DEVELOPMENT OF ITERATIVE ANALYTICAL PROCEDURE FOR BOILER TUBE ANALYSIS IN MATLAB

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering

Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

April 2013

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"DEVELOPMENT OF ITERATIVE ANALYTICAL PROCEDURE FOR BOILER TUBE ANALYSIS IN MATLAB"** was prepared by **ANG WEI BING** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ACKNOWLEDGEMENTS

I would like to thank everyone who had devoted and contributed to the successful completion of this project. First and foremost, I would like to express my utmost gratitude to my research supervisor, Mr. Yeo Wei Hong for his dedicated assistance, invaluable advice, guidance and enormous patience throughout the development of the research. He had never hesitated to lend a helping hand whenever I encountered problems so that I am motivated to cross the hurdle.

Besides that, I would also like to express my gratitude to my partner, Edwin Lim Chui Seng who had helped and encouraged me a lot along the way in completing this project. He had given me favourable suggestions in finding alternatives to do appropriate analyses and researches concerning the objectives of this project.

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ABSTRACT

Boiler tubes that operated at elevated temperature are most likely to hasten the oxide scale formation on the tube surface and deteriorate the material, which could be vulnerable to the tube failures after prolonged time. Thus, life prediction of boiler tubes is crucial in reducing the potential failure rate. An analytical iterative procedure was proposed and implemented in MATLAB to carry out analyses and predictions on the remnant life, oxide scale thickness, hardness, hoop stress, wall thinning and heat flux of the tube. A detail flow chart was depicted coupled with the descriptions on the steps of the iterative procedure implemented in MATLAB. The MATLAB program was found to be reliable after validating and comparing the results with the actual data at power station and the prediction done by other authors. There were only 2.57 % and 5.12 % of differences with the actual data at power station in terms of cumulative creep damage and scale thickness of the boiler tube respectively. Less than 6.5 % of differences between the predictions by MATLAB program and other authors in terms of average tube metal temperature, Vickers hardness, scale thickness and cumulative creep damage of the tube were reported. A correlation function between tube temperature change and scale growth was investigated and a constant B from the correlation function was estimated. The correlation function at various operating conditions was analysed. A constant value closed to one denotes the similar rate of temperature change and scale growth over time. A higher constant B showed the faster temperature change whereas a lower constant B indicated a more rapid growth of scale than temperature change.

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LIST OF SYMBOLS / ABBREVIATIONS

B	constant
C_p	specific heat capacity, J/(kg ℃)
D	tube diameter, m
G	gas mass velocity, kg/(m^2 h)
HV	Vickers hardness, HV
h	convection coefficient, W/(m^2 ℃)
i	gas constituent
I	iteration
k	thermal conductivity, W/(m ℃)
L	tube length, m
$\dot{m}$	mass flow rate, kg/h
Nu	Nusselt number
N_w	number of tube wide
P	Larson-Miller parameter
Pr	Prandtl number
p	operational internal pressure, MPa
R	thermal resistance, ℃/W
Re	Reynolds number
r	tube radius, m
S_t	transverse pitch, m
t	time, h
T	temperature, ℃
W_g	gas flow, kg/h
X	scale thickness, mm
y	volume fraction

μ	dynamic viscosity, N s/m^2
σ_h	hoop stress, MPa
CCDMG	cumulative creep damage
FEM	finite element method
LMP	Larson-Miller parameter
MW	molecular weight

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CHAPTER 1

INTRODUCTION

1.1   Background of Boiler Tube

The purpose of boiler is to convert water into steam. The steam can be used for various usages such as driving an engine to generate electricity, heating purpose and for other industrial process applications. The boiler consists of several types, which include water tube boiler, fire tube boiler, packaged boiler, fluidised bed combustion (FBC) boiler, atmospheric fluidised bed combustion (AFBC) boiler and so forth. The most popular boilers that used in many industries are water tube and fire tube boiler. Water tube boiler is the one with water flowing through the tubes that enclosed in a furnace heated externally while fire tube boiler comprises of fire or hot flue gas directed through tubes surrounded by water.

Heat recovery steam generator (HRSG) is a good example of system in power plant that utilises the boiler tube, typically a water tube boiler. In a combined cycle gas turbine power plant, there are three major systems incorporated together, which are gas turbine, steam turbine and HRSG. According to Ganapathy (2003), the combined cycle plant incurs lower capital costs than the other power plants such as conventional fossil power plants, and it is the most efficient electric generating system available today.

The function of HRSG is to recover heat from the exhaust gas discharged from the gas turbine and makes use of the heat energy to produce steam. The steam produced will flow through steam turbine to generate electricity. Large numbers of

HRSG systems are found in power generation plants due to its better efficiency provided compared to the conventional fossil fired generating systems. A HRSG system contains multiple of superheater and reheater tube units that are arranged in parallel in which the pressurised steam flows through them. At the moment steam is generated, it is in saturated form. Superheater and reheater tubes tend to raise the steam temperature until it reaches superheated state and ready to be used in power generation.

1.2   Problem Statement

In HRSG system, the steam flowing through the superheater and reheater tubes is usually heated at a very high temperature to ensure that all saturated steam is converted into superheated steam. In fact, the elevated temperature will cause the formation of oxide scales on the inner surface of the tube. The oxide scale layer will act as a thermal barrier and reduces the heat transfer from the hot flue gas into the steam within the tube. As a result, the tube metal temperature rises due to the accumulation of heat and reduced in cooling effect from steam. The metal tubes experience excessive heat energy coupled with the deterioration of mechanical properties of the tube alloy. The steam-carrying superheater and reheater tubes are now subjected to potential failures such as creep rupture. The main concern here is the consequence of failure of boiler tube can be expensive and tragic. Plant shutdown as a result of tube failure can affect the entire operation of the power generation system and pose financial losses. Therefore, a reliable estimation of the remaining life of superheater and reheater tubes has become necessary for the power generation plant boiler in reducing the tube failure rate as well as the cost by conducting life assessment activities.

1.3   Aim and Objectives

The ultimate goal of the research is to develop a reliable program that can perform iterative procedure for the purpose of estimating the oxide scale thickness formed, wall thinning, hardness, hoop stress, heat flux of the tube, and the remaining life of superheater and reheater tubes. The objectives of the project are:

1) To propose an iterative analytical procedure that can be used to investigate the integrity of boiler tubes such as oxide scale thickness, hardness, heat flux, hoop stress, wall thinning and the remaining life.
2) To develop a reliable program in MATLAB based on the proposed iterative analytical procedure.
3) To determine and investigate the correlation functions of oxide scale growth and temperature increase at various operating conditions using iterative analytical procedure.

1.4   Scope of the Research

In this project, an iterative analytical procedure has been proposed to perform various analyses and studies on the boiler tube. The iterative procedure tends to predict the remnant life of the boiler tube under an operating condition and analyse the performance characteristics of boiler tubes in terms of oxide scale thickness, hardness, heat flux, hoop stress and wall thinning. These performance characteristics are as functions of temperature and time. Since the project was only based on simple model analysis, all the parameters such as oxide scale thickness, heat flux and so forth were analysed in one dimension. For instance, the oxide scale was treated to be uniformly grown with constant increment in thickness of oxide layer rather than considering the oxide layer that covers a surface area (two dimensions).

A detailed flow chart was established before implementing the iterative procedure in MATLAB. The results obtained from the MATLAB program was compared with the work done by other authors and the actual data reported at Kapar Power Station Malaysia. The validation of the MATLAB results is important as it evaluates the reliability of the MATLAB program if the results may be used to assist in preventive maintenance of boiler tube in power plant. It is capable to perform various tasks such as graph potting and boiler tube life prediction that incorporates the thinning effect as well as other parameters. It can also be used to investigate the correlation function between the oxide scale thickness and temperature change in order to meet the objectives of the research.

The prediction of temperature increase in boiler tube was demonstrated by utilising a generated constant B that correlating the scale oxide thickness and tube metal temperature change. A few sets of relevant parameters were presented and used to study the constant estimation method in predicting the temperature increase in tube. The prediction using a constant B could be used to support the condition monitoring of boiler tubes in power plants.

1.5   Structure of Thesis

All the literature reviews related to this project are discussed in Chapter 2. This chapter starts with an introduction of the types of boiler tubes operated in power plant. The damages or failures in relative to the boiler tubes are explained and the researches done by other authors in those relevant topics are reviewed and discussed. The later part is the evaluation on the methods used by other authors in the prediction of oxide scale growth following by the fundamental of heat transfer for boiler tube analysis. This section is mainly discussed on the heat transfer-related equations and principles.

Chapter 3 describes the methodology that employed in order to achieve the aims and objectives of this project. The proposed analytical iterative procedure is explained in steps. A detailed flow chart that implements the iterative procedure in

MATLAB is presented. Further explanations of the development of the MATLAB program are discussed. Next, a method in estimating a constant correlating the temperature increase and scale thickness is proposed.

Chapter 4 discusses the results obtained from the MATLAB and the comparison between the estimated results with the work carried out by other authors and the actual data from one of the power stations in Malaysia. The effects of the changes in several parameters to the correlation function between temperature change and scale growth are investigated.

Chapter 5 explains the conclusions that can be draw from the findings in this project. Limitations of the developed MATLAB program are briefly explained and two recommendations for improvement of this project are suggested.

CHAPTER 2

LITERATURE REVIEW

2.1   Description of Heat Recovery Steam Generator (HRSG)

Figure 2.1 illustrates a schematic diagram of a boiler for HRSG system. The relevant components in the boiler tube are labelled accordingly. An understanding of the structure and the operation of the water tube boiler (HRSG) is required beforehand. The mechanism in the boiler begins with the combustion that takes place in the furnace. The fuel can be coal, oil or natural gas. The gases produced from the combustion travels up to the roof of the furnace and at the same time, convert the water inside the water wall tubes into steam. The hot flue gases follow the channel of the furnace and flow across the secondary superheater and reheater tubes and primary reheater tubes bank. Then, the gases flow downward and pass through the sections of primary superheater and economiser. Before the exhaust gases are discharged, they undergo heating process in the air preheater and also a series of cleaning processes using various devices. The dash arrows depict the flow of the combustion gases throughout the boiler.
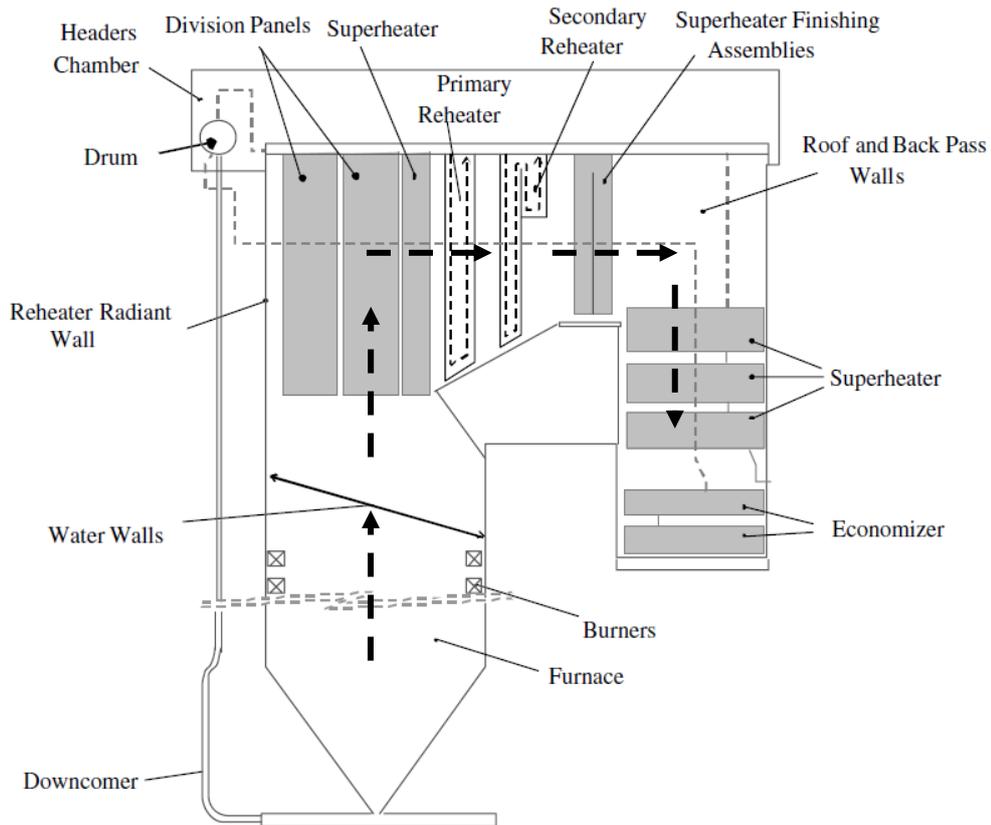
Figure 2.1: Schematic Diagram of a Boiler (Prieto et al., 2006. p. 187)

The boiler tubes can be divided into two separated fluid flows. The hot flue gases flow path involves the region at the fireside of the boiler tubes from the water wall tubes until the economiser. On the other hand, the flow of the steam and water is along the water-side of the boiler tubes. The water-side of the boiler tubes include the passages that are in dash lines as shown in Figure 2.1.

Many water tube boilers are of natural water circulation. In natural circulation systems, a steam-water separation equipment or known as drum is required to separate the steam and water and the circulation of water is by convection currents. Natural circulation is the result of density difference whereby the colder and denser fluid (water) is circulated from the drum to downcomer situated at the outside of furnace while the hotter and less dense fluid (steam) is delivered to the superheater and the high-pressure section of the turbine inlet. The steam discharged from the low-pressure section of turbine is then returned to the reheater unit. The low-pressure steam is then condensed into feedwater through condenser, feedwater heaters and

deaerators. Later, the feedwater is fed into the economizer and heated before it enters the water wall tubes.

Another type of water circulation is called forced once through circulation. The difference of the forced once through circulation compared to the natural circulation is that the water and steam is moved by pump. Besides that, the forced once through design does not have recirculation via drums and circulating pumps as in the natural circulation. Forced once through circulation is of advantage when the pressure is very high. If the pressure is very high, the density difference between the water and steam is very less, in which natural circulation is not favourable (Grote & Antonsson 2009).

The superheater and reheater consist of heat-absorbing surface that raises the steam temperature above its saturation point. One of the reasons behind for doing this is due to the elimination of the moisture or water vapour before it enters the turbine. Corrosion of the turbine components such as turbine blades results from the chemical reaction between the water vapour and the metallic surfaces. Another reason is the thermodynamic gain in efficiency.

2.2   Damage Mechanisms on Superheater and Reheater Tube

The superheater and reheater tubes in the boiler power plants are most likely to expose to a series of problems that can easily lead to tube failure at high temperature. Generally the problems can be divided into two categories, which are corrosion related problems and mechanical related problems. The typical mechanical related problems are creep fracture and overheating while corrosion related problems encountered in superheater and reheater tube is fireside corrosion. There are many else of failures occur in different components of boiler tube. However, merely few failures that have highlighted are of interest in this research.

2.2.1 Creep

The major damage mechanism in most of the power generation plants is due to creep damage. Creep is a type of time-dependent deformation that occurs under stress and elevated temperature. Failure that caused by creep is known as creep rupture or stress rupture. Creep rupture is often happened to be the final stage of failure in boiler tubes. According to the statistics reported by Jones (2004), approximately 10 % of all power plant breakdowns are resulted due to creep failures happened in boiler tubes. Some problems associated with creep rupture can be related to the high temperature exposure such as long term overheating and short term overheating, and each will be further discussed in the following subsections.

Jones (2004) described three basic mechanisms of creep rupture, which are intergranular creep facture, transgranular creep fracture and dynamic recrystallisation. Intergranular creep fracture is more likely to happen at low stresses in the ductile boiler tubes. Voids will nucleate at the grain boundaries under the applied tensile stress and leads to the growth of defects. Eventually the deformation is concentrated at the grain boundaries with small reduction in area and ductility and breaks later. Transgranular creep fracture tends to occur at high stresses. Similarly, the voids nucleate and propagate throughout the grains. However, the tensile ductility and reduction in fracture area are much greater than the intergranular creep failure. At the combination of high temperatures and stresses, dynamic recrystallisation probably will occur in which waves of recrystallisation pass through the creeping material and eliminate the microstructural damaged resulted from the formation of creep. Thus, voids will not nucleate as how will be happened in the other two fractures and the round bar metal tubes will break down to a point and failure.

Figure 2.2: Microstructure of Creep Fracture Mechanisms (Jones 2004. p. 878)

In the investigation carried out by Psyllaki, Pantazopoulos and Lefakis (2009), creep void evolution was found in the creep-failed boiler tube. Psyllaki, Pantazopoulos and Lefakis (2009) observed that the void coalescence (final stage in the failure of ductile materials) that filled with oxidation compositions resulted in intergranular surface cracks at the outside surface of the boiler tube. As a result, a zone of creep void growth was found across the tube wall. On the other hand, an initiation of individual voids was found along the grain boundaries towards the inner surface of the tube wall. This phenomenon (initiation, growth and coalescence) showed a temperature gradient across the tube wall at which the heat transfer between the combustion gases at the external surface of the boiler tube and the pressurised steam flow in the inner surface of the tube took place.

Figure 2.3: Intergranular Surface Cracks with the Creep Void Evolution (Psyllaki, Pantazopoulos and Lefakis 2009. p. 1423)

2.2.2   Long Term Overheating

Long-term overheating is a condition whereby the tube metal is subjected to temperature above its design limit for a prolonged period for days, months, or even years. This is one of the typical failures happened in boiler tubes. Figure 2.4 illustrates the failure of boiler tube due to long term overheating.

