

**The effect of steam generator tube plugging on its
overall thermal performance - A Systems CFD-Based
Study**



By

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DECLARATION

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ABSTRACT

The steam generator in a pressurized water reactor power plant acts as a fission product barrier between primary and secondary system. Material failure of the tube bundle barrier could therefore lead to a release of radioactive product into the secondary side. Several repair methods have been used to address tube leakage, with the most popular being tube plugging. The objective of this study was to quantify the effect of tube plugging on the thermal performance of a steam generator. For this purpose, the systems computational fluid dynamics (CFD) software Flownex® was used.

First, a Flownex® model of the steam generator was developed and validated via comparison of the results to a validated model from the literature. Following this, a hydro-thermal analysis was performed to determine the effect of the tube plugging on the thermal performance under normal operational conditions (excluding the possibility of a tube rupture). Tube plugging of up to 20% was investigated. The model predicted the following effects: decrease in heat transfer, primary coolant mass flowrate and primary outlet pressure. Further, primary flow velocity, pressure drop and outlet temperature increase with increasing tube plugging. On the secondary side, tube plugging lowers the mixture quality in the boiling region and steam production while the re-circulation ratio was increased. Lastly, the model predicted a plugging ratio limit of 17.3%. Beyond this point, the steam generator does not extract sufficient heat from the reactor at 100% power.

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NOMENCLATURE

Terms and Acronyms

CFD	Computational Fluid Dynamics
IAEA	International Atomic Energy Agency
NPP	Nuclear Power Plant
OTSG	Once Through Steam Generator
PWR	Pressurized Water Reactor
SCC	Stress Corrosion Cracking
SE	Simulation Environment
UTSG	U-Tube Steam Generator

Constants and Variables

A	Cross Sectional Area (m^2)
V	Velocity (m/s)
p	Pressure (Pa)
τ_w	Shear Stress (Pa)
g	Gravitational acceleration ($m.s^{-2}$)
H	Enthalpy ($kJ.kg^{-1}$)
q''	Heat generation per unit area (Wm^{-2})
P_H	Perimeter (m)
q'''	Heat generation per unit volume (Wm^{-3})
θ	Angle of flow
C_p	Specific heat at constant pressure ($Jkg^{-1} ^\circ C^{-1}$)
D_h	Hydraulic diameter (m)
F	Reynolds number factor
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)
G	Mass flux ($kgm^{-2}s^{-1}$)
h_{lg}	Latent heat of vaporisation ($J kg^{-1}$)
Pr	Prandtl number
Re	Reynolds number, effective two-phase Reynolds number
S	Suppression factor
T	Temperature ($^\circ C$)
x	Vapour quality
X_{tt}	Lockhart-Martinelli parameter

Greek Symbols

λ	Thermal conductivity ($Wm^{-1} ^\circ C^{-1}$)
Δ	Increment
μ	Dynamic viscosity ($Pa s^{-1}$)
ρ	Density ($kg m^{-3}$)
σ	Surface tension (Nm^{-1})

Subscripts

<i>e</i>	Excess
<i>g</i>	saturated vapour
<i>l</i>	saturated liquid
<i>nb</i>	nucleate boiling
<i>pi</i>	primary inlet
<i>po</i>	primary outlet
<i>sat</i>	Saturated
<i>si</i>	secondary inlet
<i>so</i>	secondary outlet
<i>sp</i>	single-phase
<i>tp</i>	two-phase
<i>w</i>	Wall

CHAPTER 1: Introduction

1.1 Background

A pressurized water reactor (PWR) is a power-generating plant that uses nuclear fuel as a source of heat. Heat is generated from the reactor through a fission process, where uranium atoms are split and a chain reaction occurs. In order to sustain the reaction, moderation is required. In the case of PWR, water is used as a moderator and a coolant. The moderator is kept under pressure to maintain a subcooled state on the primary side. As depicted in Figure 1, the primary system transports heat from the reactor to the secondary side via a steam generator.

On the secondary side of the steam generator, steam is produced to drive the main turbine generator, the turbo feed pumps and auxiliary steam during normal operation. Used steam flowing from the turbine is finally routed to the condenser.

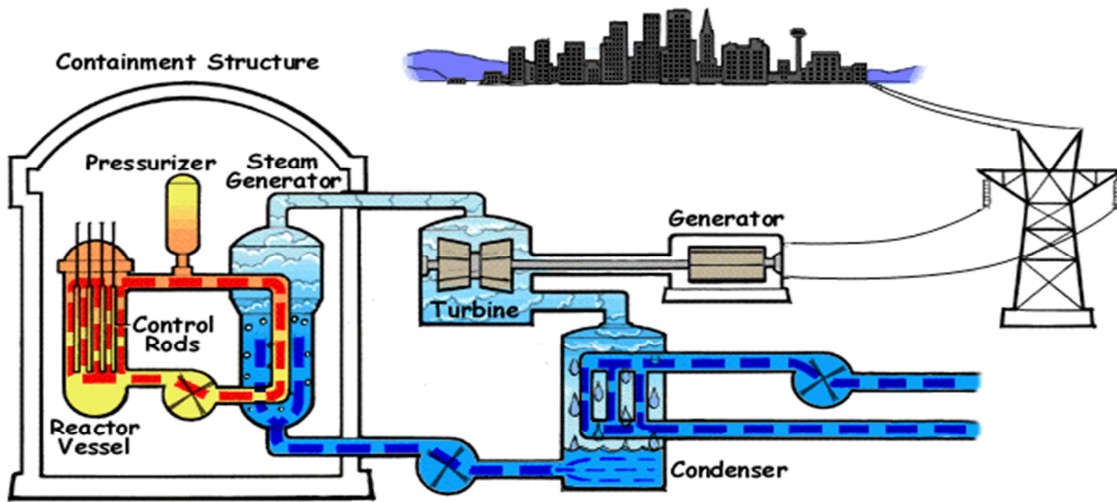


Figure 1: Sample demonstration of nuclear power plant [1]

In the nuclear power plant (NPP) depicted above, the steam generator is the boundary component between the primary and secondary systems. The steam generator plays a crucial role in ensuring that the heat generated from the reactor is removed in normal, shutdown and accident operations. Importantly, it is a fission product barrier between primary and secondary systems while providing the heat needed to generate steam [2].

There are two types of steam generators used in the PWR: U-tube steam generators (UTSG) and once-through steam generators (OTSG). Once-through steam generators produce superheated steam while U-tube steam generators produce saturated steam [3]. However, both types of steam generator are susceptible to design and operational problems. Some of these will be discussed in the next section. Furthermore, this study will focus on a UTSG used at the Koeberg Nuclear Power Plant (NPP).

1.2 U-tube steam generator and modes of failure

The steam generator is a component designed to perform three main functions in a PWR: to produce steam to drive the turbine in order to generate power; to act as a fission boundary that separates the primary and secondary water; and to remove heat from the reactor during normal operation, as well as residual heat during shutdown (Figure 1).

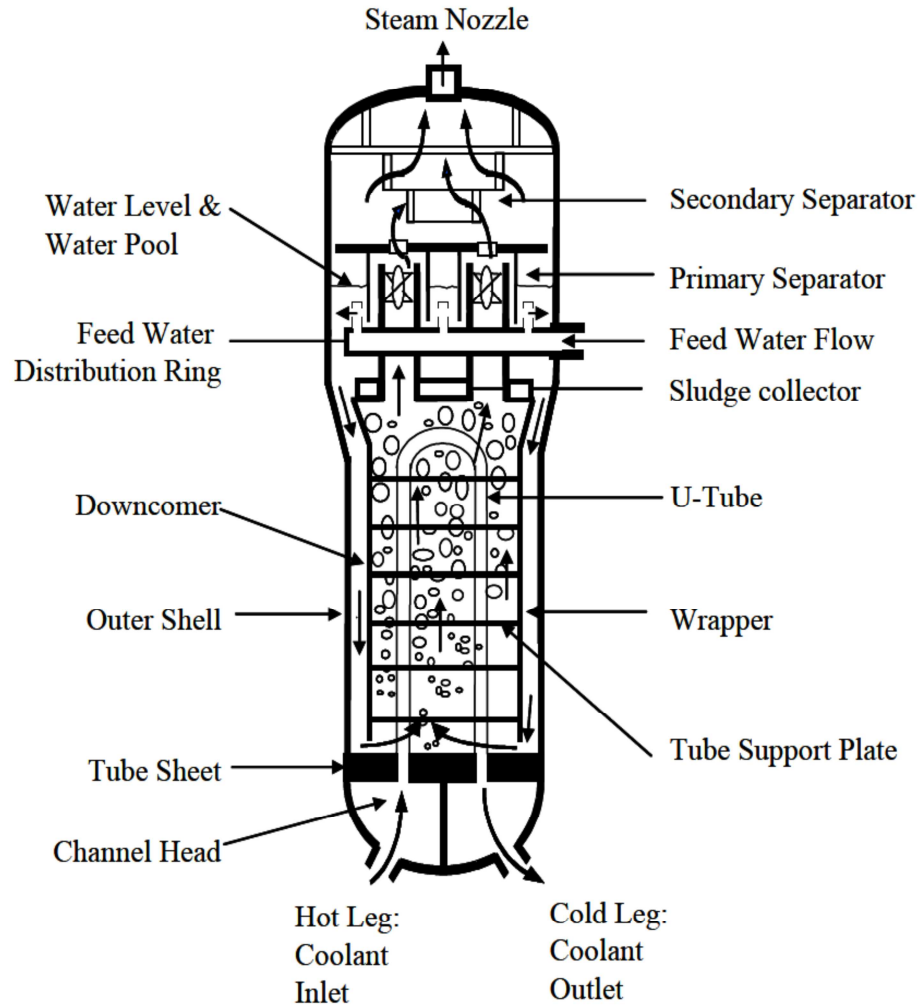


Figure 2: Schematic drawing of UTS [4].

Figure 2 shows a schematic of the U-tube steam generator, depicting heat transfer from primary to secondary water, as well as subsequent steam production. Reactor coolant enters the steam generator at the hot leg, flows through the hot leg to the U-tube bundle, passes through the inverted U-bend and enters the cold leg. As the primary coolant flows through the tube bundle, it transfers heat to the secondary fluid. The reactor coolant is kept under pressure to maintain its subcooled state.

Secondary water enters the shell side of the steam generator through the feed water distribution ring, from where it flows into the downcomer annulus. The feed water flow mixes with

recirculation flow (from the primary and secondary separators) before flowing over the tube sheet and vertically upward into the tube bundle [5]. From here the feed water continues to flow vertically upward, in contact with the heating surface of the U-tube bundle. As the secondary water passes the heating surface of the tube bundle, nucleate boiling commences which is enhanced by the forced convection flow. As the nucleate boiling develops, the secondary water bulk temperature rises, subsequently reaching saturation. Following this, steam-water emulsion is formed.

The steam-water emulsion enters primary and secondary separators near the top of the steam generator. Primary separators constitute the first stage in steam-water separation. The vanes of the separators cause centrifugal movement of the emulsion and the steam is separated from the water due to density difference. The separated water is subsequently returned and mixed with feed water flow. The steam passes through the secondary separators (driers) to remove the remaining liquid moisture and increase the steam quality. From here the steam flows to the turbine through the steam nozzle.

Due to the direct involvement of the radioactive primary side of the steam generator through the tube bundle, material failure of the tubes is of concern. Several important potential failure mechanisms include: tube denting, wastage, thinning, corrosion, fluid induced vibration and deformation of U-tube bend or plate supports, tube leakage and fracture [2]. Due to these, tube leak and rupture during normal operating could occur, compromising the integrity of the fission product barrier if not treated. To effect the latter, several maintenance procedures and repair methods have been developed to reduce degradation-related concerns and therefore extend the service life of the steam generator. Despite this, a number of nuclear power plants have undergone costly replacement of their steam generators owing to degradation.

Several repair methods have been used to address tube leakage; however, the most popular remains plugging [6], [7]. According to Wade [8], tube plugging is an operator's initial response to degrading steam generator tubes. However, plugging should be limited to a certain number of tubes in order to sustain a specific minimum heat transfer capacity of the steam generator. Furthermore, as much as the plugging of tubes minimizes the direct release of radioactive products to the environment, it has a negative impact on the thermal efficiency of the steam generator (due

to reduction of the heat transfer area). The effect of tube plugging on heat transfer is therefore a key parameter that requires quantification, which is the objective of this study. This is done via modelling, owing to the immense complexity of the heat transfer physics present in a steam generator, as well as the near impossibility of performing detailed measurements.

1.3 Steam generator thermos-flow modelling

As noted previously, the steam generator considered in this work is a shell and tube heat exchanger that involves single-phase flow on the tube side and two-phase flow on the shell side. The shell side of the steam generator is exposed to the boiling heat transfer and a highly complex two-phase, turbulent environment. These conditions make this device one of the most challenging and complex pieces of equipment in the power-generating plant to simulate. However, computation fluid dynamics (CFD) codes have the capabilities to solve complex fluid flow and heat transfer problems [9].

Recent work by Cilliers [10] has demonstrated the efficacy of using a homogeneous two-phase systems CFD approach. In the homogeneous process, it is assumed that both phases are well mixed and have the same velocity and temperature at any given location along the shell side of the steam generator [11]. Cilliers implemented this approach to model the particular steam generator considered in this study, using the Flownex® Simulation Environmental (SE) systems CFD software. Comparing predicted heat transfer from Flownex® to the heterogeneous industry standard RELAP5/MOD 3.2 code, he found them correlating to within 0.9% in terms of heat transferred between primary and secondary sides. This study clearly proved that the Flownex® software, with its homogeneous approach, was an effective steam generator modelling tool. It was therefore adopted as the starting point for this work.

As noted above, the shell side of the steam generator consists of complex two-phase boiling flow. The major complexities involved include bubble growth and departure behaviour in the flow field of the two-phase mixture as well as distribution of the two-phases relative to each other and relative to the tube wall [12]. To address this, an empirical correlation is used to determine the two-phase flow boiling heat transfer coefficient as was done in [10]. However, in the present study a slightly adapted Chen correlation for saturation flow boiling heat transfer [13] is used, as recent literature depicts it as somewhat more accurate. This will be elaborated on in a chapter to follow.

1.4 Objectives

The main objectives of this study include the following:

- The independent (with respect to the previous study [10]) development of a thermal-fluid network model for a steam generator using Flownex®;
- Validating the developed steam generator model using the cited model boundary condition inputs and comparing outputs;
- Performing the first homogeneous hydro-thermal analysis to determine the effects of tube plugging on the thermal performance of the steam generator under consideration, and
- Using the developed homogeneous model to determine the percentage of tubes that may be plugged prior to replacing the steam generator. The current steam generator has a power rating of 928.3 MWth, which is to be extracted from the primary cycle to cool the core at full power. Tube plugging that causes the steam generator to perform below this will be considered having exceeded maximum plugging.

