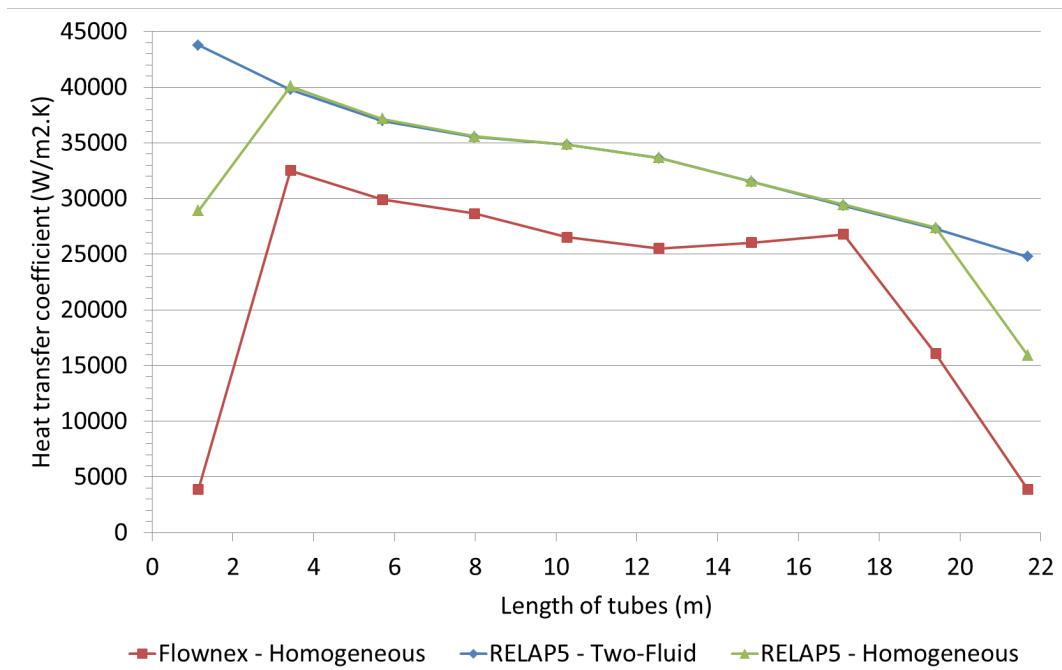


Figure 4.7: Heat transfer coefficient on the surface of the tubes at 100% power output.

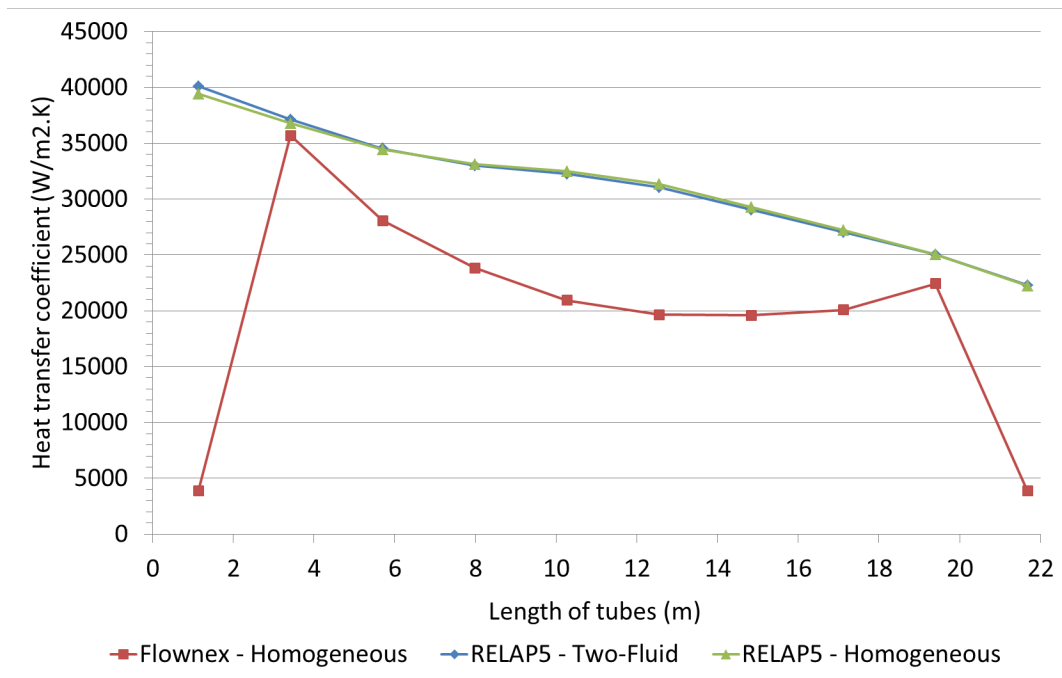


Figure 4.8: Heat transfer coefficient on the surface of the tubes at 80% power output.

4.2.4 Flow velocity through the boiler region

The flow velocity for the homogeneous, liquid and vapour fluids flowing through the boiler region are shown in Figure 4.10, Figure 4.11 and Figure 4.12 respectively.

The homogeneous model approximated the two-fluid velocity well at low elevations and low

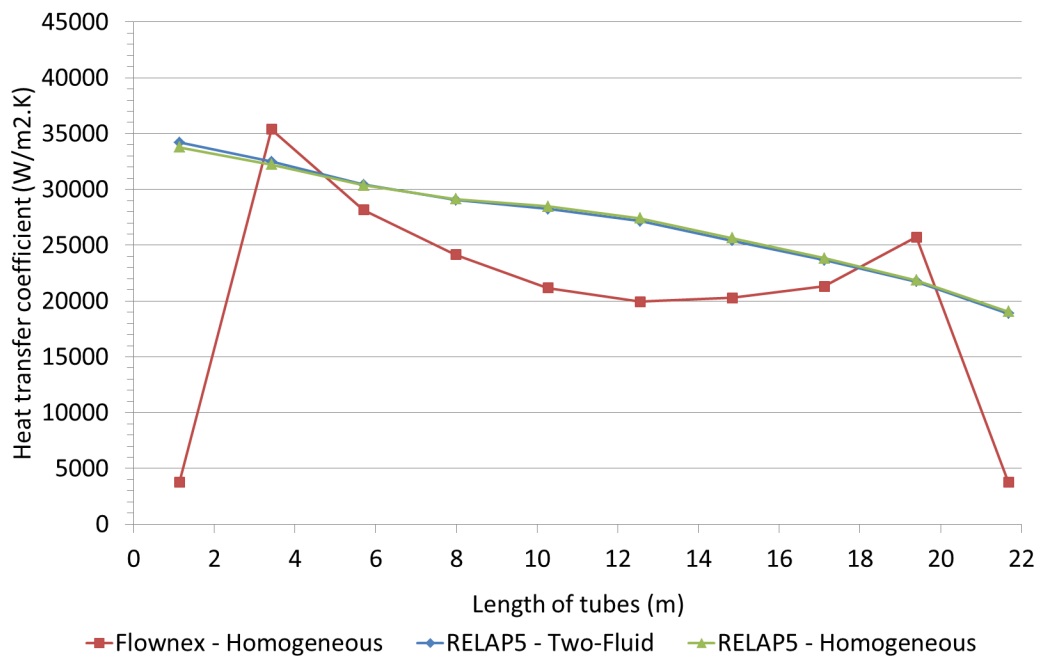


Figure 4.9: Heat transfer coefficient on the surface of the tubes at 60% power output.

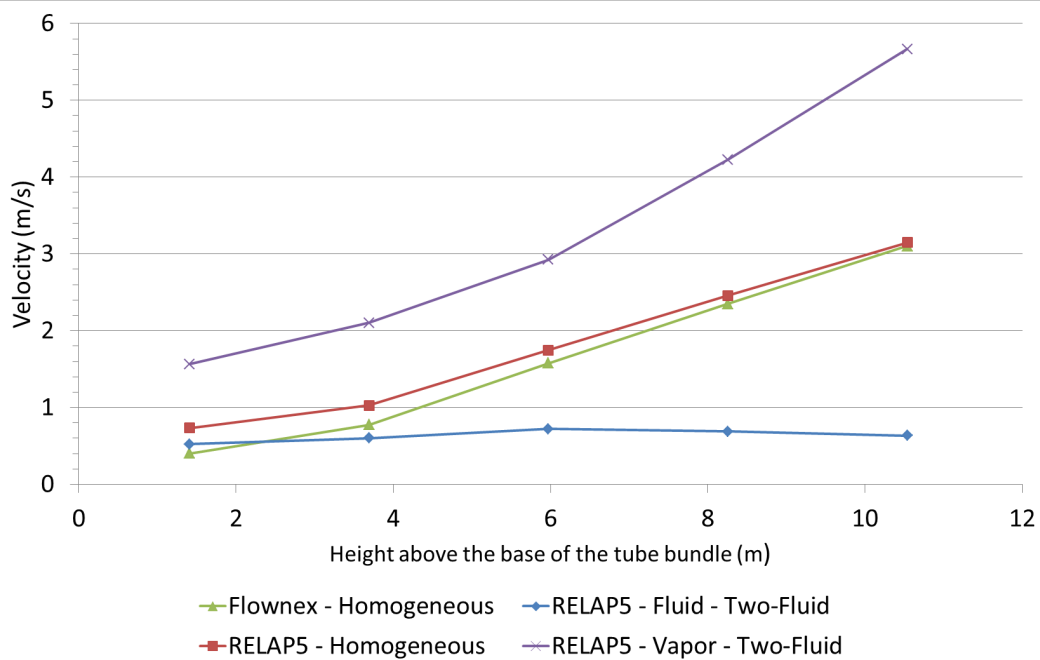


Figure 4.10: Flow velocity through the boiler region at 100% power output.

quality. Above 4m, and thus at higher quality, the homogeneous flow velocity appeared to approximate the average between the fluid and vapour velocities. At 100%, the vapour velocity at 11m was calculated by RELAP5 to be almost 6 m/s, while the homogeneous flow was calculated as 3 m/s. At 60%, the difference was smaller at 1 m/s.

There was a small difference between flow velocities calculated by RELAP5 and Flownex. At

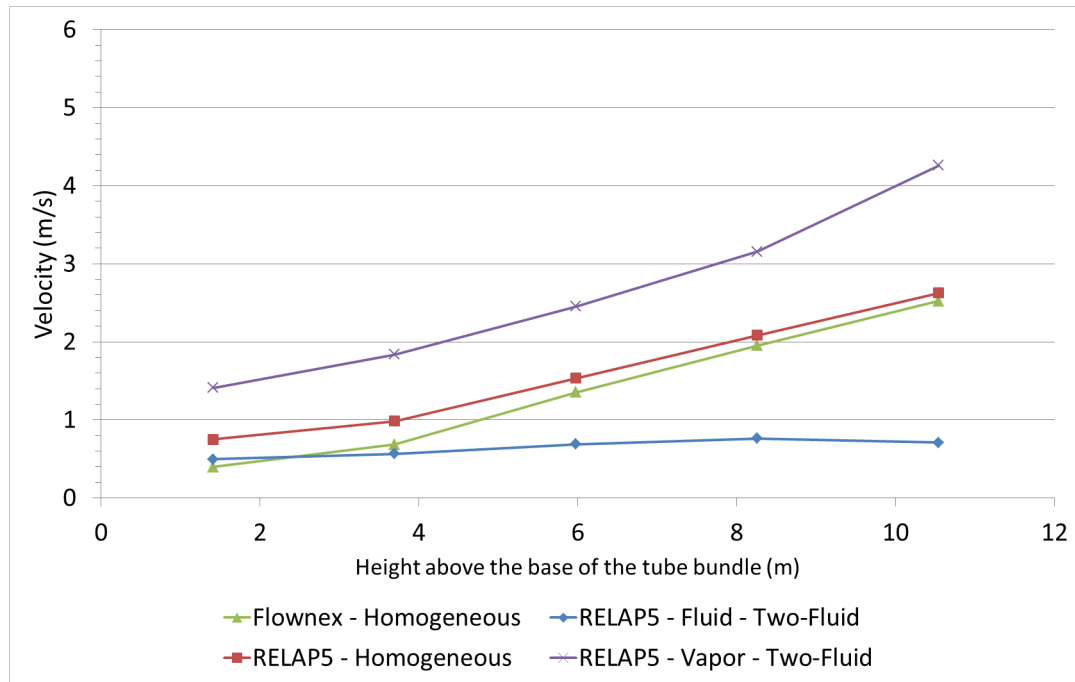


Figure 4.11: Flow velocity through the boiler region at 80% power output.