Figure 2.4: Failure Due To Long Term Overheating (Lande et al., 2011. p. 233)

Port and Herro (1991) mentioned that the superheaters, reheaters, and wall tubes are the common locations that failed due to overheating. After the exposure to overheating, boiler tubes usually have significant thick deposits accumulated on the steam-side surface and shortage of coolant flow (steam flow) in the tubes. At the same time, the tubes will receive excessive heat from the flue gas.

Port and Herro (1991) also explained that a thin coating of gas formed on the outer surface of tube will reduce the temperature across this coating by inhibiting the transfer of heat from flue gas into the boiler. Any scale or deposit on the external surfaces will slightly reduce the tube metal temperature. In addition, the thermal resistance of the boiler tube has a small effect towards the reduction of temperature across the tube wall. Contrarily, the deposits on the steam-side or inner surface of tube will inhibit the tube metal to be cooled by the steam flow, ended up with the escalation of tube metal temperature.

The failed tube caused by long term overheating usually has minimal swelling and a longitudinal split that is narrow compared to the one that caused by short term overheating in the following section. Heavy scale is often built-up on the external surface of the boiler tubes after a long period of time at high temperature exposure. Eventually the failure in superheater and reheater tubes is by creep rupture.

The fact of the long term overheating as one of the primary causes of the failure in superheater and reheater tube is supported by case studies. According to Xu, Khan and Chen (2000), Baoshan Iron and Steel (Group) Corp. had reported that the Japan's utility boiler was failed in 1988. The root cause of the boiler tube failure was long-term overheating resulted from the deviation of thermal load in lateral direction.

2.2.3   Short Term Overheating

Short term overheating failures are commonly found during the boiler start-up. In general, short term overheating failure is the rupture occurs when the tube metal temperature increases to a certain extend in which the hoop stress from the internal steam pressure reaches the tensile strength of the metallic tube at high temperature for a short period of time (minutes to months). This can be happened when there is shortage or complete loss of cooling steam or water flow while the tube metal reaches an extremely high temperature in which the deformation of yielding tends to occur. For instance, this type of failure results when the superheater tubes have not free from condensation that inhibits the steam flow during boiler start-up. A fracture in the form of thin edge fish mouth opening in the tube is normally found in short term overheated boiler tubes. Figure 2.5 shows the thin-edged fish mouth rupture of the boiler tube resulted from short term overheating.

Figure 2.5: Failure Due To Short Term Overheating (Lande et al., 2011. p. 233)

According to Port and Herro (1991), superheaters and reheaters are common failure sites due to their high operating temperatures. The investigation of Chaudhuri (2006) agrees with this statement whereby the failure of final superheater tube occurred due to short-term overheating. A short term creep test had been done for a superheater tube and the result showed that with the condition of a temperature and hoop stress level of 830 ℃ and 30 MPa respectively, 16 % of creep strain could be

found within 2 h. This proved that the boiler tube will fail as a result of short term overheating when the temperature reaches 830 ℃.

2.2.4   Fireside Erosion-Corrosion and Wall Thinning

Fireside corrosion and erosion is one of the damage mechanisms that tends to occur on the outer surface of the superheater and reheater tubes and may result in wall thinning over prolonged time. As the name implies, it is a combined corrosion and erosion processes. The fireside corrosion may defined as material wastage by the chemical reaction between the tube metal and the surrounding environment at high temperature and erosion may be define as the mechanically surface material removal by the abrasive of moving fluid interacting with the metallic surface. In short, this damage mechanism is promoted by the elevated operational temperature and high velocity of fluid or flue gas.

Hernas et al. (2004) has reported that the fireside erosion-corrosion of boiler tube is as a result of corrosive atmosphere or environment containing a composition of sulphur and chlorine compounds. Chaudhuri (2006) also found the presence of other corrosive elements such as potassium, calcium and silicon from the detriment of the outer surface of a failed reheater tube based on an extensive analysis. A research (Li et al., 2007) showed the high temperature fireside corrosion and erosion has led to the wall thinning of the superheater tube and the formation of two-layer corrosion scales: an inner layer of sulphur compound and an outer layer of oxide scales. This finding was supported by the research done by Chandra, Kain and Dey (2011). In addition, the deposition of calcium sulphate on the superheater tubes (carbon steel grade SA213-T22 or 2.25Cr-1Mo) and its spallation were repeatedly enhanced by each other, causing the reduction of tube wall thickness that was believed to be the main cause of the tube failure. The boiler tube failure associated with the fireside erosion-corrosion could be happened by the mean of either thinning of wall or formation of cracks, and eventually ended up with fatigue (Syed, Simms and Oakey 2012) or increase in hoop stress (Vikrant et al., 2013).
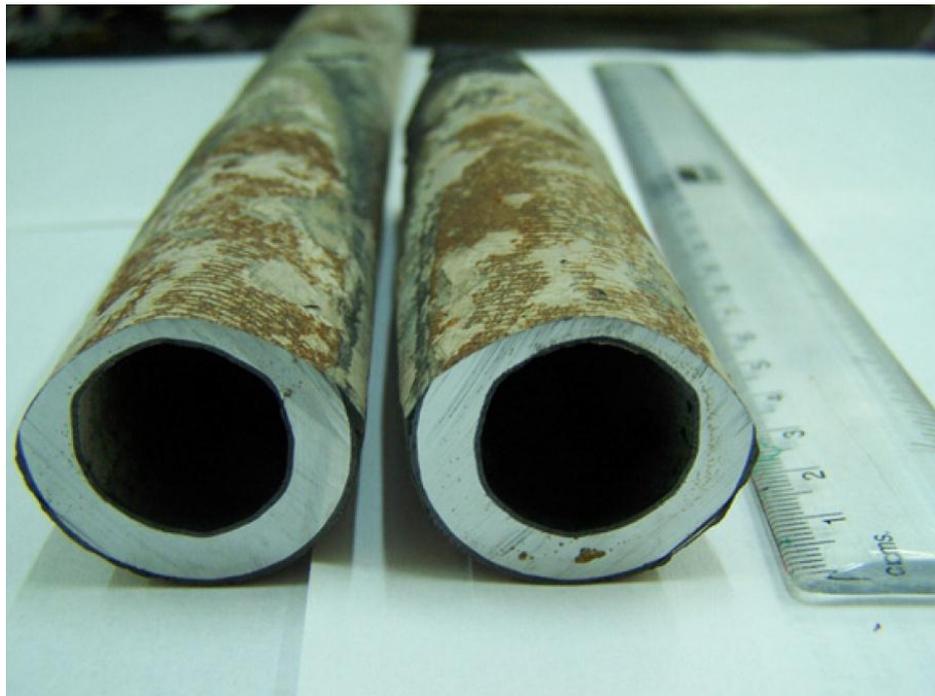
Figure 2.6: Wall Thinning on the Fireside of the Tube (Chandra, Kain and Dey 2011. p. 63)

Thus, the researches done in the past proved that wall thinning effect is one of the crucial factors to be considered in evaluating the boiler tube failures. Preventive steps can be taken to curb and alleviate the corrosion-related problems, ensuring a longer life span of the tube to be possible.

2.3   Prediction on Oxide Scale Growth

Oxide scales in the boiler tubes resulting from the prolonged exposure of elevated temperature can be determined by multiple types of analysis approach. A methodology using calculation, non-destructive and destructive evaluations to help in life prediction of boiler tubes was developed by Electric Power Research Institute (EPRI) and its contractors (Viswanathan et al., 1994). The thickest steam-side oxide scale in the tubes is identified and measured by using ultrasonic technique based on

the methodology. Further researches were done such as the validation of the ultrasonic technique in measuring scale and the identification of the appropriate stress formula and oxide growth laws.

Purbolaksono et al. (2009c) has proposed a technique for the estimation of the oxide scale thickness in superheater and reheater tube by using empirical formula and finite element modelling (FEM) simulation using ANSYS. The oxide scale thickness was found to be influenced by heat transfer parameters including the temperature of steam and flue gas, convection coefficients on the outer surface of tube and mass flow rates of steam. The computer simulation generated the temperature distribution of the superheater and reheater tube wall and illustrated the correlation between the scale thickness and the metal tube temperature. Purbolaksono et al. (2010) further on the research by incorporating the iterative procedure and evaluated two failure cases in superheater and reheater tubes. The results obtained were shown to be in good conformity with the actual data.
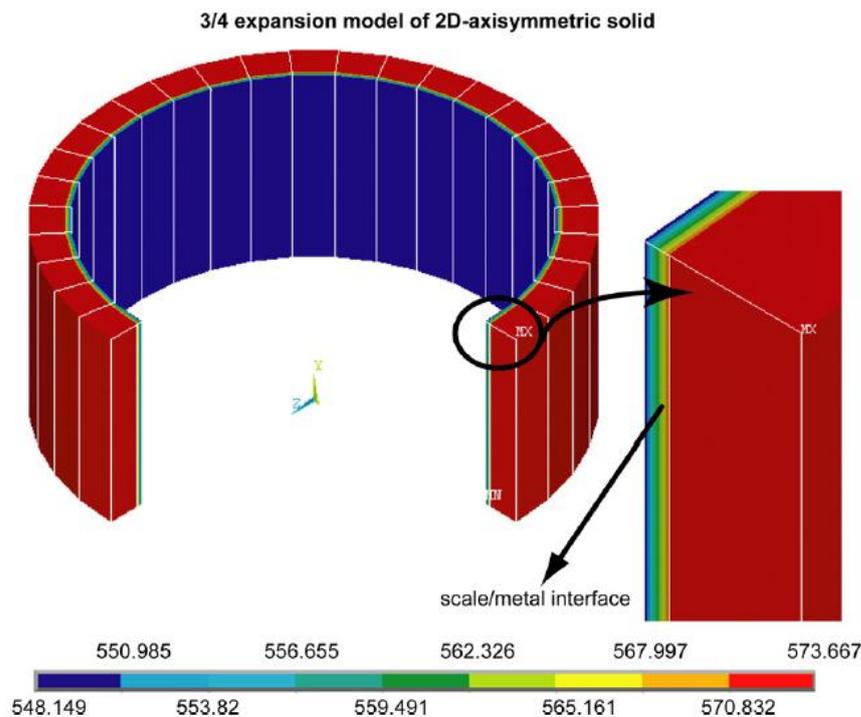
Figure 2.7: Temperature Distribution of Boiler Tube Using Simulation (Purbolaksono et al., 2010. p. 103)

2.4 Fundamental of Heat Transfer for Boiler Tube Analysis

The operation of the superheater and reheater tube involves the exchange of heat between the high pressure steam in contact with the internal surface of tube wall and the hot flue gas in contact with the outer surface of tube wall. Before any analysis on the boiler tube can be performed, one should have fundamental knowledge in heat transfer theory. Heat transfer is defined as thermal energy in transit due to a spatial temperature difference (Incropera et al., 2007). Heat transfer mechanism can be divided into three categories: conduction, convection and radiation.

Conduction process occurs when a temperature gradient exists between substances that are in direct contact with each other. The medium of conduction process may be a solid or a fluid. The heat transfer that occurs between a surface and a moving fluid at which both are at different temperatures is known as convection. Convection is the up and down movement of fluid (gas or liquid) caused by the thermal energy transmission. In a vacuum or empty space, heat transfer is also achievable. All surfaces of finite temperature emit energy in the form of electromagnetic waves. The electromagnetic waves travel through the space even in the absence of medium. This type of heat transfer is called radiation.

In this research, merely conduction and convection processes are of the interest and the radiation effect is assumed to be absent. The heat transfer across the water boiler tube wall is in the form of conduction while the heat transfer at the steam-tube interface and gas-tube interface are through convection.

A model that represents the steady state heat transfer taking place in superheater and reheater tubes is illustrated in Figure 2.8. The model indicating the tube metal wall is divided into two regions, which are scale region and tube region. Scale region is located at the inner surface of tube wall that is in contact with the steam region. This oxide scale is usually a duplex (inner spinel layer and outer magnetite layer) or triplex (inner spinel layer, middle magnetite layer and outer hematite layer) (Purbolaksono et al., 2009c). However, the material of scale is treated as all magnetite (Fe_3O_4) for the ease of analysis in this research.
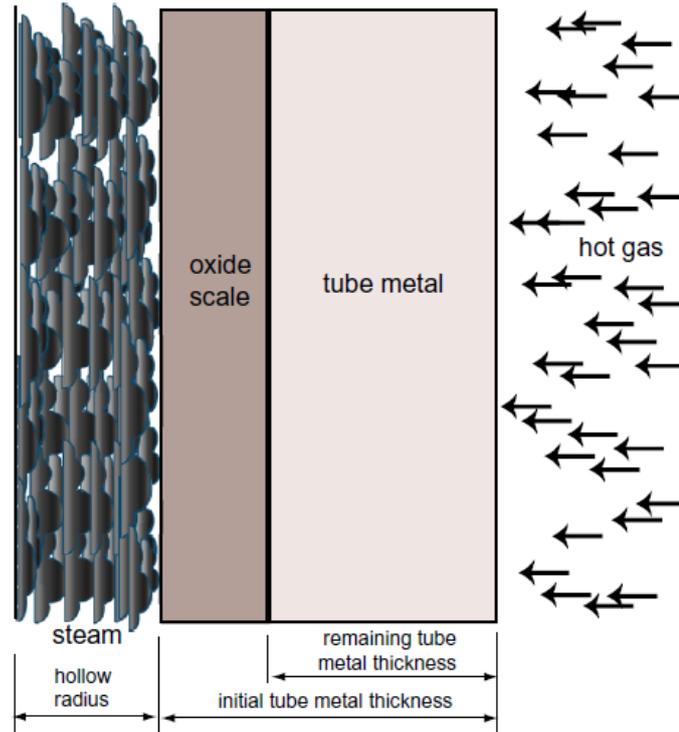
Figure 2.8: Model of the Boiler Tubes with Oxide Scale Formed On the Inner Surface (Purbolaksono et al., 2010. p. 100)

2.4.1 Convection Coefficient of Steam, h_s

The steam inside the superheater and reheater tubes is treated as a fully developed turbulent flow along the circular tube. The heat transfer inside the boiler tube is considered as an internal forced convection with turbulent flow. Thus, the Nusselt number of the steam can be computed using the Dittus-Boelter equation:

$$Nu_s = 0.0023 \left(Re_s\right)^{0.8} \left(Pr_s\right)^{0.4} \tag{2.1}$$

where Re_s is the Reynolds number of steam and the Pr_s is the Prandtl number of steam that can be expressed as:

$$Re_s = \frac{\dot{m}_s}{900\pi D_i \, \mu_s} \tag{2.2}$$

$$Pr_s = \frac{\mu_s Cp_s}{k_s} \tag{2.3}$$

where

Nu_s = Nusselt number of steam

Re_s = Reynolds number of steam

Pr_s = Prandtl number of steam

$\dot{m}_s$ = mass flow rate of steam, kg/h

D_i = inner diameter of tube, m

μ_s = dynamic viscosity of steam, N s/m^2

Cp_s = specific heat of steam, J/(kg °C)

k_s = thermal conductivity of steam, W/(m °C)

In order to obtain the values for dynamics viscosity, specific heat and thermal conductivity of steam, operating steam temperature (in degrees Fahrenheit) and pressure (in psi) are required. The values for dynamic viscosity μ_s, specific heat Cp_s and thermal conductivity k_s of the steam are extracted from the Tables of Steam Dynamic Viscosity, Specific Heat and Thermal Conductivity (Ganapathy 2003) in US customary unit.

The Equation 2.1 must comply with the following conditions (Incropera et al., 2007):

I) $0.7 < Pr < 160$

II) Re > 10 000

III) $\frac{L}{D} > 10$; where L is the length of tube, m

IV) All fluid properties are evaluated at mean temperature, T_m.