1.5 Methodology

The research method that is utilised in this study is of a quantitative nature, i.e it involves the development of the steam generator thermos-flow model using Flownex® SE. The Flownex® network has been customized by using the Mathcad® component for mathematical interpretation of the Chen correlation to calculate the secondary side heat transfer coefficient. The Chen correlation constitutes the most complex and non-linear aspect of the two phase modelling. Because of the changes of water and steam properties throughout the boiling region of the steam generator, Mathcad® is incorporated into the Flownex® network to automate the changes in heat transfer of the liquid-steam mixture. Mathcad® uses steam table functions based on the IAPWS-IF97 standard to calculate steam-water properties at any given pressures and temperatures.

The input boundary conditions used for the steam generator model are those obtained from Koeberg NPP operating parameters [14], The steam generator model has been validated via comparison to the results of the model developed in recent literature [10]. Subsequent to this, the application study involved accounting for the effect of tube plugging and quantifying its impact on the thermodynamic performance of the steam generator.

1.6 Thesis layout

Building on the above, in Chapter 2 the background literature review of the steam generator and its degradation mechanisms, including the thermal hydraulic processes that take place within the equipment will be discussed. The governing equations and Chen correlation equations will also be documented.

In Chapter 3 the development of the numerical model, including the boundary conditions will be discussed. This chapter will further validate the model using heat transfer coefficient input from the previous study [10].

In Chapter 4 the methodology used to determine the unknown boundary conditions will be discussed and this chapter will further document the boundary conditions for different plugging ratios.

In Chapter 5 the application of the model and the results for both unplugged and plugged tubes will be discussed.

The conclusion based on the results obtained and recommendations will be discussed in Chapter 6.

CHAPTER 2: Tube plugging and steam generator thermodynamic modelling

2.1 Challenges that affect the steam generator

A steam generator is a heat exchanger which, like any other mechanical component, is exposed to degradation due to corrosion and thermal related stresses. The former is due to chemical treatment used on both primary and secondary sides of the tubes. Though the nickel-chromium-steel alloys employed aid in retarding degradation, significant wear and corrosion occur over time [15].

The International Atomic Energy Agency (IAEA) has documented the current practice for assessment and management of the ageing of steam generators. Based on data analysis, the agency has developed an understanding of the dominant causes of steam generator degradation (represented graphically in Figure 3). The definitions of the categories listed in Figure 3 are presented in Table 1.

It is evident that over the years there has been a decline in the number of causes of steam generator tube degradation, thanks to strategies that have been developed to improve and mitigate steam generator tube degradation by the utility's operators, thus increasing the life span of steam generator tubes. However, stress corrosion cracking (SCC) remains a significant contributor to degradation.

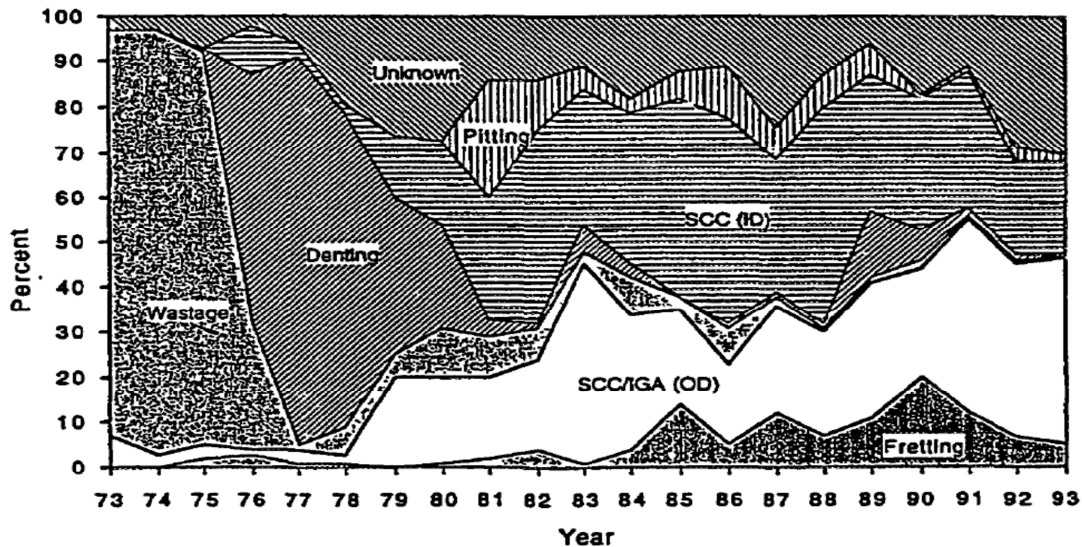


Figure 3: Worldwide causes of steam generator tube plugging [16]

Figure 3 shows the percentage of the total number of tube failures caused by each of the major degradation mechanisms for the years 1973 to 1993.

Table 1: Steam generator degradation [8]

Type of Degradation	Definition
Denting	The physical deformation of the Inconel Alloy 600 tubes as they pass through the support plate. Caused by a buildup of corrosive material in the space between the tube and the plate.
Fatigue cracking	Caused by tube vibration.
Fretting	The wearing of tubes in their supports due to flow induced vibration.
Intergranular attack/stress-corrosion cracking (outside diameter)	Caused when tube material is attacked by chemical impurities from the secondary-loop water. It occurs primarily within tube sheet crevices and other areas where impurities concentrate.
Pitting	The result of local breakdown in the protective film on the tube. Active corrosion occurs at the site of breakdown.
Stress-corrosion cracking (inside diameter)	Cracking of steam generator tubes occurring at the tangent point and apex of U-bend tubes, at the tube sheet roll transition, and in tube dents. It occurs when Inconel Alloy 600 tubing is exposed to primary-loop water.
Tube wear	A thinning of tubes caused by contact with support structures either as the tubes vibrate or as feedwater entering the vessel impinges on the tube bundle at that location.
Wastage	A general corrosion caused by chemical attack from acid phosphate residues in areas of low water flow.

Bonavigo et al [2] indicated that the degradation-related problems that affect the steam generator in a nuclear plant may have a dire negative impact in the case of leaking and rupture, compromising the integrity of the steam generator and subsequently releasing radioactive fluid into the secondary side. These problems still create significant challenges to utility operators. They then need to weigh up whether to operate the plant with high radiation exposure, high operating and maintenance costs and risk of forced outages due to leakages and tube ruptures, or whether to just replace the steam generator [8].

Once tube deterioration is identified, there are remedial actions that the utility operator implements to minimize associated consequences. These remedial reactions include water chemistry improvement, water lancing to reduce deposits of corrosion on the outside of the tubes, tube plugging, sleeving and improvement of condenser material and water-chemistry to minimize condenser-related issues.

After studies of several remedial actions to repair steam generator tubes, plugging was found to be a permanent solution to the problem [6], [7]. Tube plugging is therefore generally the initial action taken by the utility. In accordance with typical steam generator design targets, an excess in the number of tubes is provided [8]. Hence, tube plugging is considered before other interventions.

Further details of the effect of the tube plugging will be discussed in the next section.

2.2 Effect of tube plugging

The Nuclear Regulatory Commission uses three factors to establish the operating limits for steam generator tubes that have been exposed to degradation [17]. These are as follows:

- the minimum tube wall thickness required for the defective tubes to sustain the load during normal operation and incident condition;
- an operational allowance for degradation between inspections, and
- the crack size allowable to meet the leakage limit permitted per steam generator (as per the technical specification of the licence).

When the limits have been reached, the repair intervention is performed. It is accepted that when a large number of the tubes is plugged, it negatively affects the heat transfer capabilities of the steam generator. This is as the cross section area of the steam generator primary flow as well as heat exchange surface area is reduced. Because of the over-design in terms of number of tubes, it is natural to expect that a certain percentage of tubes may be plugged without negatively affecting the performance of the steam generator too dramatically. However, if deterioration persists, the plant cannot operate at its set rate of power; subsequently, power must be reduced or the steam generator replaced [6], [7].

Pla et al [6] conducted a study to determine what fraction of the tubes could be plugged in order to maintain the safe operation of the reactor should the plant experience a tube rupture incident, which implies a sudden tube break or burst due to one or more of the degradation mechanisms defined in Table 1. The analysis for this study was performed using the Relap5 Mod 3.3 simulation code, which employs a nonhomogeneous and non-equilibrium model [18]. It was found that 12% of total tube plugging was the approximate limit when dealing with a tube rupture incident. In accordance with Wade [8] in general, a typical SG can operate with up to 15% to 20%

of tubes plugged during normal operating conditions. Pla et al. [6] concurred with this finding. They further indicated that the limit to plugging is reached when the plant is not able to deliver its full rated power.

The present study will evaluate the use of the homogeneous model in investigating the effect of tube plugging on thermal performance of the steam generator during normal plant operation. The earlier study by Cilliers [10] showed a homogenous model of similar accuracy to the Relap5 version in modelling the Koeberg SG, with the added advantage of it being much easier to use.

The developed homogeneous model will further determine the plugging limit for a normal plant from a thermal management point of view. Since, the steam generator has a heat transfer rating of 928.3 MWth, the study will assess the maximum plugging ratio required in order to ensure this. Quantification of the thermodynamic processes prevalent in the steam generator is key to this, as dealt with in the next section.

2.3 Thermodynamics process

2.3.1 Boiling heat transfer

The steam generator is the largest heat exchanger in a nuclear plant exposed to multiphase flow which comprises the full range of steam qualities. The primary coolant flow from the reactor is kept under pressure and remains in the liquid phase. In contrast, the shell side flow (secondary side) is exposed to a changing steam quality of from close to zero to close to unity. The two-phase flow boiling involved consists of saturated nuclear boiling in the presence of a forced convection mechanism. Both of these conditions create a turbulent environment on the shell side of the steam generator [11], [10]. Furthermore, boiling heat transfer and two-phase flow are individually considered as highly complex phenomena to model and quantify [3].

As propounded by John Chen [19], the complexity of boiling heat transfer is well known, especially in the case of convective boiling involving generation of vapour. Kandlikar [12] describes these complexities as follows: bubble growth and departure behaviour in the flow field of a two-phase mixture; distribution of two-phases relative to each other and relative to the tube wall; departure from thermodynamics equilibrium at local conditions; and characteristics of the

heat transfer surface and the effect of fluid properties. Naturally, all of the above-mentioned have a direct bearing on the secondary side heat transfer coefficient in the steam generator.

Due to its complexity, heat transfer correlations are often used to determine and predict heat transfer coefficients for saturated flow boiling heat transfer. Kandlikar [12] developed a general correlation for saturated two-phase flow for boiling heat transfer to predict the saturated flow boiling heat transfer coefficient. In his study, he compared a general correlation to six other well-known heat transfer correlations available in the literature. Among those six correlations, the Chen correlation was quoted as the most widely used. This is because it offers a relatively simple expression for describing heat transfer as the sum of the nucleate boiling and convective related terms. However, other authors cited in Kandlikar's [12] work highlighted the fact that the Chen Correlation does tend to over-predict the effect of nucleation resulting in large inaccuracies in certain instances.

Due to the relatively simple additive form of nucleate boiling and the convective components in the Chen correlation, the present study will utilize this correlation to predict the heat transfer coefficient for a steam generator. The following section will further elaborate on the Chen correlation and quote the formulae involved. This is particularly important as Chen et al [13] found that numerous published versions of the correlation contained typographical errors, and subsequently published the definitive version in [13], which was used in this work.

2.3.2 Chen correlation for saturation flow boiling heat transfer

As noted above, the Chen correlation is regarded as one of the most influential for the quantification of two-phase nucleate boiling heat transfer. It achieves via the sum of saturated nucleate boiling and single-phase forced convection mechanisms as [13]:

$$h_{tp} = S \times h_{nb} + F \times h_{sp} \quad (1)$$

where h_{tp} is the heat transfer coefficient for two-phase flow; h_{nb} is the heat transfer coefficient due to nucleate boiling as determined by the Forster and Zuber [19] equation; h_{sp} is the single-phase forced convection as determined by the Dittus and Boelter equation [20]; S and F are respectively the suppression and Reynolds number factors.

The Forster and Zuber equation reads:

$$h_{nb} = 0.00122 \left(\frac{\lambda_l^{0.79} C_{pl}^{0.45} \rho_l^{0.49}}{\sigma^{0.5} \mu_l^{0.29} h_{lg}^{0.24} \rho_g^{0.24}} \right) \Delta T_e^{0.24} \Delta p_e^{0.75} \quad (2)$$

where λ_l is the liquid thermal conductivity, C_{pl} is specific heat at constant pressure, ρ_l is the liquid density, σ is the surface tension, μ_l is dynamic viscosity, h_{lg} is latent heat of vaporization, ρ_g is gas density, ΔT_e is excess temperature ($\Delta T_e = T_w - T_{sat}$) and Δp_e is the difference in vapour pressure: $\Delta p_e = p_w - p_{sat}$.

For single-phase forced convection, the heat transfer coefficient given by the Dittus and Boelter [20] correlation reads:

$$h_{sp} = 0.023 Re_l^{0.8} Pr_l^{0.4} \frac{\lambda_l}{D_h} \quad (3)$$

where Re_l is the liquid Reynolds number and Pr_l is the liquid Prandtl number. These are given by:

$$Pr_l = \frac{C_{pl} \mu_l}{\lambda_l} \quad (4)$$

$$Re_l = \frac{(1-x)GD_h}{\mu_l} \quad (5)$$

where x is the quality of the flow, G is mass flux and D_h the hydraulic diameter.

In accordance with the literature [13] the Reynolds number factor (F) and suppression factor (S) were originally developed graphically by Chen, and from these subsequent parametric equations were developed by other authors. However, this was done with various degrees of success. Chen et al [13] subsequently compared the aforementioned parametric equations to the proposed correct version, which is used in this work: πr^2

$$F = \begin{cases} 2.35 \left(\frac{1}{X_{tt}} + 0.213 \right)^{0.736} & \text{if } \frac{1}{X_{tt}} > 0.1 \\ 1 & \text{if } \frac{1}{X_{tt}} \leq 0.1 \end{cases} \quad (6)$$

where X_{tt} is the Martinelli parameter [19], which indicates the effective turbulence associated with two-phase flow. The latter changes with vapour fraction and is expressed as:

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{\mu_l}{\mu_g}\right)^{0.1} \quad (7)$$

The suppression factor is given by

$$S = \frac{1}{[1 + 2.53 \times 10^{-6}(Re_l F^{1.25})^{1.17}]} \quad (8)$$

The above functions were verified extensively with more than 600 data points from water and five organic fluids [13]. This spanned a quality varying from 0.01 to 0.71. Mass fluxes varied from 54 to 4070 kg/m²s⁻¹, heat flux from 6.3 to 2397.5kWm⁻², and saturation pressure from 0.055 to 3.48MPa.

