

Steam generator thermal-fluid simulation using a coupled Flownex and RELAP5/mod4.0 approach

**AS van Niekerk
21720312**

Dissertation submitted in partial fulfilment of the requirements
for the degree Magister in Nuclear Engineering at the
Potchefstroom Campus of the North-West University

Supervisor: Prof M van Eldik
Co-supervisor: Prof PG Rousseau

November 2015

Preface

I would like to thank my wife for her continued support and encouragement throughout the duration of my studies. I would also like to thank Professor Martin van Eldik and Professor Pieter Rousseau for their inputs as study leader and advisor to this project. Thanks to Tiaan Dercksen and Nicolé Leeb for their assistance with the Flownex models and helpful input. Lastly I would also like to thank Doctor Vishnu Naicker for his help with the Relap5 models.

Abstract

The steam generator (SG) is one of the biggest structural components in a nuclear power plant (NPP), and can in many respects be seen as the heart of the system. It functions as a heat exchanger between the primary and secondary loops of a NPP. In addition to this the SG also serves as an important safety barrier since it separates the primary and secondary sides to avoid contamination of the secondary loop with radioactive material.

Relap5 is a well-known thermal-fluid simulation program in the nuclear environment, used to simulate steady-state and transient scenarios. Relap5 is well suited to simulate the primary loop of a NPP. It has limitations in terms of high licensing cost and it is quite complex for a user to set up a model in the software. Flownex is another thermal-fluid network simulation package with the advantage that the user can set up a simulation with relative ease, and it can simulate detailed transients. A limitation of Flownex is the heat transfer correlations used for certain components. Flownex is also very powerful in its ability to simulate the secondary loop of the NPP. Flownex recently got the ability to couple with Relap5 and thereby gained access to its complex matrix of heat transfer correlations and Relap5's detailed approach to solving the primary side of a NPP.

The purpose of this study is to find the optimum position within the SG to couple Flownex with Relap5 in terms of accuracy and ease of obtaining a solution. Two Flownex models were developed as part of this study where Relap5 was implemented to calculate convection heat transfer coefficients. For the first model, Relap5 calculated only the convection heat transfer coefficients for the primary side of the SG and these were used as input for the Flownex model (FRHCP). For the second model Relap5 calculated the convection heat transfer coefficients for the secondary side of the SG as input for the Flownex model (FRHCS). The results of the two Flownex models were then compared to the results of a complete SG Relap5 homogeneous model as well as a Flownex model developed in an earlier study. The earlier Flownex model used a custom written C# script to calculate the convection heat transfer coefficients for the secondary side of the SG (FSHCS).

The geometry used in this study was based on technical drawings of the SG installed at Koeberg NPP and was simplified to a one-dimensional model. Plant data was used to verify the accuracy of the models at 100%, 80% and 60% power output levels.

From the study it was found that the FRHCS model over predicted the total heat transferred in the SG boiling region on average by 5% when compared to the measured data of Koeberg. The FRHCP model over-estimated the total heat transferred in the boiling region by 6% when compared to the measured data. The results obtained were mainly due to the over-estimation of the SG's secondary side convection heat transfer coefficients in both models. The Relap5 homogeneous model that was used for comparison, under predicted the heat transferred in the SG boiling region on average by 0.5%.

It was concluded that the FRHCS model offers a significant advantage in simplicity over using only a Relap5 homogeneous model for normal operational analysis. It also offers improvements in the heat transfer coefficient calculations compared to just using Flownex to simulate the steam generator where an over prediction of the heat transferred in the boiling region of the SG of about 10% can be expected. The new integrated model can be further expanded to simulate the complete system including the balance of plant components, the nuclear reactor and the auxiliaries, for an overall NPP analysis.

Keywords: Pressurized water reactor, U-tube steam generator, Flownex, Relap5, thermal-fluid simulation.

Table of Contents

Preface	i
Abstract	ii
List of Tables	vii
List of Figures	viii
Nomenclature	x
Introduction.....	1
1.1 Background	1
1.1.1 Steam generators.....	2
1.1.2 Modelling and simulation of a steam generator	4
1.2 Motivation for the study.....	5
1.3 Problem statement	6
1.4 Methodology	6
Literature study	8
2.1 Thermal fluid modelling of two-phase flow.....	8
2.1.1 Two-phase flow and phase transition	9
2.1.2 The two-fluid model	13
2.1.3 Homogeneous model	14
2.2 Simulation software	15
2.2.1 Relap5/mod4.0	15
2.2.2 Flownex	16
2.3 The simulation of steam generators	16

2.3.1	Previous work done on steam generator models	17
2.4	Summary	19
	Basis of the model	20
3.1	Data for Koeberg Nuclear Power Station	20
3.2	Steam generator geometry	22
3.3	Model geometry and heat structure input	24
3.4	Model development	26
3.4.1	Heat transfer calculations	26
3.4.2	Flownex model development.....	30
3.4.3	Relap5 model development.....	34
3.4.4	Boundary conditions	35
3.5	Summary	36
	Results and discussion	37
4.1	Comparison with empirical data	37
4.1.1	100% power output.....	37
4.1.2	80% power output.....	39
4.1.3	60% power output.....	40
4.1.4	Discussion	41
4.2	Detailed inter-model comparison.....	41
4.2.1	Primary side temperatures	42
4.2.2	Vapour quality through the boiler.....	44
4.2.3	Heat transfer coefficient on the secondary side of the SG.....	48

4.2.4	Flow velocity through the boiling region.....	51
4.2.5	Tube surface temperature on the secondary side of the SG	53
4.3	Summary of model comparisons	55
	Conclusion and recommendations	57
5.1	Conclusions	57
5.2	Recommendations for further studies.....	59
	Bibliography.....	60
	Annexure A.....	63
A.1	Relap5 code	63

List of Tables

Table 1: Heat transfer correlations used in various regimes for Relap5.	13
Table 2: Heat transfer correlations used in various regimes for Flownex.	13
Table 3: Advantages and disadvantages of using Relap5 (Cilliers, 2012).....	15
Table 4: Advantages and disadvantages of using Flownex (Cilliers, 2012).....	16
Table 5: Volumetric inputs for the steam generator.	24
Table 6: Heat structure inputs for the steam generator.	25
Table 7: Flownex elements used in the model.....	31
Table 8: Geometry of the four different configurations of the Relap5 model.....	35
Table 9: Boundary conditions at 100% generator power output (Cilliers, 2012).	36
Table 10: Boundary conditions at 80% generator power output (Cilliers, 2012).	36
Table 11: Boundary conditions at 60% generator power output (Cilliers, 2012).	36
Table 12: Variable discussion of the result tables.....	37
Table 13: Steady-state validation of the model at 100% power output.	38
Table 14: Steady-state validation of the model at 80% power output.	39
Table 15: Steady-state validation of the model at 60% output.....	40

List of Figures

Figure 1: Layout of the NSSS (Lamarsh & Baratta, 2001).....	2
Figure 2: Cut away of a steam generator (Bonavigo & De Salve, 2011).	3
Figure 3: Classification of two-phase flow (Ishii & Hibiki, 2006).....	9
Figure 4: A typical Nukiyama flow boiling curve (Flownex SE, 2015a).	10
Figure 5: Illustration of sub-cooled boiling (Flownex SE, 2015a).....	11
Figure 6: Vertical flow boiling proses (Flownex SE, 2015a).....	11
Figure 7: Schematic of a vertical flow-regime map (RELAP5, 2001a).	12
Figure 8: Geometry of the steam generator (ESKOM, 2004).....	23
Figure 9: Flownex increment distribution along the U-tube.....	25
Figure 10: Relap5-homogeneous model increment distribution along the U-tube.	26
Figure 11: Schematic of a typical heat transfer element with conduction and convection (Flownex SE, 2015b).....	27
Figure 12: Thermal resistive circuit of the heat transfer path for conduction and convection (Flownex SE, 2015b).....	27
Figure 13: Nodalization of the Flownex steam generator model.....	31
Figure 14: Flownex and Relap5 coupling flow diagram.	32
Figure 15: Resistive circuit of the heat transfer proses of one pipe increment in the SG.	33
Figure 16: Nodalization of the Relap5 model used by Flownex.	35
Figure 17: Primary side coolant temperature change at 100% power output.	43
Figure 18: Primary side coolant temperature change at 80% power output.	43

Figure 19: Primary side coolant temperature change at 60% power output.	44
Figure 20: Grid dependence results	45
Figure 21: Vapour quality through the boiling region at 100% power output.	46
Figure 22: Vapour quality through the boiling region at 80% power output.	46
Figure 23: Vapour quality through the boiling region at 60% power output.	47
Figure 24: Heat transfer coefficients on the secondary side of the SG at 100% power output.	48
Figure 25: Heat transfer coefficients on the secondary side of the SG at 80% power output.	49
Figure 26: Heat transfer coefficients on the secondary side of the SG 60% power output.	49
Figure 27: Flow velocity through the boiling region at 100% power output.	51
Figure 28: Flow velocity through the boiling region at 80% power output.	52
Figure 29: Flow velocity through the boiling region at 60% power output.	52
Figure 30: Tube surface temperature of the SG at 100% power output.	53
Figure 31: Tube surface temperature of the SG at 80% power output.	54
Figure 32: Tube surface temperature of the SG at 60% power output.	54

Nomenclature

Terms and Acronyms

AECL	Atomic Energy of Canada Limited
BWR	Boiling water reactor
CFD	Computational Fluid Dynamics
CHF	Critical heat flux
EAF	Energy availability factor
EDF	Electricité de France
EPRI	Electric Research Power Institute
FRHCP	Flownex using the Relap5 calculated convection heat transfer coefficient for the primary side of the steam generator
FRHCS	Flownex using the Relap5 calculated convection heat transfer coefficient for the secondary side of the steam generator
FSHCS	Flownex using a custom C# script to calculate the convection heat transfer coefficient for the secondary side of the steam generator
HP	High pressure
IAEA	International Atomic Energy Agency
Inc	Inclination of flow through a pipe section
INL	Idaho National Laboratory
NNR	National Nuclear Regulator
NPP	Nuclear power plant

NSSS	Nuclear steam supply system
NVG	Net vapour generation
ONB	Onset of nucleate boiling
PBMR	Pebble bed modular reactor
PWR	Pressurized water reactor
SA	Surface area
SCFD	Systems computational fluid dynamics
SG	Steam generator
USNRC	United States Nuclear Regulatory Commission
UTSG	U-tube steam generator

Constants and variables

A	Area (m^2)
d_i	Inner diameter (m)
D_h	Hydraulic diameter of pipe section (m)
d_o	Outer diameter (m)
dx	Length or thickness in the x-direction of an element (m)
FA	Flow area (m^2)
$h_1; h_2$	Convection heat transfer coefficient on the secondary loop side of a U-tube pipe segment ($\text{W}/\text{m}^2\text{K}$)
h_c	Convection heat transfer coefficient ($\text{W}/\text{m}^2\text{K}$)
H_{fg}	Heat of evaporation (J/kg)

h_i	Inlet enthalpy (kJ/kg)
$h_{in}; h_{out}$	Convection heat transfer coefficient on the primary loop side of a U-tube pipe segment (W/m ² K)
h_{NB}	Nucleate boiling heat transfer coefficient (W/m ² K)
h_{WL}	The height of the water level in the downcomer (m)
k_w	Thermal conductivity of the wall material (W/mK)
k_x	Conduction heat transfer coefficient (W/mK)
L	Length of pipe section in Flownex and Relap5 (m)
λ_0	Surface heat transfer convection coefficient (W/m ² K)
$\dot{m}$	Mass flow rate (kg/s)
$\dot{m}_{fd}$	The mass flow rate of the feed water added into the downcomer (kg/s)
$\dot{m}_p$	The mass flow rate of the primary fluid (kg/s)
μ_L	Viscosity of the saturated liquid (kg/m-s)
p_d	The pressure in the steam dome (kPa)
$p_i; p_o$	Inlet and outlet pressure (kPa)
$\dot{Q}_H$	Heat transferred (W)
R_f	Fouling factor, or resistance to heat transfer due to fouling (m ² K/W)
ρ_L, ρ_G	Liquid and vapour density (kg/m ³)
σ	Surface tension of the liquid (N/m)

T_{01}, T_{02}	Ambient temperatures (K)
$T_i; T_o$	Inlet and outlet temperature (K)
$T_{in}; T_{out}$	Inlet and outlet temperature (K)
T_{fd}	The feed water inlet temperature (K)
T_{∞}	Temperature of secondary loop feed water flowing upward in the steam generator boiling region (K)
U	Over-all heat transfer coefficient (W/m ² K)
V	Volume (m ³)

Introduction

1.1 Background

Globally the total installed capacity of nuclear power plants (NPP) is about 372 Gigawatt. This equates to about 10.9% of the global generating capacity (IAEA, 2012). By the end of 2013 there were 434 NPPs in operation which included 100 reactors from the USA, 58 from France, 48 from Japan and 33 from Russia. Of the 434 reactors in operation, about 63% are Pressurized Water Reactors (PWR) and approximately 19% are Boiling Water Reactors (BWR). During 2013 there were 72 reactors worldwide under construction, with 62 of them being PWRs. NPPs are playing a big role in electricity generation and it is thus important to ensure that all of them reach their maximum energy availability factor (EAF).

During the operations of a PWR the primary loop coolant is used to cool down the reactor core. The primary loop cooling water is heated at high pressure in the reactor core without changing phase. It then flows to the steam generator (SG) where it transfers the absorbed heat to the secondary loop feed water to produce steam at a lower pressure. The steam is then used to drive a turbine that is connected to a generator. The steam is condensed and thereafter returned to the SG as feed water (Bonavigo & De Salve, 2011).

The SG is one of the biggest structural components in a PWR and can in many respects be seen as the heart of the system, since it functions as a heat exchanger between the primary loop and secondary loop. In addition to this the SG also serves as an important safety barrier as it separates the primary side and secondary side to avoid contaminating the secondary loop with radioactive material.

The modelling of SGs is important for steady-state and transient operation analysis. Simulation models can be used to either analyse the thermal performance of a SG for certain power outputs or to assist investigations into accident scenarios. From the results obtained from these kinds of simulations, performance issues in the heat transfer abilities of the SG can be identified and outages can be planned to correct the issue. Simulations can also be used to identify certain structural components that carry a risk of failure due to the operating conditions being above its designed conditions. For instance, tubes that

experience high operating temperatures can result in tube failures, which accounts for about 40% of all SG failures (Zhang, et al., 2013).

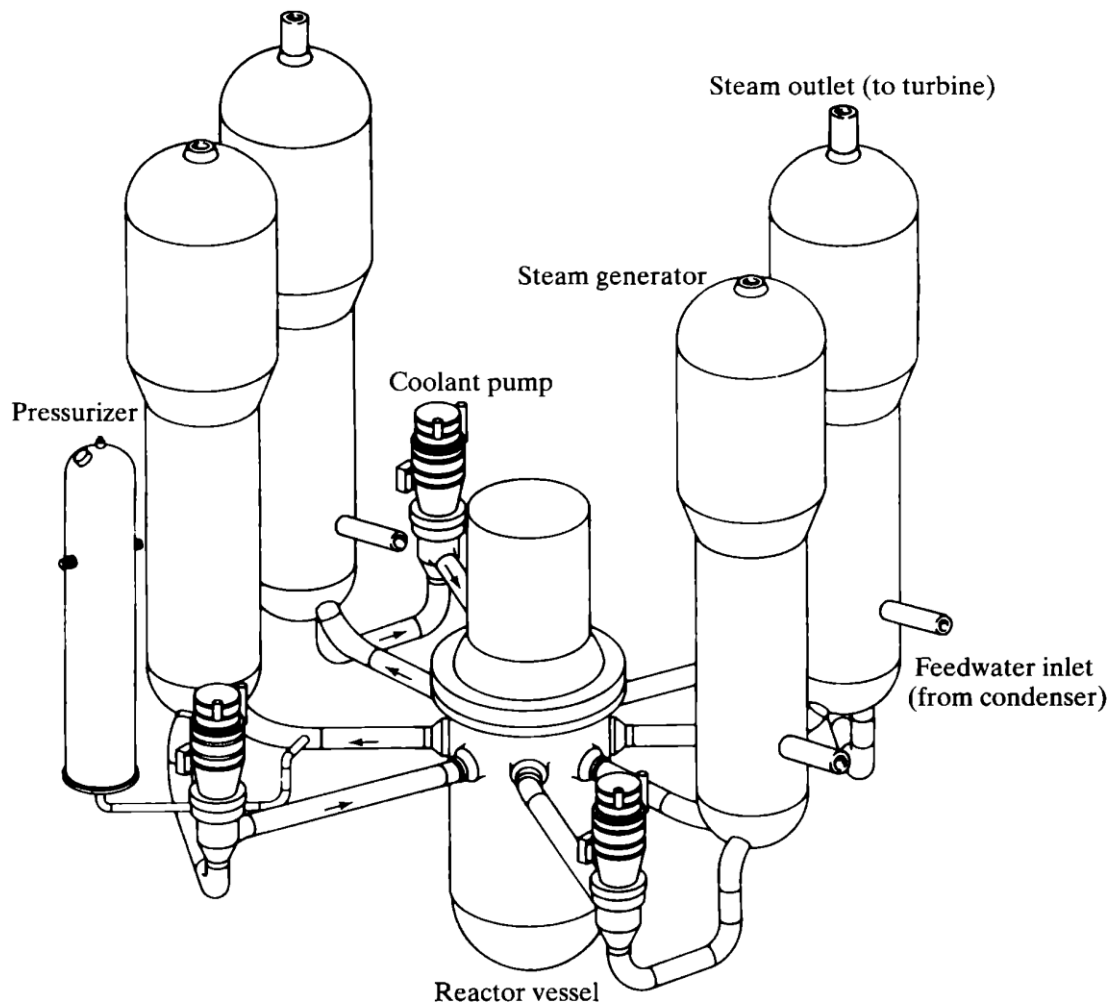


Figure 1: Layout of the NSSS (Lamarsh & Baratta, 2001).

1.1.1 Steam generators

PWR power plants can use two, three or four SGs (Figure 1) and are called two-loop, three-loop or four-loop units. The vertical U-tube SG (UTSG) consists of a heat exchanger part and a steam drum section, as can be seen in Figure 2.

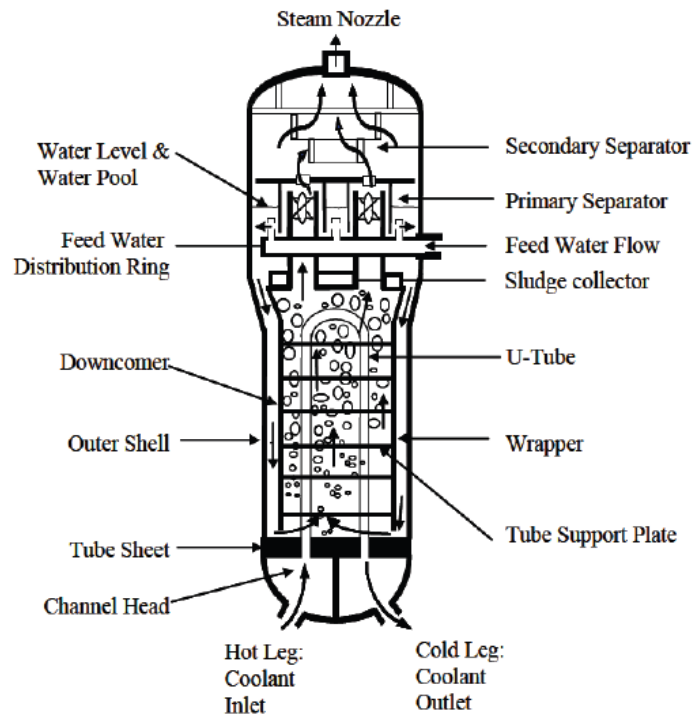


Figure 2: Cut away of a steam generator (Bonavigo & De Salve, 2011).