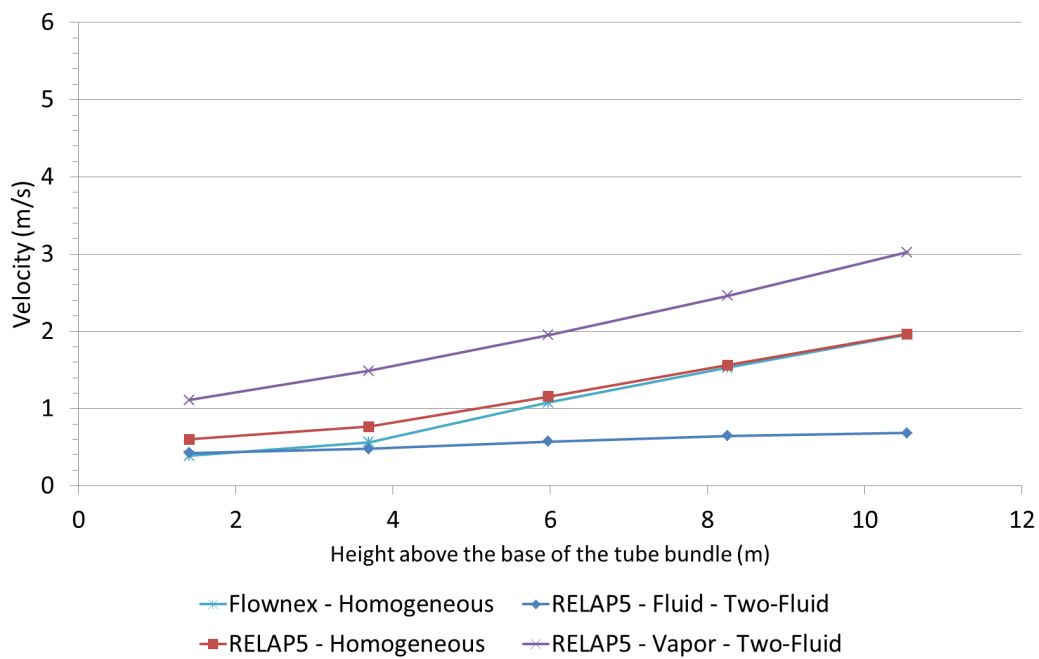


Figure 4.12: Flow velocity through the boiler region at 60% power output.

100% and 1m, the difference was 0.6 m/s. The difference gets smaller as the elevation and quality increases.

4.2.5 Tube surface temperature on secondary side

The surface temperature on the secondary side of the tubes are shown in Figure 4.13, Figure 4.14 and Figure 4.15 respectively.

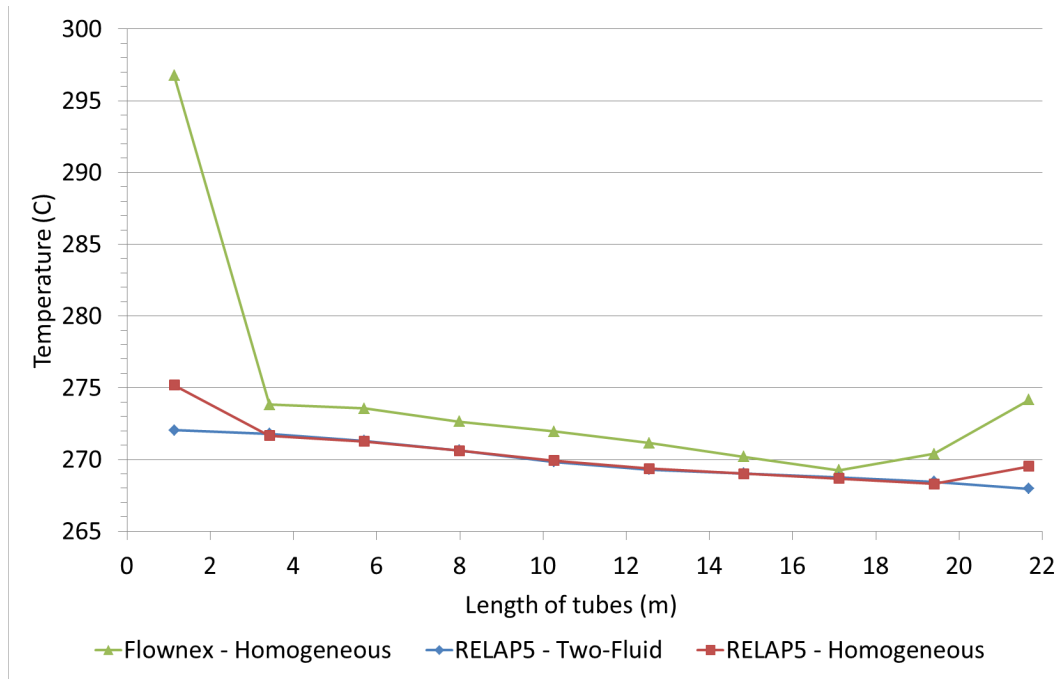


Figure 4.13: Secondary surface temperatures on the tubes 100% power output.

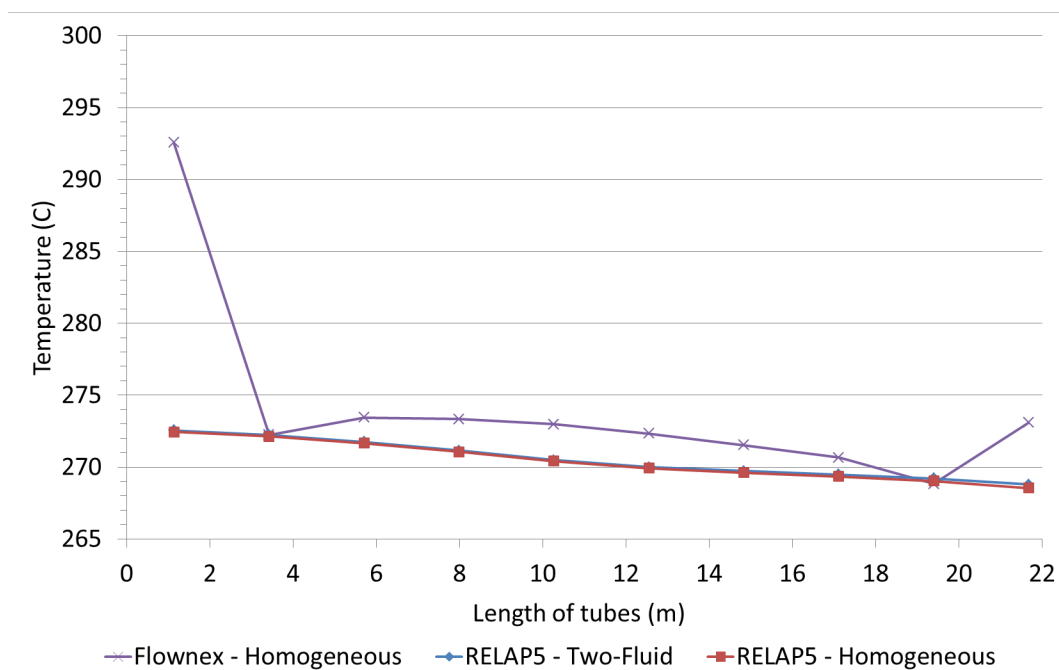


Figure 4.14: Secondary surface temperatures on the tubes 80% power output.

The difference between the homogeneous model and the two-fluid model was most apparent at

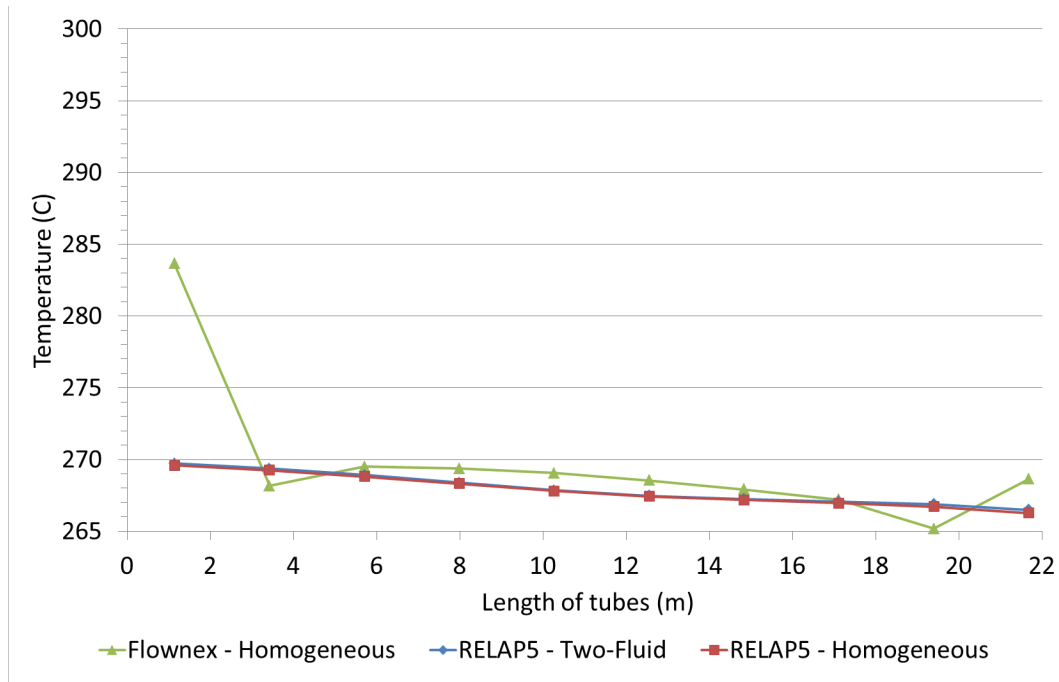


Figure 4.15: Secondary surface temperatures on the tubes 60% power output.

the end points of the tubes. There was a difference of approximately 5°C at the ends of the tubes at 100%, but no difference at lower power levels. The difference at low elevations was expected due to the inaccuracy of the homogeneous model in modelling the water-level in the boiler region.

There was a large difference between the Flownex solution and the RELAP5 solution in at the end points of the tubes. The temperature at 1m and 100% was larger in Flownex by almost 25°C. The difference decreases drastically along the tube length, and was therefore attributed to the lower quality predicted by Flownex. Over the remainder of the tube surface, the Flownex solution follows the trend of the heat transfer coefficient. The surface temperatures calculated by Flownex were slightly larger by approximately 3°C over the remainder of the tube surface.

4.2.6 Heat flux on the surface of the tubes

The heat flux calculated on the secondary surface of the tubes for the various models are shown in Figure 4.16, Figure 4.17 and Figure 4.18 respectively.

There was a slight difference between the homogeneous and the two-fluid models at the end points of the tubes. The heat flux predicted by the homogeneous model was lower by as much as $50 \frac{kW}{m^2}$ at 1m and 100%. There was less difference between the models at lower power levels.

There was a large difference between the heat flux predicted by Flownex and RELAP5. As expected, at the end points of the tubes we saw enlarged differences between the models. The difference were as large as $170 \frac{kW}{m^2}$ at 1m and 100%. At lower power levels, the difference was still large, as high as $200 \frac{kW}{m^2}$ at 4m and 80%. The Flownex solution approaches the RELAP5 solution

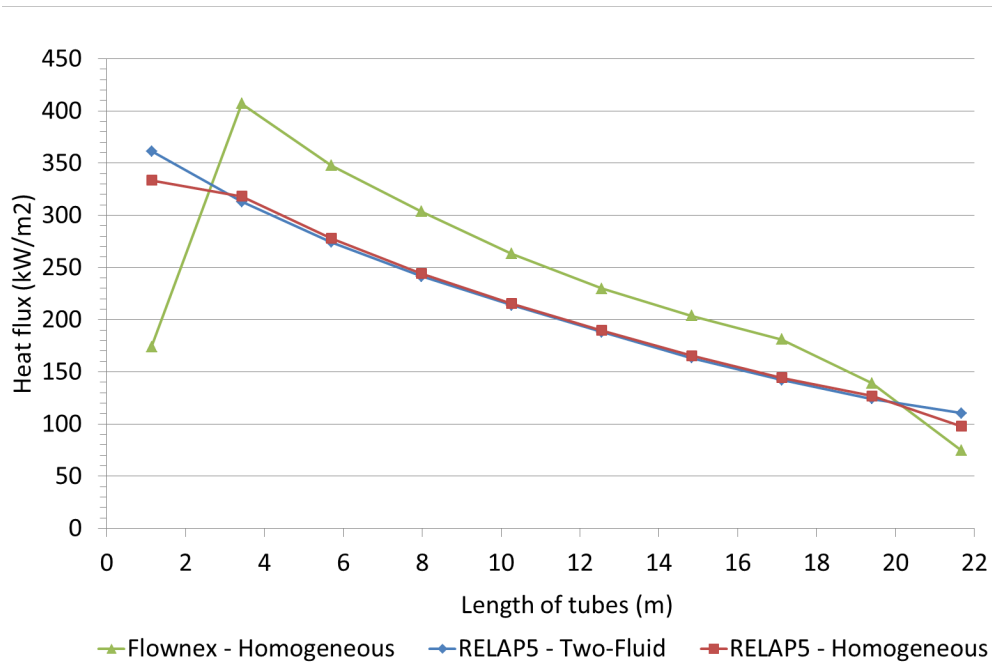


Figure 4.16: Heat flux on the surface of the tubes at 100% power output.