Cilliers [10] used the Chen correlation to predict the heat transfer coefficient of the steam generator that he developed using the Flownex® software. The results revealed that the heat transfer coefficients (which were scripted into the Flownex® homogeneous flow model) were within 70% to 80% of the parameters predicted by the industry standard non-homogeneous RELAP 5 code [10]. In accordance with Cilliers' investigation, the RELAP 5 code applied Chen correlation during nucleate boiling and transition boiling. Hence, the Chen correlation was applied to the Flownex model in this study. It was, however, noted in the work that the parametric equation for Reynold's factor used in Cilliers' model was not the one that is regarded as the best fit with Chen's curves. In addition, the liquid Reynold's number determination equation used in his model used mass flow rate (\dot{m}) instead of mass flux (G), as prescribed in subsequent literature [13]. (See Equation (5) of this work).

As noted previously, due to the success of the work by Cilliers, the heat transfer in the steam generator after tube plugging is evaluated in this work via a homogeneous systems CFD approach. The Flownex® software has proven successful in this and will be employed here. The section to follow will detail the basic governing equation and related assumptions involved.

2.3.3 Governing equations for two-phase flow

In accordance with the Flownex® theory manual [21], two-phase flow is described as the phenomenon that occurs as a result of one of the following processes: flashing, boiling or condensation. Two-phase flow is governed by the conservation of mass, momentum and energy equations. This section will table these governing equations as per [21]. The local pipe coordinates used to illustrate the governing equations are shown in Figure 4.

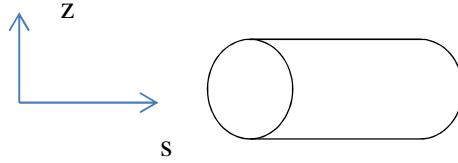


Figure 4: Coordinate system used to derive the conservation equations

General conservation of mass

$$\frac{\partial}{\partial t} \left(\int_A \rho dA \right) + \frac{\partial}{\partial s} \left(\int_A \rho V dA \right) = 0 \quad (9)$$

where ρ is density; A is cross-sectional area and V is velocity.

The general momentum conservation is described in weak form by:

$$\frac{\partial}{\partial t} \left(\int_A \rho V dA \right) + \frac{\partial}{\partial s} \left(\int_A \rho V^2 dA \right) = -A \frac{\partial p}{\partial s} - \int_p \tau_w dl - g \left(\int_A \rho dA \right) \frac{\partial z}{\partial s} \quad (10)$$

where p is pressure, τ_w is the viscous shear stress and g is gravitational acceleration.

General conservation of energy is given by

$$\begin{aligned}
& \frac{\partial}{\partial t} \left(\int_A \rho H dA \right) + \frac{\partial}{\partial s} \left(\int_A \rho V H dA \right) + \frac{\partial}{\partial t} \left(\int_A \frac{1}{2} \rho V^2 dA \right) \\
& \quad + \frac{\partial}{\partial s} \left(\int_A \frac{1}{2} \rho V^3 dA \right) \\
& = \int_{P_h} q'' ds + \int_A q''' dA + \frac{\partial}{\partial t} (pA) - g \sin \theta \int_A \rho V dA
\end{aligned} \tag{11}$$

where H is enthalpy, q'' is heat generation per unit area, P_h is perimeter, q''' is heat generation per unit volume and θ is the angle of flow conduit from the horizontal (assuming gravity works perpendicular to the horizontal). The heat flux term (q'') is written in terms of the heat transfer coefficient.

As Flownex® employs a homogeneous model for two-phase flow, it is imperative to discuss the assumptions involved. This is done in the next section.

2.3.4 Homogeneous model assumptions

Li et al [22] describe the homogenous model as a two-phase fluid, viz a vapour and liquid phase that behaves as a single, flowing fluid. This is based on the assumption that nucleation boiling flow is simulated in the nucleate regime where the vapour phase is expressed as discrete bubbling, homogeneously mixed in a continuous liquid phase. Ghiaasiaan [11] further mentions that the homogeneous model assumes that both phases are well mixed and have the same velocity at any given location. Li et al [22] further indicate that the best approach in analysing the two-phase flow process is CFD simulation. Furthermore, the homogeneous model is the most pragmatic method for modelling these complex two-phase flows.

The present study will utilize Flownex® as a pragmatic approach to studying and analysing the thermal hydraulics performance of the steam generator. This homogeneous model is governed by the conservation of mass, momentum and energy equations as previously tabled. It is also well suited for use in conjunction with the Chen correlation.

2.4 Steam generator simulation boundary conditions and outcomes

For the purpose of building a steady-state two-phase numerical model of the steam generator, the following primary side boundary conditions are to be specified [3]:

- Mass flow rate of primary fluid (based on the pump design);
- The inlet temperature of primary fluid;
- The outlet pressure of the primary fluid;

On the secondary side, the following boundary conditions were required:

- Mass flow rate of feedwater added into the downcomer;
- Feedwater inlet temperature;
- Pressure in the steam dome;
- Flow resistance to ensure that the plant operating conditions are met.

The specific systems CFD model of the steam generator developed for this study is detailed in the next chapter.

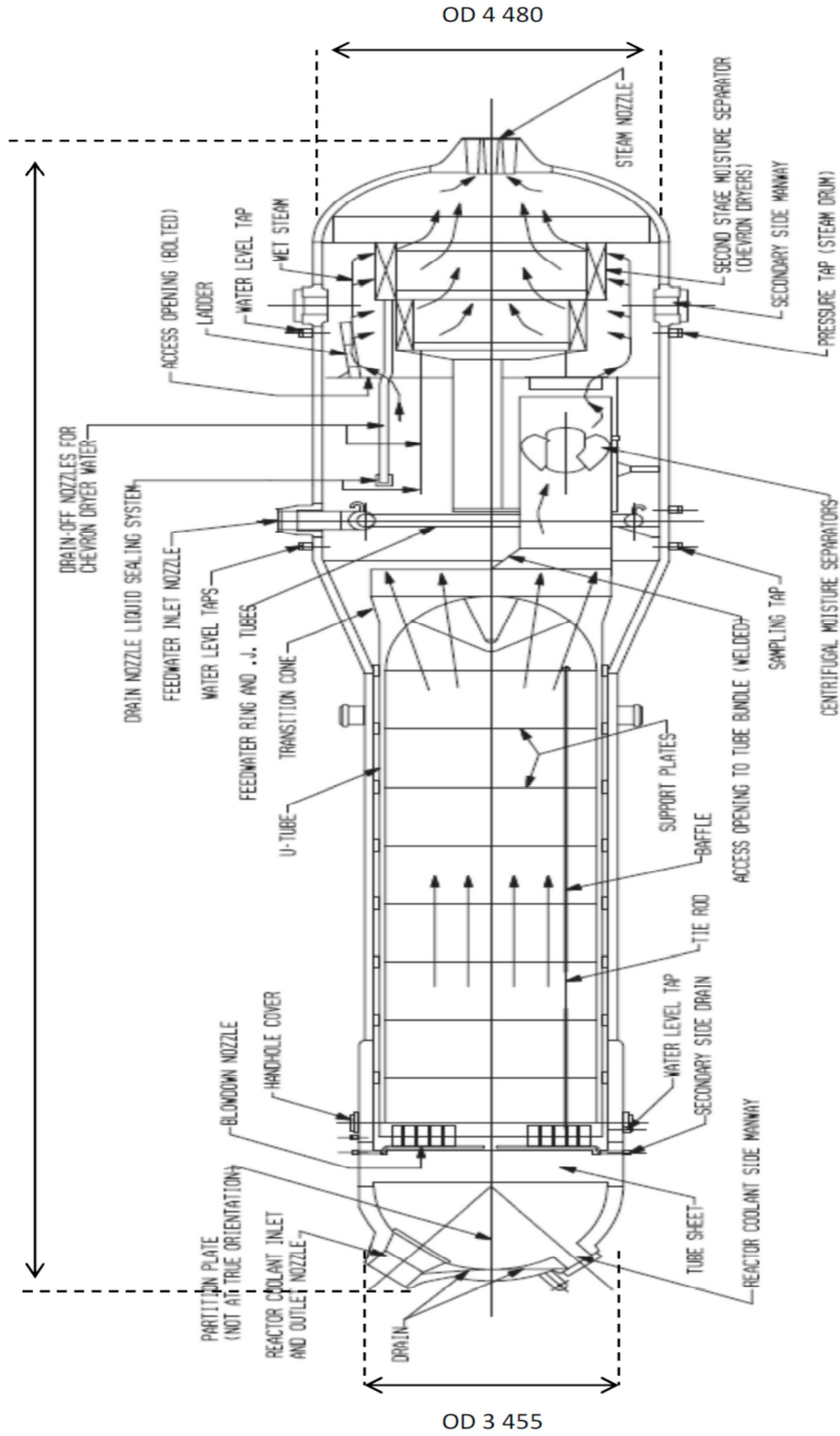
CHAPTER 3: Modelling methodology and validation

The objective of this project was to determine the thermodynamic effects of tube plugging on a U-tube steam generator. To achieve this, a thermodynamic model representing a working steam generator was developed in the Flownex® simulation environment. Flownex® was chosen due to its capabilities to perform thermal hydraulic analysis for both steady-state and transient systems. In particular, the software was demonstrated to be accurate in modelling the exact same steam generator in recent work [10]. The work described in this thesis builds on the aforementioned.

The particular steam generator device under consideration is the Eskom Koeberg Nuclear Power Plant (NPP) unit model 51B as shown in Figure 5 (general geometry showing the steam-water flow path [14]). This is a Westinghouse design series of steam generator. The Koeberg NPP operational data was used as input boundary conditions for the simulation model as documented by Cilliers [10]. This includes the primary and secondary inlet temperatures, secondary feedwater flowrate and outlet pressure.

The key geometric dimensions and thermal characteristics of the steam generator in Figure 5 are detailed in Section 3.1 below. This section will further highlight the effect of tube plugging on those thermal parameters.

20 648



S.G. 51 B.

Figure 5: Steam generator geometry and water-steam flow path

3.1 Geometry of the steam generator

The key dimensions of the secondary side (shell side) are presented in Table 2.

Table 2: Secondary side dimensions

Characteristics	Units (mm)
Height	20 648
Steam dome diameter	4 468
Down-comer (OD)	3 455
Down-comer (ID)	3 327
Down-comer thickness	64
Inter-tube distance (square pitch)	32.54

Various dimensions of the primary side (heating surface) are given in Table 3.

Table3: Heat exchange surface dimensions

Component	Value
Number of tubes (tube bundle)	3 330
Outside tube diameter, mm	22.22
Tube thickness, mm	1.27
Length of tubes, m	22.824
Mean length of tubes, m	21.282
Total exchange surface, m ²	4 699

The thermal design characteristics of the steam generator at full load, obtained from the Koeberg NPP design basis, are defined in Table 4 for the primary side and Table 5 for the secondary side [14]

Table4: Primary side thermal design heat characteristics

Characteristics	Value
Heat transfer rate, MWth	928.3
Reactor coolant inlet temperature, °C	312.37
Reactor coolant outlet temperature, °C	278.8
Reactor coolant inlet pressure, bar	155

Table5: Secondary side thermal design heat characteristics

Characteristics	Value
Feedwater inlet temperature, °C	219.4
Steam generator saturation pressure, bar	49.1
Feed/steam flowrate, t/h	1803.4
Steam generator outlet maximum moisture carryover, %	0.25

The parameters listed in Tables 4 and 5 are expected to change as follows as a result of tube plugging:

- Tube plugging will affect the number of tubes available for primary coolant flow;
- The total primary coolant flow rate is expected to reduce and pressure drop to increase because of increased flow resistance (as a function of pump curve);
- Total heat transfer area will be reduced for both the primary and secondary side;
- Heat transfer rate will be reduced owing to a drop in total heat transfer area;
- Reactor coolant outlet temperature will be affected as a result of change in both flow rate and heat transfer area;

- Steam production will be reduced.

The simulation will provide a quantitative insight into the above-mentioned effects due to tube plugging. The following section will discuss the formulation and detail of the components used from Flownex® to represent a steam generator.





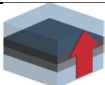

3.2 Model development

3.2.1 Flownex® components

Flownex® uses nodes (the connection points between elements) and elements (components used for simulation) to represent a thermal-fluid network [23]. The following elements were used for a model development: pipes, heat transfer elements and two-phase tank (see Table 6). This was in accordance with the Cilliers model [10].

The pipe components in the model represent the dimensions of the volumetric structure for both primary and secondary sides of the steam generator. Heat transfer through the pipe walls of the primary fluid to the secondary fluid was done using the heat transfer element. In accordance with the Flownex® library manual, the two-phase tank component is used to model a tank containing two-phase fluids with phase separation [23].

Table 6: Flownex® components used for the model

	Boundary Condition
	Node
	Pipe
	Two-phase Tank
	Composite Heat Transfer Component
	Mathcad® Worksheet

The secondary side of the steam generator consists of the two-phase fluid due to boiling heat transfer on the shell side. Furthermore, two-phase separation occurs in the two-phase tank where gas rises through the steam dome because of the density difference between steam and liquid water. The remaining liquid, after fluid separation has occurred, returns to the down-comer annulus as part of the feedwater. This process is called circulation (reflux). The presence of the circulation process has the following importance in the steam generator operation [24]:

- It ensures that the heating surface is always covered with steam-water mixture, creating a positive effect on the heat transfer process;
- It preheats the feedwater and subsequently reduces the temperature difference between the feedwater and the heating surface (reduces the thermal stress within the component).

At full load operation, the ratio of circulation (C) to fresh feedwater is 4:1, calculated as follows:

$$C = \frac{\text{downcomer flow}}{\text{exit steam flow}} \text{ or } CR = \frac{\text{riser flow}}{\text{exit steam flow}} \quad (12)$$

where CR is for recirculation, which is defined as the amount of flow in the riser to exit steam flow. The circulation ratio and recirculation ratio are both indicators of internal mixing, i.e the riser flow is equivalent to downcomer flow, hence they are numerically equal. Although circulation ratio and recirculation ratio are equivalent, for the purpose of this study and consistency of calculation, reference will be made to circulation ratio.