Since

$$Nu_s = \frac{h_s (L) D_i}{k_s} \tag{2.4}$$

the steam convection coefficient for fully developed turbulent flow in circular tube is obtained by rearranging the Equation 2.4:

$$h_s(L) = 0.0023 \frac{k_s}{D_i} (Re_s)^{0.8} (Pr_s)^{0.4} \tag{2.5}$$

where

h_s = convection coefficient of steam, W/(m^2 $\mathrm{^{\circ}C}$)

2.4.2   Convection Coefficient of Flue Gas, h_g

The heat transfer of the hot flue gas outside the boiler tube is treated as external forced convection as a result of cross flow of the flue gas over the superheater and reheater tubes. A conservative estimate of convection coefficient of flue gas, h_g for the flow of flue gas over the bare tubes in inline and staggered arrangements (see Figure 2.9) is expressed as (Ganapathy 2003):

$$h_g = 0.33 \frac{k_g}{D_o} (Re_g)^{0.6} (Pr_g)^{0.33} \tag{2.6}$$

and the Reynolds and Prandtl numbers of flue gas may be expressed as:

$$Re_g = \frac{GD_o}{3600\mu_g} \tag{2.7}$$

$$Pr_g = \frac{\mu_g Cp_g}{k_g} \tag{2.8}$$

where

h_g = convection coefficient of flue gas, W/(m^2 $\mathrm{^{\circ}C}$)

Re_g = Reynolds number of flue gas

Pr_g = Prandtl number of flue gas

k_g = thermal conductivity of flue gas, W/(m °C)

D_o = outer diameter of tube, m

μ_g = dynamic viscosity of flue gas, N s/m^2

Cp_g = specific heat of flue gas, J/(kg °C)

The corresponding gas mass velocity, G may be expressed as:

$$G = \frac{W_g}{N_w L(S_t - D_o)} \tag{2.9}$$

where

G = gas mass velocity, kg/(m^2 h)

W_g = gas flow, kg/h

N_w = number of tube wide

S_t = transverse pitch, m

L = length of tube, m

The dynamic viscosity, specific heat and thermal conductivity of flue gas can be obtained from the Tables of Steam Dynamic Viscosity, Specific Heat and Thermal Conductivity in US customary units from a book written by Ganapathy (1994) and the equations as shown in the following:

$$\mu_g = \frac{\sum y_i \mu_i (MW_i)^{-1}}{\sum y_i (MW_i)^{-1}} \tag{2.10}$$

$$Cp_g = \frac{\sum Cp_i MW_i y_i}{\sum MW_i y_i} \tag{2.11}$$

$$k_g = \frac{\sum y_i k_i (MW_i)^{-3}}{\sum y_i (MW_i)^{-3}} \tag{2.12}$$

where

MW = molecular weight

y = volume fraction

i = gas constituent
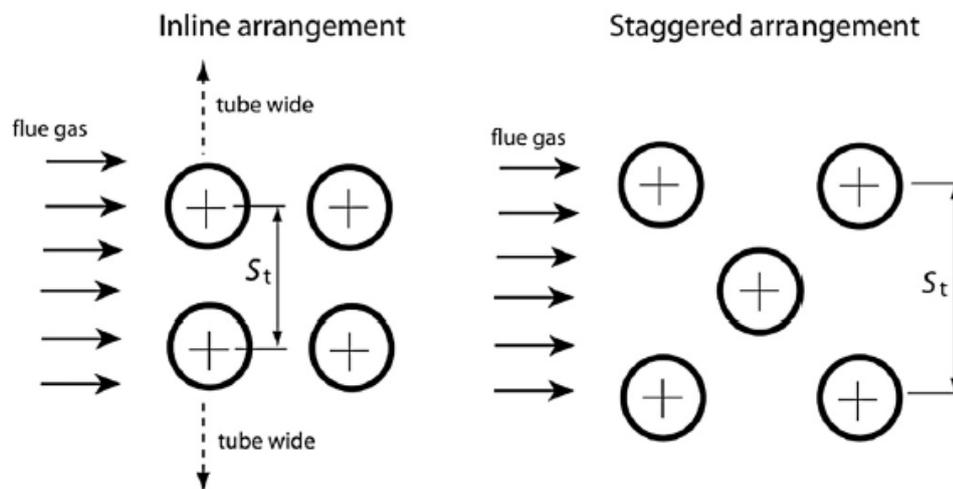
Figure 2.9: Inline and Staggered Arrangements of Bare Tubes (Purbolaksono et al., 2010. p. 101)

2.4.3 Estimation of Temperature Distribution

In this research, the superheater and reheater tubes are hollow cylinders. The heat transfer occurs by convection from the hot flue gas to the external surface of the tube wall, by conduction through the wall and the scale region, and by convection from the inner surface of the tube wall to the steam. Model of the tube section is shown in Figure 2.10.

Centre of tube
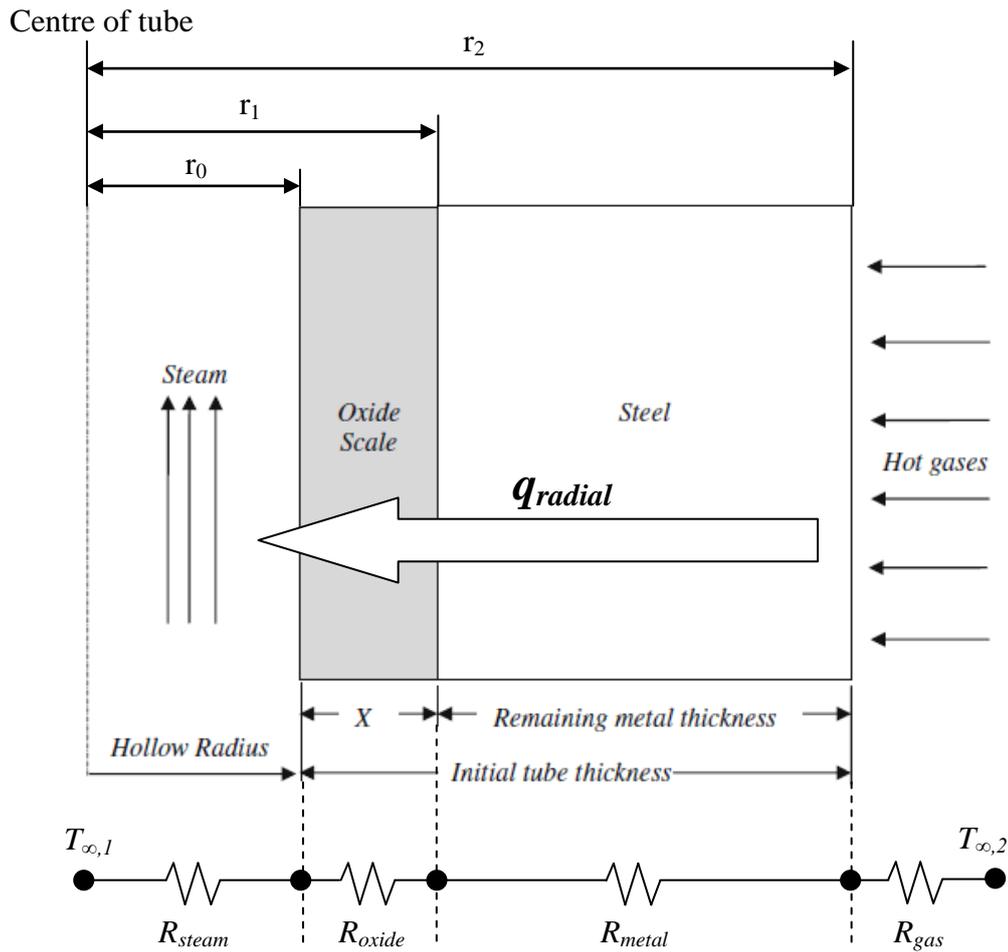
Figure 2.10: Thermal Circuit of Superheater and Reheater Tubes

The temperature distribution in the superheater and reheater tubes is associated with the correlation between the thermal resistance and the heat transfer by radial conduction through the cylindrical tube wall and the convection at the inner and outer surface of tube (Incropera et al., 2007). Thermal circuit is composed of the thermal resistances of each region (see Figure 2.10). The tube wall can be treated as a composite wall since it comprises of scale region and tube region. Therefore, the heat transfer of this composite system in radial direction, q_{radial} is expressed as:

$$q_{radial} = \frac{T_{\infty,2} - T_{\infty,1}}{R_{steam} + R_{oxide} + R_{metal} + R_{gas}}$$

(2.13)

in which

$$R_{steam} = \frac{1}{h_s \, 2\pi r_0 L} \tag{2.14}$$

$$R_{oxide} = \frac{ln\,(r_1 \,/\, r_0)}{2\pi k_{oxide} L} \tag{2.15}$$

$$R_{metal} = \frac{ln\,(r_2 \,/\, r_1)}{2\pi k_{metal} L} \tag{2.16}$$

$$R_{gas} = \frac{1}{h_g \, 2\pi r_2 L} \tag{2.17}$$

where

R_{steam} = thermal resistance of steam, °C/W

R_{oxide} = thermal resistance of oxide, °C/W

R_{metal} = thermal resistance of metal, °C/W

R_{gas} = thermal resistance of flue gas, °C/W

$T_{\infty,1}$ = temperature of steam, °C

$T_{\infty,2}$ = temperature of flue gas, °C

h_s = convection coefficient of steam, W/(m^2 °C)

h_g = convection coefficient of flue gas, W/(m^2 °C)

k_{oxide} = thermal conductivity of oxide scale, W/(m °C)

k_{metal} = thermal conductivity of tube metal, W/(m °C)

r_0 = radius up to inner surface of tube, m

r_1 = radius up to oxide scale surface of tube, m

r_2 = radius up to outer surface of tube, m

L = length of tube, m

2.4.4   Hoop Stress in Superheater and Reheater Tubes

During the operation of power plant, superheater and reheater tubes are operated under high steam pressure. At the moment tube metal wall subjected to this high pressure internally, tensile stresses are developed in the wall. The stress resulted from the expansion of tube wall is known as hoop stress. The approximate time for the superheater and reheater tubes to rupture is a function of the temperature and the hoop stress (related to internal pressure and tube dimension). Exposure to higher hoop stress coupled with elevated temperature will promote creep damage to occur more rapidly. As the circumference of the tube increases during creep formation, the wall thickness decreases in order to conserve the volume (Jones 2004). Therefore, hoop stress is one of the important parameters in the effort of life prediction of superheater and reheater tubes.

The hoop stress value is needed in the determination of the Larson-Miller parameter (LMP) of the material for superheater and reheater tubes. Details of LMP will be further explained in the following sub-subsection. The method of estimating hoop stress, σ_h developed in the tube was proposed by Rahman, Purbolaksono and Ahmad (2010):

$$\sigma_h = p \frac{(r + \frac{h}{2})}{h} \tag{2.18}$$

where

p = operational internal pressure, MPa

r = inner radius of the tube, m

h = wall thickness of the tube, m

2.4.5   Larson-Miller Parameter

Life assessment of superheater and reheater tube can be conducted by estimating the oxide scale thickness on the inner surface of tube wall. As the superheater and reheater are placed in service, oxide scale gradually grows on the tube wall and the tube metal temperature increases with respect to the time. Eventually, the creep rupture occurs due to high hoop stress in the tube wall.

According to Ganapathy (2003), creep data are available for different materials in the form of the LMP. This relates the value of rupture stress to the temperature, T in degrees Rankine (degrees Fahrenheit + 460) and the remaining lifetime t, in hours.

$$LMP = T(20 + \log t) \qquad (2.19)$$

Before estimating the remaining life of the superheater and reheater tube, the hoop stress, σ_h calculated from the Equation 2.18 is utilised in order to determine the LMP value from a diagram of LMP.

Every material has its own LMP chart. Figure 2.11 shows a LMP diagram for annealed material 2.25Cr-1Mo steel (or SA213-T22 steel) with a mean curve correlating the stress variation and the LMP value. Based on Figure 2.11, the equation of Larson-Miller parameter can be expressed in another form:

$$LMP = \frac{T_{ave}(20 + \log t)}{1000} \qquad (2.20)$$

where

T_{ave} = average temperature of tube metal, °Ra

t = rupture time, h

Rearranging the Equation 2.20 obtain

$$t = 10^{\left(\frac{p \times 1000}{T_{ave}} - 20\right)}$$

(2.21)
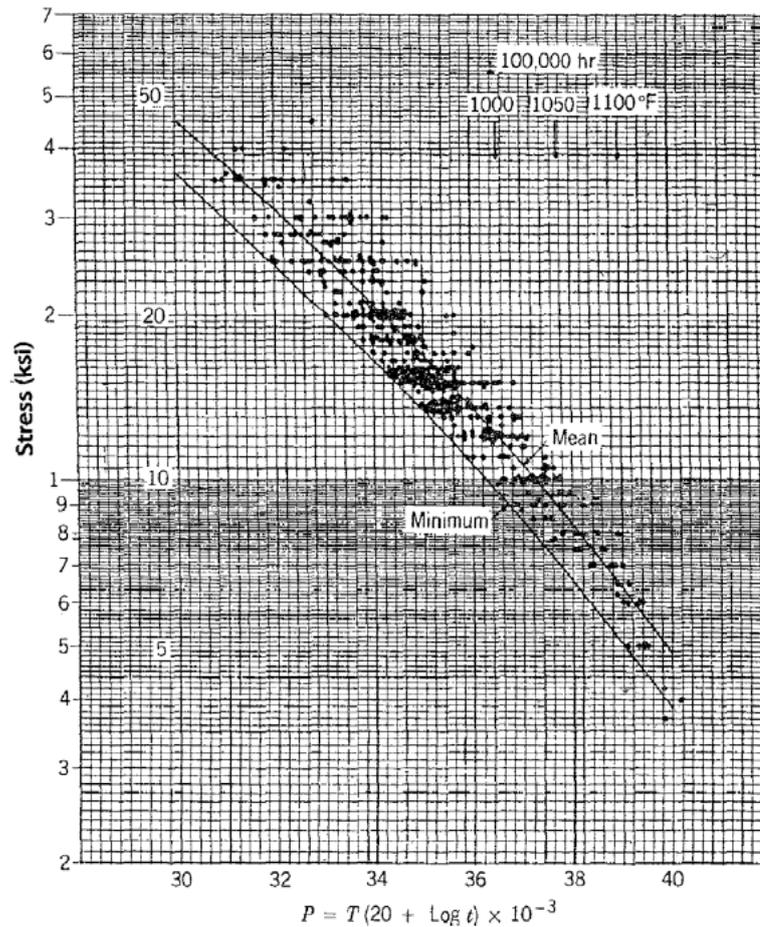
Figure 2.11: Larson-Miller parameter diagram with stress variation to rupture for 2.25Cr-1Mo steel (1 ksi = 6.895 MPa) (Smith 1971, cited in Purbolaksono et al., 2010. p. 103)

There is a common method in determining the cumulative creep damage which is calculating the lifetime of the boiler tube by employing the time fraction as measures of damage (Purbolaksono et al., 2010). When the fractional damages are added up to become unity, this indicates that the failure is likely to occur. The time fraction damage is determined from:

$$\sum \frac{t_{si}}{t_{ri}} = 1 \qquad\qquad (2.22)$$

where

t_{si} = service time, h

t_{ri} = rupture time, h

The rupture time is obtained from Equation 2.21 while the service time refers to the service life of superheater and reheater tubes. By knowing the LMP and the average tube metal temperature, the remaining life of the superheater and reheater can be estimated.

Since the tube metal temperature vary with the increment of the scale thickness formed on the inner surface of superheater and reheater tubes, average temperature of the steam-side scale as a function of time and scale thickness is utilised. In this research, the scale growth prediction is utilising the correlation between the oxide scale formation for ferritic steel of 1-3% chromium and the LMP as reported by Rehn et al. (1981, cited in Purbolaksono et al., 2010). The data of Figure 2.12 may be approximated as:

$$\log\left(\frac{X}{0.0254}\right) = 0.00\,022P - 7.25 \qquad\qquad (2.23)$$

where

X = scale thickness, mm

P = Larson-Miller parameter
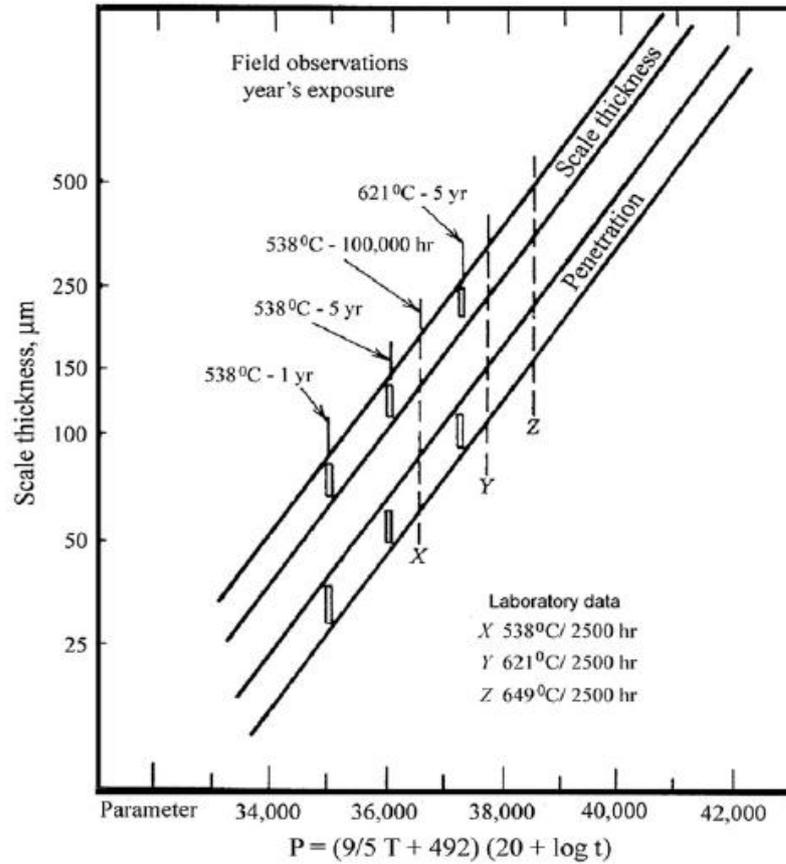
Figure 2.12: Steam-side scale formation for ferritic steels of 1-3% chromium correlated with the Larson-Miller parameter (Rehn et al., 1981, cited in Purbolaksono et al., 2010. p. 101)

The equation of LMP from Figure 2.12 is similar to Equation 2.19 with slight difference and may be expressed as:

$$LMP = \left(\frac{9}{5} T_{ave} + 492 \right) \left(20 + \log t \right) \qquad (2.24)$$

where

T_{ave} = average temperature of oxide layer, ℃

t = service time, h

2.4.6 Vickers Hardness

Hardness of the superheater or reheater tube is influenced after a long operation time with the continuous increasing temperature. In other words, the strength of the tube will deteriorate over long term exposure to the operating temperature. A soften tube poses a risk in the occurrence of rupture in the tube. This can lead to the tube burst as a result of inability to withstand the high pressure inside the tube. Therefore, the hardness of the superheater and reheater tube is examined and evaluated in line with the life assessment of the tube.