The heat exchanger section houses the vertical, inverted U-tube bundle where the primary loop coolant from the reactor flows through. The steam drum section consists of the internal moisture separating equipment and the enclosing pressure shell. Feed water from the secondary loop enters the SG just below the water level and joins the water flowing downward through the downcomer at the sides of the SG. At the tube sheet, the recirculated water and feed water are introduced to the tube bundle. When heat is transferred from the primary loop coolant to the secondary loop feed water, the feed water will start to boil and form steam. The steam is then passed through the moisture separating equipment to reduce its moisture content and dry steam is discharged through the steam outlet nozzle. The separation of the moisture from the steam takes place in three steps, where first the primary separation is done with centrifugal separators, then gravity separation takes place and lastly secondary separation takes place by means of corrugated shape separators (Bonavigo & De Salve, 2011).

The primary loop coolant contains many radioactive materials while the steam leaving the SG should be without any radioactive material. It is of the utmost importance that the separation of the primary and secondary sides is preserved to avoid radioactive contamination of the feed water. The integrity of the inverted U-tubes must be maintained

as it serves as a barrier between the radioactive and non-radioactive sides of the nuclear power plant.

1.1.2 Modelling and simulation of a steam generator

Different software packages to simulate a steam generator have been developed since the early 1970s. The Electric Research Power Institute (EPRI) released the first version of ATHOS in 1983. ATHOS experienced a number of upgrades during the years as well as the addition of a graphical user interface. The most current addition, ATHOS/SGAP 3.1, was released in 2008 (EPRI, 2012a). EPRI also started in 2012 to develop another steam generator thermal-hydraulics code, Triton, to address most of the shortcomings of ATHOS in terms of more complex SG design features and computational capabilities (EPRI, 2012b; EPRI, 2015). Other companies such as Electricité de France (EDF) also developed their own codes such as THYC and GeViBus (EPRI, 2012b) and the Atomic Energy of Canada Limited (AECL) developed the THIRST code for the simulation of Canadian CANDU designs and American PWR designs (EPRI, 1982).

The initial motivation for the development of the first computer codes were to assess the overall performance of the SG and the effects of macro design changes. Recently the focus have shifted to localised fluid flow that influences fluid induced vibrations, sludge deposits and predicting wear due to foreign objects (EPRI, 2012b; EPRI, 2008). Computational fluid dynamics (CFD) software can help the industry gain a better understanding of the intrinsic flow field in a certain region of interest inside a steam generator and also accurately simulate more complex geometries. Software packages such as ATHOS/SGAP 3.1 has CFD capabilities built into it and Triton will interact with the commercial CFD software code STAR-CCM+ (EPRI, 2015).

For the purpose of this study, which will focus on the overall performance of the SG, a typical one-dimensional dynamic mathematical model will be used for the primary loop coolant, the secondary loop feed water and the U-tubes. The following assumptions are generally made when modelling a SG using this approach

- Parameters of the primary loop, secondary loop and U-tube wall only vary in the axial direction, thus simplified to a one-dimensional model.

- The secondary loop feed water is homogenous and in thermal equilibrium. The velocities and temperatures of the liquid and vapour phases at a specific cross-section are assumed to be equal.
- The U-tube bundle is simplified to an equivalent single U-tube with its flow area the sum of all the tubes.

1.2 Motivation for the study

Simulations of the reactor core and SG have been done extensively using Relap5/mod3 (Preece & Putney, 1993; Fletcher, et al., 1997; Green & Hetsroni, 1995). Relap5's three-dimensional analysis capabilities of the reactor core, SG and auxiliaries are preferred over the capabilities of other one-dimensional programs. However, setting up the model for the secondary loop with Relap5 is difficult and time-consuming and requires detailed information of all the numerous components that need to be modelled in the secondary loop. If an alternative simulation program can be found which can integrate easily with Relap5 it will simplify and reduce the simulation development time to form an overall system simulation of a PWR. Due to its ease of use and flexibility Flownex could be considered (Cilliers, 2012) for the secondary loop even though it hasn't been extensively validated in the PWR industry and its built-in heat transfer correlations aren't as detailed as Relap5's correlations.

A study was done by Cilliers (2012) who tried to address the short comings of the built-in heat transfer correlations of Flownex. A custom written C# script was used in Flownex to change the heat transfer correlations to only use the Chen correlation for the entire boiling region of the SG. The custom written script greatly improved the heat transfer calculations of Flownex. He concluded that the custom written script can be improved further by adding a more complex map of correlations versus just using the Chen correlation (Cilliers, 2012).

The findings and recommendations made by Cilliers (2012) will be implimented in this study by using the functionality of Flownex to couple with Relap5. This will enable the Flownex models to use the complex heat transfer correlations of Relap5 to calculate the convection heat transfer coefficients in the boiling region of the SG without the use of the custom written C# script.

1.3 Problem statement

Combining Relap5 and Flownex to simulate the primary loop and secondary loop of a NPP creates the problem of determining which characteristics need to be calculated in Relap5 and which can be calculated in Flownex to achieve the most accurate results. The primary loop and secondary loop interact at the SG of a NPP which makes the SG the ideal component where the two simulation packages can interact.

Within the SG there are certain fluid characteristics that can be shared between the two simulation packages, namely:

- The primary loop coolant: Calculate the primary loop coolant characteristics in Relap5 and send the results to Flownex. Flownex then calculates the secondary loop feed water characteristics.
- The secondary loop feed water: Calculate the secondary loop feed water characteristics in Relap5 and send the results to Flownex. Flownex calculates the primary loop coolant characteristics.

Each of these fluid characteristics need to be evaluated based on the combined model's overall accuracy and the ease of setting up and using the model. Future expansion of the model should also be kept in mind when evaluating the interaction between the packages.

1.4 Methodology

Specifications of a PWR steam generator from Koeberg NPP form the basis of the Relap5 and Flownex models. The boundary conditions are obtained from a study done by Cilliers (2012).

The models developed will consist of i) a SG modelled completely in Relap5 and ii) two models simulated in Flownex using its functionality to couple with Relap5. The first Flownex model will use Relap5 to calculate the convection heat transfer coefficients for the primary loop coolant for each of its pipe segments (FRHCP model). The second Flownex model will use Relap5 to calculate the secondary loop feed water convection heat transfer coefficients for each of its pipe segments (FRHCS model). In both Flownex models, the Relap5 element will return the convection heat transfer coefficients to the Flownex heat transfer element for the respective pipe segments. Flownex will then solve

the network with the given coefficients. The models will be run at power output levels of 100%, 80% and 60% to evaluate the impact of decreased power output on the accuracy of the respective models.

Verification of the models will be done against operating data obtained from Koeberg NPP as well as a previous study's results done by Cilliers (2012). The results for the different models will be tabulated and shown visually with the use of graphs, for the various power levels. This will provide a basis for making recommendations on further improvements and extensions of the models.

Chapter 2

Literature study

The literature study will focus on the following topics relevant to SGs and the simulation thereof:

- The thermal fluid models used to simulate steam generators.
- Available simulation software packages.
- Studies done in the past with similar scope and the conclusions made.

2.1 Thermal fluid modelling of two-phase flow

Two-phase flow analysis has become increasingly important in a wide variety of engineering systems to ensure their optimum design and safe operations. It is being used in transients and accident scenarios due to its modelling accuracy. With rapid advances in engineering technologies over the past few years, the demands for accurate predictions of the critical parts and high risk areas of the systems of interest have increased (Lakehal & Labois, 2011; Coddington & Macian, 2002; Hibiki & Ishii, 2003).

In the PWR, the primary coolant is kept sub-cooled at a high pressure and thus remains in a single phase. The secondary feed water on the shell-side of the SG is heated from sub-cooled to saturated vapour. A combination of forced and boiling convective conditions in the two-phase mixture in the secondary side of the SG results in extremely turbulent flow conditions. The existing correlations used to predict two-phase thermal-hydraulic parameters are less accurate for these flow conditions and the flow phenomenon is not as well understood as for single-phase flow (Lakehal & Labois, 2011).

Single-phase flow problems are solved using the governing equations of fluid dynamics and heat transfer. The partial differential equations for mass, momentum and energy conservation are solved to obtain the mass flow, pressure- and temperature conditions throughout a network (Ishii & Hibiki, 2006).

The approaches found in literature to solve two-phase flow problems will be discussed in section 2.1.1 to 2.1.3.

2.1.1 Two-phase flow and phase transition

Single-phase flow can be classified according to the structure of flow into laminar, transitional and turbulent flow. In contrast, two-phase flow can be classified, according to the structure of the interface, into several major groups which can be called flow regimes or patterns. This includes separated flow, transitional or mixed flow, and dispersed flow as shown in Figure 3 (Ishii & Hibiki, 2006). These flow patterns are caused by several boiling regimes such as sub-cooled boiling, saturated boiling, transition boiling and film boiling as seen in Figure 4.

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 3: Classification of two-phase flow (Ishii & Hibiki, 2006).

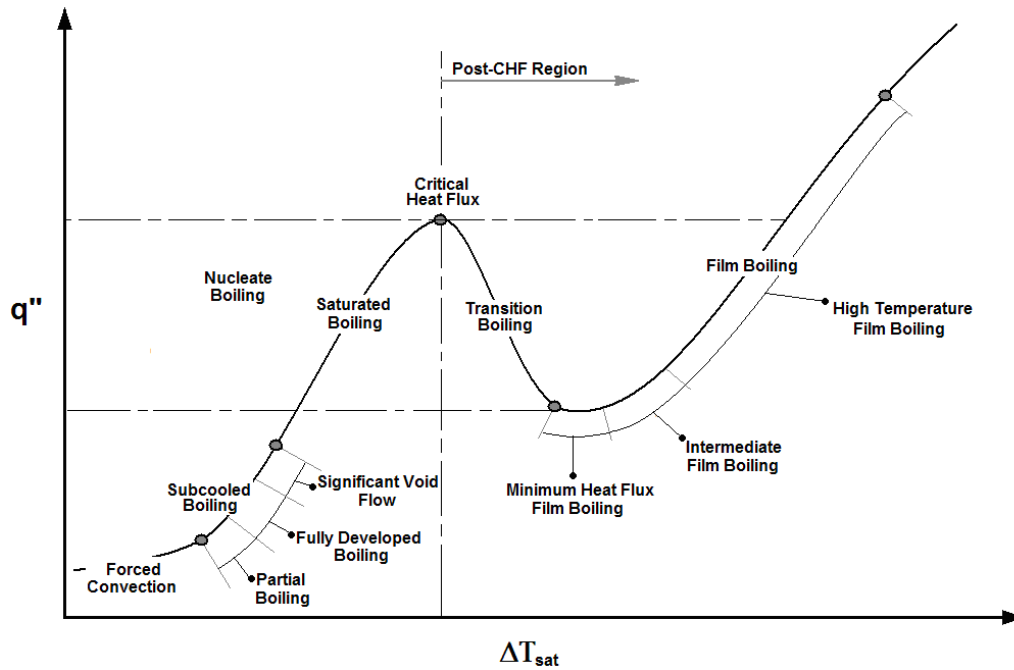


Figure 4: A typical Nukiyama flow boiling curve (Flownex SE, 2015a).

Consider a sub-cooled liquid flowing in a heated channel as seen in Figure 5. As long as the channel wall is below the local saturation temperature of the liquid, heat transfer is by single-phase models. Boiling is initiated when the wall temperature exceeds the saturation temperature depending on the heat surface and flow conditions. The first bubbles only appear at the onset of nucleate boiling (ONB) at point B of Figure 5. The wall temperature will start to level off as more nucleation sites are created beyond the ONB point. As more nucleation sites are activated in the cavities of the channel wall, the heat transfer from the nucleate boiling rises while the single-phase convection contribution diminishes. Heat transfer after the net vapour generation (NVG) point as shown in Figure 5 can be considered to be in the two-phase region. Saturation boiling is achieved at point E. (Kandlikar, 1998; Flownex SE, 2015a)

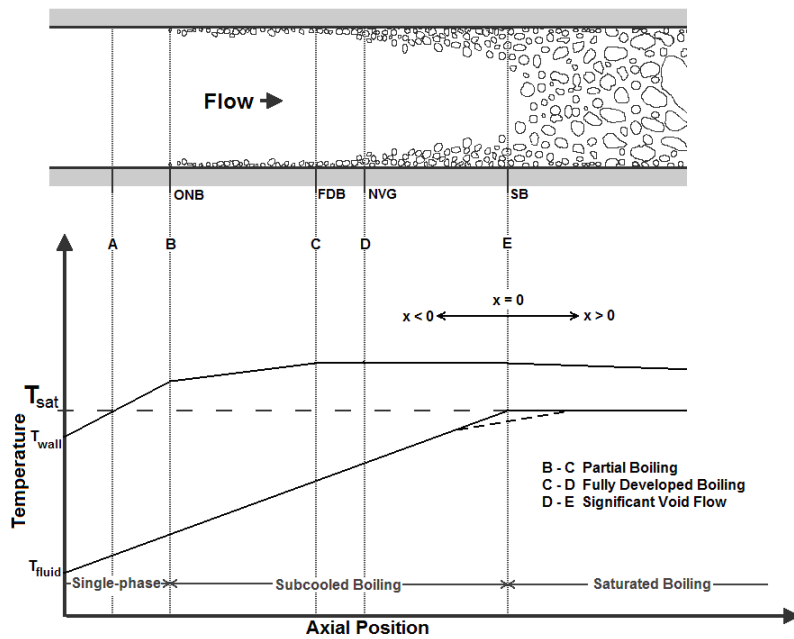


Figure 5: Illustration of sub-cooled boiling (Flownex SE, 2015a).

Saturation boiling is reached when the fluid temperature reaches its saturation state at a vapour quality of zero. Figure 6 shows the different types of flow that is evident during saturation boiling, from bubbly flow to mist flow.

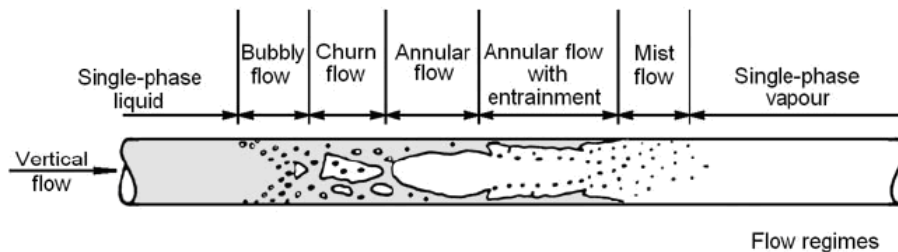


Figure 6: Vertical flow boiling regimes (Flownex SE, 2015a)

Complications arise from the fact that there are two separate fluids (liquid and vapour) being modelled in the sub-cooled and saturated boiling regions and they are subjected to multiple interfaces between the two phases. Furthermore, there exists mass and energy transfer across these interfaces as well (Hibiki & Ishii, 2003)

The flow through the secondary side of the steam generator generally falls within the mixed flow or transitional 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 & Hibiki, 2006; Schlegel, et al., 2010).

Software packages such as Relap5/mod3.3 (RELAP5, 2001a) have been coded with flow regime maps such as the one seen in Figure 7. The schematic in Figure 7 illustrates a vertical flow regime map as a function of the void fraction (α_g), the average mixture velocity (v_m) and the boiling regime to determine which flow transition best suits the flow.

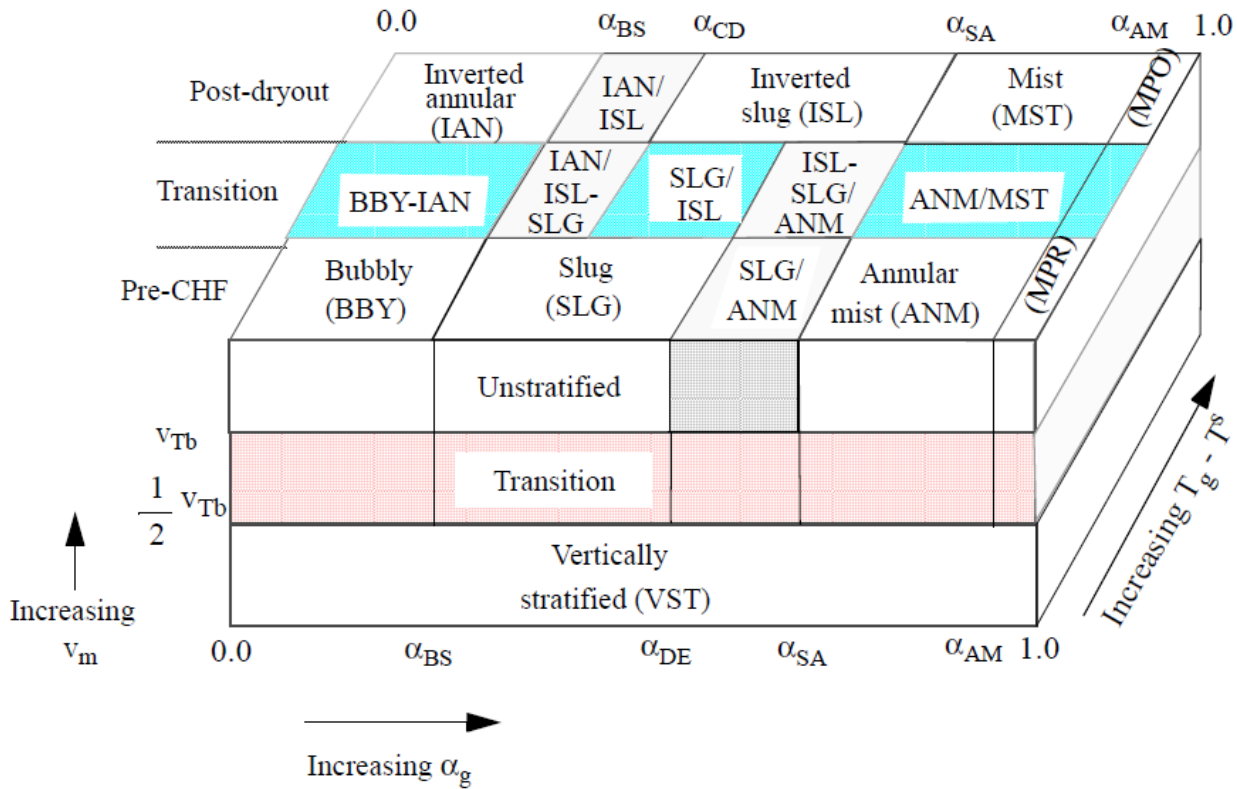


Figure 7: Schematic of a vertical flow-regime map (RELAP5, 2001a).

These flow regimes dictate which correlations should be used in inter-phase drag and shear, wall friction, heat transfer and inter-phase heat and mass transfer (RELAP5, 2001a). The boiling curve employed by Relap5 to calculate heat flux during fluid-to-wall heat transfer is similar to Figure 4 (RELAP5, 2001a).