3.2.2 Geometry of the steam generator model

In the interests of accuracy and to gain more detailed information on the thermal performance of the steam generator, the volumetric structure of the pipes was discretized into increments. The input used for the model and detailed dimensions of the component structure are listed in Tables 7 to 9.

Table 7: Geometric inputs for the primary side of the model

Component	No. of increments	Length (m)	Hydraulic diameter (m)	Circumference (m)	Area (m ²)	Volume (m ³)
Primary inlet	1	0.795				
Primary tube bundle	10	22.824	0.01968	205.882	1.0129	23.118
Primary outlet	1	0.795				

Table 8: Geometric inputs for the secondary side of the model

Component	No. of increments	Length(m)	Hydraulic diameter (m)	Circumference (m)	Area (m ²)	Volume (m ³)
Feedwater inlet pipe	1	3			0.342	1.026
Down-comer annulus	5	11.41	0.0385	20.809	0.682	7.78
Heated region	5	11.41		485.782	7.402	84.459
Unheated region	1	1.15			9.321	10.719
Separator	1	2.792			1.588	4.434
Dryer	1	2.978			15.763	46.943
Two-phase Separation tank	1	2.058			15.763	32.441
Steam dome	1	3.158			15.763	49.78
Reflux	1	4.862			15.763	76.641
Down-comer	1	2.058			15.763	32.441

The heat transfer component structure and dimensions used as input to the model are tabulated in Table 9.

Table 9: Heat transfer component input to the model

Component	Upstream	Down stream	Upstream area (m ²)	Downstream area (m ²)	Length (m)	Number of nodes	Thickness (m)
Composite heat transfer	Primary tube bundle	Heated region	4699	5305	22.824	2	0.00127

3.2.3 Two-phase separation

For the systems CFD model, a two-phase tank was used to simulate the separation of steam from water due to density differences (as noted previously). To enable modelling steam and liquid water separation for different plugging ratios, the resistance to flow on the downcomer flow path was adjusted for a 0% plugging scenario to achieve the design re-circulation ratio i.e. of circa 3.8 (based on the nominal design at 100% reactor power). This is such that, as the plugging ratio

increases, the quality in the boiling region is expected to decrease. Therefore, the re-circulation ratio is expected to increase.

3.2.4 Reactor coolant pump design

The RCP Pump is responsible for circulating reactor coolant water (primary side) between the steam generator and the reactor. A variable speed pump component was employed to model this i.e. speed is adjustable during transient simulations [23]. The pump performance curve of the actual RCP pump (see appendix B) was used to generate the pressure rise, hydraulic efficiency data and NPSH data. The pump was set-up in the simulation so as to achieve the design reactor coolant flowrate at the base scenario (0% tube plugging). The resulting coolant flow rate due to plugging is then automatically adjusted.

Heat transfer coefficient determination in the model that facilitates heat transfer and production of steam in the boiling region of the steam generator is discussed in the following section.

3.2.5 Heat transfer correlation

Flownex is a homogeneous two-phase flow model, with the Dittus-Boelter correlation being used to calculate the heat transfer coefficient for forced convection and Sato and Matsumara [21] to predict onset nucleate boiling. Dittus-Boelter is a well-known correlation and is widely used for single-phase flow [25].

For a steam generator simulation, it is imperative to simulate the conditions that occur during the heating process. Due to the boiling heat transfer that takes place inside the boiling region and two-phase formation, an appropriate homogeneous heat transfer correlation for two-phase flow is essential. As stated previously, the Chen correlation for boiling heat transfer was used. It is, however, non-linear and defined implicitly as a function of quantities such as wall temperature.

Flownex® has the capability and functionality to import and export data to other scientific applications or software. To deal with iterative interaction with the Chen correlation, the heat transfer coefficient calculations were implemented using Mathcad® (the programming code is included in Appendix A). The Mathcad® worksheet from the Flownex® component library was used to specify the properties that would be retrieved from the Flownex® network. The latter is

used to facilitate the background calculations in Mathcad® and return the solution (heat transfer coefficient) to the heat transfer component in Flownex® network. This was done iteratively during the process of the steady-state simulation until the heat transfer coefficient converged.

3.2.6 Mathcad script for secondary feedwater flowrate

At the base case scenario (0% tube plugging), the key boundary conditions of the steam generator are known as discussed in 3.1 above. Once plugging is performed, certain boundary conditions changes in accordance. The Flownex model is to adjust these accordingly. Since, tube plugging hinders heat transfer between primary and secondary sides, the steam production rate also decreases. Therefore, the unknown boundary condition in this case will be the secondary side feedwater inlet flowrate. Flownex assumes mass balance through the system, therefore, the feedwater inlet is to balance steam outlet flow. A script was developed to compute the rate of steam productions, which was then translated to feedwater inlet flow (see Chapter 4 and Mathcad script in Appendix C).

Figure 6 represents a steam generator model developed for the Flownex® simulation.

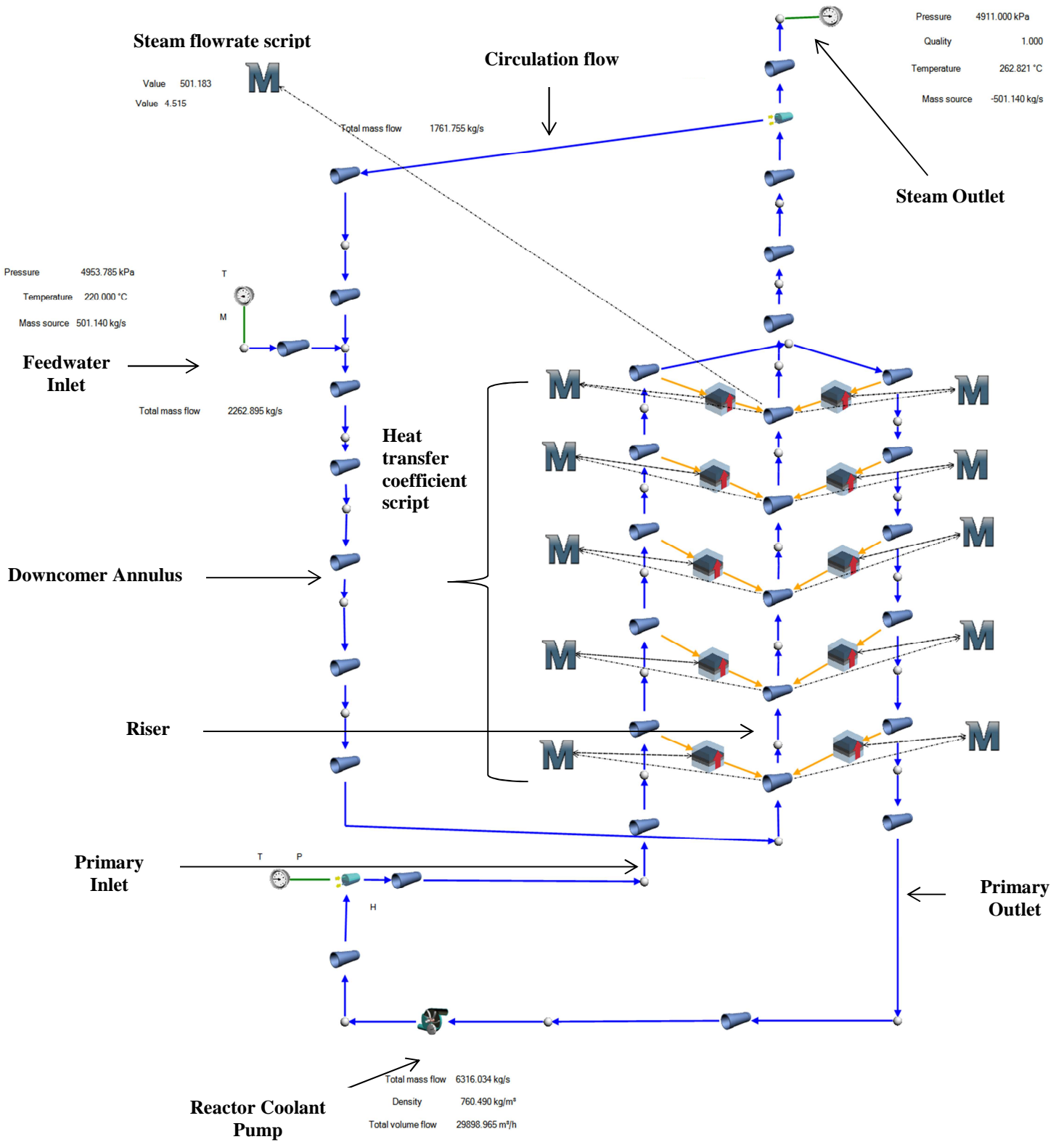


Figure 6: Flownex® steam generator model.

3.3 Model validation process

Prior to using the developed model to predict the thermodynamic effects of tube plugging, it should be validated. This is done next.

3.3.1 Operational characteristics

To validate the model, the thermal hydraulic results produced by the model developed above were compared to the results obtained from the literature [10]. In order to ensure a direct comparison, similar boundary conditions were used. The model was simulated at 100% steam generator power. Table 10 presents the boundary conditions used for the model validation.

Table 10: Boundary conditions at 100% power

	\dot{m} (kg/s)	T(°C)	P(Mpa)
Primary inlet	6316.61	312	
Secondary outlet			4.911
Secondary inlet	618	220	

To ensure a direct comparison, the heat transfer coefficients (Chen correlation) from [10] were used.

Table 11 compares results of the current model to that of Cilliers, proving accuracy and consistency. The most noticeable differences are the recirculation ratio, secondary feed pressure and heat transfer rate, which were found to be 1.846%, 0.121% and 0.042% respectively. The deviation between these two models is due to the fact that the primary inlet flowrate used in the current model was obtained by using a speed variation pump to simulate RCP pump and the best estimated flow obtained by the simulation was 6316.6kg/s (while the earlier model specified 6316kg/s). This 0.6kg/s higher primary flowrate caused the model to converge at a slightly higher recirculation ratio (see Table 11). Other results showed similarities of over 99%. This confirmed and concludes that the current model was correctly implemented.

Table 11: Current model validation

	T_{pi} (°C) Units	T_{po} (°C) Units	P_{so} (kPa)	P_{si} (kPa)	T_{si} (°C) Units	x_{so}	m (kg/s)	Q (MW)	Circ ratio
Previous model [10]	312	280	4911	4951	220	1.00	618	1092	3.80
Current model	312	280	4911	4957	220	1.00	618	1092.5	3.87
Error %	0	0	0	0.121	0.00	0	0	0.042	1.842

The nomenclature in this table is as follows:

T_{si} - Temperature of the secondary side inlet flow;

T_{po} - Temperature of the primary side outlet flow;

P_{so} - Pressure of the secondary side outlet flow (steam pressure);

P_{si} - Pressure of the secondary side inlet flow;

x_{so} - Steam quality;

m - Mass flowrate;

Q - Heat transfer.

3.3.2 Detailed comparisons of the models

This section presents a more detailed thermal hydraulic performance comparison between the model from Cilliers [10] and the current model. The results will depict when the same Chen heat transfer coefficients are employed as well as when the corrected Chen correlation is used. When the latter occurs, it is referred to as Corrected Chen, shown graphically in Figures 7 to 12.

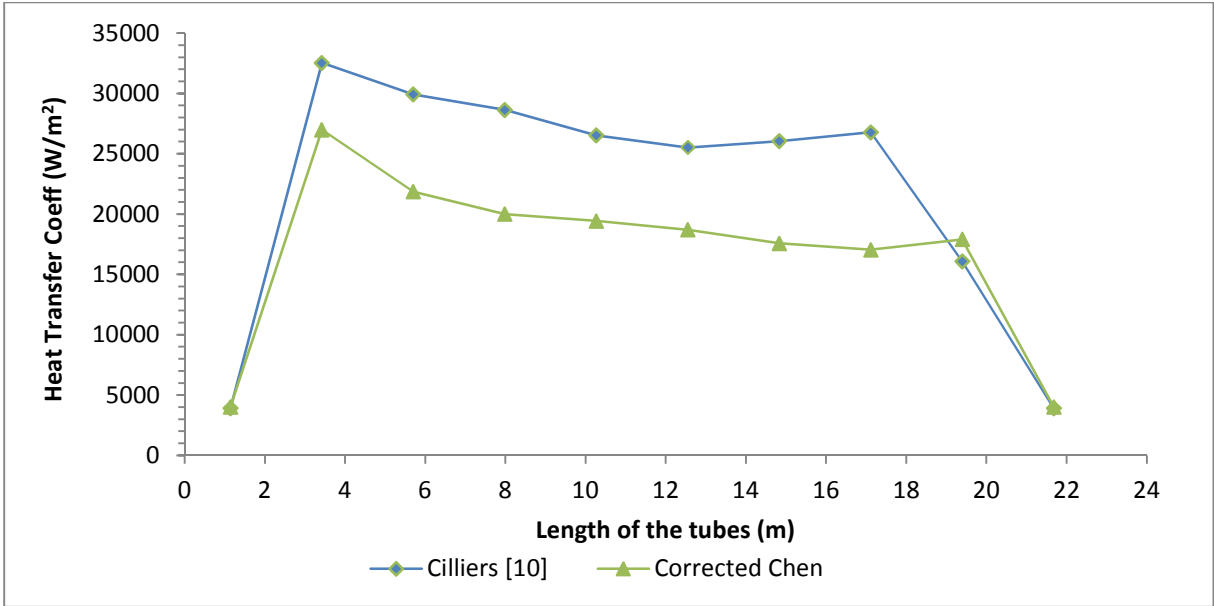


Figure 7: Heat transfer coefficient on the surface of the tubes

The noticeable differences in Figure 7 start when saturation point is reached, owing to different parametric equations for the corrected model and that used previously. The corrected parametric equation [13] is seen to predict a lower heat transfer coefficient.