An equation that correlates the Vickers hardness and the Larson-Miller parameter for 2.25Cr-1Mo steel under as-quenched condition may be expressed as (Viswanathan 1993):

$$Hardness(HV) = 961.713 - 0.020669P \qquad (2.25)$$

where
P = Larson-Miller parameter
HV = Vickers hardness, HV

2.4.7 Heat Flux

Heat flux is directly linked to the thermal efficiency of the superheater and reheater tube. It is the heat transfer rate across a surface area of the tube. The escalation of the temperature coupled with the oxide scale layer of the tube tends to impede the heat transfer to take place. Therefore, a decline heat flux indicates that less heat energy is being transferred from the flue gas to the steam (Purbolaksono et al., 2009a). This feature is usually utilised to measure the thermal efficiency in conjunction with the prediction of remaining life of superheater and reheater tube.

The distribution of heat flux at all locations of the tube can be determined from the principle of heat flux by conduction at cylindrical wall and heat flux by convection at a surface. In this study, the heat flux distribution is divided into four regions, which are heat flux at inner surface, outer surface, oxide scale layer and tube metal wall of the tube.

The heat flux by conduction is obtained from the temperature difference across the tube wall with the thermal conductivity of the solid material whereas the heat flux by convection is determined from the temperature difference between the steam and the inner surface (or flue gas and the outer surface) of tube with the temperature dependent convection coefficient. The computation equations for the heat flux distribution may be expressed as (Incropera et al., 2007):

$$q''_0 = h_s \left(T_{s,0} - T_{\infty,1} \right) \qquad (2.26)$$

$$q''_{oxide} = \frac{k_{oxide} \left(T_{s,1} - T_{s,0} \right)}{r_1 \ln \left(\dfrac{r_1}{r_0} \right)} \qquad (2.27)$$

$$q''_{metal} = \frac{k_{metal} \left(T_{s,2} - T_{s,1} \right)}{r_1 \ln \left(\dfrac{r_2}{r_1} \right)} \qquad (2.28)$$

$$q''_2 = h_g \left(T_{\infty,2} - T_{s,2} \right) \qquad (2.29)$$

where

q''_0 = heat flux at inner surface of tube, W/m^2

q''_{oxide} = heat flux at oxide scale of tube, W/m^2

q''_{metal} = heat flux at tube metal of tube, W/m^2

q''_2 = heat flux at outer surface of tube, W/m^2

$T_{\infty,1}$ = temperature of steam, ℃

$T_{\infty,2}$ = temperature of flue gas, ℃

$T_{s,0}$ = temperature of inner surface of tube, ℃

$T_{s,1}$ = temperature of scale/metal interface, ℃

$T_{s,2}$ = temperature of outer surface of tube, ℃

h_s = convection coefficient of steam, W/(m² ℃)

h_g = convection coefficient of flue gas, W/(m² ℃)

k_{oxide} = thermal conductivity of oxide scale, W/(m ℃)

k_{metal} = thermal conductivity of tube metal, W/(m ℃)

r_0 = radius up to inner surface of tube, m

r_1 = radius up to oxide scale surface of tube, m

r_2 = radius up to outer surface of tube, m

2.5   Summary

Fuels that are commonly used in HRSG system can be coal, oil or natural gas. The flue gases produced from the combustion travel along the region at the fireside of the boiler tubes while the steam and water flow through the water-side of the tubes. The superheater and reheater in HRSG system apt to heat up the steam inside the tube above its saturation point to ensure moisture free steam is being supplied to the steam turbine.

The superheater and reheater tube problems arise from the high operating temperature are divided into two categories, which are mechanical related problems and corrosion related problems. A mechanical related problem such as creep is a permanent deformation resulted from stress and elevated temperature in the tube. The failure caused by creep is called creep rupture. It can be related to the long term overheating which causes the formation of oxide scale on inner surface of the tube and short term overheating which causes rupture due to hoop stress reaches the tensile strength of the tube at high temperature over a short period of time. The fireside corrosion and erosion is one of the corrosion related problems that typically occur in superheater and reheater tubes. Fireside corrosion is the material wastage by

chemical reaction while the erosion is the material removal by abrasive effect. Eventually tube wall thinning occurs as a result of fireside erosion-corrosion.

Oxide scale growth in superheater and reheater tube can be predicted using the oxide growth laws coupled with the raw data obtained from non-destructive such as ultrasonic technique or destructive methods. The prediction of oxide scale growth in the tube can also be predicted by using finite element modelling (FEM) simulation using ANSYS.

The heat is transferred across the boiler tube by conduction and convection. The flow of steam inside the tube is treated as an internal forced convection with turbulent flow while the flow of flue gas outside the tube is treated as an external forced convection due to cross flow of the flue gas over the tube. Hoop stress is one of the parameters that may promote creep damage to occur faster at high temperature. The combination of calculated hoop stress and Larson-Miller parameter (LMP) chart is used to predict the lifetime of the boiler tube. The cumulative creep damage and scale thickness of the tube can be estimated with the aid of LMP value. Parameters such as Vickers hardness and heat flux in the tube are concerned when examining the behaviour of the boiler tube.

CHAPTER 3

METHODOLOGY

3.1 The Proposed Iterative Procedure for Boiler Tube Analysis

Life expectancy of superheater and reheater tubes can be predicted by using iterative procedure. In this project, MATLAB was employed for the implementation of the iterative procedure that could study the integrity of the boiler tubes.

As reported in the literatures, there were other techniques or methods in estimating the remaining life of tube utilised by other authors including finite element analysis using ANSYS by Purbolaksono et al. (2010), failure analysis using hardness measurements and microscopic examinations by Psyllaki, Pantazopoulos and Lefakis (2009) and so forth. However, analysis using analytical iterative technique incurs lower cost and it is easily accessible without causing damage to the tube. Furthermore, the calculated values during the numerical analysis can be recorded and stored for documentation and analysis purposes.

Since the superheater and reheater tubes are usually operated at an escalating temperature over a long period of time, the life prediction of the tube can be made as a function of tube temperature, operating pressure and time. Other analyses including oxide scale thickness, Vickers hardness and heat flux can also be carried out. The scale thickness can be estimated by using the Equation 2.23. The remaining life of tube in terms of creep damage can be estimated by using Equation 2.24.

The iterative procedure used for the prediction were performed up to 160 000 h of service life with an increment of 250 h as the time steps. Smaller increment of time is necessary to improve the accuracy of the prediction. The proposed steps for the iterative procedure are discussed in the following paragraphs.

For the first iteration ($I = 1$), the steam temperature of the superheater or reheater tube is represented by T_s. Before the operation of the superheater or reheater tube, the oxide scale layer (X_0) on the inner tube wall is assumed to be zero whereas the calculated average temperature of oxide scales $T_{ave1,o}$ is the inner surface temperature of the tube. Both of the Equations 2.23 and 2.24 are employed in determining the scale thickness X_{1a} at the service hour of 1 h and the scale thickness X_{1b} at the service hours of 250 h with the average temperature of $T_{ave1,o}$. An increment of scale thickness ΔX_1 is obtained from the difference between X_{1a} and X_{1b}. A newly formed layer of oxide scale can be obtained by $X_1 = X_0 + \Delta X_1$. Similarly, the hardness of HV_{1a} for the service hour of 1 h and the hardness of HV_{1b} for the service hours of 250 h are calculated using the $T_{ave1,m}$ coupled with the Equation 2.24 and Equation 2.25. The calculated average temperature of tube metal $T_{ave1,m}$ is referred to the average of the temperatures at the inner and outer surfaces of tube. The initial hardness HV_1 is set to HV_{1a}. The heat fluxes at various location of tube wall are calculated using Equations 2.26 to 2.29. The average heat flux is obtained from the average of heat flux at tube metal and outer wall of the tube.

In the second iteration ($I = 2$), the calculated average temperature $T_{ave2,o}$ is the mean of the temperature at inner surface and scale/metal interface. The following increment of scale thickness from service hours of 250 h to 500 h is calculated by the Equations 2.23 and 2.24 using $T_{ave2,o}$. The Larson-Miller parameters at service hours of 250 h and 500 h are calculated using Equation 2.24 while the X_{2a} (250 h) and X_{2b} (500 h) are calculated using Equation 2.23. By getting the difference between X_{2a} and X_{2b}, a new incremental scale thickness from 250 h to 500 h is obtained. This value is added to the previous scale thickness X_1 to form a new scale thickness of X_2. The calculated average temperature of $T_{ave2,m}$ is obtained from the average of temperatures at the scale/metal interface and the outer surfaces of the tube. The $T_{ave2,m}$ is used to calculate the hardness of tube for service hours of 250 h (HV_{2a}) and 500 h (HV_{2b}) using Equations 2.25 while the Larson-Miller parameter is calculated

using Equation 2.24 for both service hours of 250 h and 500 h. The new hardness HV_2 can be obtained from the average of HV_{2a} and HV_{2b}. By employing the Equations 2.26 to 2.29, the heat fluxes across the tube wall are determined. The average heat flux is obtained from the average of heat flux at tube metal and outer wall of the tube. The steps done in second iteration are repeated and continue for the predictions up to the maximum of 160 000 h, but with the increment of 250 h for the rest of the iterations.

3.2   Implementation of Iterative Analytical Method in MATLAB

The proposed iterative procedure was implemented in MATLAB to perform various boiler tube analyses and studies such as prediction of remnant life of the tube, failure analysis and constant B estimation. In order to develop the program, knowledge in principles of heat transfer coupled with the LMP chart and formulas explained in Chapter 2 are mandatory.

The flow charts of the proposed iterative procedure in MATLAB are illustrated in Figure 3.2 to Figure 3.8 and the descriptions of symbols used are shown in Table 3.1. Figure 3.1 illustrates the usage of both Off-page and On-page connectors in joining different flow charts.

The flow chart starts from Figure 3.2 and proceeds to Figure 3.3 through the Off-page Connector 1 on the right. The program continues until it reaches the Off-page Connector 2 that links to Figure 3.4. If the program in Figure 3.4 fulfils the conditions stated at the bottom left corner, it will proceed to Figure 3.5 through Off-page Connector 3 and return back to Figure 3.4 through Off-page Connector 4, otherwise follows the Off-page connector 5 to Figure 3.6 and continues to Figure 3.7 via Off-page Connector 6.

Based on Figure 3.7, the flow chart depicted on the left side brings the program back to Figure 3.3 via Off-page Connector 7 and repeats the steps as described in the previous paragraph, provided that the condition stated on the left

side of Figure 3.3 is fulfilled. When the condition is no longer satisfied, the Off-page Connector 8 connects the flow chart from Figure 3.3 to the flow chart on the right side of Figure 3.7. An Off-page Connector 9 joins the program to the left flow chart in Figure 3.8 when the condition specified on the top right corner is fulfilled and returns it back to Figure 3.7 via Off-page Connector 10 at the bottom, otherwise the flow chart follows the flow downward until it reaches Off-page Connector 11 that connects to the flow chart on the right side of Figure 3.8. Eventually, the program will end at the terminator symbol located at the middle part of the flow chart (right side) in Figure 3.8.
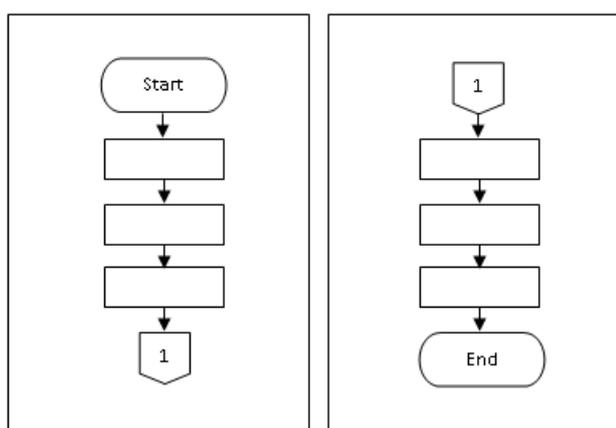
Off-page connector links two flow charts from different pages.
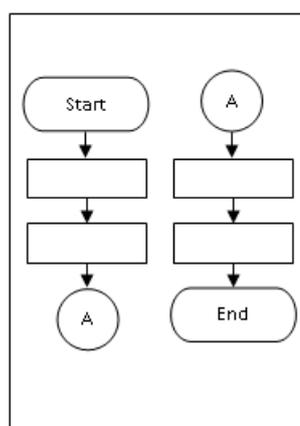
On-page connector links two flow charts on the same page.