As the physics change during phase transitions, so does the correlation required to calculate the heat flux. Table 1 shows an example of which correlations are used by Relap5 to calculate the heat flux for each boiling regime. The Chen correlation is applied

during nucleate boiling and transition boiling, and thus makes up the majority of the boiling regimes which occurs during nominal SG operation. This is because during operations all efforts go into operating the SG below or near the critical heat flux, within the nucleate or transition boiling regime, as seen in Figure 4.

Table 1: Heat transfer correlations used in various regimes for Relap5.

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

Table 2 gives an example of the different heat transfer correlations that Flownex uses. In Flownex the Chen correlation is used for the sub-cooled and saturated boiling regimes, the 1995 Groeneveld look up table is used for the critical heat flux (CHF) and the 2003 Groeneveld look up table for the film boiling regime. The Chen correlation became very popular as it delivered the first cohesive flow boiling method. (Leeb, 2015; Cilliers, 2012; Ishii & Hibiki, 2006) The correlation introduced a nucleate boiling suppression factor to the nucleate boiling heat transfer coefficient in order to account for the diminished contribution for nucleate boiling as convective effects start to dominate in the higher quality regions. The two-phase heat transfer coefficient consists of the sum of a convection heat transfer term such as the Dittus-Boelter correlation and a nucleate boiling heat transfer term such as the Foster-Zuber correlation (Leeb, 2015). The Chen correlation as used by Flownex will be discussed in Chapter 3.

Table 2: Heat transfer correlations used in various regimes for Flownex.

	Boiling regime							
	Laminar	Natural	Turbulent	Condensation	Sub-cooled boiling	Saturated boiling	Film boiling	CHF
Heat transfer correlations	Constant laminar flow Nusselt number			Empirical	Chen	Chen	2003 Groeneveld Table	1995 Groeneveld Table

2.1.2 The two-fluid model

The two-fluid model is the most detailed and accurate macroscopic formulation of the thermal-fluid dynamics of two-phase systems (Ishii & Hibiki, 2006; Schlegel, et al., 2010). The equations are expressed by the six conservation equations which include the mass, momentum and energy equations for each phase. For practical applications, the area

average of the three dimensional two-fluid model is used (Ishii & Hibiki, 2006; Schlegel, et al., 2010). Flownex furthermore reduces the four equations to three by assuming that the gas and liquid are in full equilibrium and thus the mass equation for the gas phase isn't necessary to solve (Flownex SE, 2015a).

The constituent equations describe the distribution coefficients, drag force, inter-facial shear force, heat transfer coefficients and the equations of state. Detailed information on the two-fluid model is found in many thermal-fluid texts, including Ishii and Hibiki (2006).

2.1.3 Homogeneous model

A much simpler way to analyse the two-phase flow is by using the homogeneous model approach. The homogeneous model neglects the inter-facial energy and momentum transfer as well as the inter-phase velocities. The six equations mentioned in section 2.1.2 can now be reduced to four. The mass, energy and momentum equations are written in terms of a homogeneous mixture of the two phases. The mass equation for the gas phase is still included in order to take into account the non-equilibrium of the two phases (Ishii & Hibiki, 2006).

When a homogeneous mixture is assumed, we are assuming that the relative velocity between the two phases is zero (Strohmayer, 1982; Flownex SE, 2015a). 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. Fewer equations are thus needed to be solved and fewer constituent equations are necessary to be used in the model (Ishii & Hibiki, 2006).

The homogeneous model is used most often for simple problems where the interior modelling of the SG is not the prime importance. The focus is on the relationships between the input and output variables. For safety analysis where detailed results are needed about each phase, the homogeneous model may not be appropriate (Strohmayer, 1982).

The homogeneous model for two-phase flow was compared to the two-fluid model by simulating a SG at normal operating conditions (Cilliers, 2012). An 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. It can be concluded that the homogeneous model offers a reliable alternative to the two-fluid model

(Cilliers, 2012). The scope of this study will only include the homogeneous model for two-phase flow in the two different simulation packages, Relap5 and Flownex.

2.2 Simulation software

The following software packages were used in this study and the background of each will be discussed in the sections below.

2.2.1 Relap5/mod4.0

Relap5 was developed for the U.S. Nuclear Regulatory Commission (USNRC) by Idaho National Laboratory (INL) to provide the means of independently reviewing the analysis of reactor manufacturers and utilities. The development of Relap5 has benefitted from extensive assessments against experimental data representing the behaviour from existing reactors (Fletcher, et al., 1997).

Relap5 is based on the non-homogeneous, non-equilibrium model for two-phase flow. It 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.

Relap5/mod3 was released in January 1990 as a successor for the Relap5/mod2. It uses the standard Chen correlation (RELAP5, 2001a) to present the boiling heat transfer where the Relap5/mod2 used a modified correlation. The modified correlation used a modified suppression factor which has the effect of increasing heat transfer for void fractions below 0.8. Relap5/mod3 also includes improved interphase drag models for low flow conditions in the rod bundles as well as for large diameter pipes (Preece & Putney, 1993). The advantages and disadvantages of using Relap5 are tabulated in Table 3.

Table 3: Advantages and disadvantages of using Relap5 (Cilliers, 2012).

Advantages	Disadvantages
INL support. Large amounts of knowledge and experience available. Stable. Accurately model internal flow paths.	Expensive. Complicated user interface and simulation development.

2.2.2 Flownex

Flownex has been developed as a systems computational fluid dynamics (SCFD) network solver. Flownet was initially developed in 1986 based on the Hardy Cross method. In 2001 Flownex was developed as an object orientated version of Flownet (Flownex SE, 2012b). Flownex was validated and verified in the nuclear industry especially for the simulation of the Pebble Bed Modular Reactor (PBMR) and in 2007 the National Nuclear Regulator (NNR) of South Africa found Flownex to be acceptable to support the design and safety case of the PBMR (Flownex SE, 2012a). It was also validated and verified for the use in the simulation of a high temperature gas reactor following the Brayton power conversion cycle using helium as the working fluid (Greyvenstein & Rousseau, 2003). Today it is being used in several industries including the power generation industry and mining industry. The graphical user interface of Flownex is also more intuitive for the end-user than the conventional codes from the 1960s to 1980s, such as Relap5. Table 4 lists the advantages and disadvantages of using Flownex:

Table 4: Advantages and disadvantages of using Flownex (Cilliers, 2012).

Advantages	Disadvantages
Simple formulation. Simple and quick simulation development. Inexpensive, local software. Stable. Approved by the NNR for use in PBMR studies. Real-time solving of transients as a function of CPU speed and simulation complexity.	Not widely used and recognised in the nuclear industry. Limited two-fluid model capabilities.

2.3 The simulation of steam generators

Simulations are seen as a method where computer software is used to model the operation of real world processes, systems or events. It involves creating a computational representation of the underlying theoretical logic that links the components of the simulation together (Davis & Eisenhardt, 2007). These components include but are not limited to pipes, reservoirs, accumulators, valves, separators, pumps and turbines. Geometrical properties can be specified for each component such as the hydraulic

diameter, length, volume, and height. Another aspect that can also be specified is the heat transfer characteristics which will enable the simulation to calculate the heat transferred between the primary and secondary sides of a SG.

For computations of steady state operations, the following boundary conditions can be used together with the temperatures and pressures of the feed water and primary coolant (Green & Hetsroni, 1995):

- The mass flow rate of the primary fluid, $\dot{m}_p$.
- The mass flow rate of the feed water added into the downcomer, $\dot{m}_{fd}$.
- The feed water inlet temperature, T_{fd} .
- The pressure in the steam dome, p_d .
- The height of the water level in the downcomer, h_{WL} .

The results of the thermal-hydraulic analysis should include local conditions such as pressure, temperature, steam quality, void fraction as well as the following parameters (Green & Hetsroni, 1995):

- The circulation ratio which is defined as the ratio of the total mass flow rate through the boiler region and the liquid flow rate recirculated from the separators.
- Steam quality in the boiling region which is calculated by dividing the mass of steam by the total mass of steam and condensate.
- The temperature of the downcomer water at the entry to the tube bundle region.
- The inlet temperature of the primary fluid.
- Heat transferred between the primary loop and secondary loop.

2.3.1 Previous work done on steam generator models

A preliminary modelling assessment was done of a SG found in the Wolf Creek PWR (Preece & Putney, 1993). Relap5/mod3 was used in the study based on calculations from a series of steady-state commissioning tests carried out over a range of load conditions. The data from the commissioning tests was used to assess the primary side and secondary side heat transfer. Attention was given to the effect of reverting to the standard form of the Chen heat transfer correlation in place of the modified form applied in Relap5/mod2. Comparisons between the two versions of the code are also used to show

how the new interphase drag model in Relap5/mod3 affects the calculation of the SG liquid inventory and the void fraction profile in the riser. Like Relap5/mod2, Relap5/mod3 under-predicts SG heat transfer for all load conditions examined. For both versions of the code, the error in calculating the secondary side pressure tends to reduce as the reactor power reduces (Preece & Putney, 1993).

In 1980 a comparison was done between steam generator models using the homogeneous model and the two-fluid model. The model used a finite difference method to solve the equations, and the report concluded that there were significant differences both in local and global flow parameters predicted by the two models (Singhal, et al., 1980). No experimental or operational data was available to compare either model to. Since 1980, there have been significant computer advances which meant that the results of this study may not be applicable anymore today, but it does offer an explanation that there will be visible differences in the parameters predicted by the two models.

In 1982 a two-phase flow model was developed using first principles of the one-dimensional conservation equations of mass, momentum and energy. The secondary side of the SG was divided into four sections which included the tube bundle region, the unheated riser region above the tube bundle, the saturated region of the downcomer and the sub-cooled region of the downcomer. The mass and energy conservation equations were integrated over the four sections to eliminate the space derivative. This resulted in a set of coupled, nonlinear ordinary differential equations in time. The primary side was divided into three sections namely the inlet plenum, the outlet plenum and the volume within the tubes of the tube bundle. The model was validated over a wide range of steady-state data as well as transient scenarios such as turbine trips and full length control rod drop tests. It concluded that real time execution of the model is achievable and that the model corresponds to the measured steady-state data. It was also noted that the secondary side pressure of the SG is quite sensitive to the accuracy of the inputs given to the model and that feed water- and steam flow as boundary conditions are preferable when simulating a SG. It was recommended that the model be extended to simulate lower power output levels and that the use of other boundary conditions should be investigated. (Strohmayer, 1982)

Another study was done to compare the homogeneous model for two-phase flow with the two-fluid model when applied to a SG for a typical PWR. The models were validated by

using 100%, 80% and 60% power output plant data from Eskom's Koeberg NPP. It was found that the overall heat transfer predicted with the Relap5 two-fluid model was within 1.5% of the measured data from the Koeberg plant. The results generated by the Flownex homogeneous model for the overall heat transfer were within 4.5% of the measured values (Cilliers, 2012). 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 and at the bottom tube sheet of the SG. The under prediction of the heat transfer coefficients of the Flownex model was due to the custom script that was used in Flownex to use the Chen correlation exclusively throughout the length of the U-tubes of the SG. This was done to try and improve the accuracy of the Flownex model.

It was concluded by the study 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 SG at the normal operating conditions (Cilliers, 2012). Significant differences do however occur in lower regions of the boiler where the quality is also lower. It was recommended that smaller increments be used at the beginning and end of the SG U-tubes as well as to try and improve the custom script to use different heat transfer correlations for different boiling regimes along the U-tubes (Cilliers, 2012).

2.4 Summary

A lot of research is available as well as simulation methodologies that can be used by utilities to simulate the SG to improve its performance and availability. Some models are accurate, but time consuming and difficult to implement whereas simpler models were also found to give acceptable results for certain scenarios (Cilliers, 2012).

There are also numerous simulation packages available, as mentioned in section 1.1.2, that can be used to simulate the SG with different levels of accuracy. Relap5 has been validated and are accepted globally for its use in simulating the primary loop of a NPP. Other simulation packages are entering the nuclear simulation environment and studies on the use of these simulation packages are increasing.

The following chapters will explore the use of Relap5 together with Flownex to simulate the SG.

Basis of the model

Relap5/mod4.0 and Flownex were chosen as the software packages that will be used to develop the model. Relap5 was chosen due to it being able to simulate a SG using the two-fluid model or the homogeneous model. Its complex matrix of heat transfer correlations can be used to calculate the respective heat transfer coefficients at different boiling stages in the SG.

Flownex was chosen because it can couple with Relap5 as well as its ability to solve the complete secondary loop with all the components available in its library. Flownex's ability to couple with Relap5 makes it possible for Flownex to use Relap5's accurate calculations of the heat transfer coefficients for the different boiling regimes. Flownex can also be used to expand the secondary loop to include the rest of the components for a better overall system analysis.

For this study, the steam generator that was modelled is a Westinghouse Type 51B U-tube SG.

3.1 Data for Koeberg Nuclear Power Station

Koeberg NPP is currently the only nuclear power plant in South Africa. Both reactors have been in operation since 1985. The raw data was obtained from both units over a time period of 10 years, collected from specific points throughout the plant, and captured once per day. The data points consists of tables with values for the primary inlet and outlet temperatures of the SG, the pressure in the steam drum, the feed water pressure and temperature, the feed water and steam flow rates and the active power of the generator. There are null and erroneous values scattered throughout the data as well as data for certain weeks when the reactor was being ramped up or ramped down. It was decided that only the 100%, 80% and 60% power outputs will be used as steady-state scenarios to evaluate the models, as sufficient data is available.

A statistical analysis was done by Cilliers (2012) on the Koeberg data. The important parameters that were investigated include the mean value of each parameter and its

corresponding confidence level at 95%. The confidence level can be explained with the following example:

With a mean value of 4911.1929kPa for the SG drum pressure at 100% power output and a confidence level, at 95%, of 2.4331, the mean value of the SG drum pressure is read as $\mu = 4911.1929 \pm 2.4331$. It means that 95% of all the data points of the SG drum pressure at 100% power output falls within the range 4911.1929 ± 2.4331 kPa. The maximum uncertainty of the SG drum pressure is thus 0.05% of the mean. The three power level's statistical analysis results will be discussed below. A more comprehensive analysis is available in the report written by Cilliers (2012).

For the 100% power output a total of 763 data points were analysed by Cilliers (2012). A maximum uncertainty in the confidence level was noted for the steam flow rate at 0.25% of the mean.

For the 80% power output a total of 126 data points were analysed by Cilliers (2012). A maximum uncertainty in the confidence level was noted for the feed water pressure at 2.8% of the mean.

For the 60% power output a total of 97 data points were analysed by Cilliers (2012). The maximum uncertainty was experienced to be the feed water pressure again with a maximum uncertainty of 2.8%.

The relevant primary side conditions for the model wasn't available in the form as required for inputs in the respective models. Engineering Equation Solver (EES) was used to perform a preliminary calculation to determine the primary side boundary conditions that was needed for the steady-state model (Cilliers, 2012).

3.2 Steam generator geometry

Figure 8 shows the general geometry of the original steam generators installed at Koeberg NPP. It includes the upper internals such as the geometry of the dryers and separators. The geometry of the U-tubes is also included which is important for the development of the model. An equivalent heat transfer surface area of $4\,699\text{m}^2$ is used for a total of 3 330 tubes. The inner and outer diameters as well as the square pitch of the tubes are given. The length of the SG, the spherical radius of the inlet plenums and the outside diameters of the lower and upper SG shell can also be obtained from Figure 8 .

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 (Cilliers, 2012).

The simplified cross-section of the primary inlet plenum was modelled as a cylinder, of the same radius as the spherical radius specified in the documents. The boiling region consists of the primary tubes and the channels between the tubes for the secondary flow.

The geometry of the riser consists mostly of the downcomer region that allows for recirculating flow. The flow areas for the separator stage consist of the three centrifugal separator cylinders that move vertically up through the upper shell of the SG.

The dryer stage was not modelled as custom flow resistances were added to the separator components to increase stability of the solution (RELAP5, 2001b). The dryers 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.

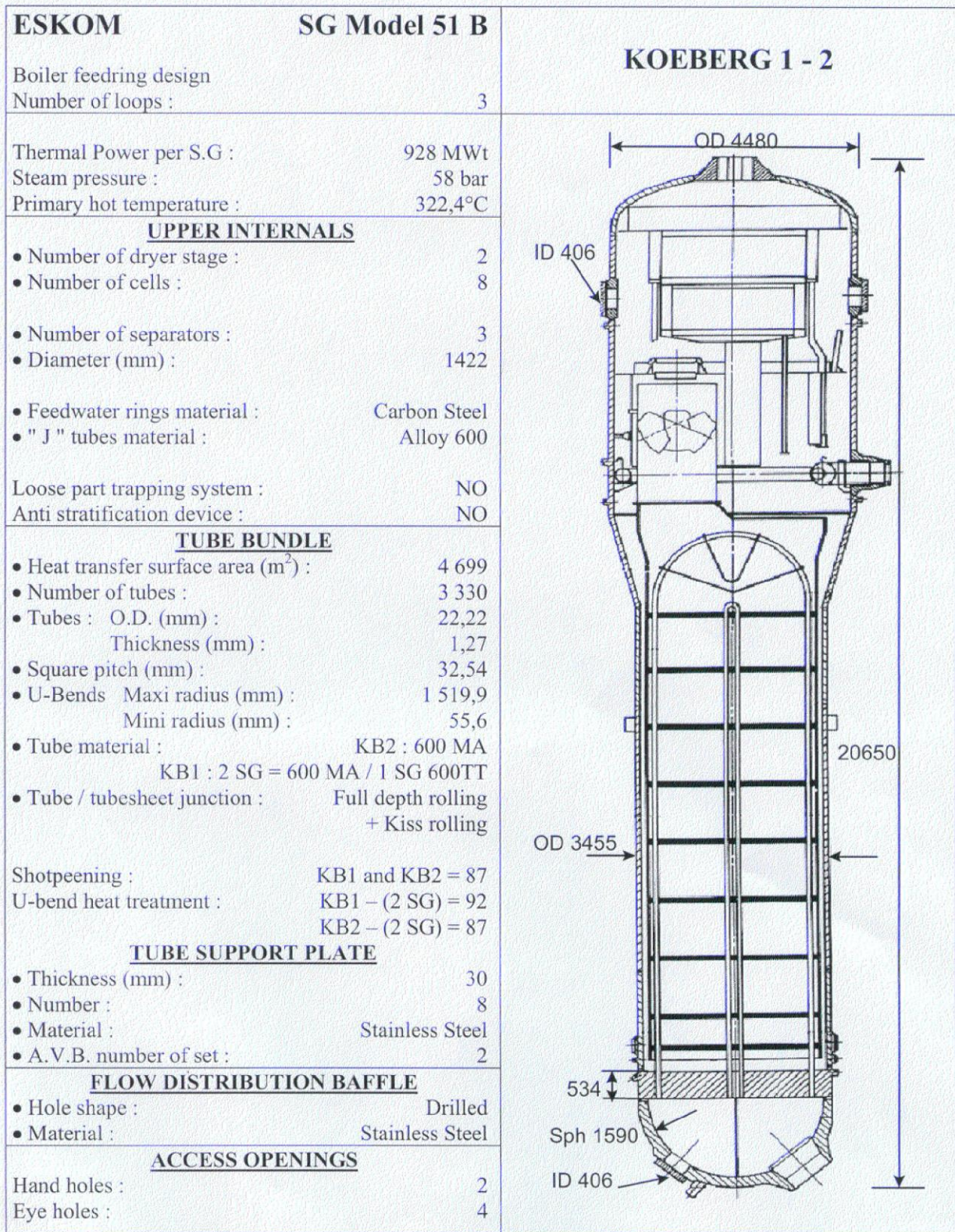


Figure 8: Geometry of the steam generator (ESKOM, 2004).