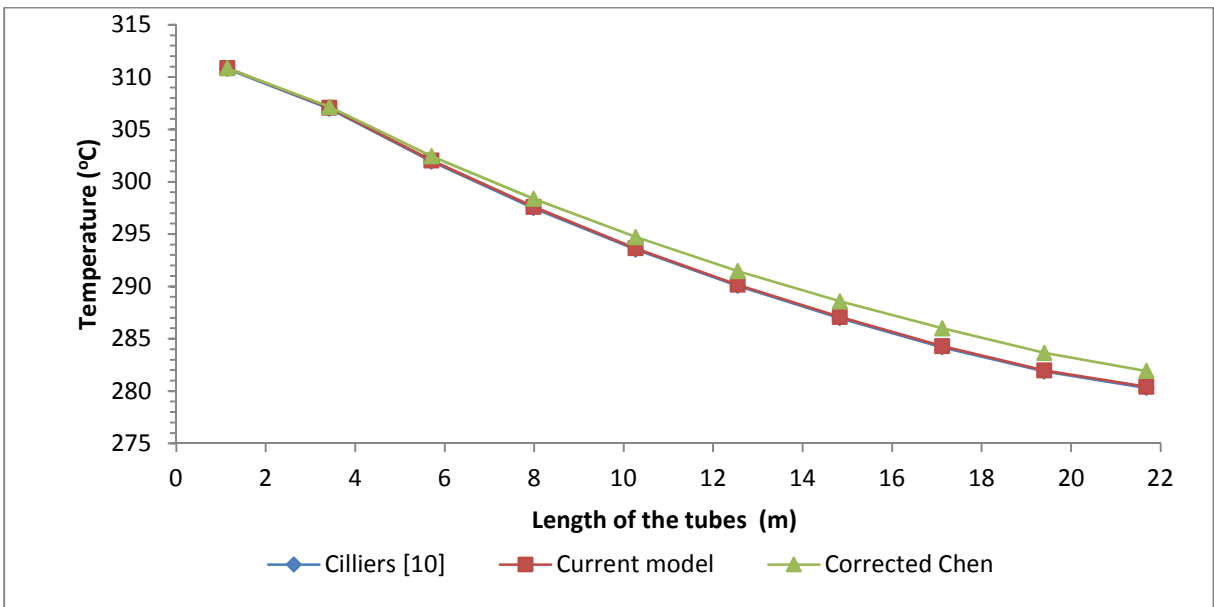


Figure 8: Primary side fluid temperature

The predicted primary side fluid temperatures for both models are identical when the same Chen heat transfer coefficients are employed (Figure 8). The corrected Chen results indicate a similar declining trend; however, predicted temperatures are on average of about 1°C higher than previously.

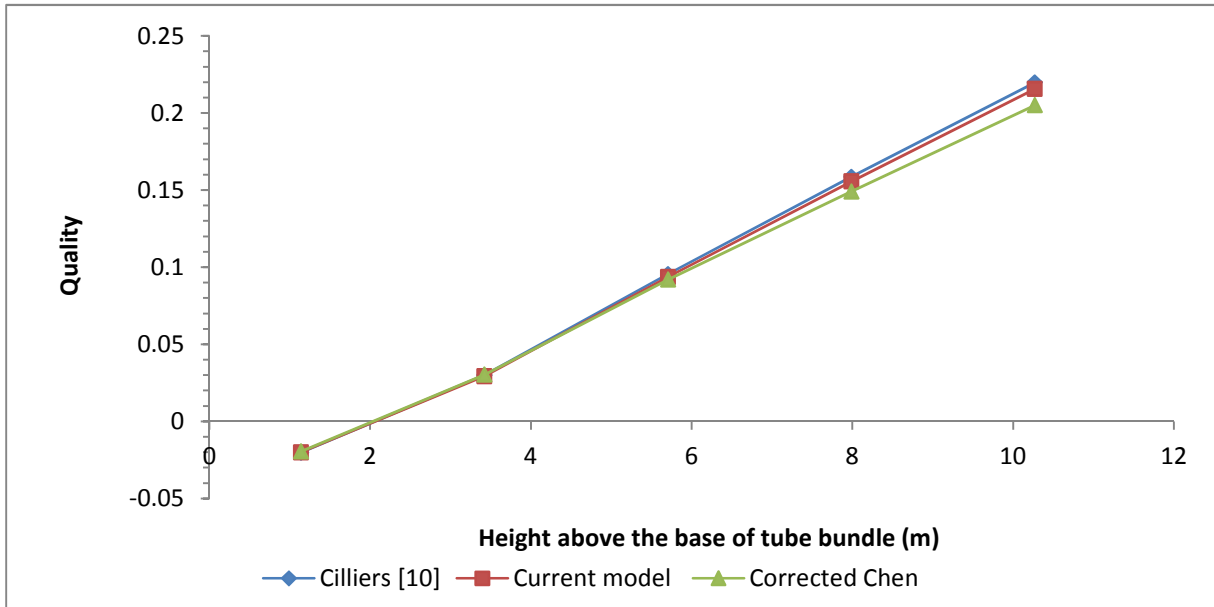


Figure 9: Secondary quality through the boiling region

The secondary side steam quality profiles (Fig. 9) are almost identical for when the same Chen correlations are employed. The slight deviation in the results is due to the slightly higher recirculation ratio indicated by the current model. The higher recirculation ratio relates to slightly less quality in the top of the tube bundle. The corrected model, however, predicts a 4% lower peak quality.

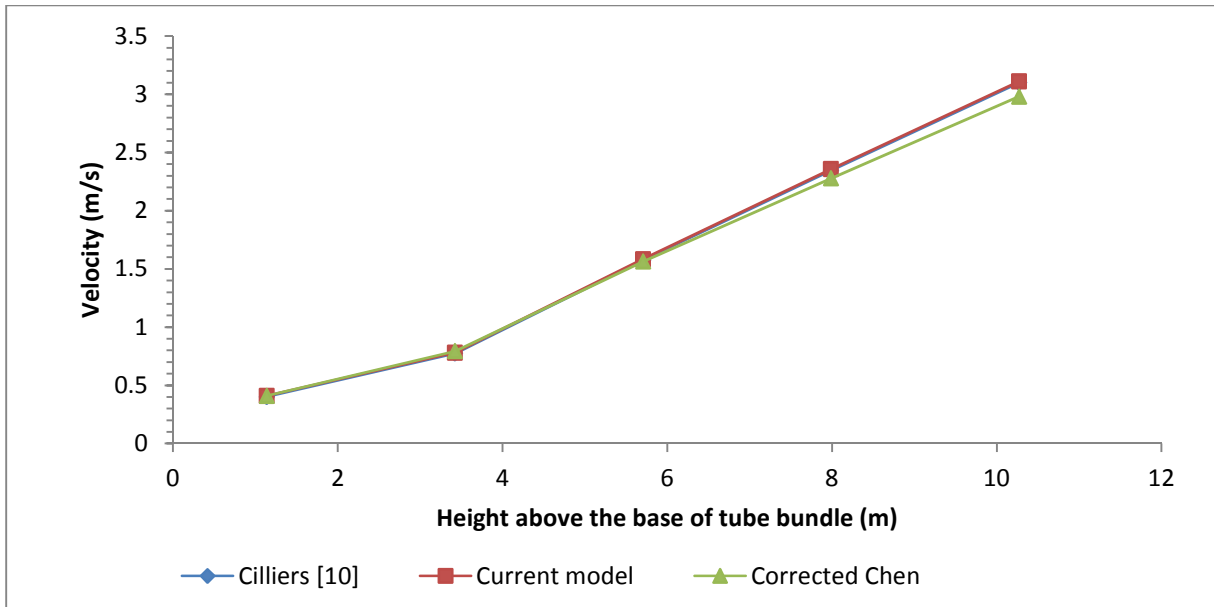


Figure 10: Flow velocity through the boiling region

Figure 10 depicts the two-phase velocity change over the tube bundle. Correcting the Chen correlation alters this by circa 4%. The predicted secondary surface temperature (Fig. 11) is again practically identical if using similar Chen correlations. However, when correcting the latter, a 0.67% maximum normalised temperature difference occurs. Finally, heat flux (Fig. 12) shows a 4% difference due to correcting the Chen correlation.

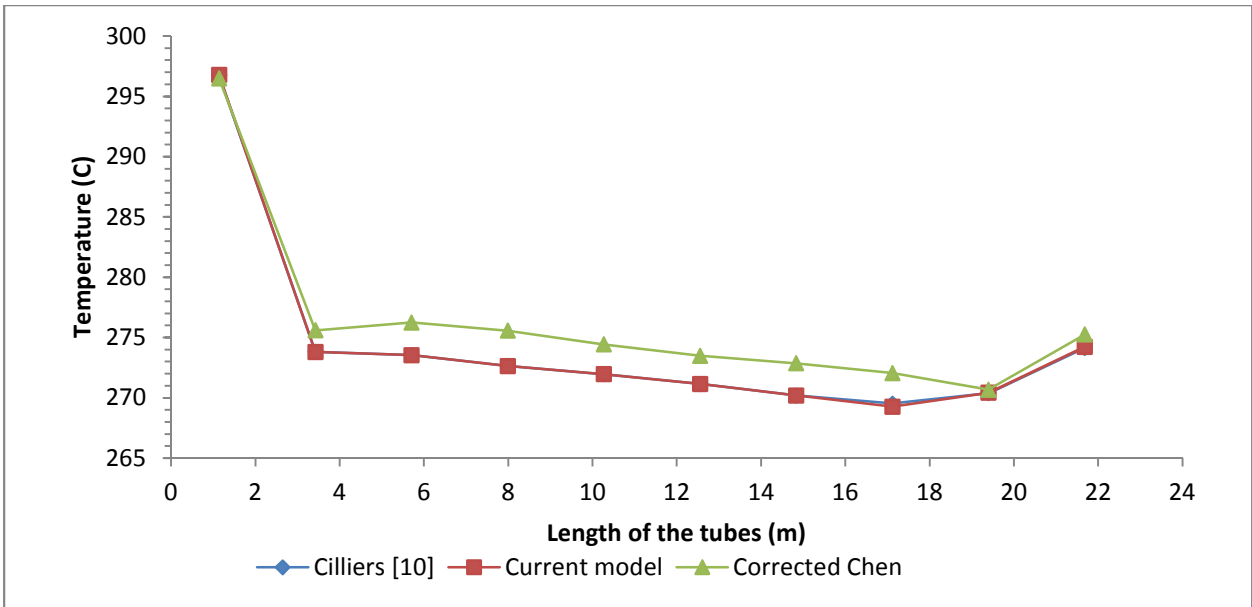


Figure 11: Secondary surface temperature on the tubes

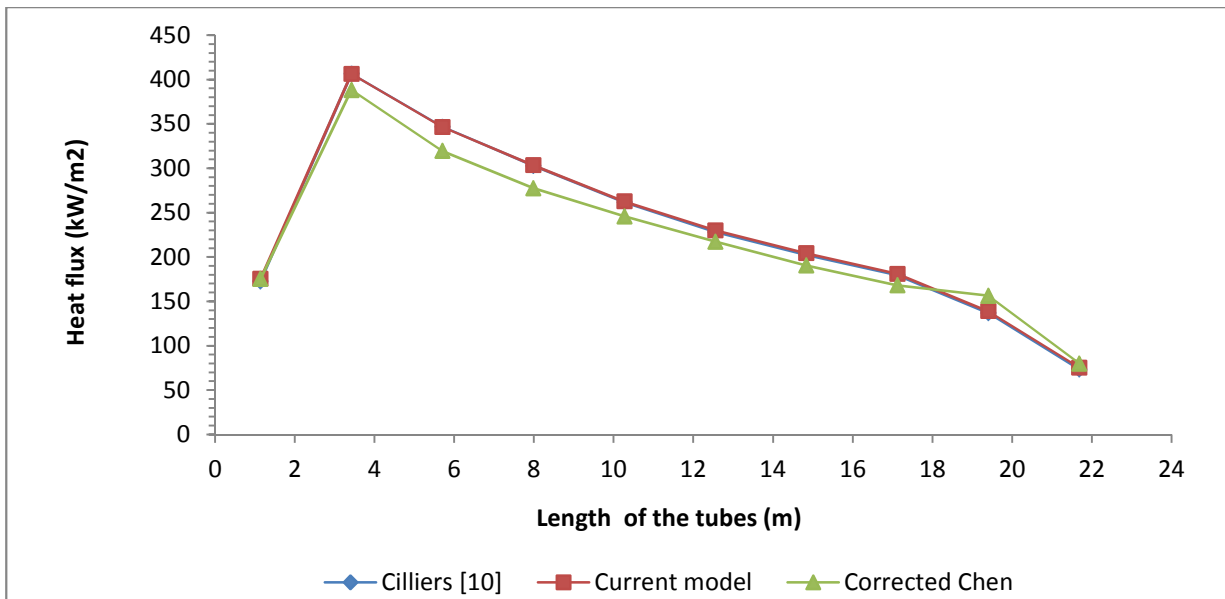


Figure 12: Heat flux on the surface of the tubes.

Figures 8 to 12 prove that the steam generator model developed in this work is correct as compared to earlier work [10]. In addition, the corrected Chen correlation is shown to alter the

results by circa 10%, and is therefore to be employed when investigating the effect of tube plugging.

CHAPTER 4: Tube plugging simulation methodology

This chapter describes the tube plugging model set-up. The base line model is assumed to be free of tube plugging. Therefore, the design base information of the steam generator [14] is used as the boundary condition for the base line model.

Different plugging ratios are used to establish the effect of plugging on thermal performance. The plugging ratios are in the range of 0% (base line model) to 20%. The limit of 20% is based on the estimate, obtained from the relevant literature, regarding a plugging ratio to ensure adequate heat removal from the reactor at full load. However, the results presented here will determine the critical parameter that will be the limiting factor when a homogeneous model is employed.

The following simplifying assumptions were employed for the tube plugging study:

- On the primary side water circuit, only the steam generator pressure loss due to flow resistance was accounted for;
- The effect of change in primary flow water properties due to tube plugging was negligible;
- The position of the plugged tubes was not taken into consideration;
- The effect of fouling was not considered;
- All tubes were the same length;
- Only one steam generator was simulated on the assumption that other steam generators in the unit were exposed to similar conditions. **NB:** Koeberg Nuclear Power Station is a three-loop unit (three steam generators per unit.);
- Density and specific volume of steam were assumed to be constant.

The boundary conditions for the base line model have already been stated. However, due to tube plugging, certain boundary conditions are affected and need to be determined. The affected parameters were:

- Steam/feedwater flowrate, and
- Primary water flow rate.

Furthermore, since the steam generator discussed in this study produces saturated steam, the parameters that remained constant throughout the simulation were the following:

- Steam pressure outlet;
- Steam temperature, and
- Steam enthalpy.

The methodology employed to determine the above for each plugging ratio is described next.

4.1. Boundary condition determination

4.1.1 Steam/feedwater flowrate

For the base line model (no plugging), the boundary conditions required are known. However, once the fraction of tubes is plugged, the amount of feedwater changes due the change in steam generated. This was applied via the development of a Mathcad script i.e. to adjust the feedwater flow rate to equal the amount of steam extracted. Detailed Mathcad script used, see appendix C.