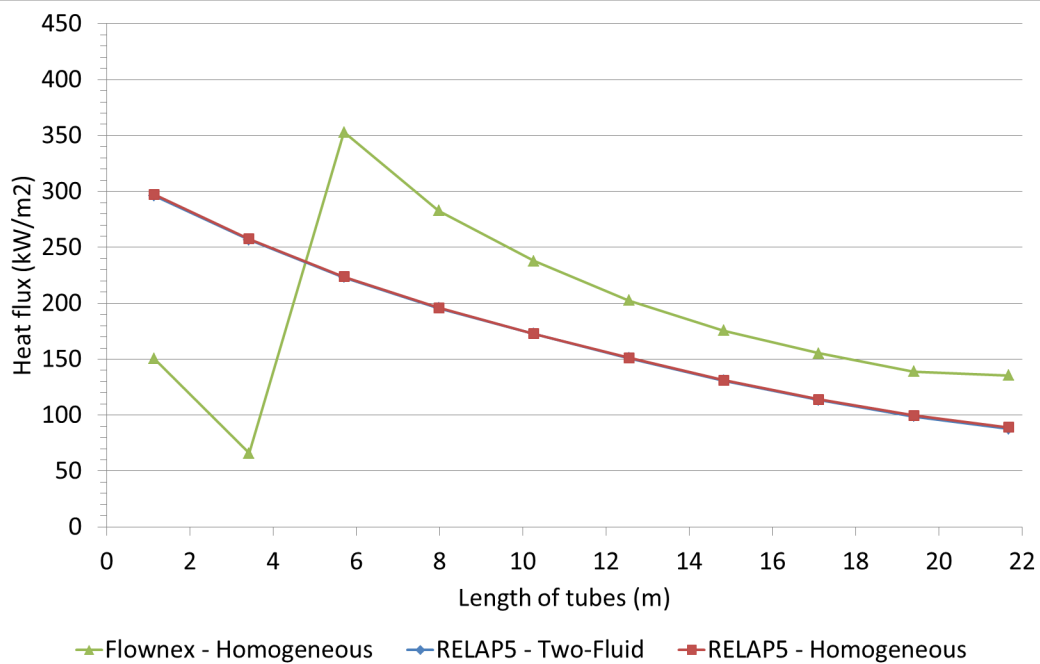


Figure 4.17: Heat flux on the surface of the tubes at 80% power output.

at higher elevations above the tube sheet. The difference being slightly lower at a maximum of $120 \frac{kW}{m^2}$ at 7m and 80%.

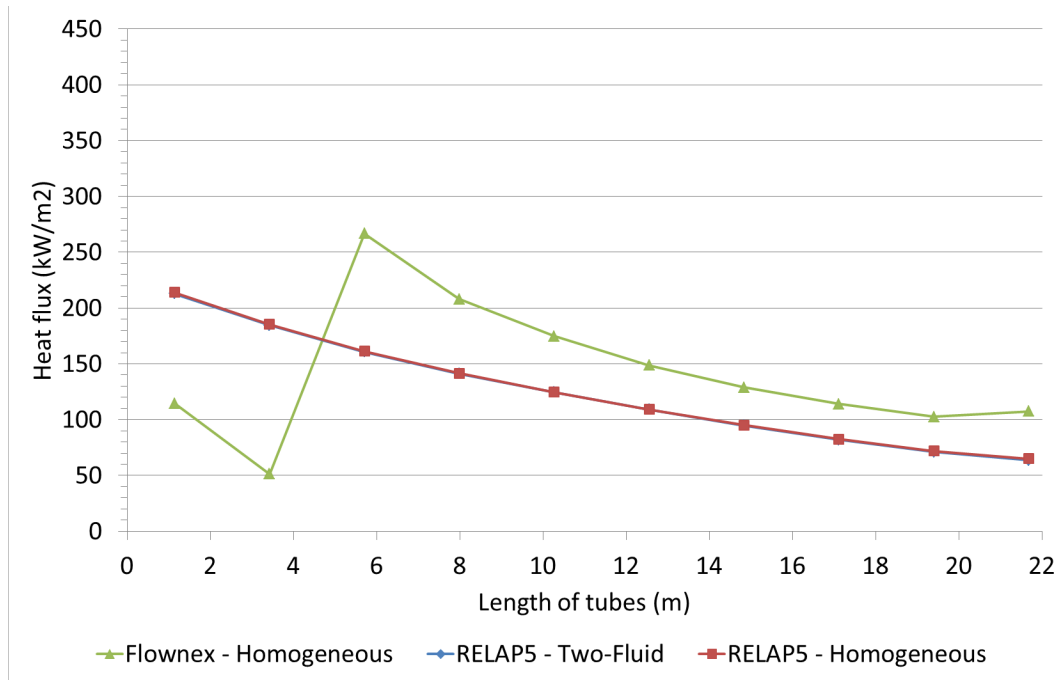


Figure 4.18: Heat flux on the surface of the tubes at 60% power output.

4.3 Summary of inter-model comparison

The results were focussed on the boiler region, where the heat transfer from primary to secondary side occurs.

The primary side temperatures calculated by Flownex deviate by a maximum of 5°C from those calculated by RELAP5. The largest deviations were observed closest to the tube-sheet, at the inlet and outlet ends of the tube bundle. Deviations between the RELAP5 homogeneous fluid solution and the RELAP5 two-fluid solution were negligible.

The secondary side quality calculated by Flownex deviated by a maximum of 5% when compared with the quality calculated by RELAP5. The largest deviation occurred in the region closest to the tube-sheet where the water-level affects the homogeneous solution. At 100% power there was negligible difference between the RELAP5 homogeneous and the RELAP5 two-fluid solutions. At 80% and 60% power levels, the quality calculated by the homogeneous solution was up to 5% lower than the quality calculated by the two-fluid solution.

Heat transfer was underestimated by the Flownex model, when compared with RELAP5. There was a large difference at the lower regions of the boiler, nearest the tube-sheet. This was due to the homogeneous solution's inability to model the water-level. This resulted in a single-phase heat transfer correlation used in that region, and a subsequent under-prediction of the heat transfer coefficient. Over the remaining volumes of the boiler region, there was no significant difference between the homogeneous and two-fluid solutions.

The large difference between the Flownex and RELAP5 solutions occurred because Flownex has been programmed to use the Chen correlation exclusively over the entire boiling regime, while RELAP5 was encoded with a matrix of correlations to use a variety of correlations depending on the boiling regime.

The flow velocity calculated by Flownex was 50% smaller than calculated by RELAP5, at the inlet of the tube bundle. The difference decreases along the boiler region and the values are equal at 10m above the tube-sheet. The homogeneous solution is, by definition, incapable of plotting vapour and liquid velocities separately.

The tube surface temperatures on the secondary side were over-estimated by Flownex by up to 7.3% in the region closest to the tube-sheet, compared to the RELAP5 solution. The Flownex solution was larger by as much as 2.2% over the remainder of the boiler region. The RELAP5 homogeneous solution also over-estimated the tube surface temperatures by up to 1.1% when compared with the RELAP5 two-fluid solution. There is a negligible difference between the RELAP5 two-fluid and homogeneous solutions over the remainder of the boiler region.

The heat flux calculated by Flownex was under-estimated at low elevations above the tube-sheet. It was over-estimated over the rest of the boiler region. The differences in the calculated heat fluxes are large. This was attributed to the script used in Flownex which only utilizes the Chen correlation across the various boiling regimes. The RELAP5 solution is more accurate, as it uses a matrix of heat transfer correlations described in Chapter 2. There is little difference between the heat fluxes calculated by the RELAP5 homogeneous and two-fluid models.

Conclusions and Recommendations

5.1 Conclusions

When the results from the two-fluid model and the homogeneous model were compared to plant data, it showed errors for the heat transfer calculation as well as the pressure calculation on the secondary side. Primary side errors were negligible for both models, as were the errors calculated in the quality of the outlet steam.

100% power output

The errors, calculated at 100% power output for the inlet pressure, were -6.4%, -6.7% and -6.2% for the RELAP5 two-fluid, RELAP5 homogeneous and Flownex homogeneous solutions respectively. There was a small difference of only 0.3% between the RELAP5 two-fluid and RELAP5 homogeneous solutions. All models calculated an error to within 0.5% of each other, and thus it may be postulated that the pressure calculation is not greatly affected by the use of the two-fluid or homogeneous models. The results at 80% and 60% further validate this argument.

The errors, calculated at 100% power output for the heat transferred in the boiler region, were -1.3%, -2.2% and 0.1%, respectively. There was a small difference of 0.9% between the RELAP5 two-fluid and homogeneous solutions, however, the Flownex model displayed an almost negligible error.

80% power output

The errors, calculated at 80% power output for the inlet pressure, were -3.1%, -3.3% and -3.3% for the RELAP5 two-fluid, RELAP5 homogeneous and Flownex homogeneous solutions respectively. As in the previous subsection, the errors in the pressure calculation for the various models at 80% were similar. A deviation of only 0.2% between the two-fluid and the homogeneous models further validates the argument raised previously, that the pressure calculation is not significantly

influenced by the choice of model.

The errors, calculated at 80% power output for the heat transferred in the boiler region, were 0.9%, 1.2% and -1.8% for the RELAP5 two-fluid, homogeneous and Flownex homogeneous solutions respectively. The error in Flownex was larger than in RELAP5, while the RELAP5 two-fluid and homogeneous solutions were similar and differed by 0.3%. This would indicate that there lies a small difference in the solution produced by the two-fluid and the homogeneous models, and that the larger error in Flownex may be attributed to the inappropriate use of the Chen correlation over all regions of the boiler. RELAP5 uses a flow regime map correlated to a table of heat transfer correlations as explained in Chapter 2.

60% power output

The errors, calculated at 60% power output for the inlet pressure, were -3.2%, -2.7% and -2.7% for the RELAP5 two-fluid, RELAP5 homogeneous and Flownex homogeneous solutions respectively. There is a difference of 0.5% between the solutions of the two-fluid model and the homogeneous model. This further adds to the argument that at varying power levels, the pressure calculation is largely unaffected by the choice of flow model.

The errors, calculated at 60% power output for the heat transferred in the boiler region, were -1.5%, -1.0% and -0.6% for the RELAP5 two-fluid, homogeneous and Flownex homogeneous solutions respectively. There is a difference of 0.5% between the RELAP5 two-fluid and homogeneous solutions. Flownex calculates a lower error than both RELAP5 models.

It may seem significant that Flownex again reports the lowest error of the models, however, it is not possible to draw a correlation between the varying power levels and the errors calculated. It would seem that at 60% power output, it is advantageous to use the homogeneous model for an over-all analysis of SG parameters. To be certain about such a statement, however, there would need to be further studies conducted with the model at more power levels. In order for the Flownex results to be more credible would also require a more complex heat transfer correlation to be implemented.

Detailed inter-model comparison

The detailed inter-model comparison showed that there was only a small difference between the homogeneous model solution and the two-fluid model solution in the majority of cases. Exceptions were in the regions close to the tube-sheet at low elevations, where the water-level could not be accurately modelled by the homogeneous solution.

The primary side temperatures were over-estimated by Flownex when compared with RELAP5,

with no significant changes with varying power levels. The difference may be attributed to the heat transfer script used in Flownex, as the homogeneous and two-fluid solutions from RELAP5 were similar. This is due to the fact that the primary side is in a single phase, and modelled with similar fluid equations in both RELAP5 and Flownex. The primary temperatures collectively decreased with decreasing power levels as expected, and the errors remain largely unaffected by the varying power levels.

The secondary steam quality was under-estimated by Flownex and as well as the RELAP5 homogeneous model, with slightly larger deviation at lower power levels in the lower regions of the boiler. The quality calculated by all models decreased with decreasing power level, as expected. The errors remained largely unaffected by the varying power levels.

The heat transfer coefficient calculated by Flownex was under-estimated due to the exclusive use of the Chen correlation in the custom script, rather than a matrix of correlations as used in RELAP5. Higher deviations were seen at low the inlet and outlet ends of the tubes, in the lower regions of the boiler. There was no consistent correlation between the error calculated and the power level. The RELAP5 homogeneous solution and the RELAP5 two-fluid solution compared favourably across the boiler region, and lead us to conclude that the error in Flownex may be attributed to the script.

The velocity profile calculated by Flownex and RELAP5 are very similar for the homogeneous solution. Naturally, the two-fluid model has the advantage of predicting both liquid and vapor velocities, so a direct comparison between the models does not reveal valuable information. As expected, at low qualities the homogeneous flow velocity is similar to the liquid flow velocity calculated by RELAP5. As the quality increases with height in the boiler region, the homogeneous velocity more closely approximates the vapour velocity from RELAP5. This behaviour is as expected, and the homogeneous solution cannot provide detailed information on velocities of multiple phases. This information is important for safety analysis of an accident scenario when the quantity of steam needs to be calculated accurately. For operational analysis, however, it is not necessary to have detailed information of each phase. Often, utilities would be interested in the plant parameters such as inlet and outlet temperatures and pressures rather than local flow velocity. In this respect, one would need to argue the trade-off between accuracy and simplicity of the solution.