3.3 Model geometry and heat structure input

The volumetric inputs for the primary loop and secondary loop of the steam generator model are shown in Table 5. The inputs include the element length (L), element volume (V), flow area (FA), hydraulic diameter (D_h), inclination (inc.) and circumference (Circum.) used for the components in the steam generator model.

Table 5: Volumetric inputs for the steam generator.

Primary side components								
Component	Flownex	No. of vol.	L (m)	Dh (m)	Circum. (m)	FA (m²)	V (m³)	Inc (°)
Primary inlet volume	P-101	1	-			0.518		90
Primary inlet header	P-103	1	1.063			3.996	4.249	90
U-tube-1	P-110-1	14	4.564	0.01968	815.965	1.013	11.56	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		13.69					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		4.564					-90
U-tube-10	P-110-10							-90
U-tube-11	P-110-11							-90
U-tube-12	P-110-12							-90
U-tube-13	P-110-13							-90
U-tube-14	P-110-14							-90
Primary outlet header	P-106	1	1.063			3.996	4.249	-90
Primary outlet volume	P-108	1	-			0.785	-	-90
Secondary side components								
Component	Flownex	No. of vol.	L (m)	Dh (m)	Circum. (m)	FA (m²)	V (m³)	Inc (°)
Feed water inlet volume	S-201	1	-			-	-	0
Feed water inlet pipe	S-203	1	3.000			0.518	1.554	0
Feed water branch	S-225	1						-90
Down comer annulus	S-214	5	11.412			0.682	7.781	-90
Heated riser region 1	S-215-1	7	4.564	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		6.846					
Heated riser region 6	S-215-6							
Heated riser region 7	S-215-7							
Unheated riser region	S-216	1	0.833			14.739	12.280	90
Seperator riser	S-221	1	2.058			4.764	9.803	90
Dryer risers	S-222	1	2.058			15.763	32.433	90
Reflux down comers	S-224	1	2.058			10.999	22.630	-90
Steam dome	S-250	1	1.627			15.763	25.647	90
Steam outlet volume	S-260	1	-			-	-	90

The composite heat transfer element inputs for Flownex are shown in Table 6 which include the left surface area (Left SA), the right surface area (Right SA), the length of the element (L), the amount of mesh points used, the thickness of the pipe wall and the length of the discretization of the tube wall (dx). The primary loop tube geometry is that of the heat structure. The material of the heat structure geometry is specified as stainless steel in both Flownex and Relap5.

Table 6: Heat structure inputs for the steam generator.

Heat structure								
Component	From	To	Left SA (m ²)	Right SA (m ²)	L (m)	Mesh points	dx (m)	Thickness (m)
U-tubes	P-125	S-225	4699	5305	22.8	5	0.0003175	0.00127

The increments at the beginning and end of the U-tube bundle as well as at the beginning of the boiling region of the SG were increased as per the recommendations of Cilliers (2012). The addition of more increments in both Flownex models will enable better analysis of the region where the vapour quality is of interest (Cilliers, 2012).

The Flownex models has the suggested additional increments (Figure 9) where the Relap5 homogeneous model doesn't (Figure 10). This is to enable a visual comparison to determine what is the effect of the additional increments. The vapour quality graphs (Figure 21, Figure 22 and Figure 23) in the next chapter will illustrate the difference in adding more increments in the beginning and end of the U-tube bundle.

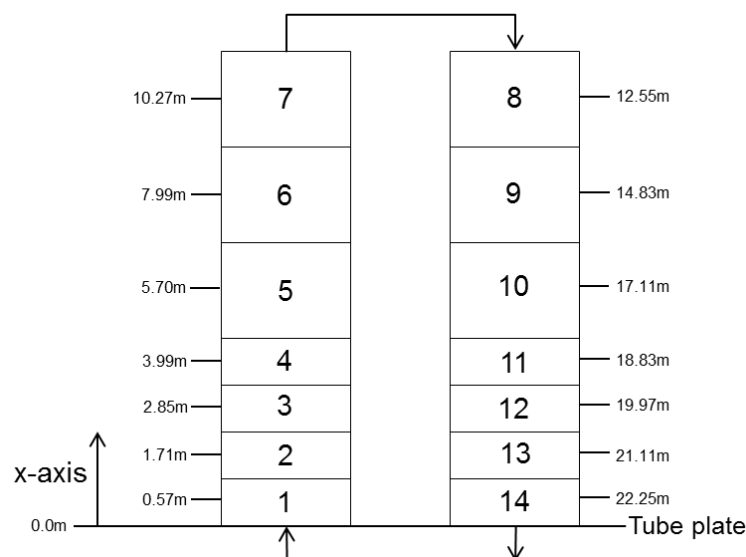


Figure 9: Flownex increment distribution along the U-tube.

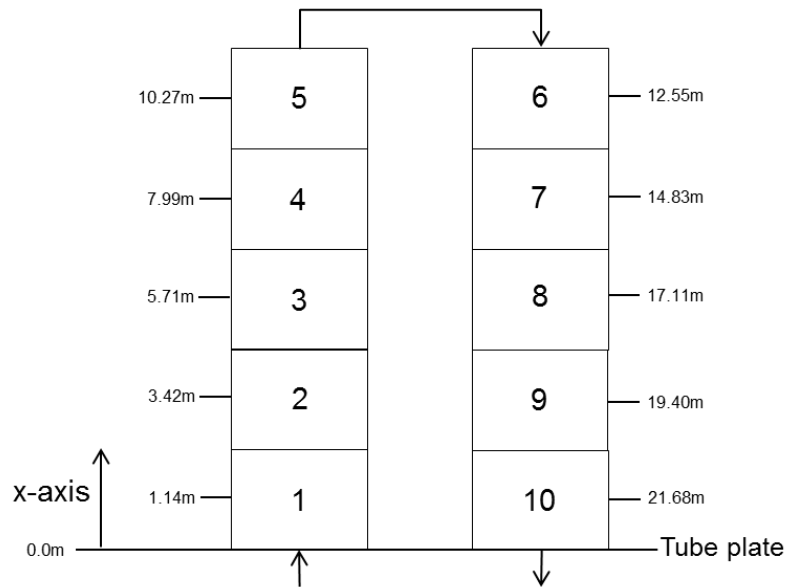


Figure 10: Relap5-homogeneous model increment distribution along the U-tube.

3.4 Model development

The Relap5 code developed for the model is given in Annexure A.1. The Relap5 homogeneous model was used from a previous study (Cilliers, 2012) and the discussion on the development of the model does not form part of the scope of this study. The Relap5 homogeneous model will only be used for comparison purposes to compare the accuracy of the results calculated by the developed Flownex models. The following sections describe how Flownex interfaces with Relap5 as well as how the composite heat transfer element calculates the heat transfer in the Flownex models.

3.4.1 Heat transfer calculations

The composite heat transfer element is used to model heat transfer in a solid structure in Flownex. The heat transfer element is able to model conduction, convection and radiation. Only the conduction and convection capabilities will be used in the Flownex models developed in this study. The validity of the composite heat transfer element is subject to the following (Flownex SE, 2015b):

- The convective heat transfer is constant throughout an element such as a pipe element.
- The temperature distribution in a solid per increment is linear.

- The conduction resistances are calculated using the relation for a plane wall.

Figure 11 and Figure 12 show a typical heat transfer path of a composite heat transfer element where only conduction and convection are considered.

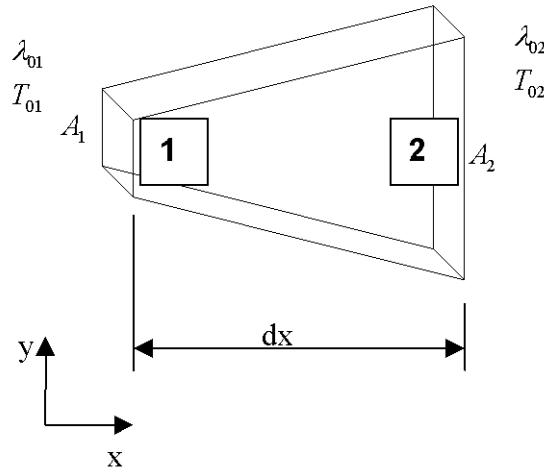


Figure 11: Schematic of a typical heat transfer element with conduction and convection (Flownex SE, 2015b).

The subscripts one and two refer to the upstream and downstream sides of the composite heat transfer element respectively. λ_0 is the surface heat transfer convection coefficient, T_0 is the ambient temperature and dx is the length or thickness of the composite heat transfer element in the x direction.

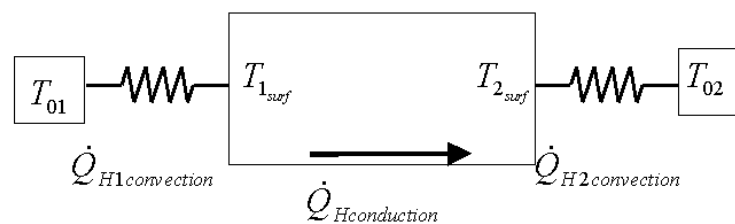


Figure 12: Thermal resistive circuit of the heat transfer path for conduction and convection (Flownex SE, 2015b).

The following equations describe the thermal resistive circuit of the heat transfer as seen in Figure 12 (Flownex SE, 2015b):

$$\dot{Q}_{H1convection} = \lambda_{01} A_1 (T_{01} - T_{1surface}) \quad [1]$$

$$\dot{Q}_{Hconduction} = \frac{k_x A}{dx} (T_{1surface} - T_{2surface}) \quad [2]$$

$$\dot{Q}_{H2convection} = \lambda_{02} A_2 (T_{2surface} - T_{02}) \quad [3]$$

where $A = \frac{A_1 + A_2}{2}$, k_x is the conduction coefficient and $T_{surface}$ is the surface temperature. The area, A needs to be specified by the user or Flownex can use the area of the elements connected to the composite heat transfer element. Flownex relates the area specified to a flat surface in order to use equation [2]. $\dot{Q}_H$ is the heat transfer and the conservation of energy requires that:

$$\dot{Q}_{H1convection} = \dot{Q}_{Hconduction} = \dot{Q}_{H2convection} \quad [4]$$

Equations [1] to [4] can be rearranged to give:

$$\dot{Q}_{Htotal} = \frac{(T_{01} - T_{02})}{\frac{1}{\lambda_{01} A_1} + \frac{dx}{k_x A} + \frac{1}{\lambda_{02} A_2}} \quad [5]$$

Equation [5] is commonly known as the thermal resistance equation. (Flownex SE, 2015b) Flownex gives the user the ability to specify fixed values for λ_{01} and λ_{02} or the user can also specify that these values must be calculated using the built-in heat transfer correlations available to Flownex as discussed in section 2.1.1. One of the correlations that Flownex will use in the two-phase part of the SG simulation is the Chen correlation.

The Chen correlation is given as (Leeb, 2015):

$$h_{TP} = Fh_c + Sh_{NB} \quad [6]$$

The convection heat transfer coefficient h_c is calculated with the liquid Reynolds number. The variables h_c and the nucleate boiling heat transfer coefficient h_{NB} are calculated using the following equations:

$$h_c = 0.023 \left(\frac{k_L}{D} \right) \left(\frac{G(1-x)D}{\mu_L} \right)^{0.8} \left(\frac{c_{pL}\mu_L}{k_L} \right)^{0.4} \quad [7]$$

$$h_{NB} = 0.0012 \left[\frac{k_L^{0.79} c_{pL}^{0.45} \rho_L^{0.49}}{\sigma^{0.5} \mu_L^{0.29} H_{fg}^{0.24} \rho_G^{0.24}} \right] \Delta T_{sat}^{0.24} \Delta p_{sat}^{0.75} \quad [8]$$

where $\Delta T_{sat} = T_{wall} - T_{sat}$ and $\Delta p_{sat} = p(T_{wall}) - p(T_{sat})$. The two-phase convection multiplier is given as:

$$F = \begin{cases} 1 & ; X_{tt} \geq 10 \\ 2.35 \left(\frac{1}{X_{tt}} + 0.213 \right)^{0.736} & ; X_{tt} \leq 10 \end{cases} \quad [9]$$

The Martinelli parameter is given as:

$$X_{tt} = \left(\frac{1-x}{x} \right)^{0.9} \left(\frac{\rho_G}{\rho_L} \right)^{0.5} \left(\frac{\mu_L}{\mu_G} \right)^{0.1} \quad [10]$$

The boiling suppression factor is given as:

$$S = \frac{1}{1 + 2.53 \times 10^{-6} \text{Re}_{TP}^{1.17}} \quad [11]$$

And the two-phase Reynolds number calculated from:

$$\text{Re}_{TP} = \frac{G(1-x)D}{\mu_L} F^{1.25} \quad [12]$$

Collier (1972) suggested that the Chen correlation can be applied to the sub-cooled region as well. F is then set to unity and S is evaluated at $x=0$. When the correlation is applied to the sub-cooled region, it is written as (Leeb, 2015):

$$q''_{TP} = h_{NB} S (T_{wall} - T_{sat}) + h_c F (T_{wall} - T_{fluid}) \quad [13]$$

The Chen correlation discussed above is valid for:

$$p < 7\text{MPa}$$

$$x < 0.7$$

$$60 < G < 500\text{kg} / \text{m}^2\text{s}$$

As discussed in section 2.1.1 the above correlation is used by Flownex for the saturated and sub-cooled boiling.

3.4.2 Flownex model development

The nodalization of the Flownex model is shown in Figure 13. The volume elements mostly consist of pipe volumes, composite heat structure elements and Relap5 simulation elements. The separator was modelled with a two-phase tank which behaves ideally by removing all steam and returning all liquid into the stream of condensate entering the steam generator.

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, 2001b). The flow losses were adjusted 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. Actual recirculation within the SG may vary due to issues experienced in the SG such as tube plugging and leaking. The flow losses were left unchanged when run at 80% and 60% power conditions (RELAP5, 2001b).

The boundary condition elements for the feed water inlet and outlet can be seen at the top and middle left of Figure 13. An inverted U-tube can be seen in the middle of Figure 13 with the boundary condition elements for the inlet and outlet of the U-tubes of the SG situated at the bottom of the figure. The downcomer of the SG can be seen tapping off from the two-phase tank at the top of Figure 13 and flowing downward on the left side of the figure to join the boiling region at the bottom.

Table 7: Flownex elements used in the model.

	Boundary condition
	Node
	Two-phase tank
	Basic pipe
	Composite heat transfer element
	Relap5 element

Table 7 lists all the Flownex elements used in Figure 13. In-depth information of each element is available in the Flownex help files (Flownex SE, 2015a).

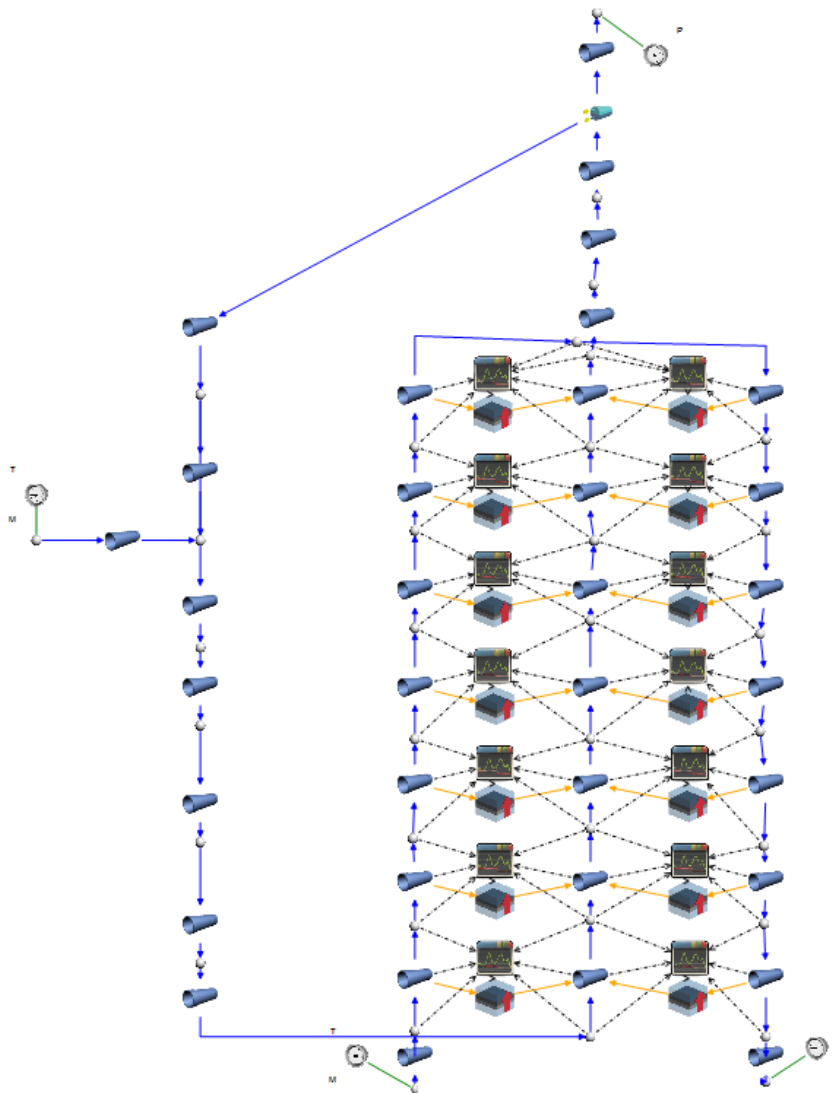


Figure 13: Nodalization of the Flownex steam generator model.

The fourteen pipe increments of the U-tubes each have their own Relap5 element. This is required as each pipe element's convection heat transfer coefficient is calculated independently from the other pipe elements. The Relap5 element receives the necessary boundary conditions from each pipe element in Flownex namely:

- The primary loop inlet node and outlet node pressures and temperatures.
- The secondary loop inlet node and outlet node pressures and temperatures.
- The primary loop pipe increment mass flow rate.
- The secondary loop pipe increment mass flow rate.

The boundary conditions are then used by the Relap5 element in Flownex to create new boundary condition input cards in the Relap5 input file. The input file is used by Relap5 to complete a simulation and generate an output file. The output file is returned to the Relap5 element in Flownex, which extracts the required convection heat transfer coefficient from it. The Flownex composite heat transfer element linked to the Relap5 element receives the convection heat transfer coefficient calculated in Relap5 and uses it to calculate the heat transfer between the two specific pipe segments. This interaction is done iteratively until the model in Flownex converges. Figure 14 is a flow diagram illustrating the methodology explained above.