4.2. Model boundary conditions

4.2.1 Base case model (0% plugging)

Chapter 3 validated the base case, which was therefore used as the initial condition to determine the boundary conditions for the first plugged case. Table 12 (repeated for ease of reference) presents boundary conditions obtained from the design base documents [14]. It must be noted that the primary flowrate was not specified, it was rather simulated via speed variable pump as per Section 3.2.4. Furthermore, the system is a closed loop on the primary side.

Table 12: Boundary conditions at 0% plugging

	$\dot{m}(\text{kg/s})$	T(°C)	P(Mpa)
Primary inlet	6316.034	312	15.5
Secondary outlet			4.911
Secondary inlet	500.94	220	

Table 13 presents the geometric input to the model that will be affected by tube plugging, i.e. plugging will affect the number of tubes available for heat transfer, and hence the primary and secondary heat transfer area. In addition, the primary flow area will be reduced.

Table 13: Model input at 0% plugging

Quantity	Input
Number of tubes	3330
Primary Surface Area, m²	4699.056
Secondary Surface Area, m²	5305.54

4.2.2 5% tube plugging

Table 14 presents the boundary conditions determined for 5% tube plugging.

Table 14: Boundary conditions at 5% plugging

	<i>m</i>(kg/s)	T(°C)	P(Mpa)
Primary inlet	6264.928	312	15.5
Secondary outlet			4.911
Secondary inlet	486.437	220	

Table 15 presents the area input at 5% tube plugging, Appendix D contains the sample calculation for determining these inputs.

Table 15: Model input at 5% plugging

Quantity	Input
Number of tubes	3164
Primary Surface Area, m²	4463.269
Secondary Surface Area, m²	5039.322

4.2.3 10% tube plugging

Table 16 presents the boundary conditions at 10% tube plugging.

Table 16: Boundary conditions at 10% plugging

	\dot{m}(kg/s)	T(°C)	P(Mpa)
Primary inlet	6208.335	312	15.5
Secondary outlet			4.911
Secondary inlet	471.892	220	

Table 17 presents the area input at 10% tube plugging

Table 17: Model input at 10% plugging

Quantity	Input
Number of tubes	2997
Primary Surface Area, m ²	4229.15
Secondary Surface Area, m ²	4774.986

4.2.4 15% tube plugging

Table 18 presents the boundary conditions at 15% tube plugging.

Table 18: Boundary conditions at 15% plugging

	<i>m</i> (kg/s)	T(°C)	P(Mpa)
Primary inlet	6144.411	312	15.5
Secondary outlet			4.911
Secondary inlet	456.011	220	

Table 19 presents the area input at 15% tube plugging.

Table 19: Model input at 15% plugging

Quantity	Input
Number of tubes	2830
Primary Surface Area, m ²	3993.492
Secondary Surface Area, m ²	4508.912

4.2.5 17.3% tube plugging

Table 20 presents the boundary conditions at 17.3% tube plugging.

Table 20: Boundary conditions at 17.3% plugging

	\dot{m} (kg/s)	T(°C)	P(Mpa)
Primary inlet	6112.26	312	15.5
Secondary outlet			4.911
Secondary inlet	447.9	220	

Table 21 presents the area input at 17.3% tube plugging.

Table 21: Boundary conditions at 17.3% plugging

Quantity	Input
Number of tubes	2754
Primary Surface Area, m ²	3886.07
Secondary Surface Area, m ²	4387.24

4.2.6 20% tube plugging

Table 22 presents the boundary conditions at 20% tube plugging.

Table 22: Boundary conditions at 20% plugging

	\dot{m} (kg/s)	T(°C)	P(Mpa)
Primary inlet		312	15.5
Secondary outlet			4.911
Secondary inlet	425.88	220	

Table 23 presents the area input at 20% tube plugging.

Table 23: Model input at 20% plugging

Quantity	Input
Circumference of the tube bundle, m	164.706
Primary Surface Area, m²	3759.245
Secondary Surface Area, m²	4244.432

Based on the information presented in the above tables, it is clearly noticeable that tube plugging has an impact on the following; these findings are in accordance with Pla et al [6]:

- Reduces the heat transfer area, which subsequently reduces heat transfer to the secondary side of the steam generator;
- Reduces the reactor coolant flow rate;
- Decreases the steam production rate, owing to less heat transfer.

Other key thermal results from the simulation at the different plugging ratios will be discussed in depth in the following chapter.

CHAPTER 5: Results and discussion

The investigation of the tube plugging of the steam generator was carried out through eliminating a certain fraction of tubes in the tube bundle, and altering the operational conditions as would be expected in practice (discussed in Chapter 4). The tube plugging ratios considered were the following: 0%, 5%, 10%, 15%, 17.3% and 20%.

From the resulting simulations, it was found that tube plugging alters the following:

- a) heat transfer rate;
- b) primary fluid mass flow rate;
- c) primary flow velocity;
- d) primary fluid outlet temperature;
- e) pressure drop through the tube bundle;
- f) primary outlet pressure;
- g) secondary side fluid mixture quality;
- h) secondary side recirculation ratio; and
- i) steam flow rate (steam produced).

The quantitative sensitivity of each of the above to tube plugging is detailed next.

5.1 Heat transfer rate

The heat transfer rate is based on the available heating surface area. Tube plugging decreases the heat transfer area and subsequently reduces heat transfer rate. The steam generator has a power rating of 928.3 MW_{th}. Irrespective of what the reactor is doing in terms of generating heat, the steam generator has to ensure that the rated thermal heat is removed at reactor full power to cool the core. From the simulation, it was found that a 12% reduction in heat rate results when 20% of the tubes are plugged. Furthermore, the simulation reveals that 17.3% of tube plugging is the limit to maintain the steam generator full rated power of 928 MW. Plugging beyond this point proves that the system is not able to remove the required heat to cool the core at full power. The linear relationship between heat transfer area and heat transfer rate is due to faster and warmer primary flow (Figure 13). The figure highlights the proportionality between heat transfer surface area and the rate at which the heat is transferred from the primary to secondary fluid.

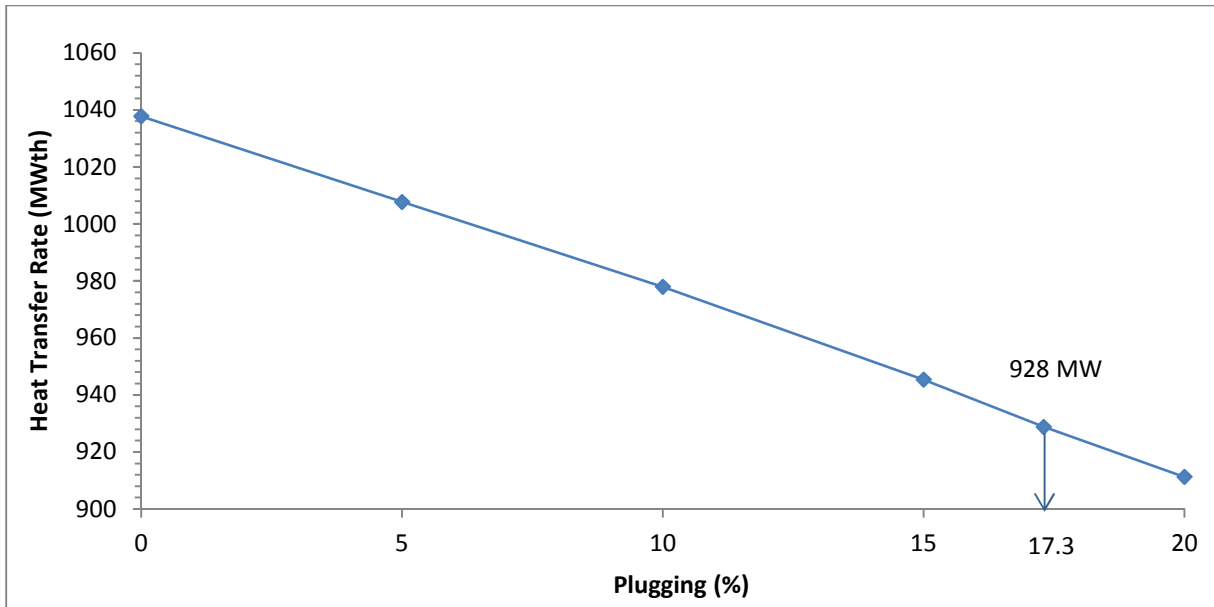


Figure 13: Heat transfer rate at the different tube plugging ratios

5.2 Primary fluid changes due to plugging

When tube plugging occurs, the primary flow area becomes less and resistance to flow increases. Due to resistance to flow, the velocity through each tube increase and mass flowrate decrease. Figure 14 shows how tube plugging affects flow changes in accordance with the primary pump’s flow vs. total head rise curve. As depicted, 20% plugging results in a circa 4% drop in flow rate. The change in flow velocity is given in Fig. 15.

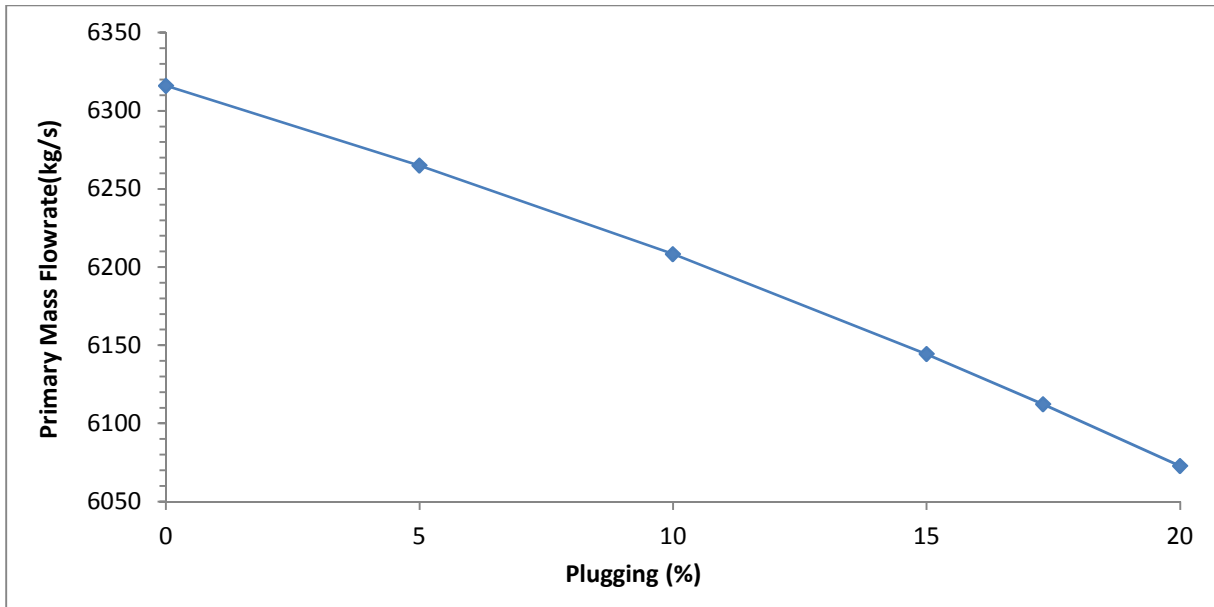


Figure 14: Primary side mass flow rate through different tube plugging ratio

Heat that is transferred from the primary fluid through the tube bundle is absorbed by the secondary fluid and subsequently boiling occurs and steam is produced. As indicated above, flow resistance due to plugging increases primary flow velocity. This phenomenon decreases the primary water heat desorption period. This, in addition to the reduced heat transfer area (due to plugging) causes the primary water outlet temperature to rise (Fig. 16).

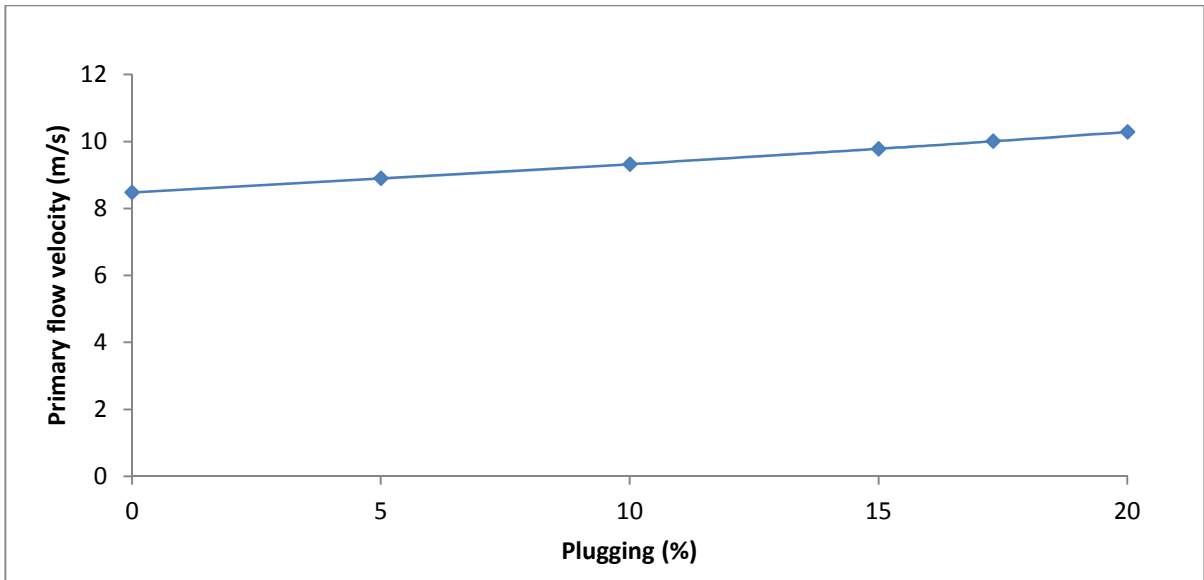


Figure 15: Primary side flow velocity at different tube plugging ratio

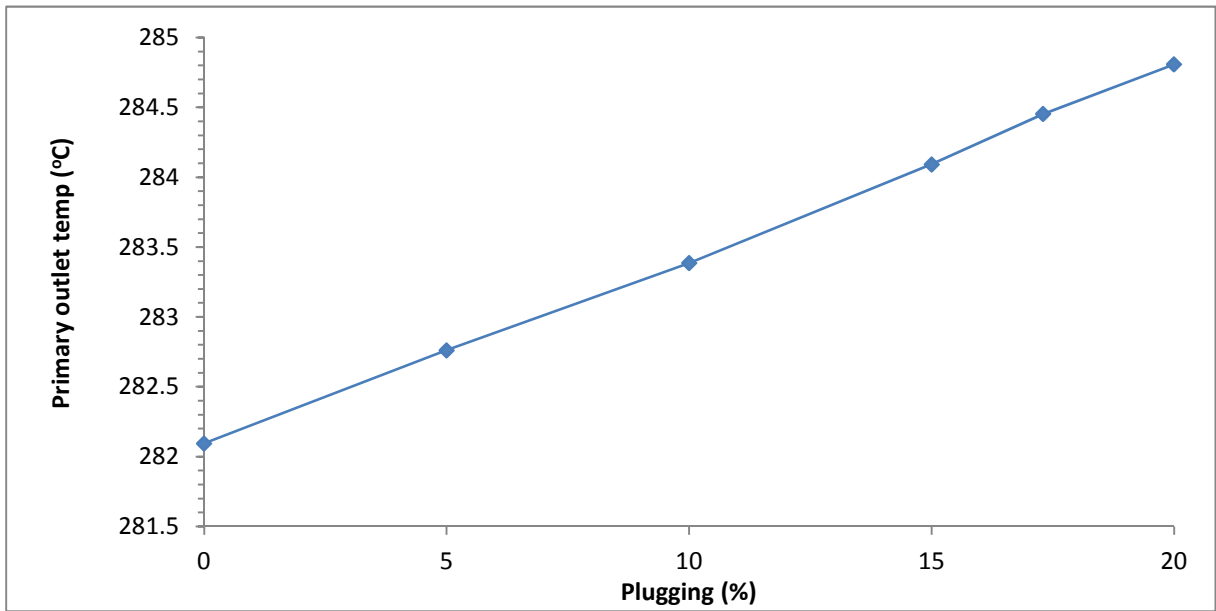


Figure 16: Primary side fluid outlet temperature at different tube plugging ratio

Figure 17, indicates a 30% increase in pressure drop through the tube bundle due to tube plugging. Figure 18 shows the resulting declining trend in outlet pressure due to this.