Figure 3.1: An Illustration of Usage of Off-page and On-page Connectors

Table 3.1: Descriptions of Flow Chart Symbol Used

Symbol	Name	Description
	Flow Line	Indicates the direction of flow
	Terminator (Start/End)	A symbol marks the starting or ending point of the system
	Process	A box that represent a single step or operation
	Input/Output	Indicates inputs and output operation
	Decision	A decision or branching point. Lines represents different decisions emerge from different points of the diamond shape
	Document	A document
	On-page Connector	A link to another part of the same page
	Off-page Connector	A link to another page
	Function	Function file that can be called
	Stored Data	A step that results in data being stored
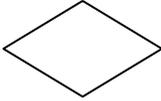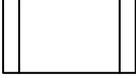
Figure 3.2: Flow Chart of Iterative Procedure (Part 1)
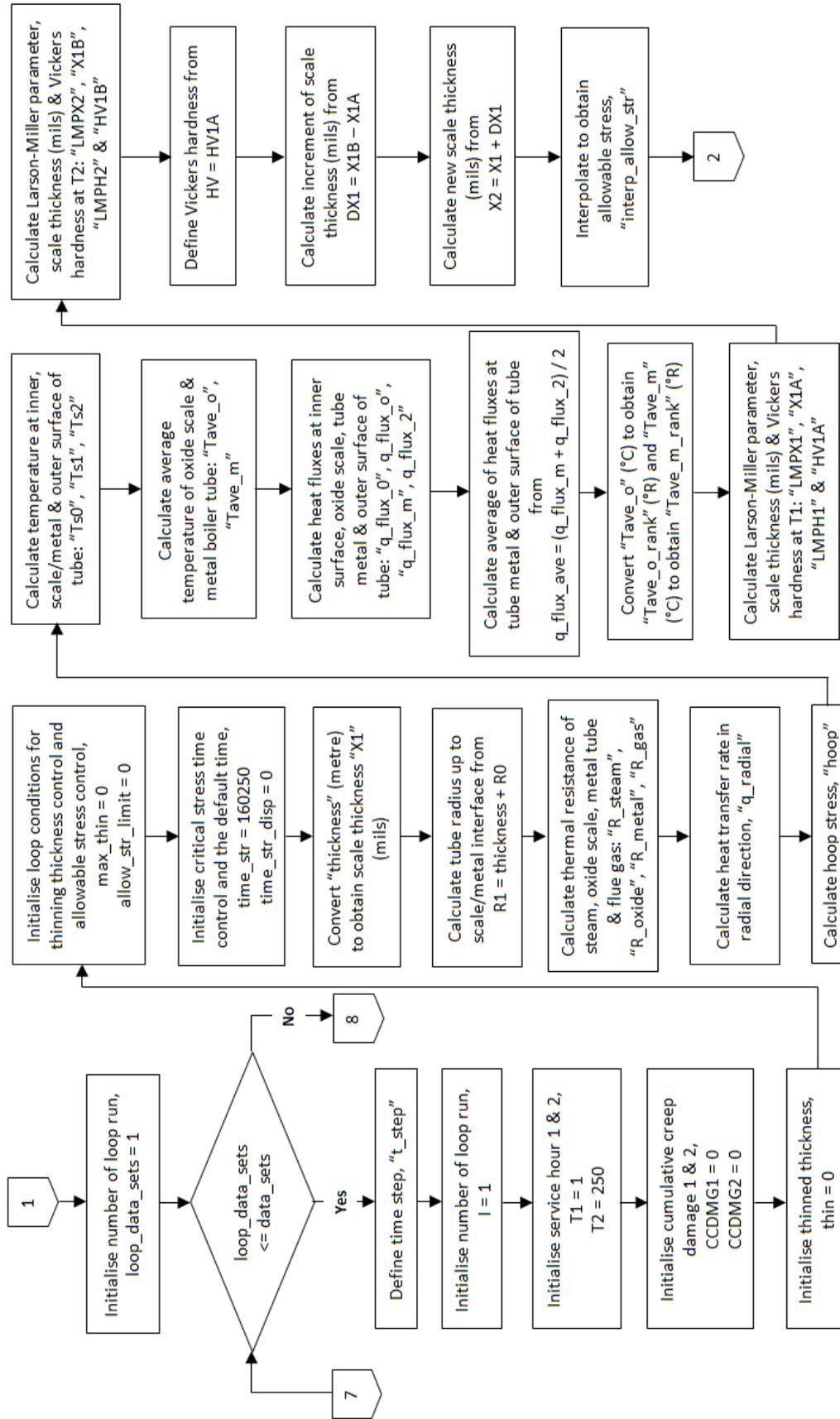
Figure 3.3: Flow Chart of Iterative Procedure (Part 2)
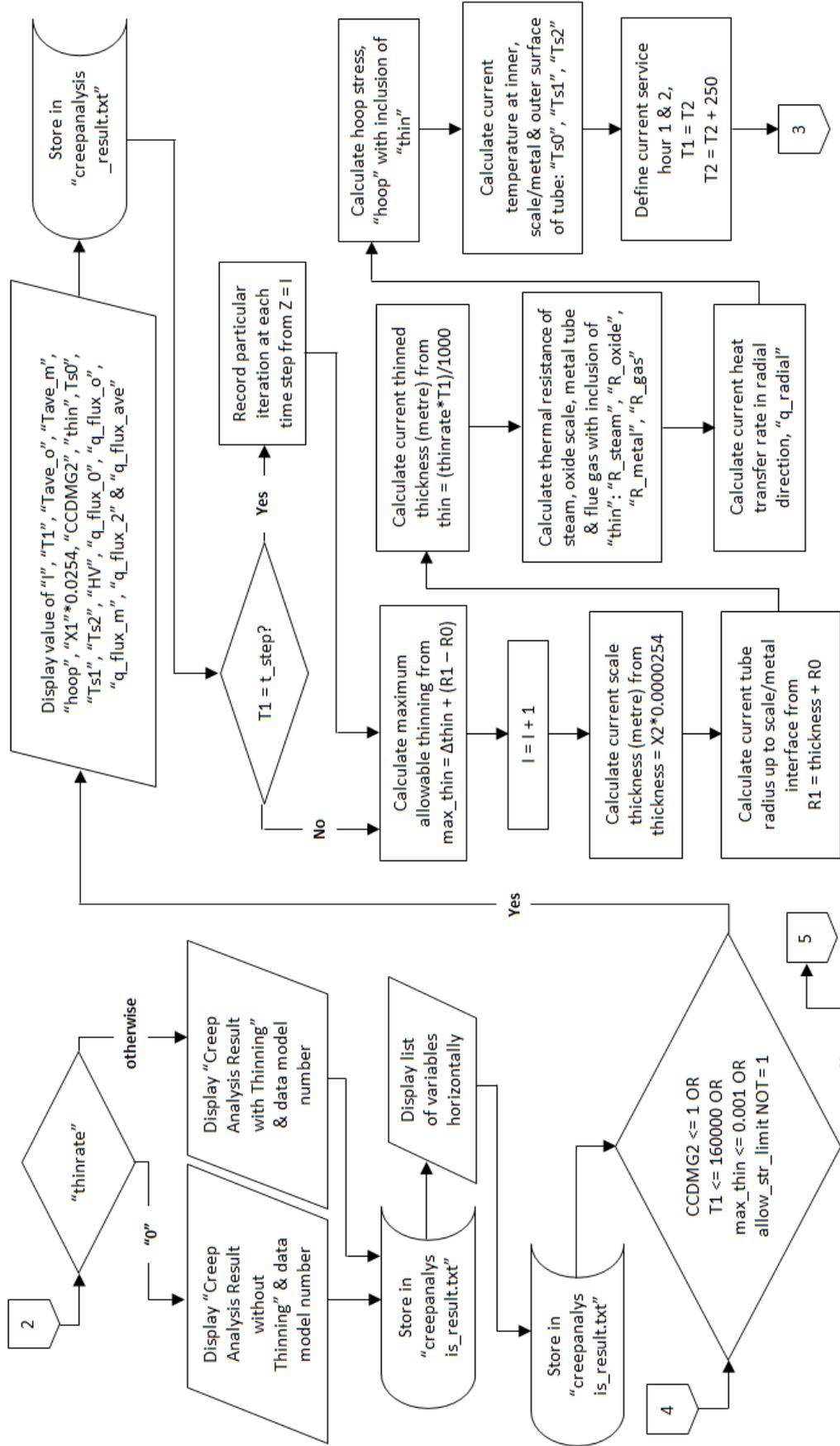
Figure 3.4: Flow Chart of Iterative Procedure (Part 3)
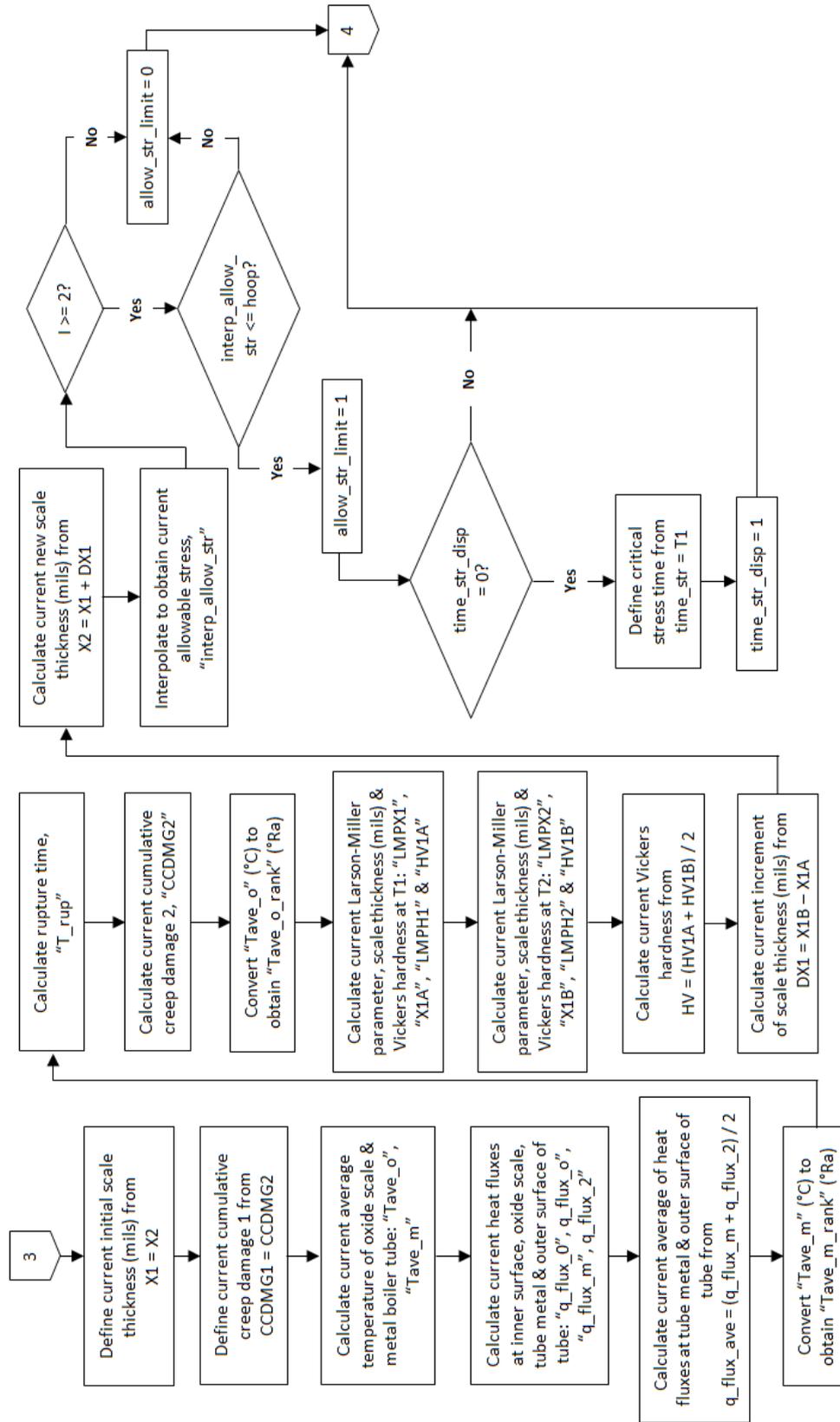
Figure 3.5: Flow Chart of Iterative Procedure (Part 4)
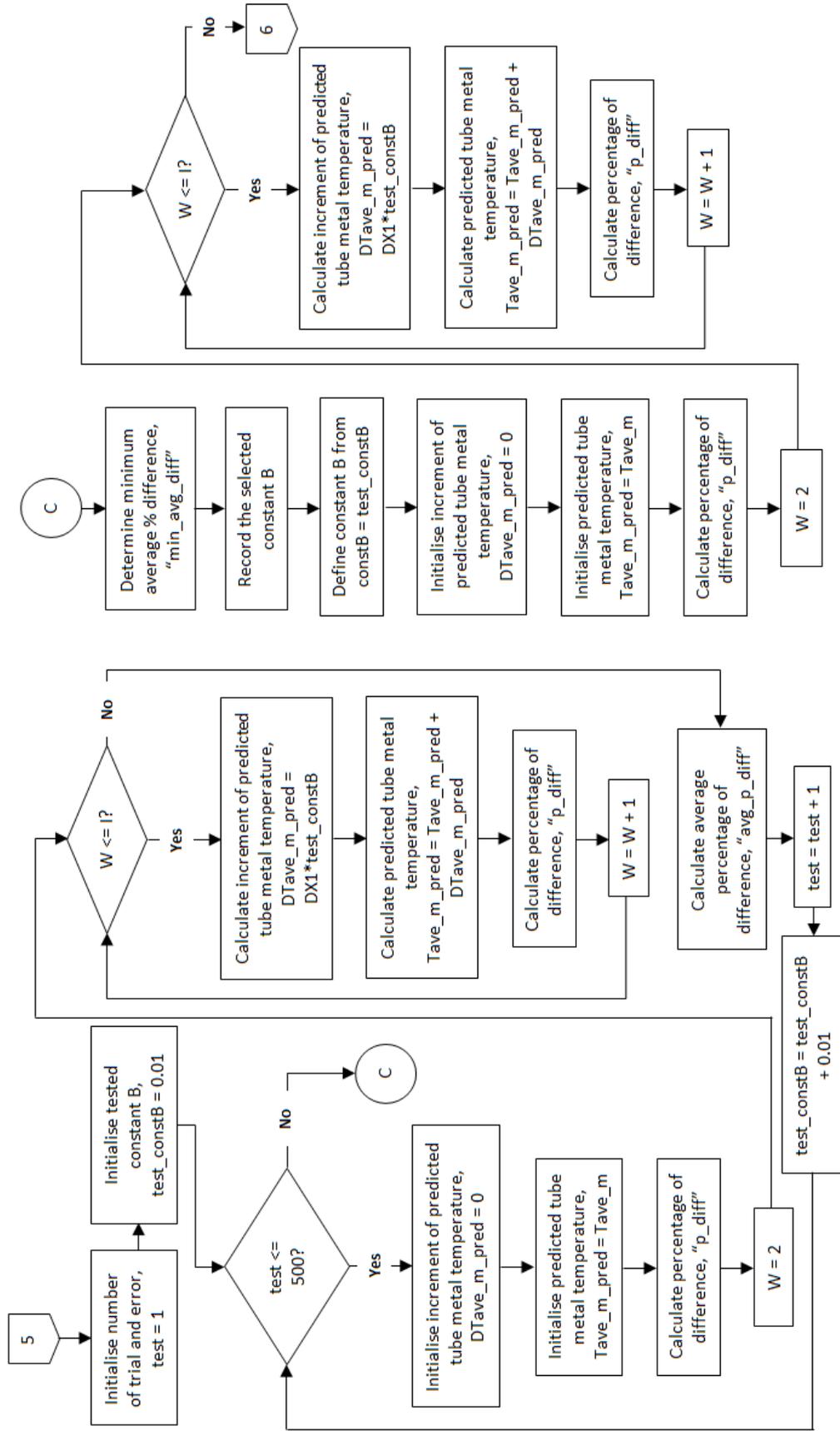
Figure 3.6: Flow Chart of Iterative Procedure (Part 5)

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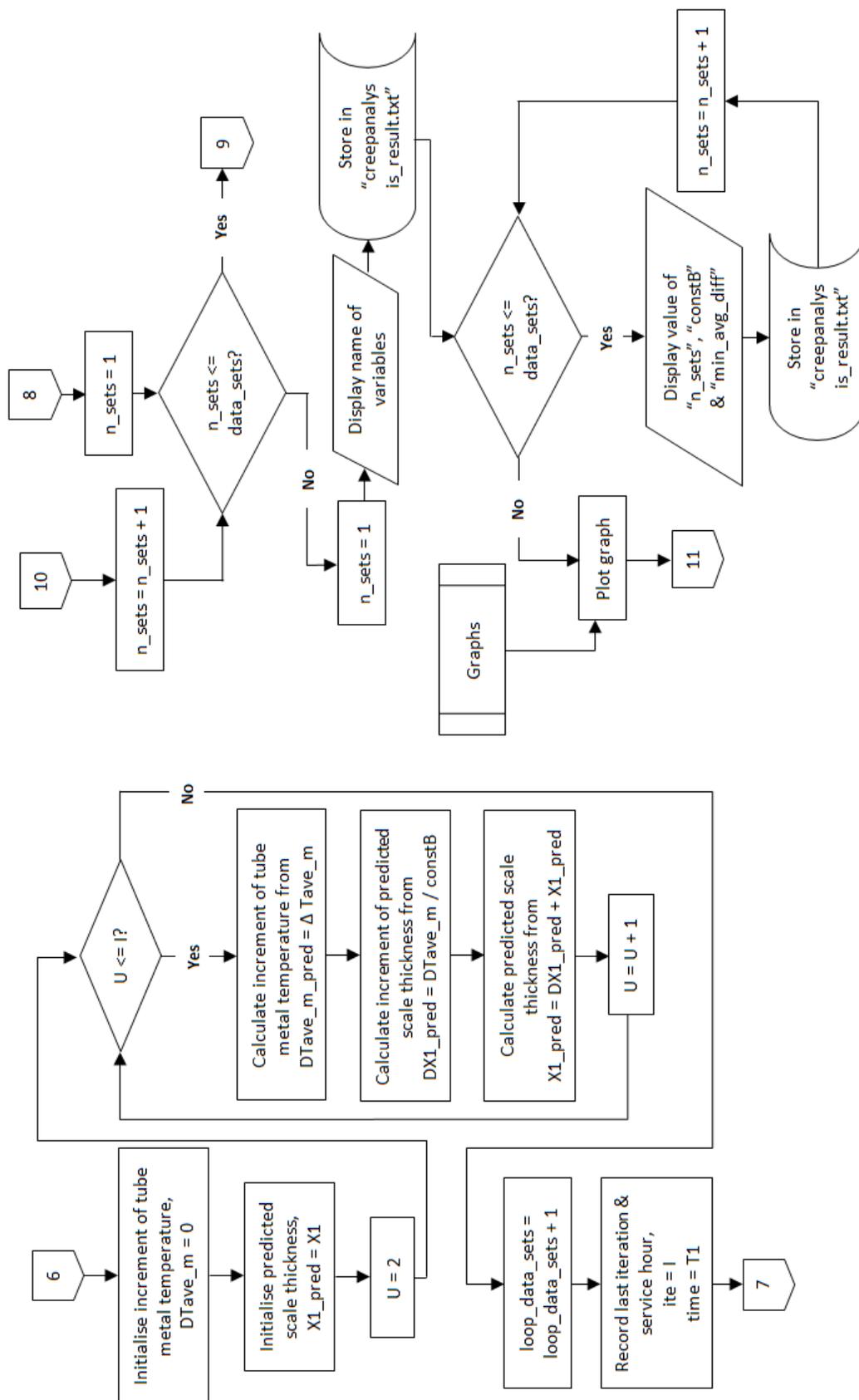
Figure 3.7: Flow Chart of Iterative Procedure (Part 6)
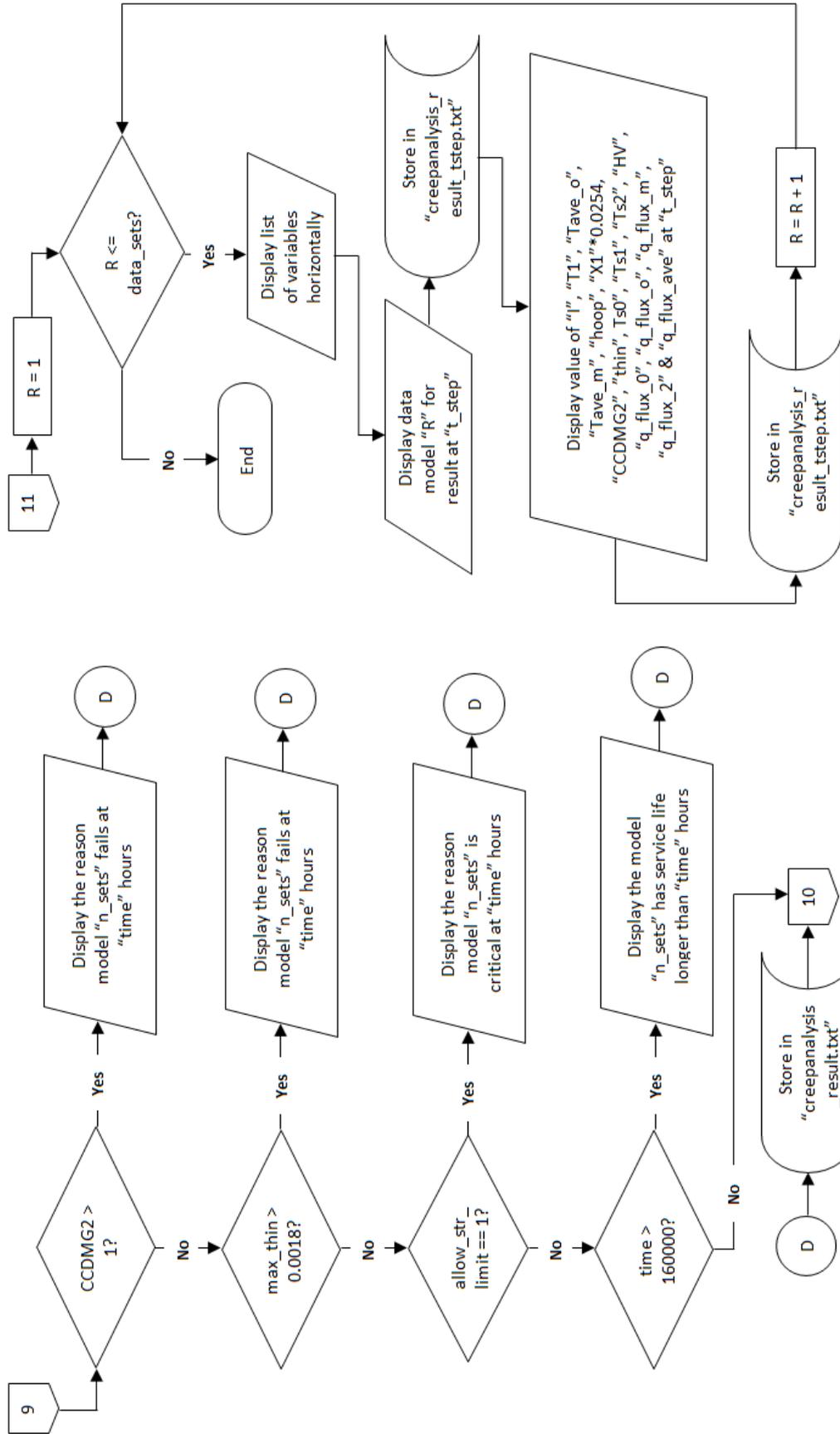
Figure 3.8: Flow Chart of Iterative Procedure (Part 7)