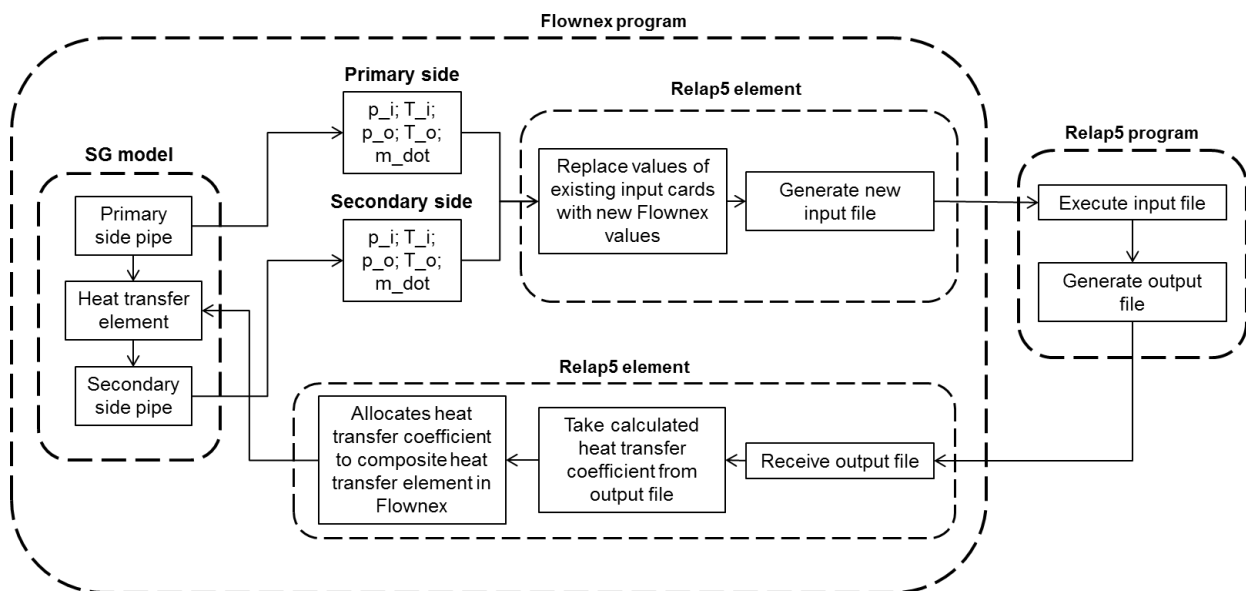


Figure 14: Flownex and Relap5 coupling flow diagram.

The convection heat transfer coefficient that the corresponding heat transfer element receives can either be the primary side convection heat transfer coefficient (FRHCP model) or the secondary side convection heat transfer coefficient (FRHCS model). Flownex then uses the Relap5 calculated convection heat transfer coefficient to solve the model iteratively. Figure 15 visually illustrates the heat transfer in the boiling region in the annulus of the SG by means of a thermal resistive circuit taking into account both legs of the U-tube for the specific increment.

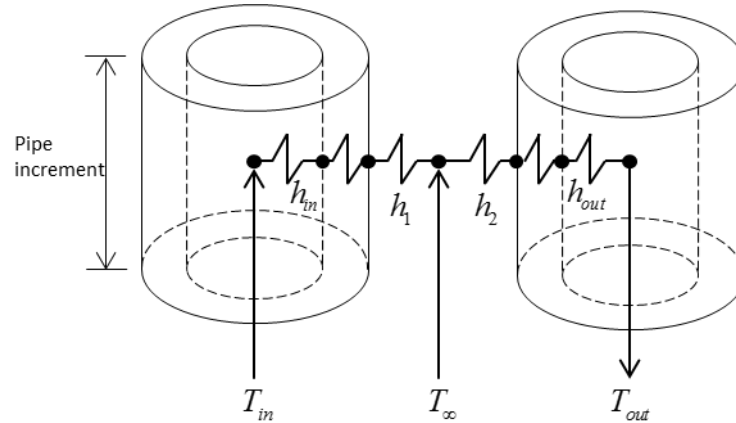


Figure 15: Resistive circuit of the heat transfer processes of one pipe increment in the SG.

The primary loop coolant flows upward in the upward leg of the U-tubes and then returns with the downward leg of the U-tubes. The secondary loop feed water flows upward in the boiling region of the SG annulus. In Figure 15 the upward pipe section of the U-tubes are at the left of the picture and the downward section is at the right of the picture. T_{in} is the temperature of the primary loop coolant flowing upwards in the upward leg of the SG. T_{out} is the temperature of the primary loop coolant flowing downward through the downward leg of the SG. T_{∞} is the temperature of the secondary loop feed water flowing upwards through the boiling region of the SG annulus.

The FRHCP model receives the convection heat transfer coefficients h_{in} and h_{out} as seen in Figure 15 from Relap5. It calculates h_1 and h_2 using its built-in heat transfer correlations and solves the thermal resistive circuit iteratively together with the rest of the model. The FRHCS model receives the convection heat transfer coefficients h_1 and h_2 from Relap5 and calculates h_{in} and h_{out} with the use of Flownex's built-in heat transfer

correlations to solve the thermal resistive circuit iteratively together with the rest of the model.

The Flownex model using the Relap5 calculated convection heat transfer coefficient for the primary side of the SG (FRHCP model) is used to determine the accuracy of Flownex's built-in heat transfer correlations for the secondary side of the SG. The primary side convection heat transfer coefficient is calculated in Relap5 and the secondary side convection heat transfer coefficient is calculated with the use of Flownex's built-in two-phase flow correlations (Flownex SE, 2015a).

The Flownex model using the Relap5 calculated convection heat transfer coefficient for the secondary side of the SG (FRHCS model) is used to determine the accuracy of using Relap5's complex matrix of heat transfer correlations when calculating the convection heat transfer coefficient for the different boiling regimes in the SG. The convection heat transfer coefficients on the primary side of the SG will be calculated using Flownex's built-in heat transfer correlations.

It is expected that the results will correspond closely to the plant operating data obtained from Koeberg as well as the results of the Relap5 homogeneous model. The use of the convection heat transfer coefficient calculated in Relap5 addresses recommendations made by Cilliers (2012) with regards to his custom written C# script. The Relap5 calculated heat transfer coefficient will replace the heat transfer coefficient calculated by the custom written script.

3.4.3 Relap5 model development

The nodalization of the Relap5 model is shown in Figure 16. The boundary conditions were represented with time dependant volumes numbered 120 and 130 for the primary side of the SG and 220 and 230 for the secondary side of the SG. The primary side pipe segment is numbered 125 and the secondary side pipe segment is numbered 225.

Separate Relap5 models were developed for the different lengths of pipe elements in Flownex as seen in Table 8, namely 2.282m and 1.141m. The Relap5 models were further modified for a specific direction of flow through the pipes. The first model caters for upward flow in the primary loop section and upward flow in the secondary loop section. The second model caters for downward flow in the primary loop section and upward flow in the secondary loop section. These differences were applied in the heat structure

section of the Relap5 model as well as in the geometry specifications. The coding can be seen in Annexure A.1.

Table 8: Geometry of the four different configurations of the Relap5 model.

	Primary side component	Inc (°)	Secondary side component	Inc (°)	Primary side component	Inc (°)	L (m)
Heated riser region 1	P-110-1	90	S-215-1	90	P-110-14	-90	1.141
Heated riser region 2	P-110-2	90	S-215-2	90	P-110-13	-90	1.141
Heated riser region 3	P-110-3	90	S-215-3	90	P-110-12	-90	1.141
Heated riser region 4	P-110-4	90	S-215-4	90	P-110-11	-90	1.141
Heated riser region 5	P-110-5	90	S-215-5	90	P-110-10	-90	2.282
Heated riser region 6	P-110-6	90	S-215-6	90	P-110-9	-90	2.282
Heated riser region 7	P-110-7	90	S-215-7	90	P-110-8	-90	2.282

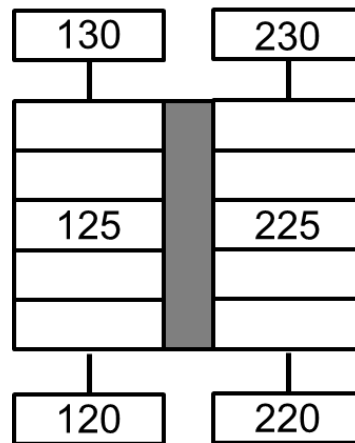


Figure 16: Nodalization of the Relap5 model used by Flownex.

3.4.4 Boundary conditions

The boundary conditions for the different power outputs as used in the two Flownex models and the Relap5 homogeneous model are shown in Table 9, Table 10 and Table 11. The secondary inlet boundary conditions are all in the sub-cooled region. The mass flow rates and temperatures were specified for the inlets of both the primary loop and secondary loop. The outlet pressures were specified for the primary loop and secondary loop. The inlet pressures are irrelevant to the calculation, as the mass-flows are specified. The model calculated the inlet pressures as tabulated in Table 13, Table 14 and Table 15 to be discussed in the next chapter.

Table 9: Boundary conditions at 100% generator power output (Cilliers, 2012).

	$\dot{m}$ (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 10: Boundary conditions at 80% generator power output (Cilliers, 2012).

	$\dot{m}$ (kg/s)	T (°C)	P (MPa)
Primary inlet BC	6051	306	
Primary outlet BC			14.886
Secondary inlet BC	479	210	
Secondary outlet BC			5.023

Table 11: Boundary conditions at 60% generator power output (Cilliers, 2012).

	$\dot{m}$ (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

3.5 Summary

The different models and their development were discussed in this chapter. The development of the two Flownex models was discussed, and how they interact with Relap5. The geometry and boundary conditions that were used in the simulations were also listed.

In chapter 4 the results of the Relap5 homogeneous model and the FRHCP model and FRHCS model will be compared with the plant operating data obtained from Koeberg NPP and the differences will be discussed. The results of the three models will also be compared with the use of graphs.

Results and discussion

The focus of this chapter is to list and discuss the results gained from the simulation models and compare it to the empirical data obtained from Koeberg NPP.

4.1 Comparison with empirical data

The simulation results were validated with the plant operating data obtained from Koeberg NPP. The values from the given plant parameters were used to describe each condition of 100%, 80% and 60% power output (Cilliers, 2012). Table 13, Table 14 and Table 15 shows the results from the Relap5 and two Flownex models as well as the Flownex model using the C# script (FSHCS model). These results are also compared with the Koeberg NPP data and an error percentage is reported for each parameter with reference to the Koeberg NPP data. Table 12 lists the variables that will be compared between the different models and the Koeberg data for the three power level outputs.

Table 12: Variable discussion of the result tables.

Variable	Description
T_{pi}	Temperature of the primary loop inlet coolant
T_{po}	Temperature of the primary loop outlet coolant
P_{so}	Pressure of the steam exiting the SG
P_{si}	Pressure of the feed water entering the SG
T_{si}	Temperature of the feed water entering the SG
x_{so}	Quality of the steam exiting the SG
$\dot{m}_s$	Mass flow of the steam exiting the SG
Q_{boiler}	Total heat transfer from the primary loop to the secondary loop in the boiling region of the SG

4.1.1 100% power output

Table 13 shows the results of the Relap5 homogeneous model and the two Flownex models compared to the Koeberg NPP data at 100% power output.

The largest errors were an under prediction of 6.4%, 5.9% and 5.9% for the SG secondary side inlet pressure calculated by the Relap5 homogeneous model, the FRHCS model and the FRHCP model respectively. The FSHCS model under predicted the secondary inlet pressure by 6.2%. The larger error experienced by the Relap5 homogeneous model is

due to the under prediction of the secondary side convection heat transfer coefficient during phase transitions (Preece & Putney, 1993). This is evident at 80% and 60% power outputs as well.

The 4% error made in the calculation of the heat transferred in the boiling region for the FRHCS model is due to the over-estimation of the convection heat transfer coefficients of the secondary side of the SG at the start of the U-tube length. This can also be seen by the lower outlet temperature of the primary side of 2°C in Table 13. The over prediction will be discussed in more details later on along with Figure 24. The over prediction of 6% of the heat transferred in the boiling region for the FRHCP model can also be attributed to the calculation of the convection heat transfer coefficient on the secondary side of the SG. The under prediction of the heat transferred in the boiling region of the SG of 4.5% by the FSHCS model is due to the exclusive use of the Chen correlation which resulted in an under prediction of the heat transfer coefficient as will be discussed later on along with Figure 24.

Table 13: 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}	$\dot{m}_s$ (kg/s)	Q_{boiler} (MW)
100% Power	Koeberg	312	279	4911	5277	219	1.00	618	1143
	RELAP5 - homogeneous	312	279	4911	4942	219	1.00	618	1131
	Error %	0.0	0.0	0.0	-6.4	0.0	0.0	0.0	-1.0
	FSHCS model	312.0	280.0	4911.0	4951.0	219	1.00	618	1092.0
	Error %	0.0	0.5	0.0	-6.2	0.0	0.0	0.0	-4.5
	FRHCS model	312	277	4911	4964	219	1.00	618	1187
	Error %	0.0	-0.7	0.0	-5.9	0.0	0.0	0.0	3.9
	FRHCP model	312	277	4911	4964	219	1.00	618	1191
	Error %	0.0	-0.7	0.0	-5.9	0.0	0.0	0.0	4.2

4.1.2 80% power output

Table 14 shows the results of the Relap5 homogeneous- and Flownex models compared to the Koeberg NPP data at 80% power output.

The largest errors were an under prediction of 3.1%, 2.9% and 2.9% for the SG secondary side inlet pressure calculated by the Relap5 homogeneous model, the FRHCS model and the FRHCP model respectively. The FSHCS model under predicted the secondary inlet pressure by 3.3%.

The 6.1% error made in the calculation of the heat transferred in the boiling region for the FRHCS model is due to the over-estimation of the convection heat transfer coefficient of the secondary side of the SG at the start of the U-tube length as mentioned in section 4.1.1. The over prediction by 7.7% of the heat transferred in the boiling region for the FRHCP model can also be attributed to the calculation of the convection heat transfer coefficient on the secondary side of the SG. The heat transferred in the boiling region of the SG was under predicted by 1.8% by the FSHCS model.

Table 14: 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}	$\dot{m}_s$ (kg/s)	Q_{boiler} (MW)
80% Power	Koeberg	306	278	5023	5221	210	1.00	479	908
	RELAP5 - homogeneous	306	277	5026	5057	210	1.00	479	916
	Error %	0.0	-0.2	0.1	-3.1	0.0	0.0	0.0	0.9
	FSHCS model	306	278	5023	5049	210	1.00	479	892
	Error %	0.0	0.0	0.0	-3.3	0.0	0.0	0.0	-1.8
	FRHCS model	306	276	5023	5068	210	1.00	479	963
	Error %	0.0	-0.8	0.0	-2.9	0.0	0.0	0.0	6.1
	FRHCP model	306	276	5023	5069	210	1.00	479	963
	Error %	0.0	-0.8	0.0	-2.9	0.0	0.0	0.0	6.1

4.1.3 60% power output

Table 15 shows the results of the Relap5 homogeneous- and Flownex models compared to the Koeberg NPP data at 60% power output.

Table 15: Steady-state validation of the model at 60% output.

		T_{pi} (°C)	T_{po} (°C)	P_{so} (kPa)	P_{si} (kPa)	T_{si} (°C)	x_{so}	$\dot{m}_s$ (kg/s)	Q_{boiler} (MW)
60% Power	Koeberg	294	273	4889	5055	195	1.00	341	670
	RELAP5 - homogeneous	294	273	4892	4892	195	1.00	341	660
	Error %	0.0	-0.1	0.1	-3.2	0.1	0.0	0.0	-1.5
	FSHCS model	294	273	4889	4919	195	1.00	341	666
	Error %	0.0	0.0	0.0	-2.7	0.0	0.0	0.0	-0.6
	FRHCS model	294	271	4889	4930	195	1.00	341	703
	Error %	0.0	-0.6	0.0	-2.5	0.1	0.0	0.0	4.9
	FRHCP model	294	271	4889	4930	195	1.00	341	701
	Error %	0.0	-0.6	0.0	-2.5	0.1	0.0	0.0	4.5

The largest errors were an under prediction of 3.2%, 2.5% and 2.5% for the SG secondary side inlet pressure calculated by the Relap5 homogeneous model, the FRHCS model and the FRHCP model respectively. The FSHCS model under predicted the secondary inlet pressure by 2.7%.

The 4.9% error made in the calculation of the heat transferred in the boiling region for the FRHCS model is due to the over-estimation of the convection heat transfer coefficient of the secondary side of the SG at the start of the U-tube length as mentioned in section 4.1.1. The over prediction by 4.5% of the heat transferred in the boiling region for the FRHCP model can also be attributed to the calculation of the convection heat transfer coefficient on the secondary side of the SG. The FSHCS model under predicted the heat transferred in the boiling region of the SG by 0.6%.

4.1.4 Discussion

The results from the FRHCS model and FRHCP model corresponds closely to the results of the Relap5 model and the Koeberg NPP data. The use of Relap5 to calculate the convection heat transfer coefficient for the secondary side of the SG in the FRHCS model makes it much more accurate when using Relap5's heat transfer correlations instead of its own built-in correlations.

The results from Cilliers (2012) with the use of the custom C# script in the FSHCS model performed better at lower power outputs than the FRHCS- and FRHCP models, but was less accurate at 100% power output. The more accurate results at lower loads can be attributed to the exclusive use of the Chen correlation, but it can be seen that it falls short at higher power outputs. The Relap5 coupling capabilities used in the FRHCP- and FRHCS models are preferable if all power output levels in the simulation needs to be examined as will be seen in the following paragraphs.

4.2 Detailed inter-model comparison

The following paragraphs discuss the results which are graphically shown in this section. The x-axis for the graphs of the temperature of the primary side coolant which flows inside the U-tubes, the heat transfer coefficients for the secondary side of the SG and the secondary side surface temperature of the tubes were taken as the length of the U-tubes of the SG. The x-axis for the graphs of the vapour quality in the boiling region of the annulus of the SG and the velocity of the feed water in the boiling region of the annulus of the SG are taken from the position of the tube sheet up to the top of the U-tube bundle at approximately 10.27m.

Each point on the graphs is the point in the middle of the respective pipe segment as seen in Figure 9 and Figure 10 of Chapter 3. As discussed in section 3.3 the amount of increments used in both Flownex models are more than the increments used in the Relap5 homogenous model and FSHCS model to visually determine the effectiveness of adding more increments at the beginning and end of the U-tubes.

4.2.1 Primary side temperatures

The primary side temperatures calculated for the three models at 100%, 80% and 60% power outputs are shown in Figure 17, Figure 18 and Figure 19 respectively. Primary side temperatures throughout the U-tubes weren't available from the Koeberg data and therefore do not form part of Figure 17, Figure 18 and Figure 19.

The middle of the graph on the horizontal axis represents the top of the U-tube bundle. The left half of the graph represents the upwards portion of the U-tube bundle and the right side represents the downward section.

There are minor differences between the Relap5 homogeneous model, the FRHCS model and the FRHCP model. The FRHCS model under predicted the temperature by 0.3% and the FRHCP model by 0.8%. The under prediction gets smaller for the 80% and 60% power output scenarios as can be seen in Figure 18 and Figure 19. The FSHCS model over predicted the primary coolant temperature with an average of 1.1%. This over prediction also decreases with the lower power output levels.

The FRHCS model has a higher temperature at the upward flow region and a lower temperature than the Relap5 homogeneous model at the downward region. This can be contributed to the over-estimation of the convection heat transfer coefficient at the beginning of the U-tube length and the under-estimation at the end of the U-tube length. The same can be said about the primary side coolant temperature of the FRHCP model. The under-estimation of the convection heat transfer coefficient for the secondary side of the SG will be discussed in more detail in section 4.2.3.