The velocity profile is especially important when analyzing vibration and deposition of solids on the SG materials. The close agreement between Flownex and RELAP5 suggests that Flownex may be capable of conducting such analysis.

The tube surface temperatures on the secondary side are similar for all the models over the majority of the tube surface. Flownex over-estimated the surface temperatures slightly for all power levels analysed. There were large differences between the Flownex results and the RELAP5 results at the inlet and outlet ends of the tube bundle. This was the same region where

the errors above were reported. The error occurred because there were not enough discrete volumes in the lower boiler region to accurately model the water-level. This resulted in the lower volume having a lower quality in the homogeneous model than in the RELAP5 model, and thus a lower rate of heat transfer. The errors did not vary significantly with varying power levels.

The heat flux calculated by Flownex was over-estimated when compared with that of RELAP5. The exception being at the inlet and outlet ends of the tube bundle where it was under-estimated. This deviation was again due to the insufficient nodalization in the lower regions of the boiler. Over the remainder of the boiler region, the heat flux from Flownex followed a similar trend to that of RELAP5, decreasing with height. There was no significant difference between the RELAP5 two-fluid and homogeneous solution. This further validates the argument that the heat transfer script implemented with the custom script in Flownex was flawed.

Final remarks

Finally we conclude that, for the power levels analysed in this study, the homogeneous model for two-phase flow offers a reliable alternative to the two-fluid model when applied in the context of normal operating conditions of nuclear steam generators. This might be due to the fact that the emulsion of steam and liquid water in the boiler region is similar to a homogeneous "broth" of fluid. We can conclude that it would be appropriate to use the homogeneous model when performing operational analysis, for example when examining causes and effects of variations in plant parameters such as temperatures and pressures. In order for Flownex to perform as well and at the same level of detail as RELAP5, the heat transfer script needs to be improved. For safety analysis where detailed results are needed about each phase, the homogeneous model may not be appropriate. This was, however, outside the scope of the current study.

5.2 Improvements and Recommendations

All three models would benefit from more detailed input data. Specifically, geometry and efficiency specifications of the centrifugal steam separators and the Chevron dryers would improve the accuracy of the steam separator components in RELAP5 and Flownex. RELAP5 offers built-in components to precisely model the separator and dryer stages, should the data be available. More steady-state data at a wider range of power outputs would improve the reliability of the boundary conditions and allow for further validation at lower power levels. Transient data from an experimental facility or from Koeberg would aid in extending the steady-state model to a transient one.

As stated in the previous subsections, it would also be beneficial to increase the number of volumes used to describe the shell and tube bundle at elevations close to the tube-sheet where

water level plays a prominent role. RELAP5 and Flownex calculates the average quality for the specified volume, so using more volumes to describe areas of interest result would allow the water level and quality to be more accurately described.

Further validation of the models are needed at more power levels and a wider ranger, in order to perform a more thorough analysis and to provide more credibility to the models. The Flownex results suffered in this study due to the custom boiling heat transfer script that was used. In the future it is recommended that a more complex map of correlations is developed, similar to RELAP5, as discussed in Chapter 2.

Potential for Future Work

There are a number of projects which may stem from this one. A steady-state model which solves is the first step in creating a number of extended projects.

6.1 Model improvements

The steady-state model may be extended to use improved data and specifications from Koeberg. The improved model will see a reduction in errors. The Flownex model may be extended further to include a more comprehensive heat transfer correlation script. Improvements are constantly being made to Flownex, and functionality will soon exist to link Flownex with RELAP5.

6.2 Model alterations

There are a number of various boundary condition configurations that may be tested. However, due to the parabolic nature of the solution, it is important to note which boundary conditions are critical for convergence. Careful analysis of the fluid flow equations is necessary to make informed decisions. Time constraints did not allow this study to progress to further levels detail.

6.3 Transient analysis

The steady-state model may be used as a basis for transient analysis. The steady-state model is needed to supply initial values for the transient solution. Transient analysis is useful for predicting the effects that changes of input parameters have on the outputs of the system. They are also useful for doing accident scenario calculations, used in safety analysis and investigations.

6.4 Model extensions

The steam generator model may be linked to a model of the remainder of the primary circuit as well as the balance-of-plant components. In this respect, it is the stepping stone to putting together a much larger model which encompasses the entire nuclear power plant. This may be useful for over-all analysis of the processes involved in the operation of the nuclear power plant. Focus can also turn to individual components with arbitrary detail, dependent on the will of the modeller.

References

- Bonavigo, L. and de Salve, M. (2011). *Steam Generator Systems: Operational Reliability and Efficiency - Chapter 17: Issues for Nuclear Power Plant Steam Generators*. InTech, Inc.
- Colorado, D., Papini, D., Hernandez, J. A., Santini, L., and Ricotti, M. E. (2011). Development and experimental validation of a computational model for a helically coiled steam generator. *International Journal of Thermal Sciences*, 50:569–580.
- Desfontaines-Leromain, G. (2004). PWR design and operation - steam generators. Presentation - Areva.
- Diercks, D. R., Shack, W. J., and Muscara, J. (1999). Overview of steam generator tube degradation and integrity and issues. *Nuclear Engineering and Design*, 194:19–30.
- Dodge, Y. (2003). *The Oxford Dictionary of Statistical Terms*. Oxford University Press.
- EPRI (2012a). Steam generator management program: Thermal-hydraulic analysis of a recirculating steam generator using commercial computational fluid dynamics software. Technical report, Electric Power Research Institute (EPRI).
- EPRI (2012b). Steam generator management (QA) - 2012 research portfolio. Technical report, Electric Power Research Institute (EPRI).
- ESKOM (2004). Koeberg safety analysis report - Part II - Chapter 3 (Steam Generator). Technical report, ESKOM Generation.
- Flownex (2011a). *Flownex Library Manual*. M.Tech Industrial Pty (Ltd).
- Flownex (2011b). *Flownex Library Theory Manual*. M.Tech Industrial Pty (Ltd).
- Flownex (2011c). *Flownex SE User Manual*. M.Tech Industrial Pty (Ltd).
- Gouws, J. J., Morris, R. M., and Visser, J. A. (2006). Modelling of a gas turbine combustor using a network solver. *South African Journal of Science*, 102:533–536.
- Green, S. J. and Hetsroni, G. (1995). PWR steam generators. *International Journal of Multiphase Flow*, 21:1–97.

REFERENCES

- Greyvenstein, G. P. and Rousseau, P. G. (2003). Design of a physical model of the PBMR with the aid of Flownet. *Nuclear Engineering and Design*, 222:203–213.
- Hoffer, N. V., Sabharwall, P., and Anderson, N. A. (2011). Modeling a helical-coil steam generator in RELAP5-3D for the next generation nuclear plant. Technical report, Idaho National Laboratory.
- IAEA (2012). Power reactor information system. Website - <http://pris.iaea.org/>.
- Ishii, M. and Hibiki, T. (2006). *Thermo-fluid dynamics of two-phase flow*. Springer, Science and Business Media, Inc.
- Janna, W. S. (2000). *Engineering Heat Transfer*. CRC Press.
- Jeong, J. H., Chang, K. S., Kim, S. J., and Lee, J. H. (2000). Preliminary RELAP5 simulations of multiple steam generator tube rupture in Korea next generation reactor. *American Society of Mechanical Engineers, Pressure Vessels and Piping Division*, 421:209–214.
- Kok, K. D., editor (2009). *Nuclear Engineering Handbook*. CRC Press - Taylor and Francis Group, LLC.
- Kolev, N. I. (2007). *Multiphase Flow Dynamics 4 - Nuclear Thermal Hydraulics*. Springer Science and Business Media LLC.
- Kreith, F., editor (1999). *Mechanical Engineering Handbook - Fluid Mechanics*. CRC Press.
- Lamarsh, J. R. and Baratta, A. J. (2001). *Introduction to Nuclear Engineering*. Prentice-Hall, Inc.
- Lewis, E. E. (2008). *Fundamentals of Nuclear Reactor Physics*. Academic Press.
- Lin, C., Wassel, A., Kalra, S., and Singh, A. (1986). The thermal-hydraulics of a simulated PWR facility during steam generator tube rupture transients. *Nuclear Engineering and Design*, 98:15–38.
- Millett, P. J. and Welty, C. J. (2010). Review of EPRI's steam generator RnD program. Technical report, EPRI.
- Nematollahi, M. R. and Zare, A. (2008). A simulation of a steam generator tube rupture in VVER-1000 plant. *Energy Conversion and Management*, 49:1972–1980.
- Preece, R. J. and Putney, J. M. (1993). Preliminary assessment of PWR steam generator modelling in RELAP5/mod3. Technical report, U.S. Nuclear Regulatory Commission.
- RELAP5 (2001a). *RELAP5/MOD3.3 Code Manual, Volume 1: Code Structure, System Models and Solution Methods*. Nuclear Safety Analysis Division, Information Systems Laboratories, Inc, Idaho Falls, U.S.A.

REFERENCES

- RELAP5 (2001b). *RELAP5/MOD3.3 Code Manual, Volume 4: Models and Correlations*. Nuclear Safety Analysis Division, Information Systems Laboratories, Inc, Idaho Falls, U.S.A.
- RELAP5 (2001c). *RELAP5/MOD3.3 Code Manual, Volume 5: User's Guidelines*. Nuclear Safety Analysis Division, Information Systems Laboratories, Inc., Idaho Falls, U.S.A.
- RELAP5 (2001d). *RELAP5/MOD3.3 Code Manual, Volume 6: Validation of Numerical Techniques*. Nuclear Safety Analysis Division, Information Systems Laboratories, Inc, Idaho Falls, U.S.A.
- Riznic, J. (2009). Steam generator ageing management in Canada - current practises and related issues. In *IAEA Consultancy Meeting on Ageing Management of Steam Generators, Vienna*.
- Rohsenow, W. M., Hartnett, J. P., and Cho, Y. I., editors (1998). *Handbook of Heat Transfer*. McGraw-Hill Book Company.
- Schwarz, T. (2001). Heat transfer and fouling behaviour of Siemens PWR steam generators - long term operating experience. *Experimental Thermal and Fluid Science*, 25:319–327.
- Shultis, J. K. and Faw, R. E. (2002). *Fundamentals of Nuclear Science and Engineering*. Marcel Dekker, Inc.
- Singhal, A. K., Keeton, L. W., Przekwas, A. J., and Weems, J. S. (1984). Athos—a computer program for thermal hydraulic analysis of steam generators. Technical Report NP-2698-CCM, EPRI.
- Singhal, A. K., Keeton, L. W., and Spalding, D. B. (1980). Predictions of thermal hydraulics of a PWR steam generator by using the homogeneous, the two-fluid, and the algebraic-slip model. *Heat Transfer - Orlando*. R.P. Stein (Ed.), New York, USA, American Institute of Chemical Engineers, 76:45–55.
- Thome, J. R. (2004). *Engineering Data Book III*. Wolverine Tube, Inc.
- van der Merwe, J. J., Bollen, R., and van Ravenswaay, J. P. (2006). Validation and verification of Flownex Nuclear. In *3rd International Topical Meeting on High Temperature Reactor Technology*.
- Woods, B. G., Groome, J., and Collins, B. (2009). An assessment of PWR steam generator condensation at the Oregon State University APEX facility. *Nuclear Engineering and Design* 239, 239:96–105.