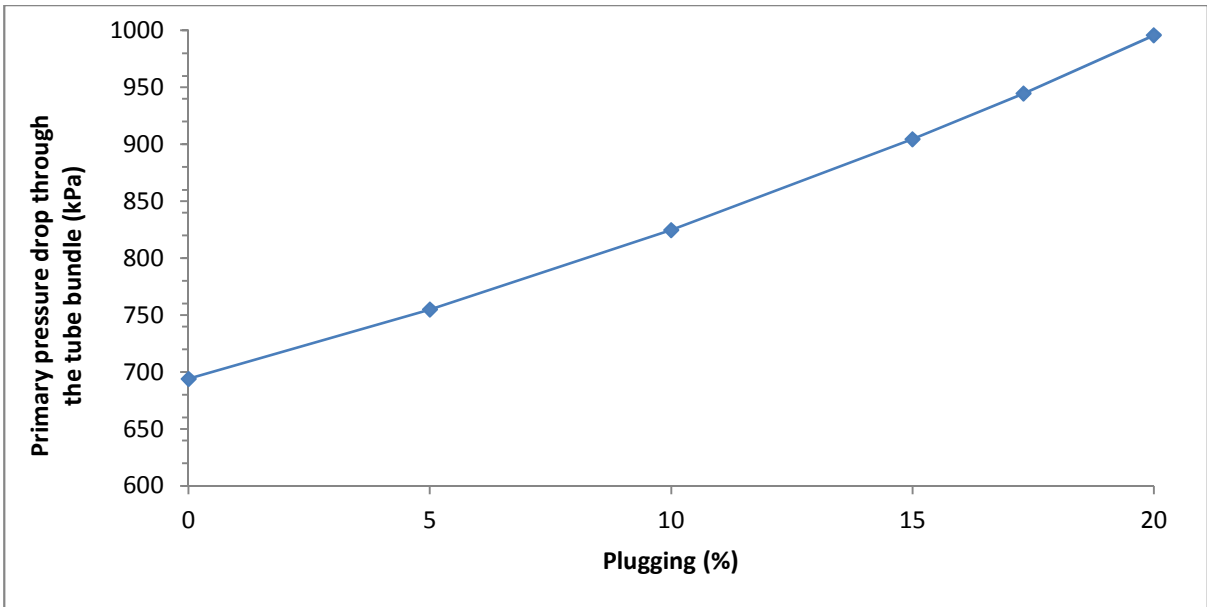


Figure 17: Primary side pressure drop through the tube bundle at different plugging ratio

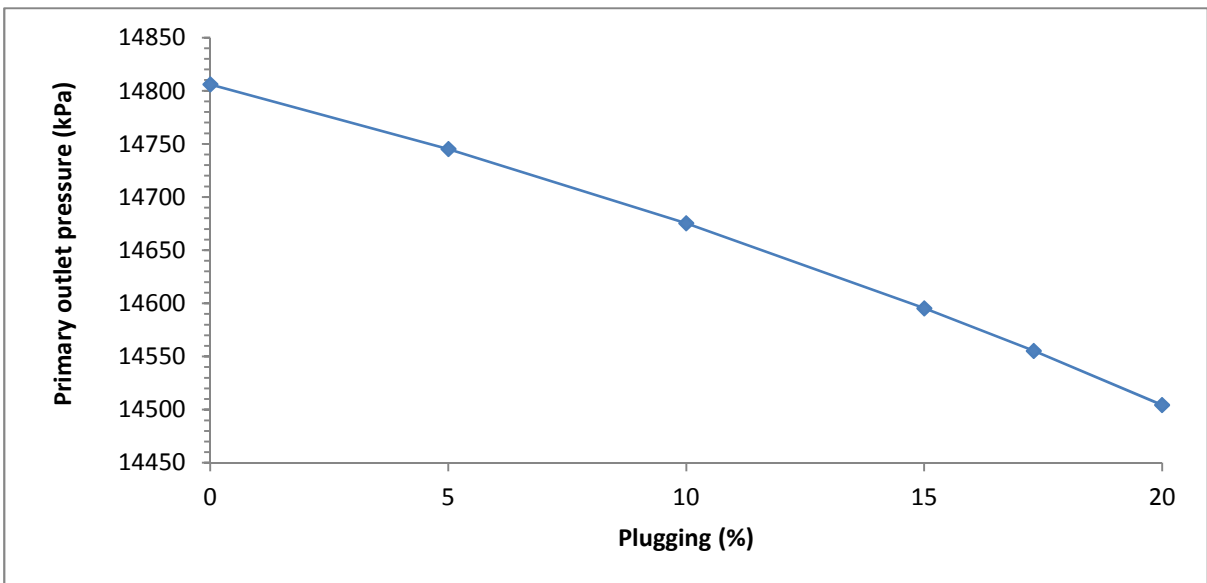


Figure 18: Primary side fluid outlet pressure at different tube plugging ratio

5.3 Secondary fluid changes due to plugging

On the secondary side of the steam generator, boiling occurs due to heat from the primary fluid heat transfer. Due to the decrease of heat transfer caused by tube plugging, the quality of the boiling mixture decreases. In other words, tube plugging affects the steam quality. Figure 19 depicts the computed drop of 12% in steam quality at the top of the tube bundle.

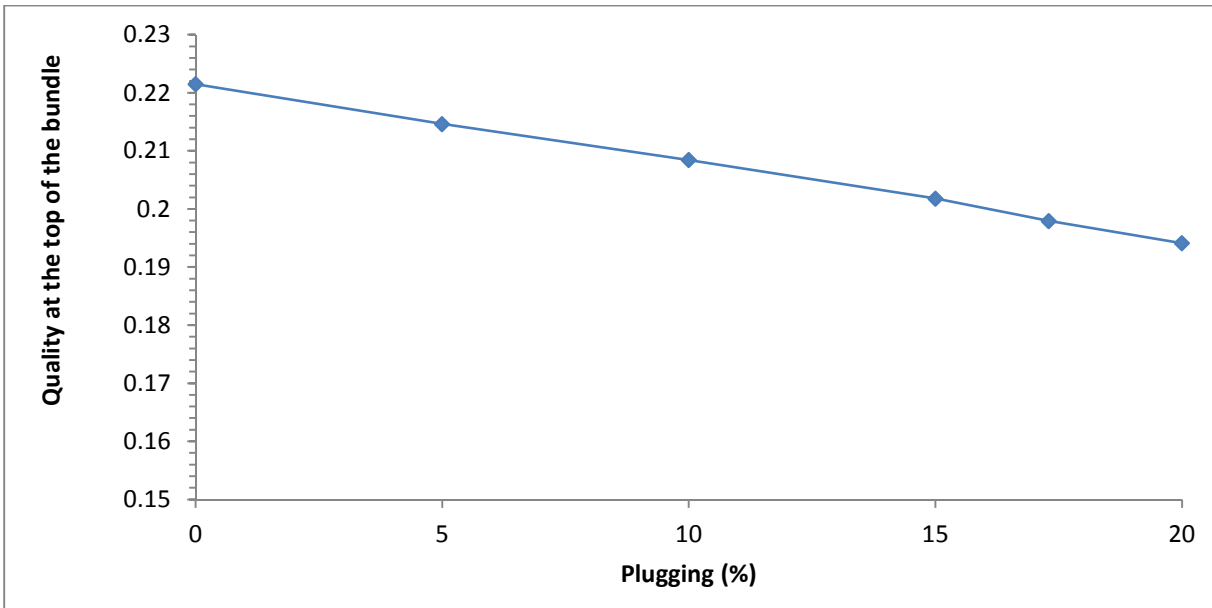


Figure 19: Secondary side fluid mixture quality at the top of the tube bundle at different plugging

When the quality of the secondary fluid mixture decreases as indicated in Figure 19, it means that the amount of liquid water has increased. This in turn increases the water reflux ratio. Figure 20, depicts that reflux ratio has further increased by circa 12%.

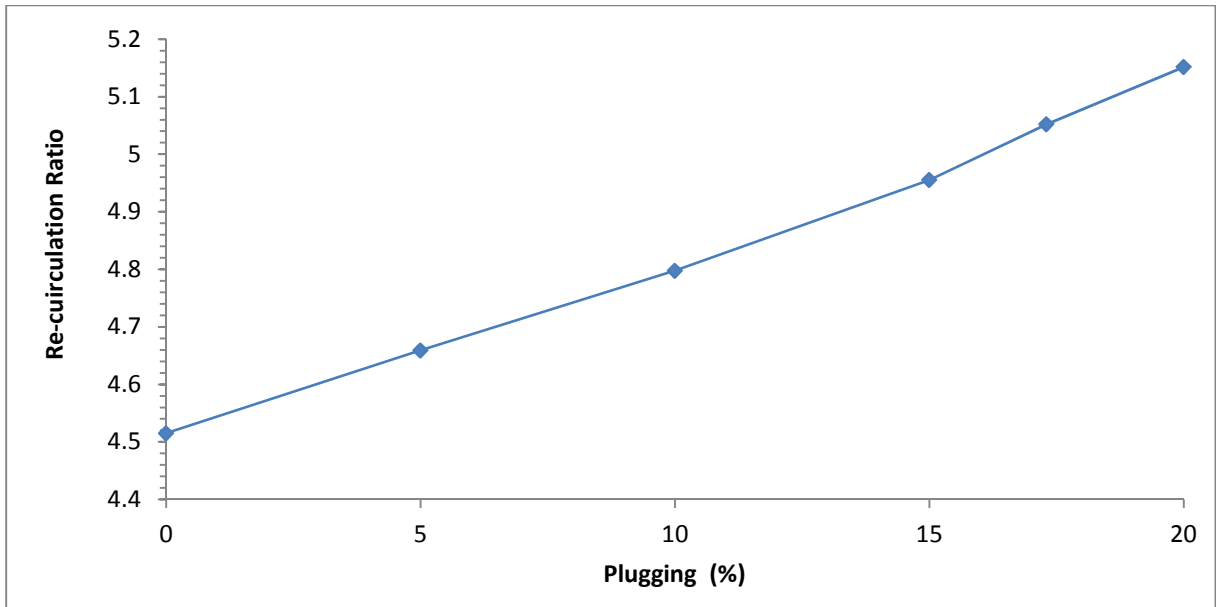


Figure 20: Secondary side fluid re-circulation ratio at different tube plugging ratio

Figure 21 depicts the computed significant drop in steam production. The figure shows a 12% drop in steam production due a 20% plugging of tubes. This essentially non-linear relationship is due the opposing effects of smaller heat transfer rate and higher average primary side water temperature.

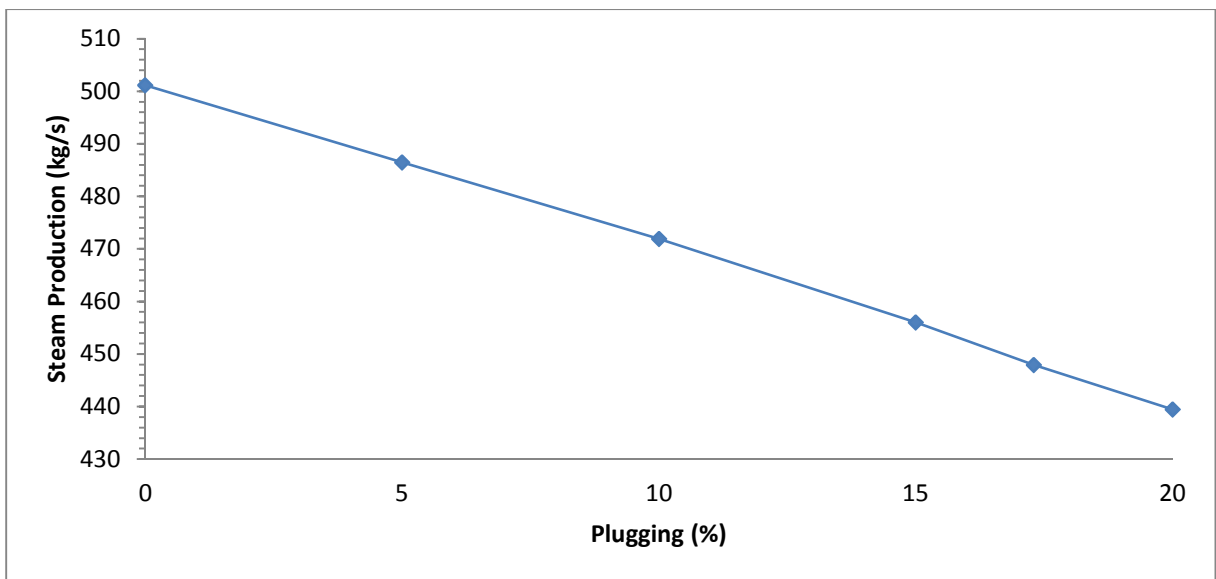


Figure 21: Steam flowrate at different tube plugging ratio

These computed figures also indicate that the current rule of thumb for limiting tube plugging to 15 to 20% is indeed correct when considering the design requirement of steam. This particular steam generator has a power rating of 928.3 MWth and it was observed that plugging ratio of 17.3% is the limit to maintain the steam generator at full rated power of 928 MWth. The operation requirements downstream of the steam generator could provide further information to validate this rule of thumb, as indicated in the literature on turbine valve opening to maintain constant power [7]. This, however, falls beyond the scope of this work.