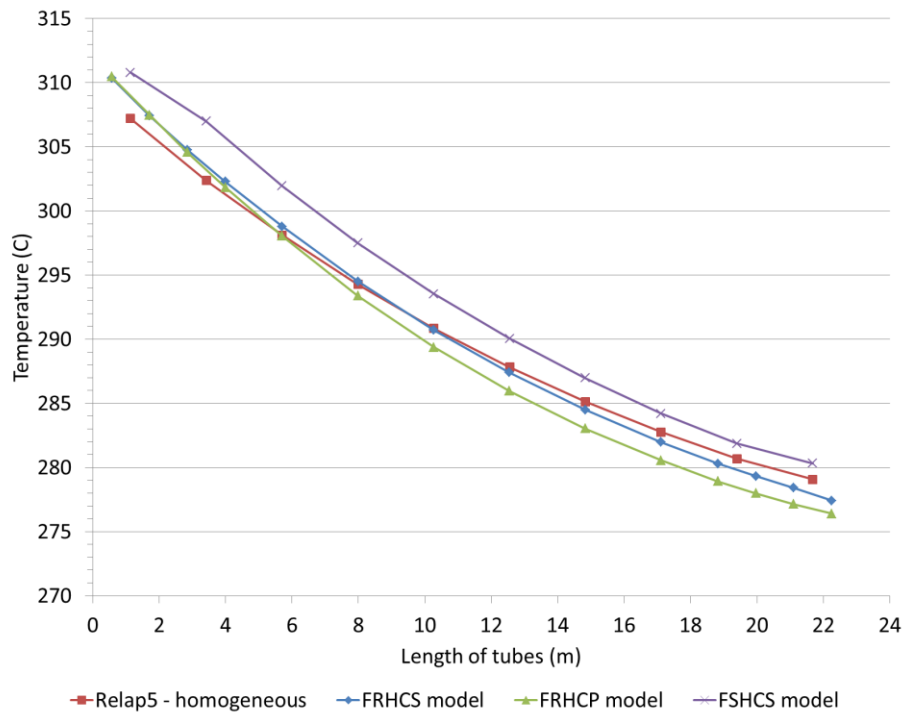


Figure 17: Primary side coolant temperature change at 100% power output.

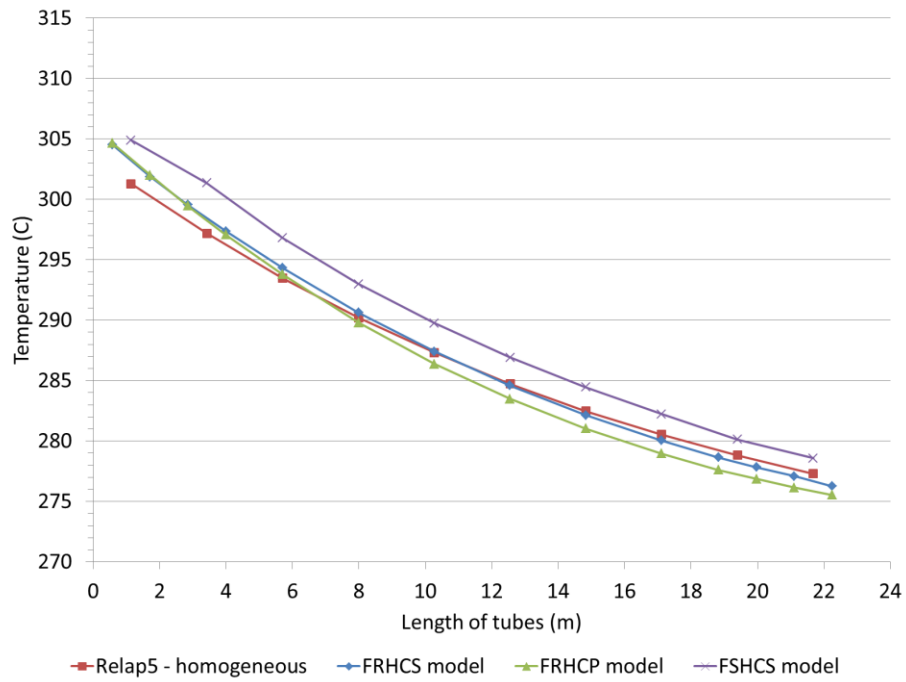


Figure 18: Primary side coolant temperature change at 80% power output.

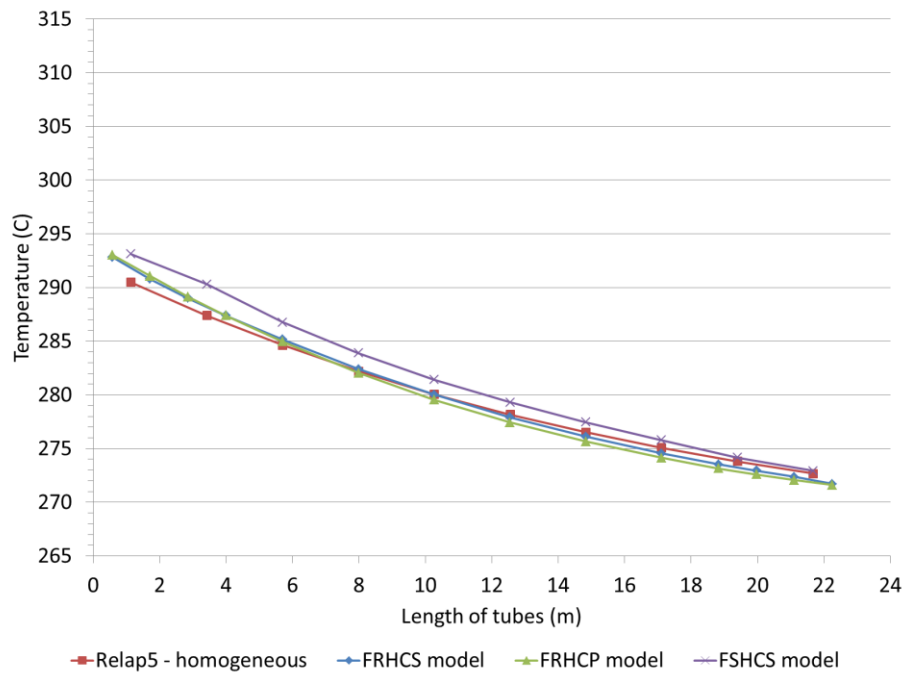


Figure 19: Primary side coolant temperature change at 60% power output.

4.2.2 Vapour quality through the boiler

The vapour quality of the feed water flowing through the boiling region in the annulus of the SG can be seen in Figure 21, Figure 22 and Figure 23 respectively. The thermodynamic quality of the water-steam mixture at the top of the bundle is about 0.17-0.33 when it enters the steam separators (Green & Hetsroni, 1995). More increments were used in the Flownex models compared to the Relap5 homogeneous model. The addition of more increments gives a better picture of how high above the tube plate boiling of the feed water starts. At all power outputs the vapour quality of the FRHCS- and FRHCP models doesn't differ significantly.

The grid dependence of the increments used was tested with the results of the vapour quality through the boiler at 80% power output for the FRHCP model and FRHCS model as can be seen in Figure 20. Literature suggests that 5 increments for the boiling region of the SG is sufficient to model all the important flow parameters (RELAP5, 2001b). However, from Figure 20 it can be seen that for both models, when using 5 increments, the physical distance from the tube plate where boiling commences in the boiling region of the SG cannot be determined. By adding two additional increments at the start of the boiling region the point where boiling starts can be determined more accurately.

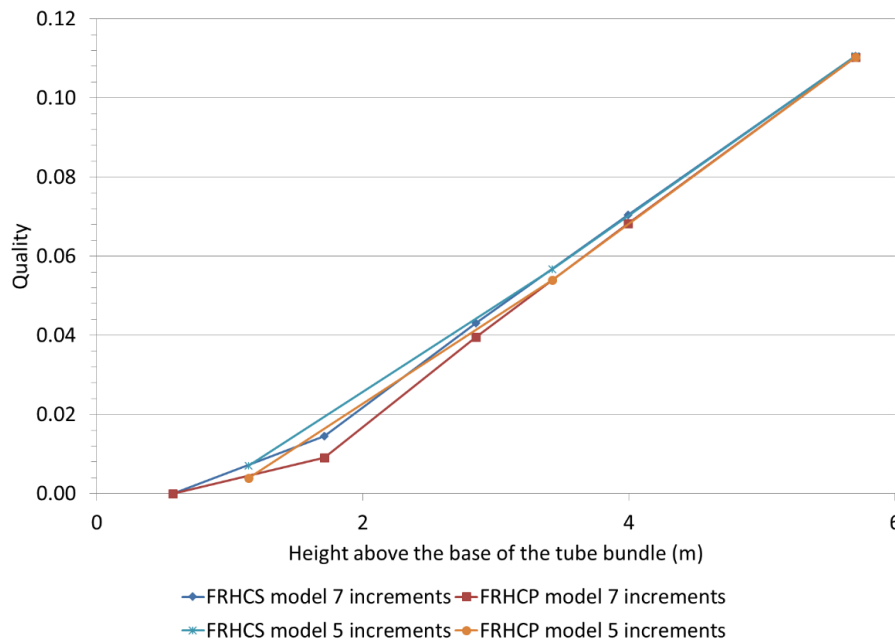


Figure 20: Grid dependence results

It can be concluded that seven increments is the coarsest discretization that gives acceptable accuracy. The addition of the two additional increments at the start of the boiling region does not have a significant impact on the total setup time and solution time of the respective models.

At 100% power output the FRHCS model and FRHCP model under predicted the vapour quality closer to the inlet of the boiling region by approximately 66% and 74% compared to the Relap5 homogeneous model. The FSHCS model under predicted the vapour quality by approximately 100% when compared to the Relap5 homogeneous model. The quality at the top of the U-tubes of the SG is approximately the same for the FRHCS and FRHCP models compared to the Relap5 homogeneous model. At 80% power output the FRHCS and FRHCP models under predicted the vapour qualities closer to the inlet of the boiling region by approximately 66% and 78% compared to the Relap5 homogeneous model. It increases linearly to over predict the vapour quality by 29% and 26% at the top of the U-tube bundle when compared to the Relap5 homogeneous model's calculated vapour quality. This number decreased to approximately 20% for both Flownex models at 60% power output for Figure 23.

At 80% the FSHCS model under predicted the vapour quality closer to the tube sheet by 100% when compared to the Relap5 homogeneous model. At the top of the U-tube

bundle it over predicted the vapour quality by approximately 4.5%. The over prediction of the vapour quality at the top of the U-tube bundle changes to approximately 3.5% for 60% power output.

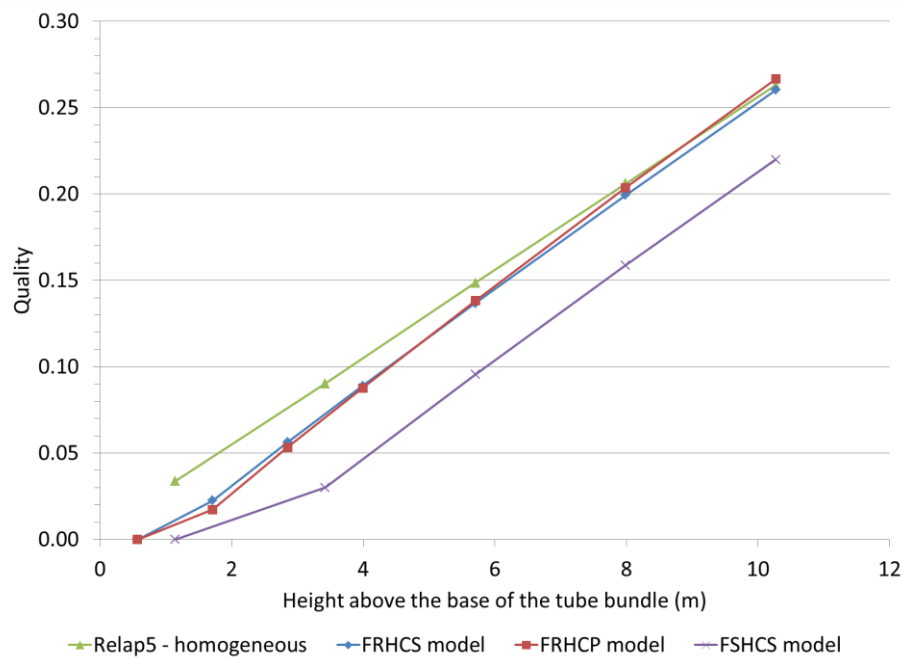


Figure 21: Vapour quality through the boiling region at 100% power output.

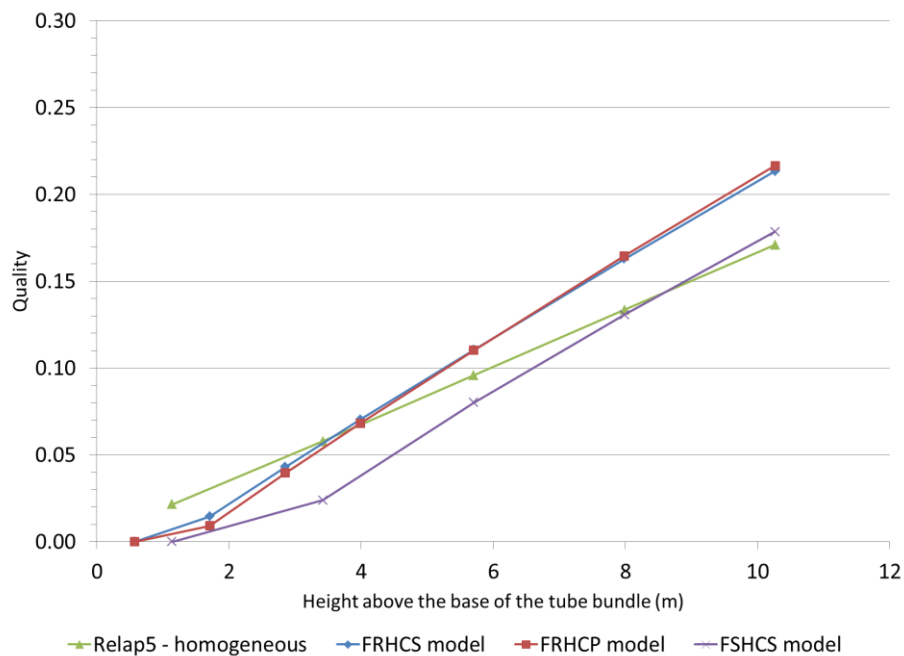


Figure 22: Vapour quality through the boiling region at 80% power output.

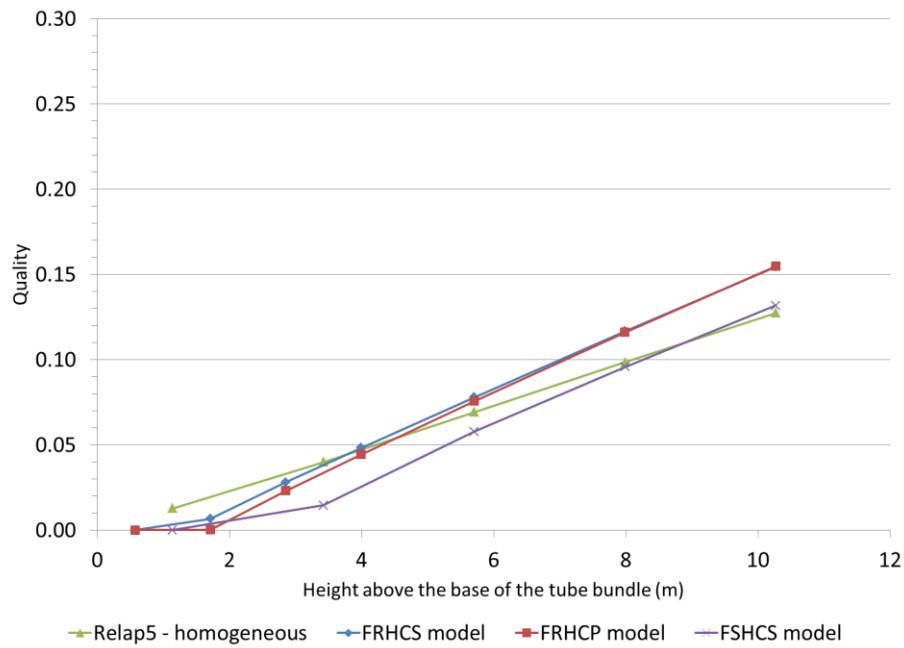


Figure 23: Vapour quality through the boiling region at 60% power output.

The differences in the quality for both Flownex models are due to the changes experienced in the convection heat transfer coefficients on the secondary side of the SG as will be discussed in section 4.2.3. The same can be said for the FSHCS model.

In both the FRHCS and FRHCP models boiling of the feed water already starts approximately 0.57m and 2m above the tube plate. The smaller increments at the beginning of the boiling region make it possible to see approximately where boiling of the feed water starts. The use of large increments in the Relap5 homogeneous model shows that boiling of the feed water already starts in the first pipe segment, yet it is unclear how high above the tube plate the boiling starts. The result of using larger increments in Relap5 is that the simulation misses the effect of the fluid that is sub-cooled for the most part of the pipe increment. The FRHCS and FRHCP models with the smaller increments are able to calculate the state of the fluid more accurately.

From the vapour quality graphs the benefit of adding more increments at the beginning of the boiling region can be justified. It enables the user to determine at what height above the tube plate the feed water starts to boil and enables the models to more accurately calculate the state of the fluid.

4.2.3 Heat transfer coefficient on the secondary side of the SG

The FRHCS model's convection heat transfer coefficients for the secondary side of the SG were calculated using the Relap5 element available in Flownex. Relap5 calculated the convection heat transfer coefficient using a matrix of correlations as described in section 2.2. The FRHCP model used the built-in heat transfer correlations available in Flownex for the calculation of the convection heat transfer coefficient for the secondary side of the SG. A comparison of the results is shown in Figure 24, Figure 25 and Figure 26 for the respective generator power outputs.

The FSHCS model used a custom C# script in Flownex to use the Chen correlation exclusively when calculating the convection heat transfer coefficient on the secondary side of the SG.

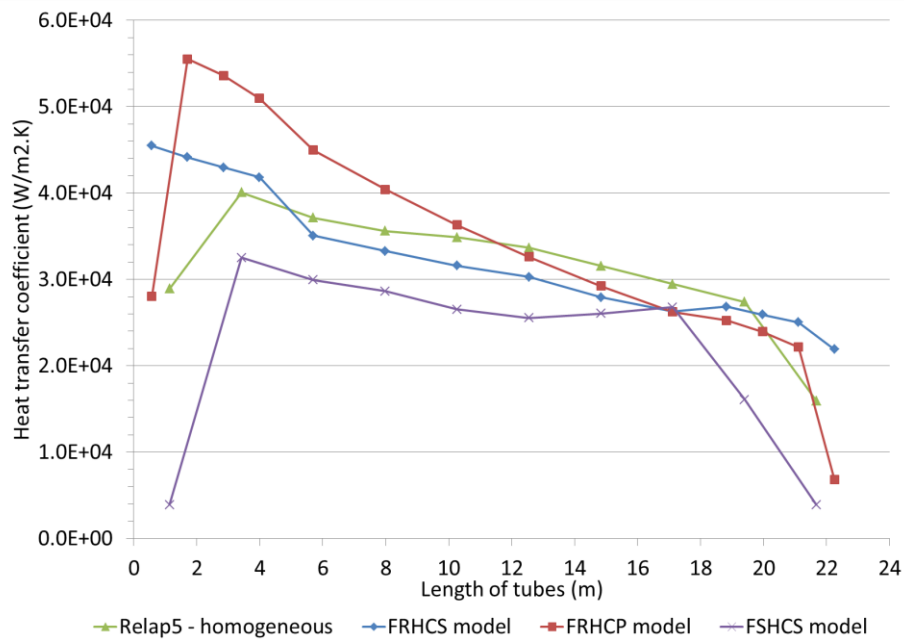


Figure 24: Heat transfer coefficients on the secondary side of the SG at 100% power output.