APPENDIX A

Primary Conditions EES script

" Secondary conditions from KBG data "

P_so = 4911.19 [kPa]

T_si = 219.74 [C]

P_si = 5277.39 [kPa]

m_dot_s = 618 [kg/s]

" Heat transfer calculated from secondary conditions "

Q = m_dot_s*(Enthalpy(Steam_IAPWS, x=1.0, P=P_so) – Enthalpy(
Steam_IAPWS, T=T_si , P=P_si))

" Primary side conditions from KBG data and outlet pressure guessed "

T_pi = 312.37 [C]

T_po = 278.67 [C]

T_avg_p = (T_pi+T_po)/2

P_pi = 15500 [kPa]

P_po = 14825 [kPa]

" Reynold's number calculated "

rho_p = Density(Steam_IAPWS, T=T_avg_p, P = P_pi)

N = 3330

A_p = N*pi*(D_h_p/2)^2

v_p =m_dot_p/(rho_p*A_p)

D_h_p = 0.00984*2 [m]

mu_p = Viscosity(Steam_IAPWS, T=T_avg_p, P=P_pi)

$$\epsilon_p = 0.00003$$

$$Re_p = \rho_p \cdot v_p \cdot D_{h_p} / \mu_p$$

" Haaland (1983), explicit correlation for friction factor in pipe "

$$f = (1 / (-1.8 \cdot \log_{10} (((\epsilon_p / D_{h_p}) / 3.7)^{1.11} + 6.9 / Re_p)))^2$$

$$L_p = 22.824 \text{ [m]}$$

$$g = 9.81 \text{ [m/s}^2\text{]}$$

$$h_l = f \cdot (L_p / D_{h_p}) \cdot ((v_p^2) / (2 \cdot g))$$

" Pressure drop calculated from friction factor "

$$\Delta P_p = \rho_p \cdot g \cdot h_l / 1000$$

$$P_{po_2} = P_{pi} - \Delta P_p$$

" Mass flow calculated from primary conditions and heat transferred "

$$m_{dot_p} = Q / (\text{Enthalpy}(\text{Steam_IAPWS}, T=T_{pi}, P=P_{pi}) - \text{Enthalpy}(\text{Steam_IAPWS}, T=T_{po}, P=P_{po}))$$

APPENDIX B

Two-fluid parameters EES script

```
$Import 'Inputs.txt', T_sat, T_wall, x, d_i, m_dot_A

// Specific heat capacity
c_pL=Cp(Steam_IAPWS,x=0,T=T_sat)
c_pG=Cp(Steam_IAPWS,x=1,T=T_sat)

// Density
rho_G=Density(Steam_IAPWS,x=1,T=T_sat)
rho_L=Density(Steam_IAPWS,x=0,T=T_sat)

// Conductivity of the liquid
k_L=Conductivity(Steam_IAPWS,x=0,T=T_sat)

// Viscosity
mu_G=Viscosity(Steam_IAPWS,x=1,T=T_sat)
mu_L=Viscosity(Steam_IAPWS,x=0,T=T_sat)

// Enthalpy of vaporization
h_LG = (Enthalpy(Steam_IAPWS,x=1,T=T_sat) - Enthalpy(Steam_IAPWS,x=0,T=
    T_sat))

// Surface Tension
sigma = SurfaceTension(Steam_IAPWS,T=T_sat)
```

APPENDIX B: TWO-FLUID PARAMETERS EES SCRIPT

```
// Vapor Pressure
P_wall = Pressure(Steam_IAPWS, T=T_wall)
P_sat = Pressure(Steam_IAPWS, T=T_sat)

$Export 'water_properties.txt', rho_G, rho_L, k_L, mu_G, sigma, h_LG,
      P_wall, P_sat, c_pL, mu_L, T_wall, T_sat, x, d_i, m_dot,A
```

Chen correlation C# script

```
//script using directives
//css_ref IPS.Core.dll;
//css_ref IPS.PluginInterface.dll;
//css_ref IPS.Units.dll;
using System;
using IPS.Properties;
using IPS.Scripting;

//script must be derived from IComponentScript
public class Script: IPS.Scripting.IComponentScript
{
    IPS.Properties.Double _Pr_L;
    IPS.Properties.Double _Re_L;
    IPS.Properties.Double _d_i;
    IPS.Properties.Double _m_dot_A;
    IPS.Properties.Double _x;

    IPS.Properties.Double _rho_L;
    IPS.Properties.Double _k_L;
    IPS.Properties.Double _c_pL;
    IPS.Properties.Double _sigma;
    IPS.Properties.Double _mu_L;
    IPS.Properties.Double _h_LG;
    IPS.Properties.Double _rho_G;
    IPS.Properties.Double _deltaT_sat;
    IPS.Properties.Double _deltap_sat;
    IPS.Properties.Double _p_wall;
```

```

IPS.Properties.Double _p_sat;
IPS.Properties.Double _T_wall;
IPS.Properties.Double _T_sat;

IPS.Properties.Double _alpha_FZ;
IPS.Properties.Double _alpha_L;
IPS.Properties.Double _F;
IPS.Properties.Double _X_tt;
IPS.Properties.Double _mu_G;
IPS.Properties.Double _Re_tp;
IPS.Properties.Double _S;
IPS.Properties.Double _alpha_TP;

//do pre simulation initialisation here
public override void Initialise()
{
}

//do post simulation cleanup here
public override void Cleanup()
{
}

//script main execution function – called every cycle
public override void Execute(double Time)
{
    if (_x.Value > 0) {
        _Pr_L.Value = _c_pL.Value*_mu_L.Value/_k_L.Value;
        _Re_L.Value = (_m_dot_A.Value*(1-_x.Value)*_d_i.Value)/
            _mu_L.Value;
        _X_tt.Value = Math.Pow((1-_x.Value)/_x.Value, 0.9)*Math
            .Pow(_rho_G.Value/_rho_L.Value, 0.5)*Math.Pow(_mu_L.
            Value/_mu_G.Value, 0.1);
        _F.Value = Math.Pow((1/_X_tt.Value) + 0.213, 0.736);
        _Re_tp.Value = _Re_L.Value*Math.Pow(_F.Value, 1.25);
        _S.Value = 1/(1+0.00000253*Math.Pow(_Re_tp.Value, 1.17)
            );
    }
}

```

```

_deltaT_sat.Value = _T_wall.Value - _T_sat.Value;
_deltap_sat.Value = _p_wall.Value - _p_sat.Value;

_alpha_L.Value = 0.023*Math.Pow(_Re_L.Value, 0.8)*Math.
    Pow(_Pr_L.Value, 0.4)*(_k_L.Value/_d_i.Value);
_alpha_FZ.Value = 0.00122*((Math.Pow(_k_L.Value,0.79)*
    Math.Pow(_c_pL.Value, 0.45)*Math.Pow(_rho_L.Value,
    0.49))/(Math.Pow(_sigma.Value, 0.5)*Math.Pow(_mu_L.
    Value, 0.29)*Math.Pow(_h_LG.Value, 0.24)*Math.Pow(
    _rho_G.Value, 0.24)))*Math.Pow(_deltaT_sat.Value,
    0.24)*Math.Pow(_deltap_sat.Value, 0.75);
_alpha_TP.Value = _alpha_FZ.Value*_S.Value + _alpha_L.
    Value*_F.Value;
}
else
{
    _Pr_L.Value = _c_pL.Value*_mu_L.Value/
        _k_L.Value;
    _Re_L.Value = (_m_dot_A.Value*_d_i.
        Value)/_mu_L.Value;
    _alpha_TP.Value=0.023*Math.Pow(_Re_L.
        Value, 0.8)*Math.Pow(_Pr_L.Value,
        0.4)*(_k_L.Value/_d_i.Value);
}

}

//any processing you want to do before steady state
public override void ExecuteBeforeSteadyState()
{
    Execute(0.0);
}

//any processing you want to do while solving steady state
public override void ExecuteSteadyState()
{
    Execute(0.0);
}

```

```

    }

    //any processing you want to do after steady state
    public override void ExecuteAfterSteadyState()
    {
        Execute(0.0);
    }

    //constructor initialises parameters
    public Script()
    {
        _alpha_TP = new IPS.Properties.Double();
        _alpha_TP.Value = 0;

        _Pr_L = new IPS.Properties.Double();
        _Pr_L.Value = 0;

        _T_wall = new IPS.Properties.Double();
        _T_wall.Value = 0;

        _T_sat = new IPS.Properties.Double();
        _T_sat.Value = 0;

        _deltap_sat = new IPS.Properties.Double();
        _deltap_sat.Value = 0;

        _p_wall = new IPS.Properties.Double();
        _p_wall.Value = 0;

        _p_sat = new IPS.Properties.Double();
        _p_sat.Value = 0;

        _alpha_FZ = new IPS.Properties.Double();
        _alpha_FZ.Value = 0;

        _sigma = new IPS.Properties.Double();
        _sigma.Value = 0;
    }

```

```

_deltaT_sat = new IPS.Properties.Double();
_deltaT_sat.Value = 0;

_S = new IPS.Properties.Double();
_S.Value = 0;

_Re_tp = new IPS.Properties.Double();
_Re_tp.Value = 0;

_F = new IPS.Properties.Double();
_F.Value = 0;

_mu_G = new IPS.Properties.Double();
_mu_G.Value = 0;

_rho_L = new IPS.Properties.Double();
_rho_L.Value = 0;

_rho_G = new IPS.Properties.Double();
_rho_G.Value = 0;

_X_tt = new IPS.Properties.Double();
_X_tt.Value = 0;

_d_i = new IPS.Properties.Double();
_d_i.Value = 0;

_x = new IPS.Properties.Double();
_x.Value = 0;

_m_dot_A = new IPS.Properties.Double();
_m_dot_A.Value = 0;

_Re_L = new IPS.Properties.Double();
_Re_L.Value = 0;

_k_L = new IPS.Properties.Double();
_k_L.Value = 0;

```

```

        _mu_L = new IPS.Properties.Double();
        _mu_L.Value = 0;

        _c_pL = new IPS.Properties.Double();
        _c_pL.Value = 0;

        _alpha_L = new IPS.Properties.Double();
        _alpha_L.Value = 0;

        _h_LG = new IPS.Properties.Double();
        _h_LG.Value = 0;

    }

    //property declarations to make
    //parameters visible to outside world
    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double alpha_TP
    {
        get
        {
            return _alpha_TP;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double d_i
    {
        get
        {
            return _d_i;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double m_dot_A
    {

```

```

        get
        {
            return _m_dot_A;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double x
    {
        get
        {
            return _x;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double T_wall
    {
        get
        {
            return _T_wall;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double T_sat
    {
        get
        {
            return _T_sat;
        }
    }

    [PropertyUsage(UseProperty.DYNAMIC)]
    public IPS.Properties.Double c_pL
    {
        get
        {

```

```

        return _c_pL;
    }
}

[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double mu_L
{
    get
    {
        return _mu_L;
    }
}

[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double k_L
{
    get
    {
        return _k_L;
    }
}

[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double mu_G
{
    get
    {
        return _mu_G;
    }
}

[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double rho_G
{
    get
    {
        return _rho_G;
    }
}

[PropertyUsage(UseProperty.DYNAMIC)]

```

```

public IPS.Properties.Double rho_L
{
    get
    {
        return _rho_L;
    }
}
[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double p_wall
{
    get
    {
        return _p_wall;
    }
}
[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double p_sat
{
    get
    {
        return _p_sat;
    }
}
[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double sigma
{
    get
    {
        return _sigma;
    }
}
[PropertyUsage(UseProperty.DYNAMIC)]
public IPS.Properties.Double h_LG
{
    get
    {
        return _h_LG;
    }
}

```

APPENDIX C: CHEN CORRELATION C# SCRIPT

```
    }  
}
```

APPENDIX D

RELAP5 Code

= Steady State Steam Generator of the Model Type 51B 100% Two-Fluid

* Control Flags Key *

* jefvcahs - j : Jet junction , pool surface condensation is enhanced in
the volume above

* e : Modified PV term in energy equations , 0 = off , 1 = on

* f : CCFL options. 0 = not applied , 1 = applied

* v : Horizontal stratification entrainment/pullthrough
options , for junctions connected to horizontal volumes.

* 0 = not applied , 1 = upward-oriented junction , 2 =
downward orientation , 3 = centrally (side) oriented

* c : Choking options , 0 = applied , 1 = not applied , 2 =
modified Henry-Fauske choking model applied

* a : Area change options , 0 = smooth area change or none , 1
= full abrupt area change , 2 = partial abrupt area change

* h : Non-homogeneous or homogeneous , 0 = non-homogeneous , 1
= homogeneous = 2

* s : Momentum flux options , 0 = momentum flux in both TO
and FROM volume , 1 = uses momentum flux in the FROM volume , 2 =
momentum flux in the TO volume

* 3 = no momentum flux in either

*

* tlpvbfe - t : Thermal front tracking model - 0 = off , 1 = on

* l : Mixture level tracking model - 0 = off , 1 = on

* p : Water packing scheme - 0 = on , 1 = off

APPENDIX D: RELAP5 CODE

```

*          v : Vertical stratification model - 0 = on, 1 = off
*          b : Interphase friction - 0 = pipe interphase friction , 1
= rod bundle interphase friction
*          f : Wall friction - 0 = wall friction computed along x-
axis , 1 = not computed along x-axis
*          e : Equilibrium or non-equilibrium - 0 = non-equilibrium
calculation , 1 = equilibrium calculation
*
*  ssdtt  - ss - 1 - Heat structure temperature blocks omitted
*                    - All standard major output is given
*
*                    2 - Second portion of junction block
omitted
*                    -
*
*                    4 - Third and fourth portions of the
volume block omitted
*                    -
*
*                    8 - Statistics block omitted
*                    -
*
*          - d - 1 - Major edits obtained every successful
time step
*          - Standard output at requested frequency using max
time step
*
*                    2 - Minor edits are obtained every
successful time step
*                    -
*
*                    4 - Plot records are written every
successful time step
*                    -
*
*          -tt 1 - Mass error analysis to control time
step size