CHAPTER 6: Conclusions and recommendations

6.1 Conclusions

In this study, a Flownex® simulation environment was used to develop a model of a PWR steam generator. Flownex® uses a single-phase heat transfer coefficient, Dittus-Boelter, to predict forced convection heat transfer and Sato and Matsumara for nucleate boiling. As the steam generator operates in the two-phase environment, the Chen correlation was used to predict the heat transfer coefficient. In the preceding study [10], it was observed that comparing the Flownex and Relap5 codes of the PWR, the relatively small deviation was due the exclusive use of the boiling aspect of the Chen correlation in the developed Flownex script. According to the literature [13], the Chen correlation is however not applicable for a vapour quality below 0.01. Hence, the script developed for this study employed Chen for vapor qualities above 0.01 and Dittus-Boelter when the vapour quality was below 0.01s (See appendix A).

The results of the model development and simulation of tube plugging revealed the following:

Model validation

The model developed in this work was validated by using the boundary conditions and heat transfer coefficient from the literature. The results of the model were then compared to those reported in the literature. An almost exact agreement was achieved and validating the developed model. Furthermore, it was observed that the use of the corrected Chen correlation [13] for heat transfer resulted in significant differences in steam generator performance. These were therefore used for the plugging simulations.

Tube plugging investigation

The tube plugging investigation was performed using 0% to 20% plugging ratios. This investigation was undertaken to determine and understand the impact of plugging on the thermal performance of the steam generator. Because of the non-linear and undocumented changes in certain boundary conditions due to tube plugging, a Mathcad script was developed to automatically account for the change in feedwater flow. This enabled computing the full thermodynamic response of the steam generator at each specific plugging ratio.

The apparent observation when plugging the tubes is that it reduces the cross-section of the reactor coolant flow and heat transfer surface area [7]. This is quantified below, together with the resultant change in other thermodynamic parameters.

Primary side effect

There is a circa linear proportionality between heat transfer rate and heat transfer area. The results show a 12% decline of heat transfer rate when tubes are plugged up to 20%. The somewhat less than linear relationship is due to an increased water flow velocity. The reactor coolant flow is also reduced by almost 4% when 20% of the primary side tubes are plugged.

Secondary side effect

As indicated above, heat transfer decreases due to plugging. The heat available for boiling on the secondary side decreases and the mixture quality is therefore reduced, which in turn has an impact on the recirculation ratio. The results show that a decrease in mixture quality causes the recirculation ratio to increase by circa 12%. Furthermore, with decline in mixture quality and increase in recirculation ratio, steam production declines by 12%.

Plugging limits

The results obtained through this investigation lead to the conclusion that the plugging limit ratio is between 15% and 20%. This is based on the design requirement of the steam generator with regards to the power rating of 928.3 MWth. The simulation revealed that at 17.3% of tube plugging is the limit to maintain the required heat transfer steam generator full rated power of 928 MW at reactor full power.

Impact of plugging on other equipment

Given the outcome of the simulation, other primary and secondary equipment will be effected. An increase in the primary outlet temperature will lead to a negative reactivity, meaning that the reactor power will decrease, which is an unwanted effect. On the secondary side, the lower steam production and subsequently the steam turbine will be impacted negatively.

6.2 Improvements and recommendations

The analysis can be further detailed by scrutinising the impact caused by tube plugging on the upstream equipment (nuclear reactor) and downstream equipment (steam turbine). This could further assist in determining more operating limits for tube plugging ratio. One such example is the steam governor valves which can be analysed in terms of valve opening limits.

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APPENDIX A: Chen correlation program code

$$t := t \text{ } ^\circ\text{C} = \blacksquare \cdot ^\circ\text{C}$$

$$t_{\text{wall}} := t_{\text{wall}} \text{ } ^\circ\text{C} = \blacksquare \cdot ^\circ\text{C}$$

$$p := p \cdot \text{Pa} = \blacksquare$$

$$t_{\text{sat}} := t_{\text{sat}} \text{ } ^\circ\text{C} = \blacksquare \cdot ^\circ\text{C}$$

$$G_f := G_f \cdot \frac{\text{kg}}{\text{m}^2 \cdot \text{s}} = \blacksquare$$

$$d_h := 0.0385 \quad \text{m}$$

$$x := \blacksquare$$

$$\rho_{\text{L}} := \rho_{\text{steam}}(\text{""}, t, 0, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\rho_{\text{G}} := \rho_{\text{steam}}(\text{""}, t, 1, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{kg}}{\text{m}^3}$$

$$\mu_{\text{L}} := \mu_{\text{steam}}(\text{""}, t, \text{""}, 0, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{kg}}{\text{m} \cdot \text{s}}$$

$$\mu_{\text{G}} := \mu_{\text{steam}}(\text{""}, t, \text{""}, 1, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{kg}}{\text{m} \cdot \text{s}}$$

$$c_{p_{\text{L}}} := C_{p_{\text{steam}}}(\text{""}, t, \text{""}, 0, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{J}}{\text{kg} \cdot \text{K}}$$

$$k_{\text{L}} := \lambda_{\text{steam}}(\text{""}, t, \text{""}, 0, \text{""}, \text{""}) = \blacksquare \cdot \frac{\text{W}}{\text{m} \cdot \text{K}}$$

$$h_{\text{L}} := h_{\text{steam}}(\text{""}, t, \text{""}, 0, \text{""}) = \blacksquare \cdot \frac{\text{J}}{\text{kg}}$$

$$h_{\text{G}} := h_{\text{steam}}(\text{""}, t, \text{""}, 1, \text{""}) = \blacksquare \cdot \frac{\text{J}}{\text{kg}}$$

$$h_{\text{LG}} := h_{\text{G}} - h_{\text{L}} = \blacksquare \cdot \frac{\text{J}}{\text{kg}}$$

$$\sigma := \sigma_{\text{steam}}(\text{""}, \mathbf{t}) = \mathbf{\cdot} \frac{\text{N}}{\text{m}}$$

$$p_{\text{wall}} := p_{\text{steam}}(\mathbf{t_{wall}}, \text{""}, \text{""}, \text{""}) = \mathbf{\cdot} \text{Pa}$$

$$p_{\text{sat}} := p_{\text{steam}}(\mathbf{t_{sat}}, \text{""}, \text{""}, \text{""}) = \mathbf{\cdot} \text{Pa}$$

$$\Delta P := (p_{\text{wall}} - p_{\text{sat}}) = \mathbf{\cdot} \text{kPa}$$

$$\Delta T := (\mathbf{t_{wall}} - t_{\text{sat}}) = \mathbf{\cdot}$$

$$\text{Pr}_L := \frac{(\mathbf{cp}_L \cdot \mu_L)}{k_L} = \mathbf{\cdot}$$

$$h_{\text{nb}} := 0.00122 \left(\frac{k_L^{0.79} \cdot cp_L^{0.45} \cdot \rho_L^{0.49}}{\sigma^{0.5} \cdot \mu_L^{0.29} \cdot h_{\text{LG}}^{0.24} \cdot \rho_G^{0.24}} \right) \cdot \Delta T^{0.24} \cdot \Delta P^{0.75} = \mathbf{\cdot} \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

Liquid Reynolds number

$$\text{Re}_L := \frac{(1-x) \cdot \mathbf{G}_f \cdot d_h}{\mu_L} = \mathbf{\cdot}$$

$$h_{\text{sp}} := 0.023 \text{Re}_L^{0.8} \cdot \text{Pr}_L^{0.4} \cdot \left(\frac{k_L}{d_h} \right) = \mathbf{\cdot} \frac{\text{W}}{\text{m}^2 \cdot \text{K}}$$

$$h_{\text{tp}} := \begin{cases} \text{if } x \geq 0.01 \\ \left| \begin{array}{l} X_{\text{tt}} \leftarrow \left(\frac{1-x}{x} \right)^{0.9} \cdot \left(\frac{\rho_G}{\rho_L} \right)^{0.5} \cdot \left(\frac{\mu_L}{\mu_G} \right)^{0.1} \\ F \leftarrow \begin{cases} 2.35 \left(0.213 + \frac{1}{X_{\text{tt}}} \right)^{0.736} & \text{if } \frac{1}{X_{\text{tt}}} > 0.1 \\ 1 & \text{if } \frac{1}{X_{\text{tt}}} \leq 0.1 \end{cases} \\ \text{Re}_{\text{tp}} \leftarrow (\text{Re}_L \cdot F^{1.25}) \\ S \leftarrow \frac{1}{\left(1 + 2.53 \cdot 10^{-6} \cdot \text{Re}_{\text{tp}}^{1.17} \right)} \\ S \cdot h_{\text{nb}} + F \cdot h_{\text{sp}} \end{array} \right. \\ 0.023 \text{Re}_L^{0.8} \cdot \text{Pr}_L^{0.4} \cdot \frac{k_L}{d_h} \quad \text{if } x < 0.01 \end{cases}$$

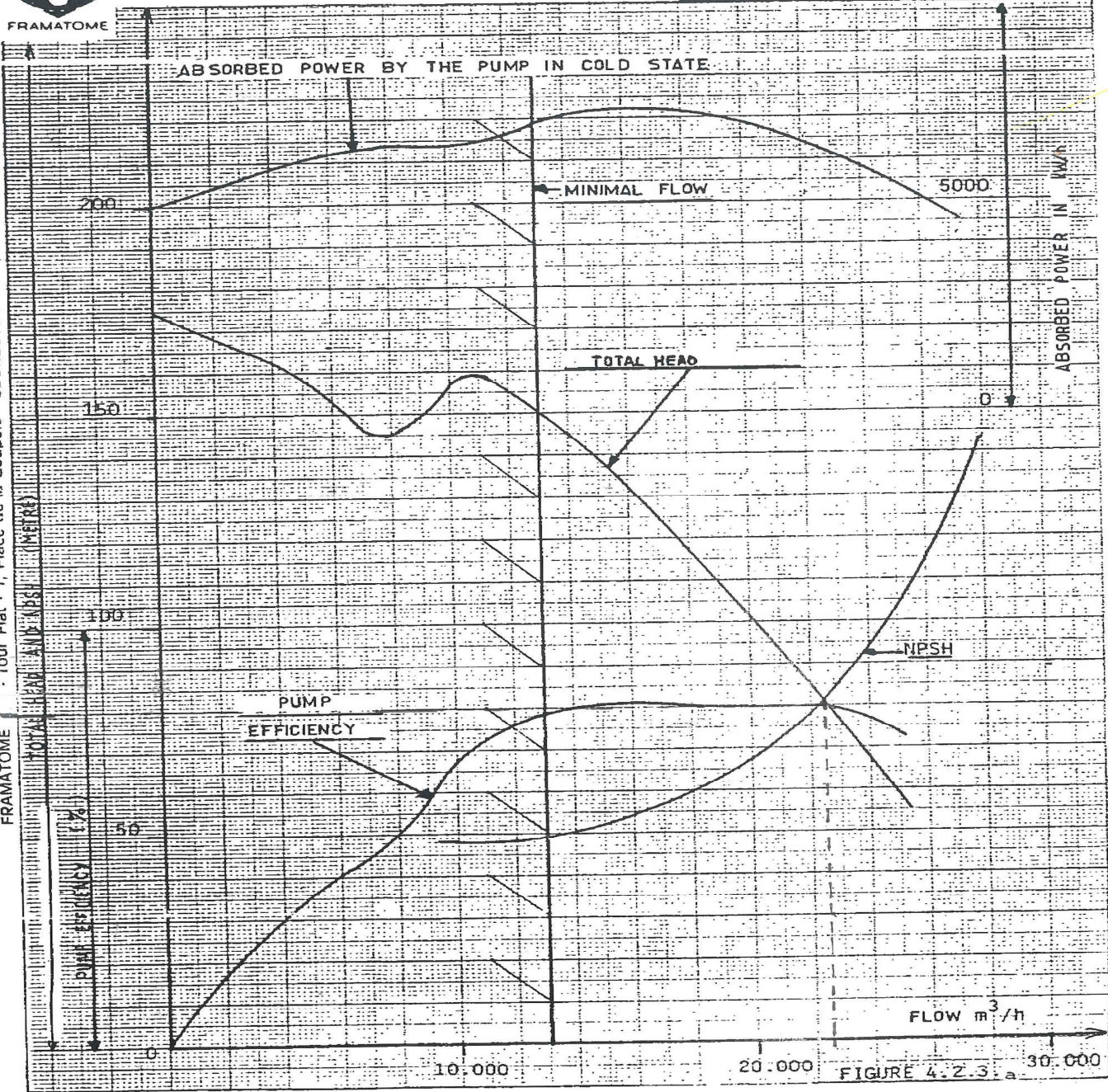
$$h_{tp} = \frac{W}{m^2K}$$

APPENDIX B: Reactor coolant pump curve



CHARACTERISTIC CURVES
OF REACTOR COOLANT PUMPS AT 1485 tr/min

4 PAGE 18
N° TP/PC -DC- 0583
REV. D



APPENDIX C: Mathcad script for steam produced

$$x := \blacksquare$$

$$M_{\text{total}} := \blacksquare \cdot \frac{\text{kg}}{\text{s}}$$

$$M_{\text{vap}} := x M_{\text{total}} = \blacksquare$$

$$\text{CR} := \frac{M_{\text{total}}}{M_{\text{vap}}} = \blacksquare$$

APPENDIX D: Sample calculation for heat transfer area input at 5% plugging

Specified data

$$N_{pt} := 3163$$

$$\pi := 3.1415$$

$$Dh_p := 0.01968 \text{ m}$$

$$D_{pod} := 0.02222 \text{ m}$$

Calculated data

$$\text{Circum} := \pi \cdot Dh_p \cdot N_{pt} = 195.552 \text{ m}$$

$$A_p := N_{pt} \cdot \pi \cdot \frac{Dh_p^2}{4} = 0.962 \text{ m}^2$$

Heat transfer surface area calculations

$$A_{up} := \pi \cdot Dh_p \cdot l_p \cdot N_{pt} = 4463.269 \text{ m}^2$$

$$A_{dwn} := \pi \cdot D_{pod} \cdot l_p \cdot N_{pt} = 5039.322 \text{ m}^2$$