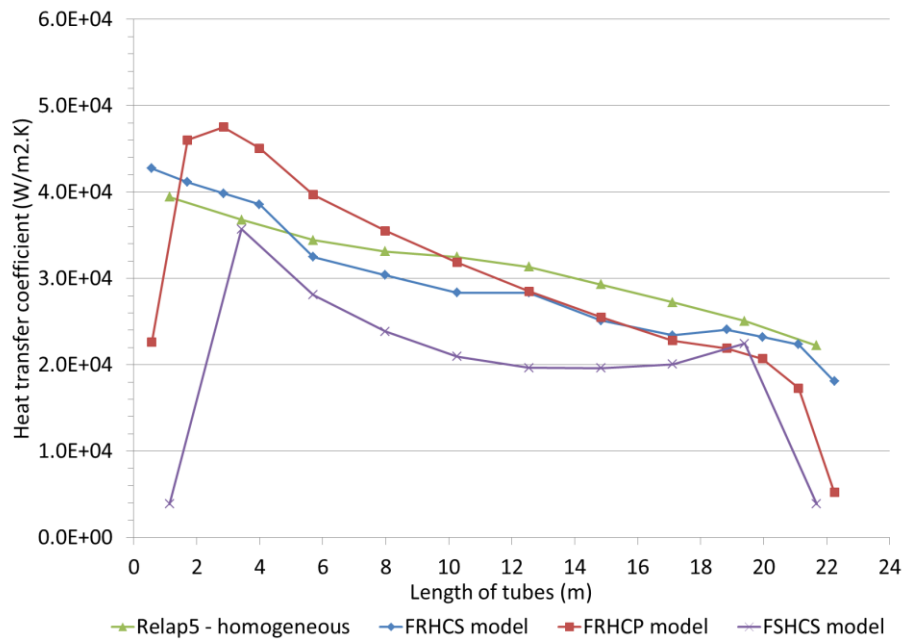


Figure 25: Heat transfer coefficients on the secondary side of the SG at 80% power output.

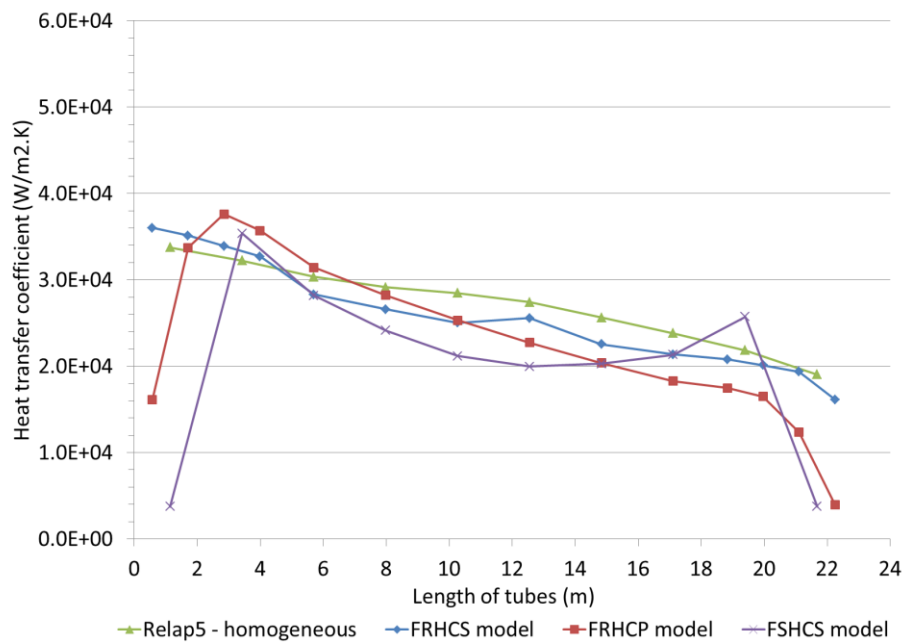


Figure 26: Heat transfer coefficients on the secondary side of the SG 60% power output.

In all three power output scenarios the FRHCS model's convection heat transfer coefficients were calculated lower than the Relap5 homogeneous model for the greater part of the U-tube length. At the inlet the convection heat transfer coefficient of the FRHCS model is higher than the Relap5 model for approximately the first four meters of the U-tubes. The slight increase in the convection heat transfer coefficient of the FRHCS model at the beginning and end of the U-tube length can be attributed to the water level existing in the lowest volumes in the boiling region of the SG because of the lower vapour quality calculated for the FRHCS model compared to the Relap5 homogeneous model. The smaller increments that the FRHCS model used enabled the model to accurately identify which part of the feed water is still sub-cooled. It thus uses the single-phase heat transfer correlations more accurately in the smaller increments together with the two-phase flow heat transfer correlations to calculate a higher heat transfer coefficient for the lower pipe segments of the SG. The bigger increments of the Relap5 homogeneous model, limits the model in identifying exactly where the feed water is still sub-cooled. This causes difficulty in selecting the appropriate heat transfer correlations.

The largest under-estimation by the FRHCS model compared to the Relap5 homogeneous model is approximately 10% at 100% power output, 14% at 80% power output and 15% at 60% power output. The difference that exists in the heat transfer coefficients of the FRHCS model and the Relap5 homogeneous model can be attributed to the boundary conditions of each pipe volume that Flownex gives Relap5 to calculate the heat transfer coefficients with. The pressure loss and temperature loss/gain over each pipe volume is calculated in Flownex and then given to Relap5, which can be different from the pressures and temperatures used in the Relap5 homogeneous model.

The FRHCP model's over-estimation of the convection heat transfer coefficients at the beginning of the U-tubes and the under-estimation for the rest of the length of the U-tubes can be attributed to Flownex's two-phase heat transfer correlations which are not as advanced as the matrix of heat transfer correlations that Relap5 uses. The FRHCP model also estimated that the feed water is sub-cooled for longer and used the single-phase heat transfer correlations at the start of the U-tube length.

The FSHCS model's convection heat transfer coefficient predictions suffered due to the exclusive use of the Chen correlation to determine the convection heat transfer coefficient

for the secondary side of the SG. Cilliers (2012) concluded that the Chen correlation script needs to be improved in order to calculate the heat transfer coefficients more accurately.

4.2.4 Flow velocity through the boiling region

The flow velocities of the homogeneous feed water through the boiling region for the different power outputs of the generator are shown in Figure 27, Figure 28 and Figure 29.

The difference between the flow velocities of the FRHCP and FRHCS models are negligible at 100% and 60% power output. The FRHCP model under predicted the flow velocity by an average of approximately 3% when compared to the FRHCS model.

The difference between the flow velocities of the FRHCS model and the Relap5 homogeneous model is the largest for 100% power output with an average over prediction of approximately 19% when compared to the Relap5 homogeneous model. The difference between these two models decreased with lower power output levels to an error of 18% for 80% power output and 14% for 60% power output. The difference between the two models can be attributed to the difference in vapour quality in the boiling region of the SG (Figure 21, Figure 22 and Figure 23) for the respective models.

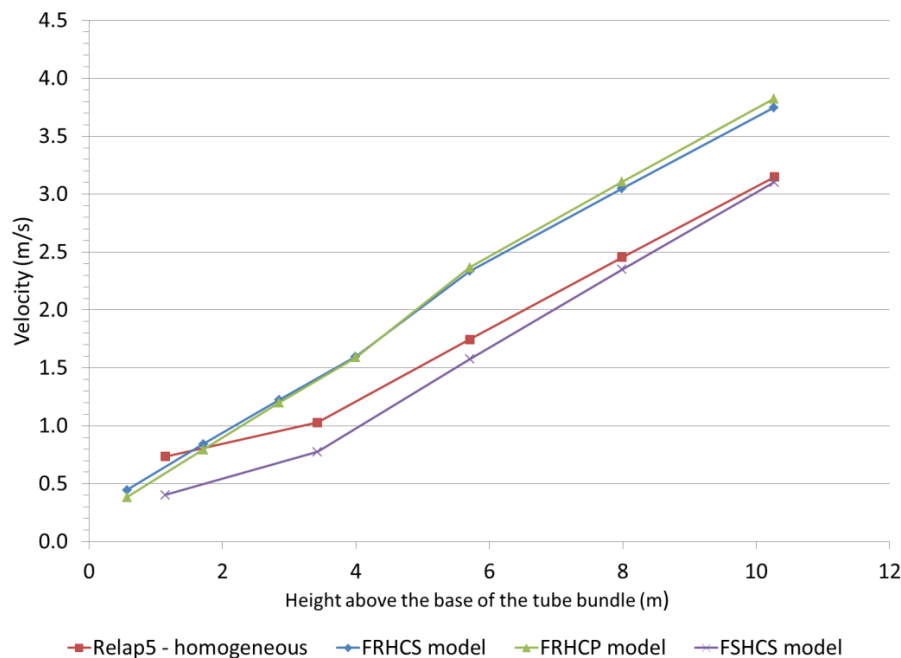


Figure 27: Flow velocity through the boiling region at 100% power output.

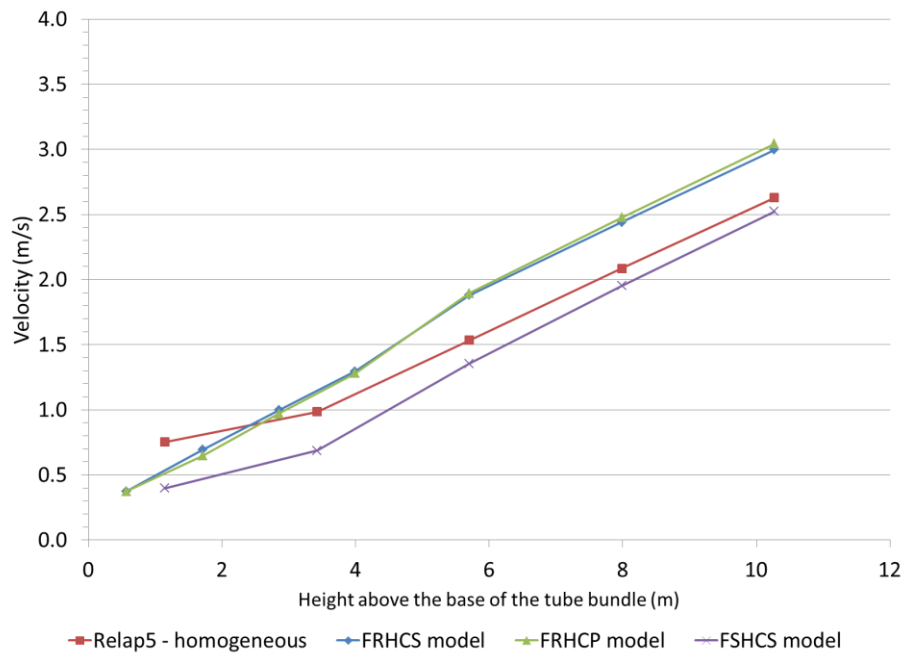


Figure 28: Flow velocity through the boiling region at 80% power output.

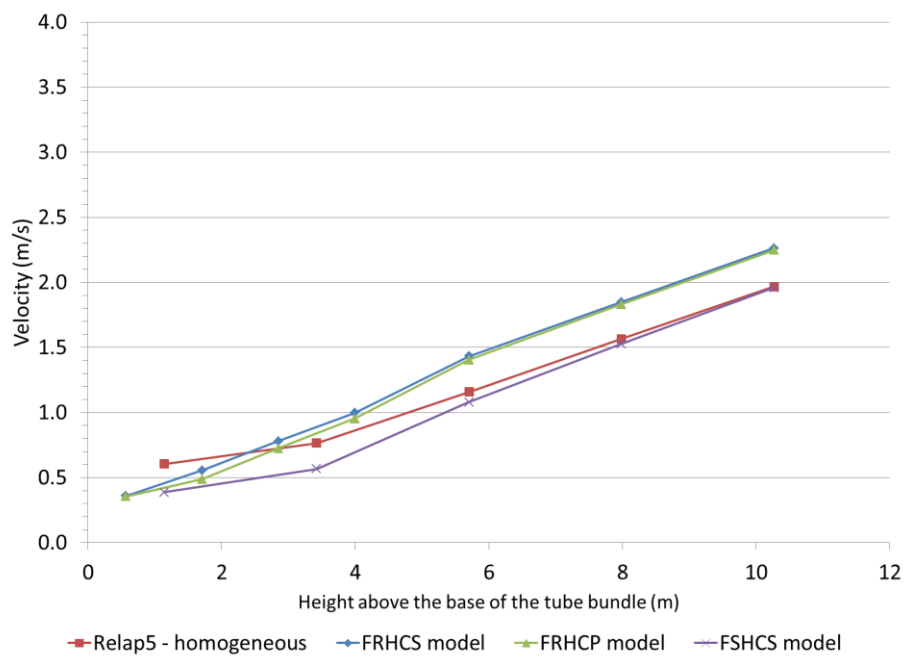


Figure 29: Flow velocity through the boiling region at 60% power output.

The FSHCS model over predicted the feed water flow velocity by approximately 5.2% at 100% power output, 7.4% at 80% power output and 3.2% at 60% power output.

4.2.5 Tube surface temperature on the secondary side of the SG

The surface temperature of the tubes on the secondary side of the SG is shown for different power outputs in Figure 30, Figure 31 and Figure 32.

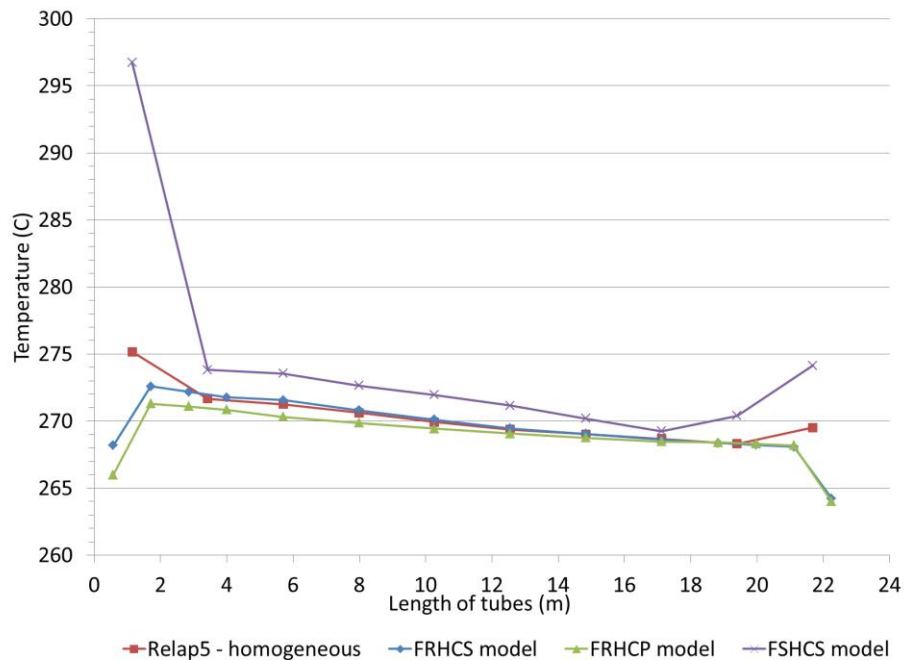


Figure 30: Tube surface temperature of the SG at 100% power output.

The maximum under prediction of the FRHCS model compared to the Relap5 homogeneous model occurs at the ends of the U-tube. The under prediction was on average 1.5% at 100% power output, 0.6% at 80% power output and 0.7% at 60% power output. The under prediction of the FRHCP model when compared to the Relap5 homogeneous model is also evident at the ends of the U-tubes with an average of 1.9% at 100% power output, 0.8% at 80% power output and 0.6% at 60% power output. The FSHCS model over predicted the tube surface temperature of the SG at the ends of the U-tube by 4.8% at 100% power output, 4% at 80% power output and 3% at 60% power output. The errors experienced by the FRHCP and FRHCS models can be attributed to the lower quality calculated by both Flownex models when compared to the Relap5 homogenous model (section 4.2.2).

Over the remainder of the tube surface the FRHCP, FRHCS and FSHCS models follow the trend of their respective convection heat transfer coefficients.

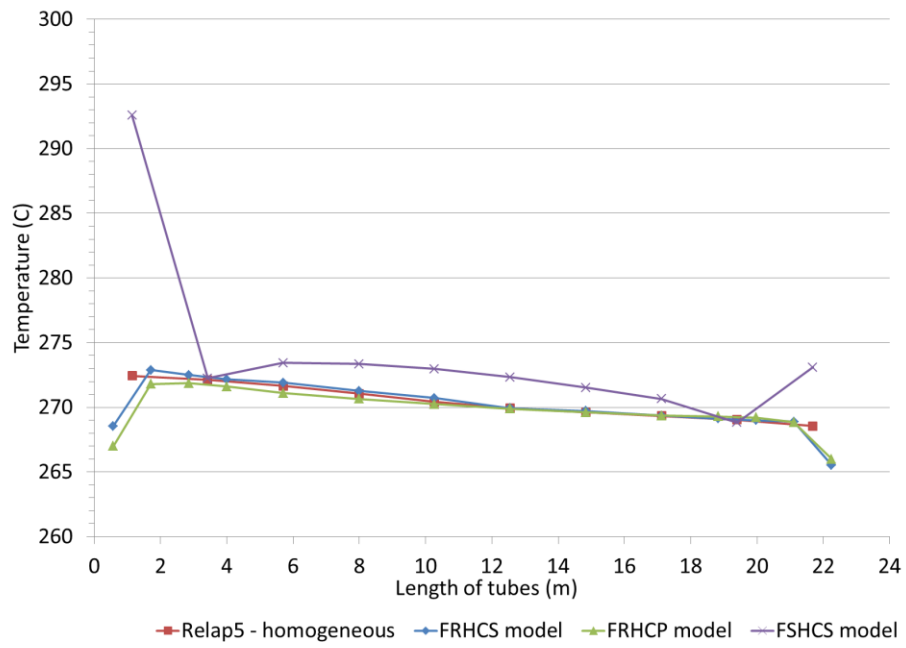


Figure 31: Tube surface temperature of the SG at 80% power output.