```

```

*                               - No error estimate time step control
, and maximum time step is attempted for hydrodynamic and heat
structure
*
*                               2 - Heat conduction/transfer time step
same as hydrodynamic time step
*                               - Heat conduction/transfer time step
uses maximum time step
*
*                               4 - Heat transfer and hydrodynamics
coupled implicitly
*                               - Heat transfer and hydrodynamics
coupled explicitly , and advanced separately
*
*                               8 - Nearly-implicit scheme is used to
advance hydrodynamics
*                               - Semi-implicit scheme is used to
advance hydrodynamics
*
*                               16 - Test for convergence of steady-
state is not made
*                               - Test for convergence of steady-
state is made
*
*
*
*   ebt - e : fluid - 0 = default , 1 = H2O, 2 = D2O
*           b : boron - 0 = no boron , 1 = concentration specidied in
mass boron/mass liquid
*           t : Following words for thermodynamic state:
*               If t = 0, the next four words are interpreted as
pressure (Pa, lbf /in2), liquid
*               specific internal energy (J/kg, Btu/lbm), vapor
specific internal energy (J/kg,
*               Btu/lbm), and vapor void fraction. These quantities
will be interpreted as
*               nonequilibrium or equilibrium conditions , depending
on the internal energies

```

APPENDIX D: RELAP5 CODE

```

*                used to define the thermodynamic state. W6 should
be 0.0.
*                If t = 1, the next two words are interpreted as
temperature (K, oF) and static
*                quality in equilibrium condition. W4, W5, and W6
should be 0.0.
*                If t = 2, the next two words are interpreted as
pressure (Pa, lbf /in2) and static
*                quality in equilibrium condition. W4, W5, and W6
should be 0.0.
*                If t = 3, the next two words are interpreted as
pressure (Pa, lbf /in2) and
*                temperature (K, oF) in equilibrium condition. W4,
W5, and W6 should be 0.0.
*
*****

*****

*                Setup
*****

*100 new stdy-st
100 new transnt

102 si si

*                end time    min dt    max dt    ssdtt    minor, major and restart
frequencies
201    150.0    1.0E-6    1.0E-2    00031    100 100 100

*****

*                Additional Plot Requests
*****

20800001 mflowgj 208000000
20800002 mflowgj 215010000
20800003 mflowgj 215020000
20800004 mflowgj 215030000
20800005 mflowgj 215040000
20800006 mflowgj 206000000

```

APPENDIX D: RELAP5 CODE

```

*****
*
*           Primary Side Components
*****
1010000      "P-hotleg"      tmdpvvol
*           fa      l      V      Az      Inc      dz
1010101      100.0      1.0      0.0      0.0      90.0      1.0
*           rough      D_h      tlpvbfef
1010102      0.0000457      0.0      0000000

*           ebt
1010200      003
*           t      P (Pa)      T (K)
1010201      0.0      15500000.0      585.0

* CCC0301 – Non-Condensable mass fraction card
*****
1020000      "P-in"      tmdpjun
*           from      to      ja
1020101      101010002      103010001      0.5178

1020200      1 * Specifies mass flows on next card, can specify trip on
               this card
*           t      l. Mass Flow      v. Mass Flow      Interphase v.
1020201      0      6316.0      0      0

*****
1030000      "P-iplen"      snglvvol
*           fa      l      V      Az      Inc      dz
1030101      3.996      1.063      0.0      0.0      90.0      1.063
*           rough      D_h      tlpvbfef
1030102      0.0000457      0.0      0000000

* CCC0111 – ORNL ANS Interphase model pitch and span values
* CCC0131 – Additional Laminar Wall Friction Card
* CCC0141 – Alternate Turbulent Wall Friction Data

*           ebt      P (Pa)      T (K)
1030200      003      15500000.0      585.0

```

* CCC0300 – Single-volume variable volume control

1040000 "P-tubei" sngljun

* from to ja A_F A_R jefcahs

1040101 103010002 110010001 0.0 0.0 0.0 0000000

* W7, W8 and W9 – Specifies the discharge coefficients for the chosen
choking model in jefcahs.

* – Coefficients are 1.0 by default.

* CCC0110 – Diameter and CCFL Data card

* specify mass l. mass flow v. mass flow int. velocity

1040201 1 6316.0 0.0 0.0

1100000 "P-tubes" pipe

* nv

1100001 10

* CCC0002 – Angles and elevation options

* fa nv

1100101 1.013 10

* CCC0201 – Junction flow areas

* l nv

1100301 2.282 10

* CCC02901 – Elbow/spiral angle/radius of curvature

* V nv

1100401 0.0 10

* vert angle nv

1100601 90.0 5

1100602 -90.0 10

* CCC0701 – X-coordinate elevation changes different to lengths

* wall roughness D_h nv

1100801 0.0000457 0.01968 10

* CCC2501 – Additional laminar wall friction data

* CCC2601 – Alternate turbulent wall friction data

* CCC0901 – Junction Loss Coefficients

APPENDIX D: RELAP5 CODE

```

*          tlpvbf     nv
1101001    0000000    10
*          efvcchs     nj
1101101    0000000     9

*          ebt      P (Pa)      T (K)          nv
1101201    103      15500000.0  585.0      0 0 0    10
1101300    1  * Specifies mass flow on following cards
*          l. mass flow      v. mass flow      int. velocity      nj
1101301    6316.0          0.0          0.0          9

* CCC1401 – Junction diameter and CCFL data cards
* CCC3001 – Junction form loss data card
* CCC3101 – ORNL ANDS interphase model pitch and span values
* CCC3201 – Non-condensable mass fractions
*****
1050000    "P-tubeo"    sngljun
*          from      to      ja      A_F      A_R      jefcchs
1050101    110100002  106010001  0.0      0.0      0.0      0000000

* The following card specifies the discharge coefficients for
* subcooled, two-phase and superheated flow based on
* the chosen choking model.
1050102    1.0      1.0      1.0
*          specify mass      l. mass flow      v. mass flow      int. velocity
1050201    1          6316.0          0.0          0.0
*****
1060000    "P-oplen"    snglvol
*          fa      l      V
1060101    3.996    1.063    0.0
*          Az      Inc      dz
1060102    0.0      -90.0    -1.063
*          r          D_h      tlpvbf
1060103    0.00003    0.0      0000000

*          ebt      P (Pa)      T (K)
1060200    103      15500000.0  585.00
*****

```

APPENDIX D: RELAP5 CODE

```

1070000      "P-out"      sngljun
*           from        to          ja      A_F      A_R      jefcahs
1070101      106010002   108010001   0.785    0.0      0.0      0000000

* The following card specifies the discharge coefficients for
* subcooled, two-phase and superheated flow based on
* the chosen choking model.
1070102      1.0      1.0      1.0
*           specify mass    l. mass flow    v. mass flow    int. velocity
1070201      1                6316.0                0.0                0.0
*****

1080000      "P-cldleg"    tmdpvvol
*           fa          l          V
1080101      100.0      1.0      0.0
*           Az          Inc          dz
1080102      0.0      -90.0      -1.0
*           r                D_h      tlpvbfe
1080103      0.00003      0.0      0000000

*           ebt
1080200      002
*           t          P (Pa)          T (K)
1080201      0.0      14825000.0   0.0
*****

*           Secondary Side Components
*****

2010000      "S-fwivol"    tmdpvvol
*           fa          l          V
2010101      100.0      1.0      0.0
*           Az          Inc          dz
2010102      0.0      0.0      0.0
*           r                D_h      tlpvbfe
2010103      0.00003      0.0      0000000

*           ebt
2010200      003
*           t          P (Pa)          T (K)
2010201      0.0      5277000.0   493.0

```

APPENDIX D: RELAP5 CODE

```

*****
2020000      "S-fwi"      tmdpjun
*           from        to        ja
2020101      201010002  203010001  0.518

2020200  1 * Specifies mass flows on the next card
*           t  L. Mass Flow  V Mass Flow  Interphase v.
2020201  0  617.63          0          0
*****
2030000      "S-fwipip"    snglvol
*           fa          l          V
2030101      0.518      3.0      0.0
*           Az          Inc      dz
2030102      0.0      0.0      0.0
*           r           D_h      tlpvbf
2030103      0.00003      0.0      0000000

*           ebt          P (Pa)      T (K)
2030200      103          5277000.0  492.89
*****
2040000      "S-mixin"    sngljun
*           from        to        ja      A_F      A_R      jefcahs
2040101      203010002  225010001  0.0      0.0      0.0      0000000

* The following card specifies the discharge coefficients for
* subcooled , two-phase and superheated flow based on
* the chosen choking model.
2040102      1.0      1.0      1.0
*           specify mass  l. mass flow      v. mass flow      int. velocity
2040201      1          617.0          0.0          0.0
*****
2050000      "S-boili"    sngljun
*           from        to        ja      A_F      A_R      jefcahs
2050101      214050002  215010001  0.0      0.0      0.0      0000000

* The following card specifies the discharge coefficients for
* subcooled , two-phase and superheated flow based on
* the chosen choking model.

```

APPENDIX D: RELAP5 CODE

```

2050102      1.0      1.0      1.0
*           specify mass      l. mass flow      v. mass flow      int. velocity
2050201      1              2345.0              0.0              0.0
*****
2060000      "S-riseri"      sngljun
*           from              to              ja              A_F              A_R              jefcahs
2060101      215050002      216010001      0.0              25.0              25.0              0000000

* The following card specifies the discharge coefficients for
* subcooled , two-phase and superheated flow based on
* the chosen choking model.
2060102      1.0      1.0      1.0
*           specify mass      l. mass flow      v. mass flow      int. velocity
2060201      1              2345.0              0.0              0.0
*****
2070000      "S-separi"      sngljun
*           from              to              ja              A_F              A_R              jefcahs
2070101      216010002      221010001      0.0              0.0              0.0              0000000

* The following card specifies the discharge coefficients for
* subcooled , two-phase and superheated flow based on
* the chosen choking model.
2070102      1.0      1.0      1.0
*           specify mass      l. mass flow      v. mass flow      int. velocity
2070201      1              2345.0              0.0              0.0
*****
2080000      "S-so"      sngljun
*           from              to              ja              A_F              A_R              jefcahs
2080101      250010002      260010001      0.0              0.0              0.0              0000000

* The following card specifies the discharge coefficients for
* subcooled , two-phase and superheated flow based on
* the chosen choking model.
2080102      1.0      1.0      1.0
*           specify mass      l. mass flow      v. mass flow      int. velocity
2080201      1              0.0              617.0              0.0
*****
2140000      "S-dwncmr"      annulus

```

APPENDIX D: RELAP5 CODE

```

*          nv
2140001    5
*          fa          nv
2140101    0.682      5
*          l          nv
2140301    2.282  5
*          V          nv
2140401    0.0      5
*          vert angle  nv
2140601    -90.0      5
*          wall roughness  D_h      nv
2140801    0.0000457      0.064      5
*          tlpvbf     nv
2141001    0000000      5
*          efvcachs   nj
2141101    0000000      4
*          ebt      P (Pa)      T (K)      nv
2141201    103      4911190.0      492.89      0 0 0      5

2141300    1 * Specifies mass flow on following cards
*          l. mass flow      v. masas flow      int. velocity      nj
2141301    2345.0      0.0      0.0      4
*****
2150000    "S-boil"      pipe
*          nv
2150001    5
*          fa          nv
2150101    7.402      5
*          l          nv
2150301    2.282  5
*          V          nv
2150401    0.0      5
*          vert angle  nv
2150601    90.0      5
*          wall roughness  D_h      nv
2150801    0.0000457      0.0      5
*          tlpvbf     nv
2151001    0000000      5

```

APPENDIX D: RELAP5 CODE

```

*          efvcahs      nj
2151101    0000000      4
*          ebt      P (Pa)      T (K)      nv
2151201    103 4911190.0    492.89      0 0 0    5

2151300    1 * Specifies mass flow on following cards
*          l. mass flow      v. masas flow      int. velocity      nj
2151301    2345.0      0.0      0.0      4
*****
2160000    "S-riser"      snglvol
*          fa          l      V      Az.      Inc.      dz      rough      D_h
2160101    14.739    0.833 0.0  0.0    90.0    0.833  0.0000457 0.0
*          tlpvbf
2160102    0000000
*          ebt      P (Pa)      T (K)
2160200    103      4911190.0    492.89
*****
2210000    "S-separ"      snglvol
*          fa          l      V      Az.      Inc.      dz      rough      D_h
2210101    4.764    2.058 0.0  0.0    90.0    2.058  0.0000457 0.0
*          tlpvbf
2210102    0000000
*          ebt      P (Pa)      T (K)
2210200    103      4911190.0    492.89
*****
2220000    "S-dryer"      separatr
*          nj          mass flow initial cond.
2220001    3          1
*          fa          l      vol      az.      inc.      dz
2220101    15.763    2.058    0.0      0.0    90.0    2.058
*          rough      D_h      tlpvbf
2220102    0.0000457    0.0    0000000    1
*          ebt      P (Pa)      T (K)
2220200    103      4911190.0    492.89

* Vapor Outlet
*          from      to      ja      A_f      A_r
          efvcahs