3.2.1   Replacement of Old Data

The MATLAB program starts with a while loop that prompts user to decide if the previous old data file is to be kept. It is set to allow only two inputs, which are input "1" and input "2" before the program can proceed to the next operation. Input "1" indicates if the user is creating a new data file whereas an input "2" refers to the old data is preserved, otherwise an error message will be displayed to inform user. This is to ensure an appropriate input is keyed in.

```matlab
loop_outputdata_input = 0;

while (loop_outputdata_input == 0)   % Overwriting output data file

    disp(' ');
    disp(' ');
    disp('Do you want to overwrite the output data file?');
    outputdata_input = input('Please enter 1 to overwrite or 2 to continue append at the end : ');

    switch (outputdata_input)
        case (1)
            fileID = fopen('creepanalysis_result.txt','w');
            disp(' ');
            loop_outputdata_input = 1;
        case (2)
            fileID = fopen('creepanalysis_result.txt','a');
            disp(' ');
            loop_outputdata_input = 1;
        otherwise
            disp('Wrong input. Please key in again.');
    end
end
```

Figure 3.9: Prompt User to Decide in Overwriting Old Output Data File

3.2.2   Types of Input File

The developed MATLAB program tends to read any of the two input files (in ".txt" format) including all the desired input parameters, one with all the raw input data in which certain parameters are used to calculate the convection coefficient of steam and flue gas, and another input file is utilised if the user has obtained the values of convection coefficients prior to the analysis.

The necessary input parameters that are required in both types of input file are as shown in Table 3.2. When a raw input file is selected (input "1"), two MATLAB function files will be called to calculate the convection coefficients of

steam, h_s and flue gas, h_g. Input "2" is chosen if the values of h_s and h_g are known. Figure 3.10 shows the prompt for user input file in a command window.

Table 3.2: Input Parameters Required in Performing Analysis

Number	Input Parameters	
	Raw Values	Raw & Convection Coefficient Values
1	Steam mass flow rate (kg/h)	Steam convection coefficient (W/(m² ℃)
2	Inner tube diameter (m)	Flue gas convection coefficient (W/(m² ℃)
3	Steam temperature (℃)	Steam temperature (℃)
4	Steam pressure (MPa)	Steam pressure (MPa)
5	Flue gas temperature (℃)	Flue gas temperature (℃)
6	Volume fraction of CO_2	Length of boiler tube (m)
7	Volume fraction of H_2O	LMP ($\times 10^3$)
8	Volume fraction of N_2	Thermal conductivity (oxide) (W/(m ℃)
9	Volume fraction of O_2	Thermal conductivity (tube metal) (W/(m ℃)
10	Volume fraction of SO_2	Inner tube radius (m)
11	Volume fraction of HCl	Outer tube radius (m)
12	Gas flow (kg/h)	Scale thickness (m)
13	Number of tube wide	Thin rate (mm/h)
14	Transverse pitch (m)	
15	Length of boiler tube (m)	
16	Outer tube diameter (m)	
17	LMP ($\times 10^3$)	
18	Thermal conductivity (oxide) (W/(m ℃)	
19	Thermal conductivity (tube metal) (W/(m ℃)	
20	Inner tube radius (m)	
21	Outer tube radius (m)	
22	Scale thickness (m)	
23	Thin rate (mm/h)	

```
Do you want to overwrite the output data file?
Please enter 1 to overwrite or 2 to continue append at the end : 1

fx Please enter 1 to read input_raw_values.txt OR 2 to read input_conv_values.txt:
```

Figure 3.10: An Example of User Prompt in Command Window

3.2.3 Tube Life Prediction Conditional Control

There are few criteria which are most likely to cause rupture in boiler tube directly or indirectly. A cumulative creep damage that reaches unity signifies the tube failure is occurred. The reduction of thickness and stress accumulated in the tube wall constitute to the critical state of the operating boiler tube. In the proposed analytical iterative procedure, four stopping criteria are being used in controlling the loop. The loop or iteration is forced to stop if any of the condition is unsatisfied, which pinpoints the boiler tube is either in critical condition or has high risk in resulting failure.

One of the conditions is the cumulative creep damage (CCDMG), which is used to analyse the creep life of the boiler tube and indicates the possible service life the tube has. The value of CCDMG must be equal or less than unity or one. For a boiler tube that is in safe condition over a long period of time, the service life is anticipated to operate longer than the optimum service hours of 160 000 h. Thus, the maximum iteration is performed until service hours of 160 000 h.

The previous two conditions are treated as minimum requirements to be fulfilled to ensure the boiler tube is safe to use. Another important factor to be observed is the wall thinning effect of the tube. Thinning effect is more likely to hasten the rupture of tube and reduce its service life provided that the operating pressure is high. On the other hand, a boiler tube is not recommended to operate at operational pressure that is too high as the hoop stress as a function of steam pressure tends to exceed the maximum allowable stress of the tube. In this situation, the boiler tube is said to be in critical state. On top of that, the tube will rupture if the stress reaches its yield strength. A value of "0" refers to the hoop stress is still below the maximum allowable stress while a value of "1" signal a warning of the critical state experienced by the tube.

User has the options to turn off any of the last two conditions by placing a symbol of "%" in front of the condition to convert the command code into a comment tag. It is informed that the first two conditions should not be turning off as they act as the fundamental requirements for the iterative procedure to perform. An

illustration of the while loops with three and four conditional controls are shown in Figure 3.11. Figure 3.12 shows an example of the analysis' summary indicating the root cause of the exiting loop.

```
while (CCDMG2(setnum,I)<=1 && T1<=160000 && max_thin(setnum,1)<=0.0018 && allow_str_limit(setnum,1)~=1)

while (CCDMG2(setnum,I)<=1 && T1<=160000 && max_thin(setnum,1)<=0.0018)% && allow_str_limit(setnum,1)~=1)
```

Figure 3.11: Illustration of Four Conditional Controls (Top) and Three Conditional Controls (Bottom)

```
SUMMARY:

Model 1 has service life longer than 160000 hours.

Model 2 is in critical state at 18500 hours due to hoop stress exceeds max allowable stress.

Model 3 fails at 95750 hours due to creep damage.

Model 4 is in critical state at 21250 hours due to tube wall thinning more than 1.8 mm.
```

Figure 3.12: An Example of Summary of the Analysis

3.2.4   Results Display and Graph Plotting

There are two types of displayed results from the MATLAB program, one that including all the variable values in each iteration (increment of 250 h) as depicted in Figure 3.13 while the other type displays extracted data at predetermined time step as shown in Figure 3.14. The results also show if a particular model with or without the wall thinning effect.

Furthermore, the developed MATLAB program has the ability to plot various graphs by recalling separate function files as shown in Figure 3.15. The circled parts show the file names of the graph. Similarly, the function file recalling can be turned off by placing a "%" symbol in front of the command to convert it into a comment tag. The MATLAB program limits maximum of six models for better visibility and clarity of the plotted graph.

378	94250	583.912	617.109	13.445	1.3747	0.9785	0.00000	552.172	615.653	618.564
379	94500	583.918	617.121	13.445	1.3751	0.9817	0.00000	552.171	615.666	618.576
380	94750	583.924	617.133	13.445	1.3754	0.9849	0.00000	552.170	615.678	618.588
381	95000	583.930	617.145	13.445	1.3758	0.9881	0.00000	552.169	615.690	618.600
382	95250	583.935	617.157	13.445	1.3762	0.9913	0.00000	552.168	615.702	618.611
383	95500	583.941	617.169	13.445	1.3766	0.9945	0.00000	552.168	615.715	618.623
384	95750	583.947	617.181	13.445	1.3770	0.9977	0.00000	552.167	615.727	618.635

CREEP ANALYSIS RESULT WITH THINNING: (DATA MODEL 4)

I	T1	Tave_o	Tave_m	hoop	X1*0.0254	CCDMG2	thin	Ts0	Ts1	Ts2
1	1	555.205	557.313	21.467	0.0000	0.0000	0.00000	555.205	555.205	559.421
2	250	555.911	558.791	21.467	0.0267	0.0001	0.00000	555.114	556.709	560.872
3	500	556.118	559.224	21.554	0.0349	0.0001	0.00002	555.076	557.160	561.288
4	750	556.260	559.521	21.641	0.0408	0.0002	0.00004	555.047	557.473	561.569
5	1000	556.370	559.753	21.730	0.0454	0.0002	0.00006	555.022	557.719	561.787
6	1250	556.462	559.945	21.819	0.0493	0.0003	0.00008	554.999	557.924	561.965
7	1500	556.540	560.109	21.909	0.0527	0.0004	0.00010	554.978	558.102	562.117
8	1750	556.609	560.254	22.000	0.0558	0.0004	0.00012	554.958	558.260	562.249
9	2000	556.670	560.384	22.092	0.0586	0.0005	0.00014	554.939	558.401	562.366
10	2250	556.726	560.501	22.184	0.0612	0.0006	0.00016	554.922	558.531	562.471
11	2500	556.777	560.608	22.278	0.0636	0.0006	0.00018	554.904	558.649	562.566

Figure 3.13: Part of the Results Displayed (Complete Iterations)

CREEP ANALYSIS RESULT IN t_step: (DATA MODEL 1)

t_step	Tave_o	Tave_m	hoop	X1*0.0254	CCDMG2	thin	Ts0	Ts1	Ts2	HV
1	554.600	556.206	27.029	0.0000	0.0000	0.00000	554.600	554.600	557.812	344.466
250	555.273	557.614	27.029	0.0263	0.0001	0.00000	554.517	556.030	559.197	264.634
500	555.480	558.046	27.029	0.0345	0.0001	0.00000	554.491	556.469	559.623	256.892
1000	555.740	558.589	27.029	0.0448	0.0002	0.00000	554.459	557.021	560.158	248.340
2500	556.189	559.528	27.029	0.0627	0.0006	0.00000	554.403	557.975	561.082	236.064
5000	556.631	560.453	27.029	0.0805	0.0012	0.00000	554.348	558.914	561.992	226.234
10000	557.188	561.618	27.029	0.1031	0.0026	0.00000	554.279	560.097	563.138	216.018
20000	557.889	563.084	27.029	0.1320	0.0056	0.00000	554.192	561.586	564.582	205.424
40000	558.773	564.932	27.029	0.1689	0.0124	0.00000	554.083	563.463	566.400	194.407
60000	559.394	566.230	27.029	0.1952	0.0199	0.00000	554.006	564.781	567.678	187.733
80000	559.888	567.264	27.029	0.2164	0.0282	0.00000	553.944	565.832	568.696	182.879
100000	560.306	568.138	27.029	0.2344	0.0370	0.00000	553.892	566.720	569.556	179.039
120000	560.672	568.903	27.029	0.2504	0.0463	0.00000	553.847	567.497	570.309	175.849
140000	560.999	569.588	27.029	0.2647	0.0562	0.00000	553.806	568.192	570.983	173.113
160000	561.297	570.210	27.029	0.2779	0.0665	0.00000	553.769	568.825	571.596	170.712

CREEP ANALYSIS RESULT IN t_step: (DATA MODEL 2)

t_step	Tave_o	Tave_m	hoop	X1*0.0254	CCDMG2	thin	Ts0	Ts1	Ts2	HV
1	555.205	557.313	21.467	0.0000	0.0000	0.00000	555.205	555.205	559.421	343.642
250	555.911	558.791	21.467	0.0267	0.0001	0.00000	555.114	556.709	560.872	263.647

Figure 3.14: Part of the Results Displayed At Predetermined Time Steps

```
% Graph Plotting Functions %
% --Comparison between data sets:--

[X1_step]= X1_graph(time,ite,data_sets,X1,t_step);
[CCDMG2_step]= CCDMG2_graph(time,ite,data_sets,CCDMG2,t_step);
[Tave_m_step]= Tave_m_graph(time,ite,data_sets,Tave_m,t_step);
[HV_step]= HV_graph(time,ite,data_sets,HV,t_step);
[q_flux_m_step]= q_flux_m_graph(time,ite,data_sets,q_flux_m,t_step);
[q_flux_ave_step]= q_flux_ave_graph(time,ite,data_sets,q_flux_ave,t_step);
[k_value_p,k_value_p_ave]= k_value_p_graph(time,ite,data_sets,X1);
[k_value_q,k_value_q_ave]= k_value_q_graph(time,ite,data_sets,X1);
[Tave_m_pred_step]= Tavem_pred_graph(time,ite,constB,data_sets,Tave_m_pred,t_step);
[X1_pred_step]= X1_constB_graph(time,ite,constB,data_sets,X1_pred,t_step);

% --Plots of single set:--

[Tave_step_o,Tave_step_m]= Tave_graph(time,ite,Tave_o,Tave_m,t_step);
[q_flux_step_inner,q_flux_step_o,q_flux_step_m,q_flux_step_outer]= ...
    q_flux_graph(time, ite,q_flux_0, q_flux_o,q_flux_m,q_flux_2,t_step);
[Ts_inner_step,Ts_om_step,Ts_outer_step]= Ts_graph(time,ite,Ts0,Ts1,Ts2,t_step);
[interp_allow_str_step] = allowable_stress_graph(time,time_str,...
    ite,interp_allow_str, hoop,t_step);
[Tavem_step_pred,Tavem_step]= corr_fn_graph(time,ite,constB,Tave_m_pred, ...
    min_avg_diff,Tave_m,t_step);
```

Figure 3.15: Separate Function Files for Graph Plotting

3.3   Correlation Function between Tube Metal Temperature Rise and Scale Growth

The temperature increase in the tube metal wall and steam-side scale growth on the inner tube wall are closely related. In the past, the common root cause that lead to the failed superheater or reheater tubes were reported to be overheating of the tube over long period of time. The formation of the scale on the inner wall of the tube can inhibit the heat transfer and result in accumulation of temperature in the tube metal.

It was found that the linear relationship between the scale growth of superheater and reheater tubes and the tube metal temperature increase could be correlated with a constant *B*. This allows a study of the various operating conditions of the boiler tube with respect to the correlation function. The increment of tube metal temperature $\Delta T_{ave,m}$ as a function of increment of scale thickness ΔX over long service hours can be expressed as:

$$\Delta T = B \, \Delta X \qquad\qquad (3.1)$$

where

ΔT = increment of tube metal temperature, ℃

ΔX = increment of scale thickness, mils

B = constant correlating the temperature increase and scale growth

The increasing scale thickness is the scale thickness in mils. One mil is equivalent to one thousandth (1×10^{-3}) of an inch or 0.0254 mm. From the Equation 3.1, it could be deduced that a constant B acts as a multiplier to every increment of scale thickness corresponding to each increment of tube metal temperature. When the constant B is greater than one, it describes that the increment is more significant in temperature or relatively less in scale thickness and vice versa.

In order to embark on the development of a constant, a set of data for the scale thickness or temperature of the tube metal over the service hours is necessary. In this project, the data of scale thickness was used in the prediction of temperature increase in the tube. By using the iterative procedure proposed in this chapter, the values for scale thickness for all the iterations up to a maximum time step of 160 000 h were stored. The increment of scale thickness ΔX at every time step was determined.

After the data collection of the incremental thickness of scale, a constant B was estimated by undergoing trial and error process and selected a value which produced the lowest percentage of difference from the estimated incremental tube metal temperature. The first increment of tube metal temperature estimated by the constant B was added to the average tube metal temperature at the first iteration ($I = 1$) to form new temperature. The second temperature rise was added to this new temperature to estimate the temperature at second iteration ($I = 2$). This step was repeated for the rest of iterations. An inverse way can be done to estimate the scale thickness by using the tube metal temperature increase obtained from the iterative procedure instead of scale thickness. It was proposed that the trial and error process arises with an initial of 0.01 until a constant of 5. The range of the tested constant

value can be decided by the user. A total of 500 possible constant B values can be used.