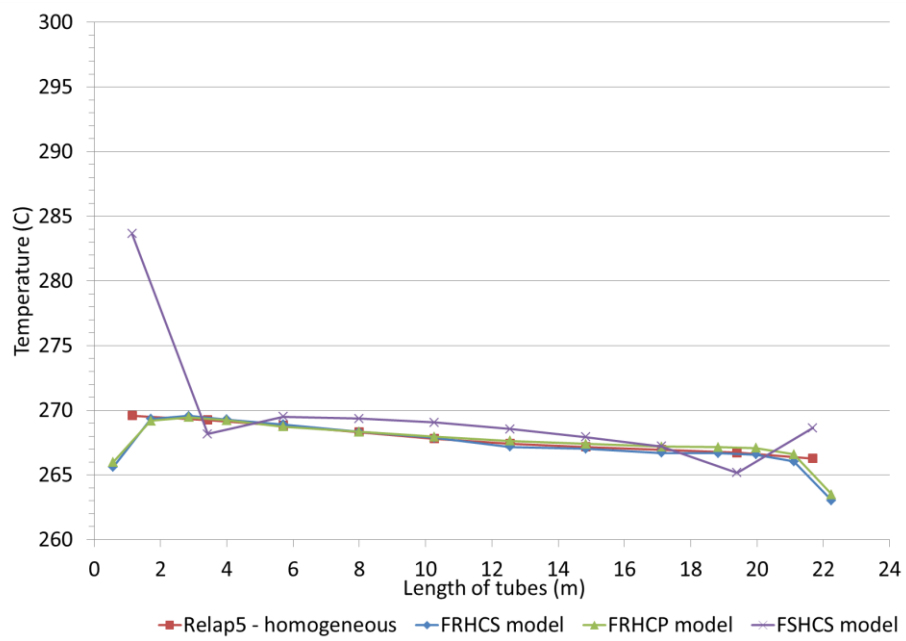


Figure 32: Tube surface temperature of the SG at 60% power output.

4.3 Summary of model comparisons

The results discussed in this chapter focussed on the boiling region of the SG where the heat transfer between the primary loop coolant and secondary loop feed water takes place.

The FRHCP model over-estimated the heat transferred in the boiling region of the SG by 6% for 100% power output, 7.7% for 80% power output and 4.4% for 60% power output. This was due to the over prediction of its convection heat transfer coefficients for the secondary side of the SG for approximately the first half of the U-tube length compared to the Relap5 homogeneous model. The heat transfer coefficients calculated resulted in the vapour quality and outside tube surface temperature being under-estimated and the feed water velocity in the boiling region being over-estimated when compared to the Relap5 homogeneous model. It is evident from the results that Flownex's built-in heat transfer correlations can calculate the heat transfer coefficients for the secondary side of the SG to an extent, but it is still not as accurate as implementing the heat transfer correlations of Relap5 used by the FRHCS model.

The FRHCS model and the Relap5 homogeneous model compared very closely to each other when looking at the results discussed in this chapter.

A maximum deviation of approximately 0.6% of the primary side temperature for all power output results was noted for the FRHCS model compared to the Relap5 homogeneous model.

The difference in quality calculated for the 100% power output for the two models is a maximum at the beginning of the boiling region with the vapour quality of the Relap5 homogeneous model being higher. It converged at the top of the U-tube bundle with negligible difference in the calculated vapour quality. For the 80% and 60% power output the vapour quality of the FRHCS model were calculated higher than the Relap5 homogeneous model. Errors of approximately 24% and 20% for the predicted vapour quality was observed for the 80% and 60% power output levels when the FRHCS model was compared to the Relap5 homogeneous model.

The convection heat transfer coefficient for the secondary side of the SG for the FRHCS model was under-estimated compared to the Relap5 homogeneous model. The

differences in the heat transfer coefficients were due to Flownex giving the Relap5 element certain boundary conditions for each pipe segment which can differ from the conditions used in the Relap5 homogeneous model.

The velocities of the feed water in the boiling region for the FRHCS model are over-estimated compared to the Relap5 homogeneous model. It reaches a constant difference of 19% approximately 6m above the tube plate. This difference decreases to approximately 18% and 14% for the 80% and 60% power output levels respectively.

The difference in tube surface temperature on the secondary side of the SG was negligible after the first 2m of the U-tubes for the FRHCS model and the Relap5 homogeneous model. A difference was observed of approximately 1.5% in tube surface temperatures at the beginning and end of the U-tubes. This difference decreased to approximately 0.6% and 0.7% for the 80% and 60% power outputs.

Conclusion and recommendations

This chapter gives concluding remarks and recommendations on the previous chapter's results. Recommendations are also made with regards to suggested improvements that can be done to the model and the potential for future work that exists for this study.

5.1 Conclusions

The purpose of this study was to find the optimum position within the SG to couple Flownex with Relap5 in terms of accuracy and ease of the solution. The results of the FRHCP and the FRHCS models were compared to the Relap5 homogeneous model, the FSHCS model and the Koeberg NPP data to establish which interaction point would suit the best. Accuracy and ease of use of the FRHCP and FRHCS models were investigated through comparisons and graphs to come to a conclusion.

The additional time that is needed to model the coupling between Relap5 and Flownex can be ignored when considering the use of the combined model approach or a Flownex only model. The solution times of the FRHCS model and FRHCP model are also negligible when compared to a Flownex only model. The FRHCS model is still preferable to the Relap5 only model which requires expert knowledge of the program and requires detailed information on the geometry of the SG. The FRHCS model only requires you to understand the Relap5 modelling of heat transfer in the boiling region of the SG which can be learnt by going through the examples that are included in the program files.

The FRHCP model over-estimated the convection heat transfer coefficients for the secondary side of the SG for the upward leg of the U-tube bundle when compared to the Relap5 homogeneous model. It also under predicted the convection heat transfer coefficients for the downward leg of the U-tube bundle. This over and under predictions of the convection heat transfer coefficients for the secondary side of the SG resulted in an average over-estimation of 6% of the total heat transferred in the boiling region of the SG when compared to the operating data of Koeberg NPP. The FRHCP model that uses the built-in heat transfer correlations of Flownex is able to simulate the operation of the

SG for the three different steady state scenarios investigated with an acceptable error margin.

The FRHCS model's convection heat transfer coefficients for the secondary side of the SG corresponded more closely to the Relap5 homogeneous model's convection heat transfer coefficients than for the FRHCP and FSHCS models. The FRHCS model's convection heat transfer coefficients for the secondary side of the SG were over-estimated for the first four meters of the U-tube length and were then under-estimated when compared to the Relap5 homogeneous model's convection heat transfer coefficients. Both the FRHCS model and the Relap5 homogeneous model heat transfer coefficients are calculated with the use of Relap5's matrix of heat transfer correlations, yet the results are not exactly the same. The difference can be attributed to the fact that the boundary conditions used by the respective models to calculate the convection heat transfer coefficients are different. The FRHCS model's pressure loss and temperature loss/gain per pipe segment are different from those calculated in the Relap5 homogeneous model. This is evident when looking at the results where the FRHCS model's secondary inlet pressure, primary outlet temperature and heat transferred in the boiling region of the SG are different from the Relap5 homogeneous model's results. The FRHCS model can successfully simulate the heat transferred in the SG for the three different steady state scenarios investigated with an acceptable error margin.

It can be concluded that for the different power levels analysed in this study, the FRHCS model offers a reliable alternative to the Relap5 homogeneous model when applied in the context of normal operating conditions of a NPP steam generator. The ability of Flownex's heat transfer correlations to calculate the convection heat transfer coefficient for the secondary side of the SG proved satisfactory for the scope of this study, but when looking at accuracy and ease of use the FRHCS model is preferable. The use of the Relap5 element in Flownex to calculate the convection heat transfer coefficient for the secondary side of the SG increases the accuracy of the Flownex SG model.

The improvement in accuracy makes it possible to extend the model to include the balance of plant components of the secondary loop of a NPP in Flownex as well as the primary loop components in Relap5 to form an accurate model representing a nuclear power plant.

5.2 Recommendations for further studies

Additional steady-state data at a wider range of power outputs would improve the reliability of the boundary conditions and will allow for further validation at lower power levels. The model developed can be extended from a steady-state to analyse transient scenarios with the aid of transient data from an experimental facility or from Koeberg NPP. This is necessary if the model is going to be used for safety analysis of an accident scenario or certain scenarios such as the start-up and shut-down of the reactor.

The model can also be extended to include the balance of plant components of a NPP. The primary loop can be developed in Relap5 which has the ability to accurately simulate the reactor, pressurizer and reactor coolant pumps. The secondary loop can be simulated in Flownex and the FRHCS model can then be used to couple the primary and secondary loops together. This will create a complete model of a NPP which can be used for an overall system analysis. It also gives the user the combined accuracy and power of Relap5 and the friendly graphical user interface and simplicity of Flownex.

The Flownex software is continuously being improved and in future the FRHCS model can become obsolete by incorporating more comprehensive heat transfer correlations into Flownex. The Relap5 element in Flownex will still be relevant in ensuring the primary loop in Relap5 and the secondary loop in Flownex can be coupled to form a more accurate model.

Bibliography

Bonavigo, L. & De Salve, M., 2011. Issues for Nuclear Power Plants Steam Generators. In: *Steam Generator Systems: Operational Reliability and Efficiency*. s.l.:s.n.

Cilliers, C., 2012. *Thermal-fluid simulation of nuclear steam generator performance using Flownex and RELAP5/mod3.4*. s.l.:North West University.

Coddington, P. & Macian, R., 2002. A study of the performance of void fraction correlations used in the context of drift-flux two-phase flow models. *Nuclear Engineering and Design*, Volume 215, pp. 199-216.

Davis, J. P. & Eisenhardt, K. M., 2007. Developing Theory through Simulation Methods. *Academy of Management Review*, pp. 480-499.

Desfontaines-Leromain, G., 2004. *PWR design and operation - steam generators*, s.l.: Areva.

EPRI, 1982. *Thermal-Hydraulic Analysis of the Westinghouse Model 51 Steam Generator*, Palo Alto, CA: s.n.

EPRI, 2008. *Steam Generator Management Program: Thermal-Hydraulics and Studies of Foreign Objects in Steam Generators*, Palo Alto, CA: s.n.

EPRI, 2012a. *Steam Generator Management Program: Thermal-Hydraulic Analysis of a Recirculating Steam Generator Using Commercial Computational Fluid Dynamics Software*, Palo Alto, CA: s.n.

EPRI, 2012b. *Steam Generator Management Program: Benchmark Study of EPRI and EDF Steam Generator Thermal-Hydraulic and Flow Induced Vibration Codes*, Palo Alto, CA: s.n.

EPRI, 2015. *Triton Steam Generator Thermal-Hydraulics Code: Interim Report on Validation Using Experimental Test Results*, Palo Alto, CA: s.n.

ESKOM, 2004. *Koeberg Safety Analysis Report*, s.l.: Eskom Generation.

Fletcher, C. D. et al., 1997. *Adequacy evaluation of RELAP5/MOD3, version 3.2.1.2 for simulating AP600 small break loss-of-coolant accidents*, s.l.: U.S. Nuclear Regulatory Commission.

Flownex SE, 2012a. *Flownex Certification*. [Online]
Available at: <http://www.flownex.com/about-us/certification>

Flownex SE, 2012b. *Flownex History*. [Online]
Available at: <http://www.flownex.com/about-us/flownex-history>

Flownex SE, 2015a. *Flownex Library Theory Manual*. s.l.:s.n.

Flownex SE, 2015b. *Flownex Library Manual*. s.l.:s.n.

Green, S. J. & Hetsroni, G., 1995. PWR Steam Generators. *International Journal of Multiphase Flow*, pp. 1-97.

Greyvenstein, G. P. & Rousseau, P. G., 2003. Design of a physical model of the PBMR with the aid of Flownet. *Nuclear Engineering and Design*, pp. 203-213.

Hibiki, T. & Ishii, M., 2003. One-dimensional drift-flux model for two-phase flow in a large diameter pipe. *Internasional Journal of Heat and Mass Transfer*, Volume 46, pp. 1779-1790.

IAEA, 2012. *PRIS*. [Online]
Available at: <http://www.iaea.org/pris/>

Ishii, M. & Hibiki, T., 2006. *Thermo-fluid Dynamics of Two-phase Flow*. s.l.:Springer.

Kandlikar, S. G., 1998. Heat Transfer Characteristics in Partial Boiling, Fully Developed Boiling and Significant Void Flow Regions of Subcooled Flow Boiling. *Journal of heat transfer*, Volume 120, pp. 395-401.

Lakehal, D. & Labois, M., 2011. A new modelling strategy for phase-change heat transfer in turbulent interfacial two-phase flow. *Internasional Journal of Multiphase Flow*, Volume 37, pp. 637-639.

Lamarsh, J. R. & Baratta, A. J., 2001. *Introduction to Nuclear Engineering*. s.l.:s.n.

Leeb, N., 2015. *Chen correlation used in Flownex* [Interview] (November 2015).

Preece, R. J. & Putney, J. M., 1993. *Preliminary Assessment of PWR Steam Generator Modelling in RELAP5/MOD3*, s.l.: U.S. Nuclear Regulatory Commission.

RELAP5, 2001a. *RELAP5/MOD3.3 Code Manual Volume IV: Models and Correlations*. s.l.:Nuclear Safety Analysis Division, Information Systems Laboratories, Inc. Idaho Falls, U.S.A..

RELAP5, 2001b. *RELAP5/MOD3.3 Code Manual Volume V: User's Guideline*, Nuclear Safety Analysis Division, Information Systems Laboratories, Inc. Idaho Falls, U.S.A.: s.n.

Schlegel, J., Hibiki, T. & Ishii, M., 2010. Development of a comprehensive set of drift-flux constitutive models for pipes of various hydraulic diameters. *Progress in Nuclear Energy*, Volume 52, pp. 666-677.

Singhal, A. K., Keeton, L. W. & Spalding, D. B., 1980. *A comparison between steam generator models using the homogeneous model, the two-fluid, and the algebraic-slip model..* Orlando, New York, USA: American Institute of Chemical Engineers.

Strohmayer, W. H., 1982. *Dynamic modeling of vertical U-tube steam generators for operational safety systems*. s.l.:Massachusetts Institute of Technology.

Zhang, G. et al., 2013. Dynamic heat transfer performance study of steam generator based on distributed parameter method. *Annals of Nuclear Energy*, pp. 658-664.

Annexure A

A.1 Relap5 code

= Pipe element

*

* Setup

100 new stdy-st

102 si si

105 10.0 40.0 200.0

* end time min dt max dt ssdtt minor,major and restart frequencies

201 5.000E+001 1.0e-6 1.000E-001 3 5000 5000 5000

* Additional Plot Requests

20300011 mflowj 127000000 1

20300012 mflowj 227000000 1

20300021 httemp 125000501 1 httemp 125000401 1 httemp 125000301 1

* Primary Side Components

1100000 "source" tmdpvol

* fa l vol azi vert dz rough hyd d flags

1100101 100.0 1.0 0.0 0.0 90.0 1.0 0.0 0.0 0000000

* ebt

1100200 003

* time P (Pa) T (K)

1100201 0.0 15489200.0 565.43

1200000 "sngljuni" sngljun

* from vol to vol fa A_F A_R jefcahs

1200101 110010002 125010001 0.0 0.0 0.0 0000110

* flag liq mass flow vap mass flow inter. veloc.

1200201 1 0.0 0.0 0.0

1250000 "stmpipe" pipe

* no. of vols

1250001 5

* fa vol no.

1250101 1.0129 5

* l (m) vol no.

1250301 2.282 5

```

*      az. ang vol no

1250501 0.0 5

*      vt. ang vol no

1250601 90.0 5

*      rough (m) hyd vol no.

1250801 0.0000457 0.01968 5

*      f loss r loss jun. no.

1250901 0.0 0.0 4

*      tlpvbf e vol no

1251001 0000000 5

*      efvcahs jun. no

1251101 0000000 4

*      ebt P (Pa) T (K) vol. no.

1251201 003 15489200.0 565.43 0.0 0.0 0.0 5

*      flag

1251300 1

*      liq. mass flow vap. mass flow int. mass flow jun no.

1251301 0.0 0.0 0.0 4

*****

1270000 "tmdpjuno" tmdpjuno

*      from to fa

1270101 125050002 130010001 0.0

```

*

1270200 1 * Specifies mass flows on the next card

* t liq mass flow vap mass flow inter. veloc.

1270201 0 4600.0 0.0 0.0

1270202 1000.0 4600.0 0.0 0.0

1300000 "sink" tmdpvol

* fa l vol azi vert dz rough hyd d flags

1300101 100.0 1.0 0.0 0.0 90.0 1.0 0.0 0.0 0000000

* ebt

1300200 3

* time press (Pa) temp (K)

1300201 0.0 15432400.0 561.482

* Secondary Side Components

2100000 "source" tmdpvol

* fa l vol azi vert dz rough hyd d flags

2100101 100.0 1.0 0.0 0.0 90.0 1.0 0.0 0.0 0000000

* ebt

2100200 003

* time P (Pa) T (K)

2100201 0.0 4921590.0 533.15

2200000 "sngljuni" sngljun

* from vol to vol fa A_F A_R jefcahs

2200101 210010002 225010001 0.0 0.0 0.0 0000110

* flag liq mass flow vap mass flow inter. veloc.

2200201 1 0.0 0.0 0.0

2250000 "stmpipe" pipe

* no. of vols

2250001 5

* fa vol no.

2250101 1.0129 5

* l (m) vol no.

2250301 2.282 5

* az. ang vol no

2250501 0.0 5

* vt. ang vol no

2250601 90.0 5

* rough (m) hyd vol no.

2250801 0.0000457 0.01032 5

* f loss r loss jun. no.

2250901 0.0 0.0 4

* tlpvbf vol no

2251001 0000000 5

* efvcahs jun. no

2251101 0000000 4

* ebt P (Pa) T (K) vol. no.

2251201 003 4921590.0 533.15 0.0 0.0 0.0 5

* flag

2251300 1

* liq. mass flow vap. mass flow int. mass flow jun no.

2251301 0.0 0.0 0.0 4

2270000 "tmdpjuno" tmdpjuno

* from to fa

2270101 225050002 230010001 0.0

*

2270200 1 * Specifies mass flows on the next card

* t liq mass flow vap mass flow inter. veloc.

2270201 0 2262.0 0.0 0.0

2270202 1000.0 2262.0 0.0 0.0

2300000 "sink" tmdpvol

* fa l vol azi vert dz rough hyd d flags

2300101 100.0 1.0 0.0 0.0 90.0 1.0 0.0 0.0 0000000

* ebt

2300200 3

* time press (Pa) temp (K)

2300201 0.0 4921440.0 536.103

* Heat Structures

* Heat structure for tubing

* nh np cyl Left boundary

11250000 5 5 2 1 0.00984

* Specifies format for following card

11250100 0 2

*

11250101 0.0003175 4

*

11250201 5 4

*

11250301 0.0 4

* Specifies initial temperatures (K)

11250401 583.0 5

* Left boundary conditions card

* comp. incr. type

11250501 125010000 010000 111 1 7600.0 5

* Right boundary conditions card

11250601 225010000 10000 111 1 7600.0 5

* Heat source data card

11250701 0 0 0 0 5

* Additional boundary cards (Check Manual!)

11250800 1

11250801 0.01968 10.0 10.0 0.0 0.0 0.0 0.0 1.0 2.282 1.464 1.0 5

11250900 1

11250901 0.01032 10.0 10.0 0.0 0.0 0.0 0.0 1.0 2.282 1.464 1.0 5

* Material Properties

20100500 s-steel

*=====

*=====

.End of Input.