```

APPENDIX D: RELAP5 CODE

```

2221101      222010002 250010001  0.0      150.0      150.0
      0001000
*           Void fraction limit
2221102      0.1

* Liquid Fall Back
*           from      to      ja      A_f      A_r
      efvcahs
2222101      222010001 224010001  0.0      150.0      150.0
      0001000
*           Void fraction limit
2222102      0.1

* Separator Inlet
*           from      to      ja      A_f      A_r
      efvcahs
2223101      221010002 222010001  0.0      29.0      29.0
      0001000

*           Initial liquid mass flow      Init. vapor mass flow
2221201      0.0      618.0
      0
*           Initial liquid mass flow      Init. vapor mass flow
2222201      1728.0      0.0
      0
*           Initial liquid mass flow      Init. vapor mass flow
2223201      2345.0      0.0
      0

*****
2240000      "S-rflxs"      branch
*           nj      mass flow initial cond.
2240001      1      1
*           fa      l      vol      az.      inc.      dz      rough      D_h
      tlpvbfe
2240101      10.999      2.058      0.0      0.0      -90.0      -2.058      0.0000457
      0.0      0000000
*           ebt      P (Pa)      T (K)
2240200      103      4911190.0      492.00

```

APPENDIX D: RELAP5 CODE

```

*          from      to          ja          A_f          A_r          efvcahs
2241101      224010002 225010001 0.0          0.0          0.0          0000000
*          Subcooled discharge coeff.          Two-phase discharge
          coeff.          Superheated discharge coeff.
2241102      1.0          1.0
          1.0

*          Initial liquid mass flow          Init. vapor mass flow
2241201      1728.0          0.0          0
*****
2250000      "S-mix"      branch
*          nj      mass flow initial cond.
2250001      2          1
*          fa      l      vol      az.      inc.      dz      rough      D_h
          tlpvbf
2250101      14.739 0.833 0.0          0.0      -90.0      -0.833      0.0000457
          0.0      0000000
*          ebt          P (Pa)          T (K)
2250200      103          4911190.0      492.89

*          from      to          ja          A_f          A_r
          efvcahs
2251101      224010002 225010001      0.0          0.0          0.0
          0000000
*          Subcooled Discharge Coeff.          Two-phase discharge
          coeff.          Superheated discharge coeff.
2251102      1.0          1.0
          1.0

*          from      to          ja          A_f          A_r          efvcahs
2252101      225010002 214010001 0.0          0.0          0.0          0000000
*          Subcooled discharge coeff.          Two-phase discharge
          coeff.          Superheated discharge coeff.
2252102      1.0          1.0
          1.0

*          Initial liquid mass flow          Init. vapor mass flow

```

APPENDIX D: RELAP5 CODE

```

2251201      1728.0                      0.0                      0
2252201      2345.0                      0.0                      0

```

```

2500000      "S-stmdm"      snglvol
*           fa           l           vol           az .           inc .           dz
2500101      15.763  1.627      0.0           0.0           90.0           1.627
*           rough      D_h      tlpvbf
2500102      0.0000457      0.0      0000000      1
*           ebt           P (Pa)           T (K)
2500200      103           4911190.0      492.89

```

```

2600000      "S-steam0"      tmdpv
*           fa           l           V
2600101      100.0  1.0      0.0
*           Az           Inc      dz
2600102      0.0      90.0      0.4
*           r           D_h      tlpvbf
2600103      0.0      0.0      0000000
* No wall friction to be computed
*           ebt
2600200      002
2600201      0  4911190.0      1.0

```

* Heat Structures

```

* Heat structure for tubing
*           nh      np      cyl      Left boundary
11100000  10      5      2      1      0.00984
*           Specifies format for following card
11100100  0  2
*           dx           ni
11100101  0.0003175      4
*           Specifies composition data for each interval
11100201  1  4
*           Specifies heat source data for each interval
11100301  0.0  4
*           Specifies initial temperatures

```

APPENDIX D: RELAP5 CODE

```
11100401 583.0 5
* Left boundary conditions card
*          comp.      incr.   type
11100501   110010000   10000   111   1 7600.0 10
* Right boundary conditions card
11100601   215010000   10000   111   1 7600.0 5
11100602   215050000  -10000   111   1 7600.0 10
* Heat source data card
11100701 0 0.0 0.0 0.0 10
* Additional boundary cards (Check Manual!)
11100800 1
11100801 0.01968 10.0 1.0 0.0 0.0 0.0 0.0 1.0 2.282 1.464 1.0 10
11100900 1
11100901 0.01032 10.0 1.0 0.0 0.0 0.0 0.0 1.0 2.282 1.464 1.0 10

*****
*                               Material Properties
*****
20100100 s-steel

. End
```

APPENDIX E

Inputs to the Flownex Model

Please note: The Excel spreadsheet is also available on CD-Rom for better viewing.

This space left intentionally blank.

General			
Identifier	Solving		Description
Primary Inlet		TRUE	Primary Inlet Boundary Conditions
Primary Outlet		TRUE	
Secondary Inlet		TRUE	Feedwater Boundary Conditions
Secondary Outlet		TRUE	Secondary Outlet Boundary Conditions

Enthalpy boundary condition	Mass source boundary condition		Mass source (kg/s)
		Fixed on user value	6057
Not specified			
		Fixed on user value	341
Not specified			

Boundary Conditions			
Pressure boundary condition	Pressure (kPa)	Temperature boundary condition	Temperature (°C)
Fixed on user value	14.897	Fixed on user value	294
		Not specified	
Fixed on user value	4889	Fixed on user value	195
		Not specified	

Mass Source Conditions

Specify mass source conditions

FALSE

FALSE

Quality boundary condition

Not specified

Not specified

General			Conduction	
Identifier	Solving	Description	General	0 Geometry
			Description	Thickness in element direction (mm)
HT-110-1	TRUE		Pipe Material	1.27
HT-110-10	TRUE		Pipe Material	1.27
HT-110-2	TRUE		Pipe Material	1.27
HT-110-3	TRUE		Pipe Material	1.27
HT-110-4	TRUE		Pipe Material	1.27
HT-110-5	TRUE		Pipe Material	1.27
HT-110-6	TRUE		Pipe Material	1.27
HT-110-7	TRUE		Pipe Material	1.27
HT-110-8	TRUE		Pipe Material	1.27
HT-110-9	TRUE		Pipe Material	1.27

[illegible]

Material Data

[illegible]

[illegible]

[illegible]

Upstream Entity				Downstream Entity
h (W/m ² .K)	Zero flow Nusselt number	Description	Type	Description
3744.067403		4.364 P-110-1	Flownex.Components.Pipe	S-215-1
3744.067403		4.364 P-110-10	Flownex.Components.Pipe	S-215-1
35389.10274		4.364 P-110-2	Flownex.Components.Pipe	S-215-2
28166.91734		4.364 P-110-3	Flownex.Components.Pipe	S-215-3
24136.05436		4.364 P-104-4	Flownex.Components.Pipe	S-215-4
21162.01287		4.364 P-110-5	Flownex.Components.Pipe	S-215-5
19946.37197		4.364 P-110-6	Flownex.Components.Pipe	S-215-5
20287.40952		4.364 P-110-7	Flownex.Components.Pipe	S-215-4
21320.66037		4.364 P-110-8	Flownex.Components.Pipe	S-215-3
25730.41195		4.364 P-110-9	Flownex.Components.Pipe	S-215-2

[illegible]

General			Geometry		0
			Volume Fraction		
Identifier	Solving	Description	Specify		Description
N-13	TRUE	U-Tube		FALSE	P-104-4
N-14	TRUE	U-Tube		FALSE	P-110-5
N-15	TRUE	U bend		FALSE	P-110-5
N-16	TRUE	U-Tube		FALSE	P-110-6
N-17	TRUE	U-Tube		FALSE	P-110-7
N-18	TRUE	U-Tube		FALSE	P-110-8
N-19	TRUE	Tubesheet		FALSE	P-110-9
N-204	TRUE	Downcomer/Riser		FALSE	S-215-1
N-206	TRUE	Riser		FALSE	S-216
N-215-1	TRUE			FALSE	S-215-2
N-215-2	TRUE	Riser		FALSE	S-215-3
N-215-3	TRUE	Riser		FALSE	S-215-4
N-215-4	TRUE	Riser		FALSE	S-215-5
Node - 1	TRUE			FALSE	S-223
Node - 10	TRUE			FALSE	P-106
Node - 6	TRUE			FALSE	S-214
Node - 7	TRUE			FALSE	Pipe - 5
Node - 8	TRUE			FALSE	Pipe - 4
Node - 9	TRUE			FALSE	Pipe - 3
P-101	TRUE	Primary Inlet Volume		FALSE	P-103
P-108	TRUE	Primary Outlet Boundary Conditions		FALSE	P-106
P-Node-2	TRUE			FALSE	P-103
P-Node-3	TRUE			FALSE	P-110-2
P-Node-4	TRUE			FALSE	P-110-3
S-201	TRUE	Feedwater Inlet Volume		FALSE	S-203
S-225	TRUE	Downcomer Branch		FALSE	S-203
S-Node-10	TRUE			FALSE	S-222
S-Node-12	TRUE	Secondary Outlet Boundary Conditions		FALSE	S-250
S-Node-9	TRUE	Riser/Separators		FALSE	S-216

1			
Volume Fraction			
Specify	Description	Geometry specification	Geometry option
FALSE	P-110-3	Not specified	
FALSE	P-104-4	Not specified	
FALSE	P-110-6	Not specified	
FALSE	P-110-7	Not specified	
FALSE	P-110-8	Not specified	
FALSE	P-110-9	Not specified	
FALSE	P-110-10	Not specified	
FALSE	Pipe - 2	Not specified	
FALSE	S-215-5	Not specified	
FALSE	S-215-1	Not specified	
FALSE	S-215-2	Not specified	
FALSE	S-215-3	Not specified	
FALSE	S-215-4	Not specified	
FALSE	Pipe - 0	Not specified	
FALSE	P-110-10	Not specified	
FALSE	Pipe - 5	Not specified	
FALSE	Pipe - 4	Not specified	
FALSE	Pipe - 3	Not specified	
FALSE	Pipe - 2	Not specified	
		Specified	Specify geometry
		Specified	Specify geometry
FALSE	P-110-1	Not specified	
FALSE	P-110-1	Not specified	
FALSE	P-110-2	Not specified	
		Specified	Specify geometry
FALSE	S-214	Not specified	
FALSE	S-221	Not specified	
		Specified	Specify volume
FALSE	S-221	Not specified	

Vessel shape	Table option	Volume (m³)	Diameter (m)	Height (m)	Length (m)

Cylindrical vertical	Simple specification			1	1
Cylindrical vertical	Simple specification			1	1
Cylindrical horizontal				1	1
Cylindrical vertical		0.902		1.694	

[illegible]

Solver Guess Values

Specify guess values	Specify pressure guess value
TRUE	TRUE
TRUE	TRUE
TRUE	
TRUE	TRUE
TRUE	TRUE
TRUE	TRUE
TRUE	TRUE
TRUE	TRUE
FALSE	
FALSE	
FALSE	
FALSE	
FALSE	
TRUE	TRUE
TRUE	TRUE
FALSE	
FALSE	
TRUE	FALSE
FALSE	
FALSE	
TRUE	TRUE
TRUE	TRUE
TRUE	TRUE
TRUE	
FALSE	
FALSE	
FALSE	

Pressure guess value (kPa)	Specify temperature guess value	
	15000	TRUE
	15	TRUE
		TRUE
	15000	TRUE
	15000	TRUE
	15000	TRUE
	15000	TRUE
	5000	TRUE
	4920	TRUE
	15000	TRUE
		FALSE
	15500	TRUE
	15000	TRUE
	15000	TRUE
		TRUE

Temperature guess value (°C)	Specify quality guess value		Quality guess value
	300		
	300		
	300	TRUE	0
	300		
	300		
	300		
	300		
	250		
	250		
	300		
		FALSE	
	312		
	300		
	300		
	250	TRUE	0

Boundary Conditions	
Elevation boundary condition	Elevation (mm)
Not specified	
Not specified	
Specified	12207
Not specified	
Not specified	
Not specified	
Specified	1620
Specified	1063
Specified	12207
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Not specified	
Specified	0
Specified	0
Not specified	
Specified	1620
Not specified	
Specified	13397
Specified	13397
Not specified	
Specified	20658
Not specified	

Solver Incondensable Concentration Guess Values

Specify incondensable concentration guess value

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

[illegible]