3.4   Models Preparation of Analysis

Table 3.3 shows three different geometries of superheater and reheater tubes used in the analysis. These three tubes were evaluated. The correlation function of the seven models with different operating conditions and heat transfer parameters used in this study are shown in Table 3.4. Model 1 was set as the default model in each analysis. Apart from that, other relevant parameters that required in the analytical iterative method are tabulated in Tables 3.5 to 3.7. The assumptions made in the analysis are stated as below:

1. The heat transfer is in steady state and one-dimensional.
2. The thermal conductivity of oxide layer and tube metal remained constant for the whole analysis
3. The convection coefficients of steam and flue gas are uniform over the inner surface and outer surface of the boiler tubes respectively.
4. Oxide scale growth rate and wall thinning rate of the boiler tubes are uniform.
5. The steam temperature and flue gas temperature are kept constant throughout the entire process.
6. The thermal properties of the boiler tube have no changes during the operations.

Table 3.3: Geometries of Tube

Tube	Inner Radius (m)	Outer Radius (m)	Wall Thickness (m)
1	0.0219	0.0254	0.0035
2	0.0219	0.0264	0.0045
3	0.0219	0.0274	0.0055

Table 3.4: Models for Failure Analysis of Tube

Model	Tube	Steam Temperature (℃)	Steam Mass Flow Rate (kg/h)	Flue Gas Temperature (℃)	Operating Internal Pressure (MPa)
1	1	540	3600	800	4
2	1	540	3800	800	4
3	1	540	4000	800	4
4	1	560	3600	800	4
5	1	580	3600	800	4
6	1	540	3600	900	4
7	1	540	3600	1000	4
8	2	540	3600	800	4
9	3	540	3600	800	4

Table 3.5: Solid Material Properties for Boiler Tube

Water Wall Properties	
Tube Material	SA213-T22
Thermal Conductivity, k_m (W/m ℃)	34.606
Fe_3O_4 Iron Oxide (Magnetite)	
Thermal Conductivity, k_o (W/m ℃)	0.592

Table 3.6: Parameters Required in Determining Gas Mass Velocity, G

Gas Flow (kg/h)	400 000
Number of Tube Wide	32
Transverse Pitch (m)	0.1016
Tube Length (m)	10

Table 3.7: Compositions of Flue Gas at 15 % Air

Nitrogen (mole %)	71.08
Oxygen (mole %)	2.46
Carbon Dioxide (mole %)	8.29
Water (mole %)	18.17

CHAPTER 4

RESULTS AND DISCUSSION

4.1   Validation of the Developed MATLAB Program

The accuracy of the scale thickness and cumulative creep damage obtained by the proposed iterative technique using developed MATLAB program is crucial to the prediction of the remaining life of superheater and reheater tubes. In the literature, Purbolaksono et al. (2009b) have reported the details of reheater tube failed in Kapar Power Station Malaysia. Those details such as service life, scale thickness and other heat transfer parameters were adopted in this project for results validation purposes.

The reheater tube failed at Kapar Power Station Malaysia has been analysed and examined by Purbolaksono et al. (2009b). The tube was situated at a distance from the burner and operated under average steam pressure of 4 MPa. The operating steam temperature and flue gas temperature for the tubes were 576 ℃ and 800 ℃ respectively. The details of the reheater tube are tabulated in Table 4.1 to 4.3.

Few parameters including gas flow W_g, number of tube wide N_w, transverse pitch S_t and tube length L that are needed to calculate the gas mass velocity G are shown in Table 4.2. The estimated steam convection coefficient h_s at internal tube surface and the flue gas convection coefficient h_g at external tube surface are tabulated in Table 4.3.

Table 4.1: Geometry, Service Time and Inner Scale Thickness of the Tubes and the Year of Failure

Inner Radius (m)	Tube Thickness (mm)	Service Time (h)	Scale Thickness (mm)	Year of Failure
0.0219	3.5	117 522	0.58	2003

(Purbolaksono et al., 2009b. p.906)

Table 4.2: Parameters Required in Determining Gas Mass Velocity *G*

Gas Flow (kg/h)	500 000
Number of Tube Wide	50
Transverse Pitch (m)	0.1016
Tube Length (m)	8

(Purbolaksono et al., 2009b. p.906)

Table 4.3: The Estimated Steam and Flue Gas Convection Coefficients

h_s (W/m^2 $°$C)	h_g (W/m^2 $°$C)
2053.65	126.01

(Purbolaksono et al., 2009b. p.907)

The Larson-Miller parameter (LMP) can be determined by the Equations 2.18 – 2.20 and the LMP chart shown in Figure 2.11. Purbolaksono et al. (2009b) have estimated the LMP value to be 39 900. With the aid of LMP value, cumulative creep damage can be obtained as a measure of damage for boiler tube. The cumulative creep damage denotes the life expectancy of tube. Once the cumulative creep damage is equal or greater than unity (one), the tube is said to be failed and ruptured.

In this project, the proposed iterative technique using MATLAB program was capable to generate similar results with the Finite Element Method (FEM) reported by Purbolaksono et al. (2009b). By using the same operational heat transfer parameters, the estimated remaining life of reheater tube in terms of cumulative creep damage and other parameters such as scale thickness, tube metal temperature

and hardness were obtained. Table 4.4 shows the comparison of estimated scale thickness and the cumulative creep damage while Table 4.5 shows the comparison of estimated values for average tube metal temperature and Vickers hardness.

Table 4.4: Estimations of Scale Thickness and Cumulative Creep Damage by MATLAB Program and Other Authors (FEM)

Service Hour (h)	Scale Thickness (mm)			Cumulative Creep Damage		
	MATLAB	FEM[*]	Percentage Difference (%)	MATLAB	FEM[*]	Percentage Difference (%)
1	0.0000	0.0000	0.00	0.0000	0.0000	0.00
250	0.0559	0.0556	0.49	0.0007	0.0007	3.77
500	0.0740	0.0736	0.50	0.0015	0.0015	0.37
1000	0.0972	0.0965	0.69	0.0031	0.0031	0.56
2500	0.1383	0.1371	0.89	0.0085	0.0086	1.59
5000	0.1801	0.1783	1.02	0.0185	0.0189	2.23
10 000	0.2344	0.2315	1.24	0.0415	0.0429	3.38
20 000	0.3052	0.3008	1.47	0.0962	0.1010	4.79
40 000	0.3986	0.3916	1.79	0.2326	0.2485	6.38
60 000	0.4669	0.4584	1.85	0.3994	0.4231	5.60
80 000	0.5229	0.5133	1.88	0.5934	0.6227	4.70
100 000	0.5715	0.5610	1.87	0.8130	0.8463	3.93
117 522	0.6097	0.5982	1.92	1.0257	1.0613	3.35

* The results were obtained from the work done by Purbolaksono et al. (2009b)

Table 4.5: Estimations of Average Temperature of Tube Metal and Vickers Hardness by MATLAB Program and Other Authors (FEM)

Service Hour (h)	Average Temperature of Tube Metal (°C)			Vickers Hardness (HV)		
	MATLAB	FEM[*]	Percentage Difference (%)	MATLAB	FEM[*]	Percentage Difference (%)
1	592.11	591.88	0.04	317.75	317.92	0.05
250	594.70	594.46	0.04	233.53	233.72	0.08
500	595.52	594.98	0.09	225.12	223.56	0.70
1000	596.56	596.31	0.04	215.78	211.12	2.21
2500	598.39	598.11	0.05	202.21	198.24	2.00
5000	600.20	599.91	0.05	191.17	186.88	2.30
10 000	602.51	602.18	0.05	179.50	175.06	2.54
20 000	605.43	605.05	0.06	167.13	162.65	2.76
40 000	609.14	608.67	0.08	153.94	151.53	1.59
60 000	611.76	611.25	0.08	145.76	144.20	1.08
80 000	613.85	613.31	0.09	139.71	138.64	0.77
100 000	615.62	615.06	0.09	134.88	134.11	0.57
117 522	616.99	616.49	0.08	131.28	131.61	0.25

* The results were obtained from the work done by Purbolaksono et al. (2009b)

According to the Table 4.4, the estimated scale thickness using MATLAB program was found to have less than 2 % of differences from the results estimated by Finite Element Method. However, the results from the MATLAB and FEM have the differences of less than 6.5 % and were fairly consistent throughout the reheater tube operation. Apart from that, the values of average tube metal temperature and Vickers hardness were very similar between the two prediction methods. In overall, the estimated results using MATLAB program have insignificant differences compared to the works done by Purbolaksono et al. (2009b) using FEM. Therefore, it shows that the prediction method of MATLAB program is in good conformity with the FEM results. Figure 4.1 to 4.4 depict the comparison between the estimated results and the actual data.
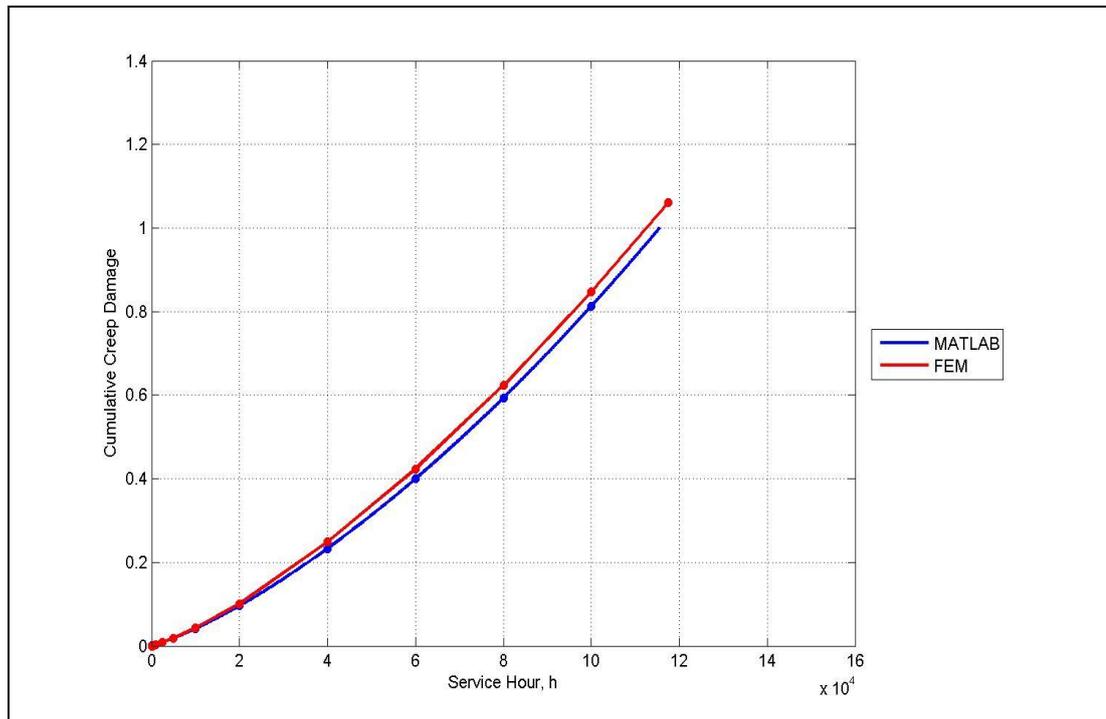
Figure 4.1: Comparison between the MATLAB and FEM Results In Terms of Cumulative Creep Damage
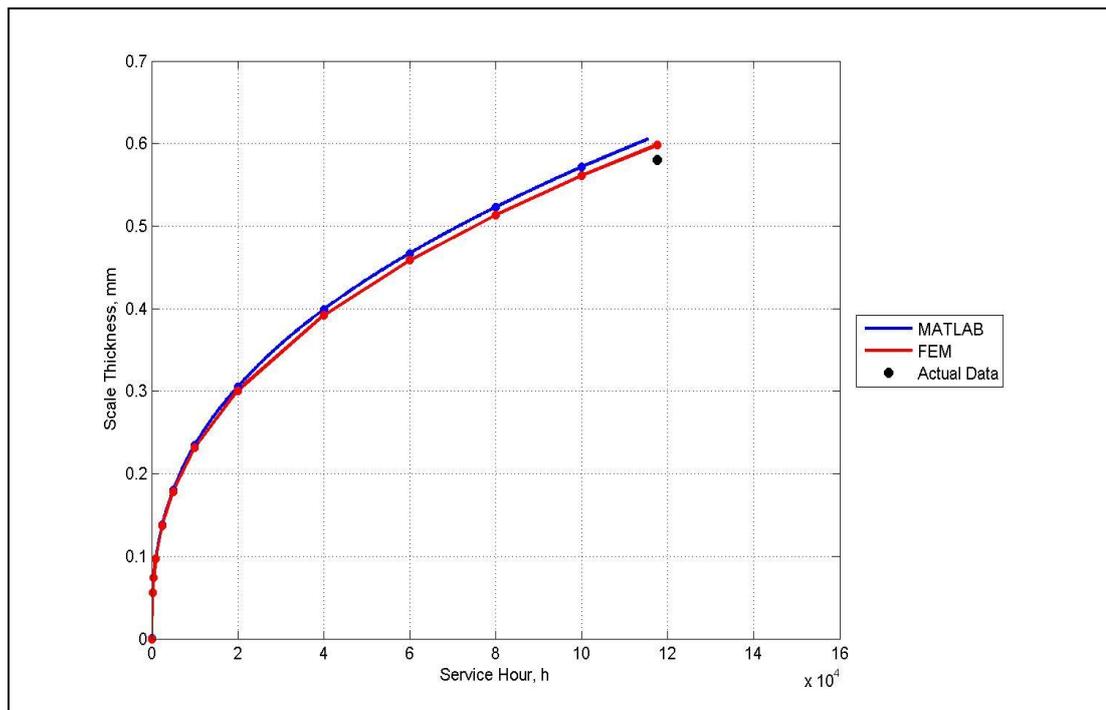
Figure 4.2: Comparison of MATLAB, FEM and Actual Data In Terms of Scale Thickness
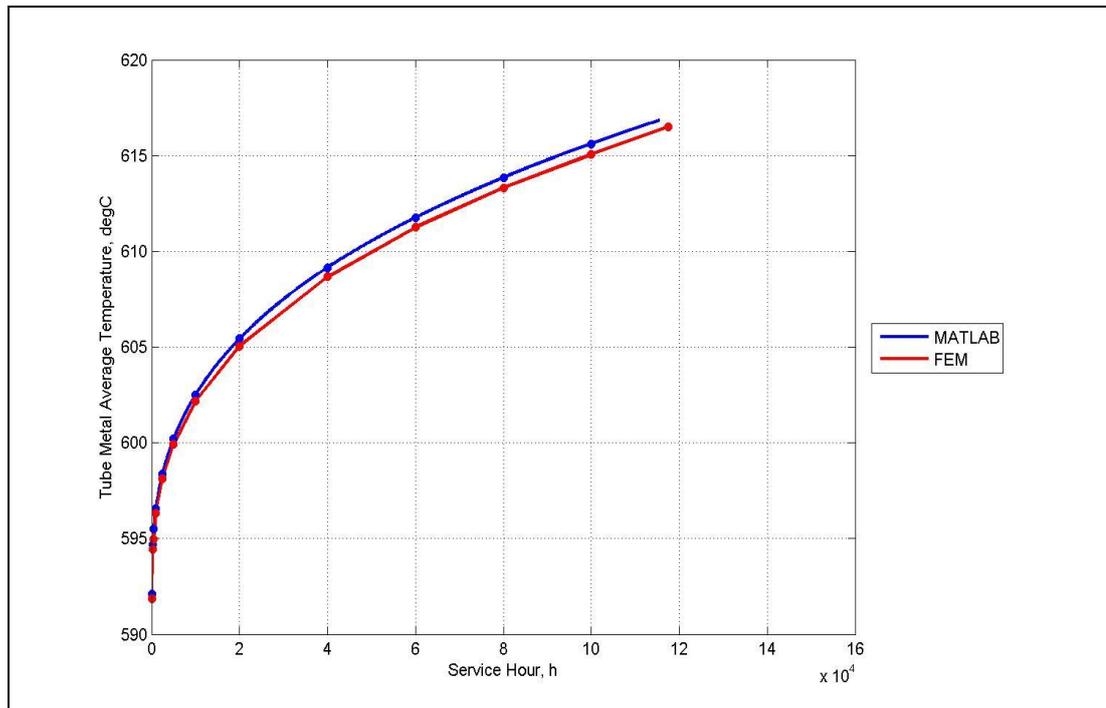
Figure 4.3: Comparison between the MATLAB and FEM Results In Terms of Tube Metal Temperature
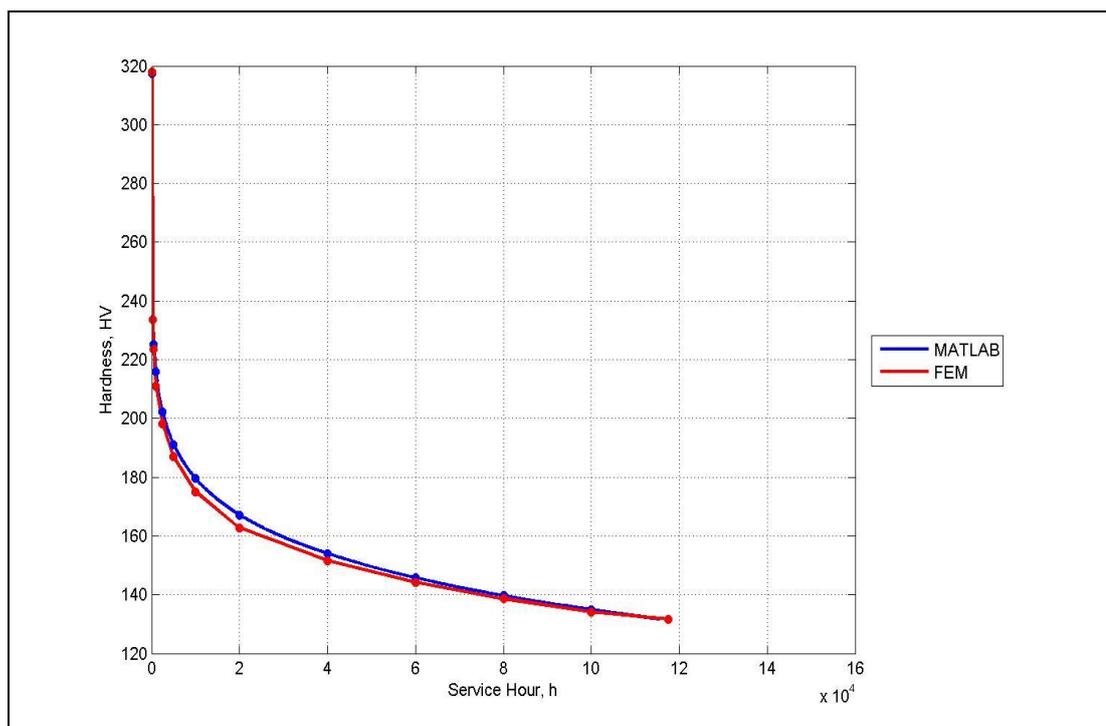
Figure 4.4: Comparison between the MATLAB and FEM Results In Terms of Vickers Hardness