Radial Pressure Gradient

Radial pressure boundary condition

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

FALSE

General		Connected Nodes		Fluids	Geometry		Options			Inlet		Losses					
Identifier	Solving	Description	Upstream Node	Downstream Node	Fluid	Node	Geometry	Options	Thickness (mm)	Length (m)	Cross section	Variable	Diameter (mm)	Circumfer	Area (m ²)	Primary Loss	Loss option
P-103	TRUE	Primary Inlet Header	P-Node-1	P-Node-2	Water	Specify/Two Phase	Fluids	1620	Diameter	FALSE		323				Darcy Weisbach	Specify manually
P-104-4	TRUE	U-Tube-4	N-13	N-14	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-106	TRUE	Primary Outlet Header	P-Node-108		Water	Specify/Two Phase	Fluids	1620	Diameter	FALSE		323				Darcy Weisbach	Specify manually
P-110-1	TRUE	U-Tube-1	P-Node-2	P-Node-3	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-10	TRUE	U-Tube-10	N-19	Node - 10	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-2	TRUE	U-Tube-2	P-Node-3	P-Node-4	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-3	TRUE	U-Tube-3	P-Node-4	N-13	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-5	TRUE	U-Tube-5	N-14	N-15	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-6	TRUE	U-Tube-6	N-15	N-16	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-7	TRUE	U-Tube-7	N-16	N-17	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-8	TRUE	U-Tube-8	N-17	N-18	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
P-110-9	TRUE	U-Tube-9	N-18	N-19	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			205.882	1.0129		Darcy Weisbach	Specify manually
Pipe - 0	TRUE	Dryers Refill	Node - 1	S-225	Water	Specify/Two Phase	Fluids	2058	Diameter	FALSE		4480				Darcy Weisbach	Specify manually
Pipe - 2	TRUE	Downcomer	Node 8	N-204	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			20.809	0.6819		Darcy Weisbach	Specify manually
Pipe - 3	TRUE	Downcomer	Node 8	Node - 9	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			20.809	0.6819		Darcy Weisbach	Specify manually
Pipe - 4	TRUE	Downcomer	Node 7	Node - 8	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			20.809	0.6819		Darcy Weisbach	Specify manually
Pipe - 5	TRUE	Downcomer	Node 6	Node - 7	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE			20.809	0.6819		Darcy Weisbach	Specify manually
S-203	TRUE	Feedwater	S-203	Pipe 5	S-225	Water	Specify/Two Phase	Fluids	1.62	Diameter	FALSE		0.66			Darcy Weisbach	Specify manually
S-214	TRUE	Downcomer	S-225	Region	Node - 6	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		20.809	0.6819		Darcy Weisbach	Specify manually
S-215-1	TRUE	Heated Risers	S-225	Region	N-215-1	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		485.782	7.4022		Darcy Weisbach	Specify manually
S-215-2	TRUE	Heated Risers	S-225	Region	N-215-2	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		485.782	7.4022		Darcy Weisbach	Specify manually
S-215-3	TRUE	Heated Risers	S-225	Region	N-215-3	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		485.782	7.4022		Darcy Weisbach	Specify manually
S-215-4	TRUE	Heated Risers	S-225	Region	N-215-4	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		485.782	7.4022		Darcy Weisbach	Specify manually
S-215-5	TRUE	Heated Risers	S-225	Region	N-206	Water	Specify/Two Phase	Fluids	2282	Circumference	FALSE		485.782	7.4022		Darcy Weisbach	Specify manually
S-216	TRUE	Unheated Risers	S-206	Region	Node-9	Water	Specify/Two Phase	Fluids	1150	Diameter	FALSE		3445			Darcy Weisbach	Specify manually
S-221	TRUE	Separator	S-Node-9	S-Node-10	Water	Specify/Two Phase	Fluids	2792	Diameter	FALSE		1.422				Darcy Weisbach	Specify manually
S-222	TRUE	Dryers Risers	S-Node-10	Two Phase	Water	Specify/Two Phase	Fluids	2978	Diameter	FALSE		4.48				Darcy Weisbach	Specify manually
S-223	TRUE	Dryers Refill	Two Phase	Atank-13	Water	Specify/Two Phase	Fluids	2058	Diameter	FALSE		4480				Darcy Weisbach	Specify manually
S-250	TRUE	Steam Down	Two Phase	S-Node-12	Water	Specify/Two Phase	Fluids	1627	Diameter	FALSE		4480				Darcy Weisbach	Specify manually

Discretisation Orifice Heat Transfer Water Hammer Parameters													
Heat Distribution Curve													
Roughness (µm)	base diameter (mm)	difference (mm)	reference diameter (mm)	orifice diameter (mm)	orifice thickness (mm)	orifice shape	heat transfer coefficient (W/m²K)	heat input (J)	use heat distribution curve	disturbance (mm)	volume (m³)	pressure (kPa)	coefficient
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	3330	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.30329
47	FALSE	FALSE	500	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
30	FALSE	FALSE	1561	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
30	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
30	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
30	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
30	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	3	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	0	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	500	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25
47	FALSE	FALSE	500	1	1	1 Fixed heat transfer	0	FALSE	Specify Youngs Modulus	0	Calculate Longitudinal	0	1.25

Static Preserved Optimization Option

Apply simple fixed cost rates to production in addition

[illegible]

General		
Identifier	Solving	
Two Phase Tank - 3		TRUE
		2
Volume Fraction		
Description	Specify	
S-222		TRUE
Volume (m³)	Diameter (m)	
32.433		4.48
Solver Incondensable Concentration Guess Values		
Elevation (m)	Specify incondensable concentration guess value	
17.5	FALSE	

Geometry		0
Volume Fraction		
Description	Specify	
TRUE		

		0
Description	Fraction	
S-223		

Fluids	
Cylinder has endcaps	Fluid data reference
FALSE	Water General (Two Phase Fluids)

Solution Scheme		Heat Transfer
Use explicit pressure calculation	Heat input (kW)	
FALSE	0	

Description	Fraction	
S-250		1

Apply dynamic height	Geometry option	
TRUE	Specify volume	

Solver Guess Values	Boundary Conditions	
Specify guess values	Elevation boundary condition	
FALSE	Specified	

		1
		Volume Fraction
Apply dynamic height	Specify	
TRUE	FALSE	

Vessel shape	
Cylindrical vertical	

General			EES					
			13		14			12
			General		General		General	
Identifier	Solving	Description	Description	Value	Description	Value	Description	
Chen Input Prep	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
Chen Input Prep 2	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
Chen Input Prep 3	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 0	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 1	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 24	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 30	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 36	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 42	TRUE		d_i	0.03845	m_dot_A	301.797917	x	
EES File - 8	TRUE		d_i	0.03845	m_dot_A	301.797917	x	

5		8		9		7	
General		General		General		General	
Value	Description	Description	Value	Value	Description	Description	Value
1680760.43	h_LG	c_pL	4941.98443	0.000103213	mu_L	P_sat	4433409.29
1653070.7	h_LG	c_pL	5004.02972	0.000101036	mu_L	P_sat	4813144.08
1645238.79	h_LG	c_pL	5022.18649	0.000100444	mu_L	P_sat	4922524.51
1645983.29	h_LG	c_pL	5020.44866	0.0001005	mu_L	P_sat	4912090.62
1645983.29	h_LG	c_pL	5020.44866	0.0001005	mu_L	P_sat	4912090.62
1645259.32	h_LG	c_pL	5022.13853	0.000100445	mu_L	P_sat	4922236.67
1645238.79	h_LG	c_pL	5022.18649	0.000100444	mu_L	P_sat	4922524.51
1653070.7	h_LG	c_pL	5004.02972	0.000101036	mu_L	P_sat	4813144.08
1680760.43	h_LG	c_pL	4941.98443	0.000103213	mu_L	P_sat	4433409.29
1645259.32	h_LG	c_pL	5022.13853	0.000100445	mu_L	P_sat	4922236.67

11			10		0		3
General		Description	General		General		General
Value	Value		Description	Value	Value	Description	Description
-0.021047781	256.528918	T_sat	T_wall	283.584417	22.3458511	rho_G	mu_G
0.013535812	261.570578	T_sat	T_wall	269.686915	24.3521984	rho_G	mu_G
0.054086264	262.966209	T_sat	T_wall	270.952966	24.9353965	rho_G	mu_G
0.124389392	262.834107	T_sat	T_wall	270.385594	24.8796601	rho_G	mu_G
0.124389392	262.834107	T_sat	T_wall	269.878373	24.8796601	rho_G	mu_G
0.089929503	262.962567	T_sat	T_wall	269.400176	24.9338586	rho_G	mu_G
0.054086264	262.966209	T_sat	T_wall	268.869784	24.9353965	rho_G	mu_G
0.013535812	261.570578	T_sat	T_wall	267.409541	24.3521984	rho_G	mu_G
-0.021047781	256.528918	T_sat	T_wall	269.521446	22.3458511	rho_G	mu_G
0.089929503	262.962567	T_sat	T_wall	270.796209	24.9338586	rho_G	mu_G

Steady State Behaviour				
6				
General				
Value	Description	Execute before steady state	Execute during steady state	Execute after steady state
6770740.5	P_wall	TRUE	FALSE	FALSE
5476100.33	P_wall	TRUE	FALSE	FALSE
5585491.7	P_wall	TRUE	FALSE	FALSE
5536264.32	P_wall	TRUE	FALSE	FALSE
5492537.01	P_wall	TRUE	FALSE	FALSE
5451554	P_wall	TRUE	FALSE	FALSE
5406371.21	P_wall	TRUE	FALSE	FALSE
5283453.73	P_wall	TRUE	FALSE	FALSE
5461925.04	P_wall	TRUE	FALSE	FALSE
5571857.52	P_wall	TRUE	FALSE	FALSE

		4			2			1
General			General			General		
Value	Description	Value	Description	Value	Value	Description		
1.77425E-05	sigma	0.024500427	k_L	0.613656896	789.127971	rho_L		
1.79384E-05	sigma	0.023313479	k_L	0.607369048	781.267903	rho_L		
1.79935E-05	sigma	0.022985008	k_L	0.605566351	779.05176	rho_L		
1.79882E-05	sigma	0.023016096	k_L	0.60573815	779.262296	rho_L		
1.79882E-05	sigma	0.023016096	k_L	0.60573815	779.262296	rho_L		
1.79933E-05	sigma	0.022985865	k_L	0.60557109	779.057566	rho_L		
1.79935E-05	sigma	0.022985008	k_L	0.605566351	779.05176	rho_L		
1.79384E-05	sigma	0.023313479	k_L	0.607369048	781.267903	rho_L		
1.77425E-05	sigma	0.024500427	k_L	0.613656896	789.127971	rho_L		
1.79933E-05	sigma	0.022985865	k_L	0.60557109	779.057566	rho_L		

General			Script General General					
Identifier	Solving	Description	mu_G	rho_G	mu_L	k_L	rho_L	
Chen Script	TRUE			1.77425E-05	22.3458511	0.000103213	0.613656896	789.127971
Chen Script 2	TRUE			1.79384E-05	24.3521984	0.000101036	0.607369048	781.267903
Chen Script 3	TRUE			1.79935E-05	24.9353965	0.000100444	0.605566351	779.05176
Script - 1	TRUE			1.79882E-05	24.8796601	0.0001005	0.60573815	779.262296
Script - 2	TRUE			1.79882E-05	24.8796601	0.0001005	0.60573815	779.262296
Script - 25	TRUE			1.79933E-05	24.9338586	0.000100445	0.60557109	779.057566
Script - 31	TRUE			1.79935E-05	24.9353965	0.000100444	0.605566351	779.05176
Script - 37	TRUE			1.79384E-05	24.3521984	0.000101036	0.607369048	781.267903
Script - 43	TRUE			1.77425E-05	22.3458511	0.000103213	0.613656896	789.127971
Script - 9	TRUE			1.79933E-05	24.9338586	0.000100445	0.60557109	779.057566

m_dot_A	d_i	alpha_TP	x	c_pL	
	301.797917	0.03845	3744.067403	-0.021047781	4941.98443
	301.797917	0.03845	35389.10274	0.013535812	5004.02972
	301.797917	0.03845	28166.91734	0.054086264	5022.18649
	301.797917	0.03845	21162.01287	0.124389392	5020.44866
	301.797917	0.03845	19946.37197	0.124389392	5020.44866
	301.797917	0.03845	20287.40952	0.089929503	5022.13853
	301.797917	0.03845	21320.66037	0.054086264	5022.18649
	301.797917	0.03845	25730.41195	0.013535812	5004.02972
	301.797917	0.03845	3744.067403	-0.021047781	4941.98443
	301.797917	0.03845	24136.05436	0.089929503	5022.13853

[illegible]

sigma	h_LG	p_wall	p_sat	
0.024500427	1680760.43		6770740.5	4433409.29
0.023313479	1653070.7		5476100.33	4813144.08
0.022985008	1645238.79		5585491.7	4922524.51
0.023016096	1645983.29		5536264.32	4912090.62
0.023016096	1645983.29		5492537.01	4912090.62
0.022985865	1645259.32		5451554	4922236.67
0.022985008	1645238.79		5406371.21	4922524.51
0.023313479	1653070.7		5283453.73	4813144.08
0.024500427	1680760.43		5461925.04	4433409.29
0.022985865	1645259.32		5571857.52	4922236.67

T_sat	T_wall	Script Inputs And Outputs	Use repository script	Script
256.528918	283.584417		FALSE	
261.570578	269.686915		FALSE	
262.966209	270.952966		FALSE	
262.834107	270.385594		FALSE	
262.834107	269.878373		FALSE	
262.962567	269.400176		FALSE	
262.966209	268.869784		FALSE	
261.570578	267.409541		FALSE	
256.528918	269.521446		FALSE	
262.962567	270.796209		FALSE	