Figure 4.1 depicts the comparison of the predicted cumulative creep damage between the MATLAB program and the FEM. The comparisons of the MATLAB and FEM results with the actual data (Kapar Power Station Malaysia) are presented in Table 4.6 and 4.7. According to the Table 4.6, the cumulative creep damage of actual data is considered as unity (one) in which reheater tube failure has occurred. At the service hours of 117 522 h, it was found that the predicted cumulative creep damage obtained from MATLAB and FEM have only small variations as compared to the actual situation. Table 4.7 shows that the MATLAB result has a difference of 2.57 % from the actual data whereas the FEM result has 6.13 % of difference. It could be seen that the life expectancy by MATLAB program is closer to the actual failure service hours reported by Kapar Power Station Malaysia than the prediction by other authors. This has proved that the utilisation of developed MATLAB program in predicting the remnant life of the boiler tubes is reliable.

Table 4.6: Cumulative Creep Damage at Failure Service Hours

Type of Result	Cumulative Creep Damage	Failure Service Hour (h)
MATLAB	1.0257	
FEM	1.0613	117 522
Actual Data	1	

Table 4.7: Percentage Differences between Estimated Results and Actual Data (Life Expectancy)

	Percentage of Difference (%)	
	MATLAB	FEM
Service Life of Actual Data	2.57	6.13

The results obtained from the MATLAB program were also compared with the FEM results and actual data in terms of scale thickness as shown in Table 4.8. From Table 4.8, thicker oxide scale layer was found on the inner surface of the reheater tube than the scale thickness reported at Kapar Power Station Malaysia. Based on Table 4.9, the Finite Element Method proposed by Purbolaksono et al.

(2009b) has closer scale thickness prediction, which is 3.14 % difference from the measured scale thickness. The percentage difference of the results from MATLAB program is also small despite greater variation than FEM. The difference of 5.12 % or 0.0297 mm in terms of scale thickness is acceptable.

Table 4.8: Scale Thickness at Failure Service Hours

Type of Result	Scale Thickness (mm)	Failure Service Hour (h)
MATLAB	0.6097	
FEM	0.5982	117 522
Actual Data	0.58	

Table 4.9: Percentage Differences between Estimate Results and Actual Data (Scale Thickness)

	Percentage of Difference (%)	
	MATLAB	FEM
Scale Thickness of Actual Data	5.12	3.14

The percentage differences with less than 7 % in both predictions of remnant life and scale thickness of the reheater tube implies that the results from MATLAB program is capable in signalling warning signs before the failure tends to occur. The proposed iterative method using MATLAB program may be used to assist predictive maintenance of boiler tube in power plant. However, it is recommended to set up a range of the service time for a conservative prediction of the remnant life and scale thickness of boiler tube. By evaluating the obtained results, a suggestion of ± 10 % from the predicted service hours and scale thickness is sufficient. The workers or maintenance teams should carry out maintenance activities including inspections and condition monitoring more regularly especially within the range of failure service hour. During that period, awareness and cautious observation are very important in order to identify the presence of defect prior to failure.

4.2 Evaluation of Constant *B* in Correlation Function

A constant value that correlates the oxide scale formation on the inner surface of boiler tube wall and the increasing temperature in the tube metal is affected by different operating heat transfer parameters. The effects by these parameters are discussed in the following sub-subsections. The average percentage difference of predicted tube metal temperature from each model is calculated for accuracy checking.

4.2.1 Tube Geometry

The models with different outer tube radii as shown in Table 4.10 were assessed with the generated constant *B*. The Model 1 has the smallest outer tube radius with the thinnest thickness, following by Model 8 and Model 9. The constant *B* for each model with their respective accuracy is tabulated in Table 4.11.

Table 4.10: Models Used for Tube Geometry Analysis

	Model 1 (Tube 1)	Model 8 (Tube 2)	Model 9 (Tube 3)
Inner Radius (m)	0.0219	0.0219	0.0219
Outer Radius (m)	0.0254	0.0264	0.0274
Steam Temperature, T_s (°C)	540	540	540
Flue Gas Temperature, T_g (°C)	800	800	800
Calculated Convection Coefficient, h_s (W/m^2 °C)	2344.27	2344.27	2344.27
Calculated Convection Coefficient, h_g (W/m^2 °C)	121.85	122.91	124.17
Steam Mass Flow Rate, $\dot{m}_s$ (kg/h)	3600	3600	3600

Table 4.11: Generated Constant *B* and Average Percentage of Difference In Terms of Tube Metal Temperature (Model 1, 8, 9)

Model	Constant *B*	Average Percentage of Difference (%)
1	1.29	0.0162
8	1.34	0.0175
9	1.38	0.0193

According to Figure 4.5, it could be seen that the thicker tubes (greater outer radius) result in higher tube metal temperature. The gradient of the curve is significantly steeper for Model 9 than the rest. At the same time, the oxide scale growth is also greater in thicker tubes (greater outer radius) as shown in Figure 4.6, even though the difference is not significant.

The increasing constant *B* describes the phenomenon in which the increment of the temperature in tube wall as a function of time and scale thickness is relatively greater than the increment of scale thickness and vice versa. This may be explained as the oxide scale formation as a result of material deterioration from the changes of material microstructure form a thermal barrier, which eventually leads to higher temperature accumulated in the thicker tube wall. The higher constant *B* denotes greater impact to the increment of tube metal temperature than the oxide scale growth. In fact, the superheater and reheater tube geometry has a direct effect to the steam-side oxide scale growth and the temperature increase in the tube.
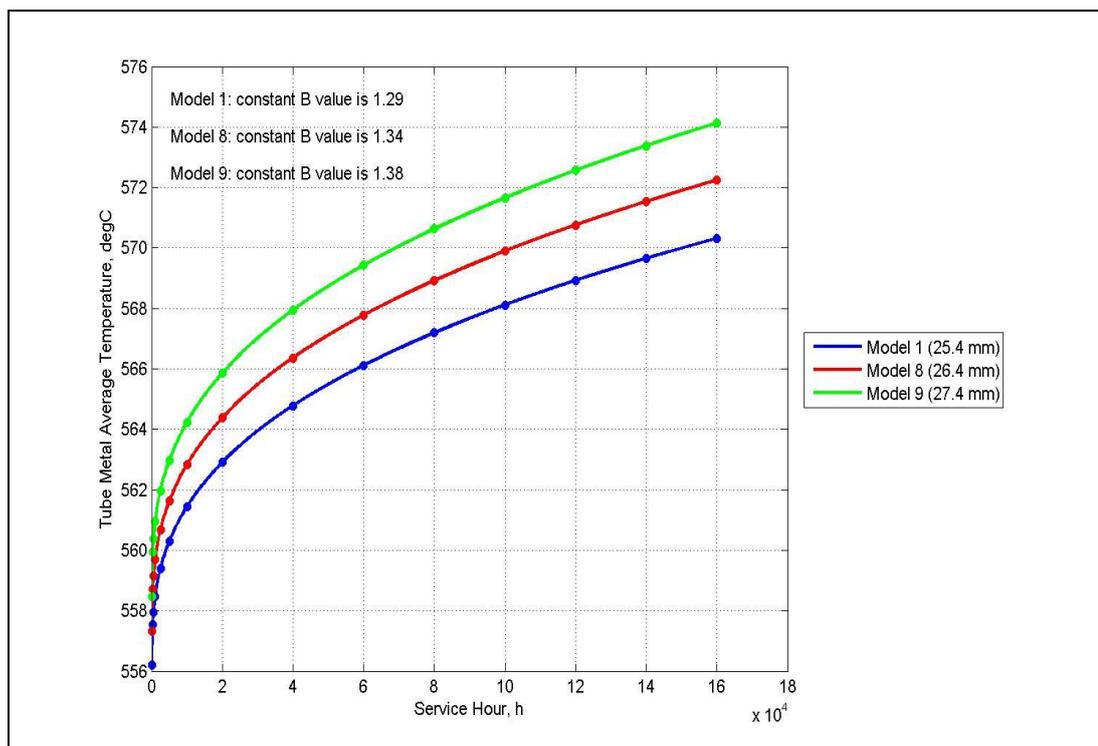
Figure 4.5: Estimated Tube Metal Temperature with Different Outer Radius (Tube) by Constant Estimation
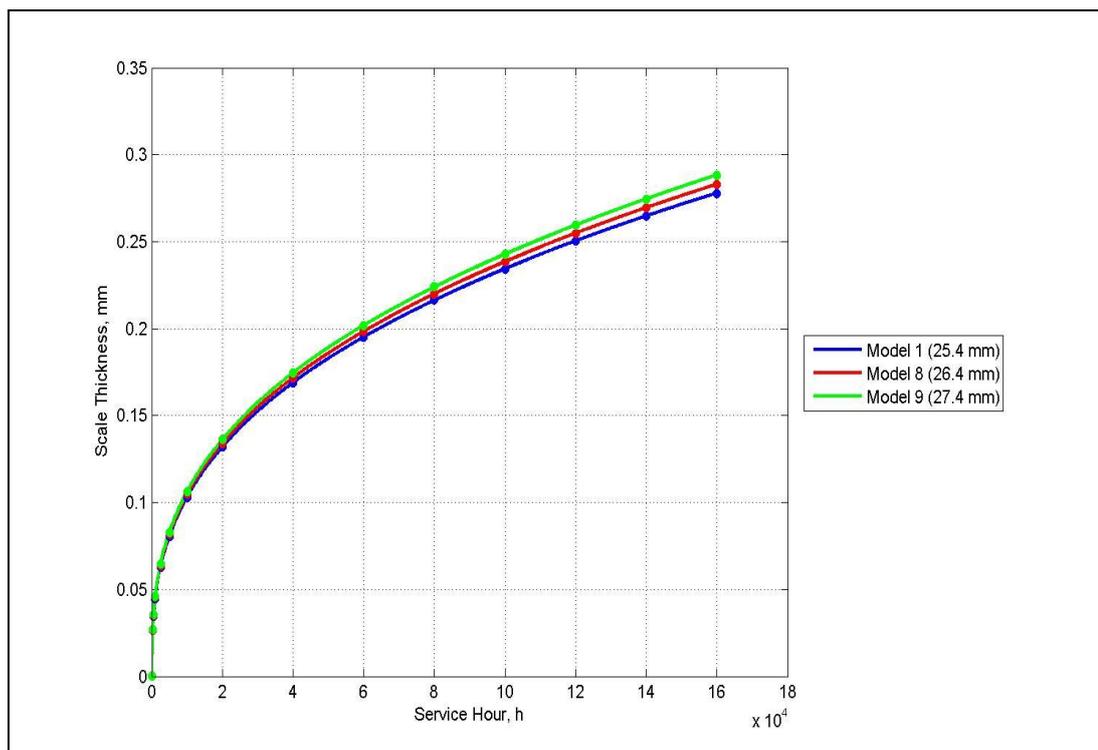
Figure 4.6: Estimated Scale Thickness with Different Outer Radius (Tube)

4.2.2   Steam Mass Flow Rate

The steam mass flow rate is essential in the heat transfer from the tube wall to the steam region inside the tube. Model 1, Model 2 and Model 3 were employed in this analysis as shown in Table 4.12. Higher steam mass flow rate contributes to higher convection coefficient of steam and reduces the temperature increased in tube metal. An insignificant increase in value of constant B describes that the incremental tube wall temperature drops at the similar rate, but slightly further than the scale thickness.

Table 4.12: Models Used for Mass Flow Rate Analysis

	Model 1 (Tube 1)	Model 2 (Tube 1)	Model 3 (Tube 1)
Inner Radius (m)	0.0219	0.0219	0.0219
Outer Radius (m)	0.0254	0.0254	0.0254
Steam Temperature, T_s (°C)	540	540	540
Flue Gas Temperature, T_g (°C)	800	800	800
Calculated Convection Coefficient, h_s (W/m^2 °C)	2344.27	2447.89	2550.43
Calculated Convection Coefficient, h_g (W/m^2 °C)	121.85	121.85	121.85
Steam Mass Flow Rate, $\dot{m}_s$ (kg/h)	3600	3800	4000

Since the constant B generated as presented in Table 4.13 are greater than one, the increasing of temperature is still higher than the increment of scale thickness by comparing Figure 4.7 and Figure 4.8. Contrarily, poor mass flow rate of the steam may cause tube wall to have higher temperature and thicker oxide scale layer, which could to lead to the early tube rupture.

Table 4.13: Generated Constant B and Average Percentage of Difference In Terms of Tube Metal Temperature (Model 1, 2, 3)

Model	Constant B	Average Percentage of Difference (%)
1	1.29	0.0162
2	1.3	0.0154
3	1.31	0.0154
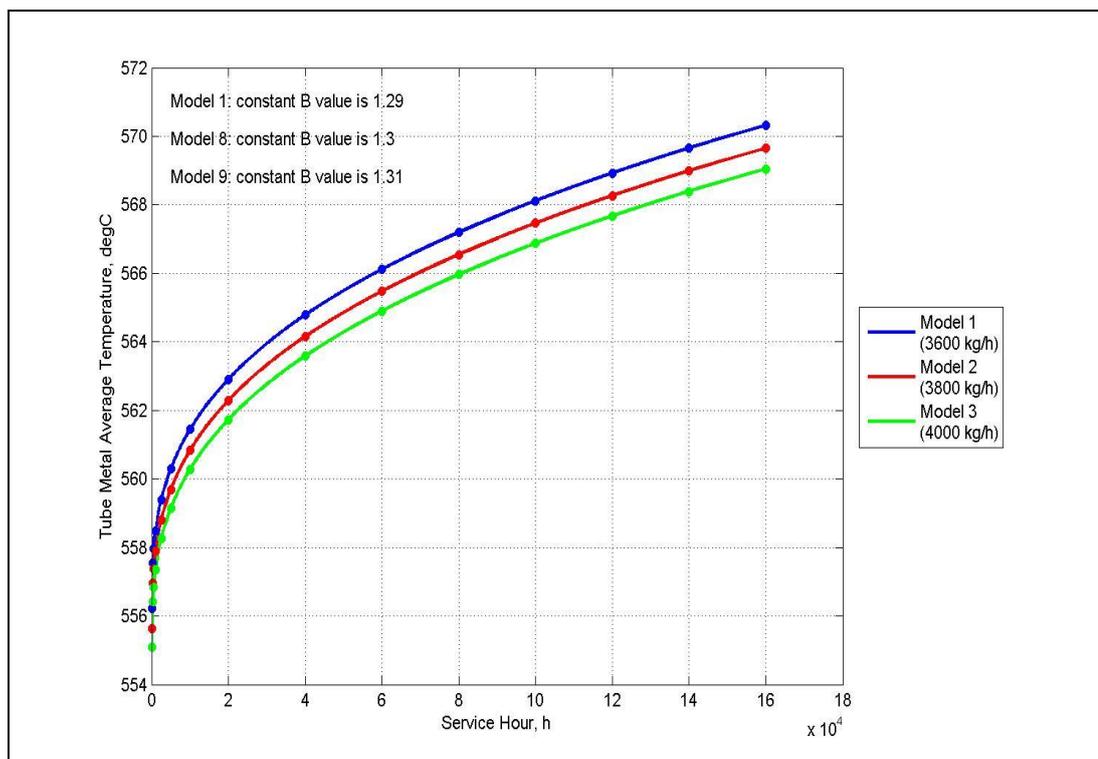
Figure 4.7: Estimated Tube Metal Temperature with Different Steam Mass Flow Rate by Constant Estimation
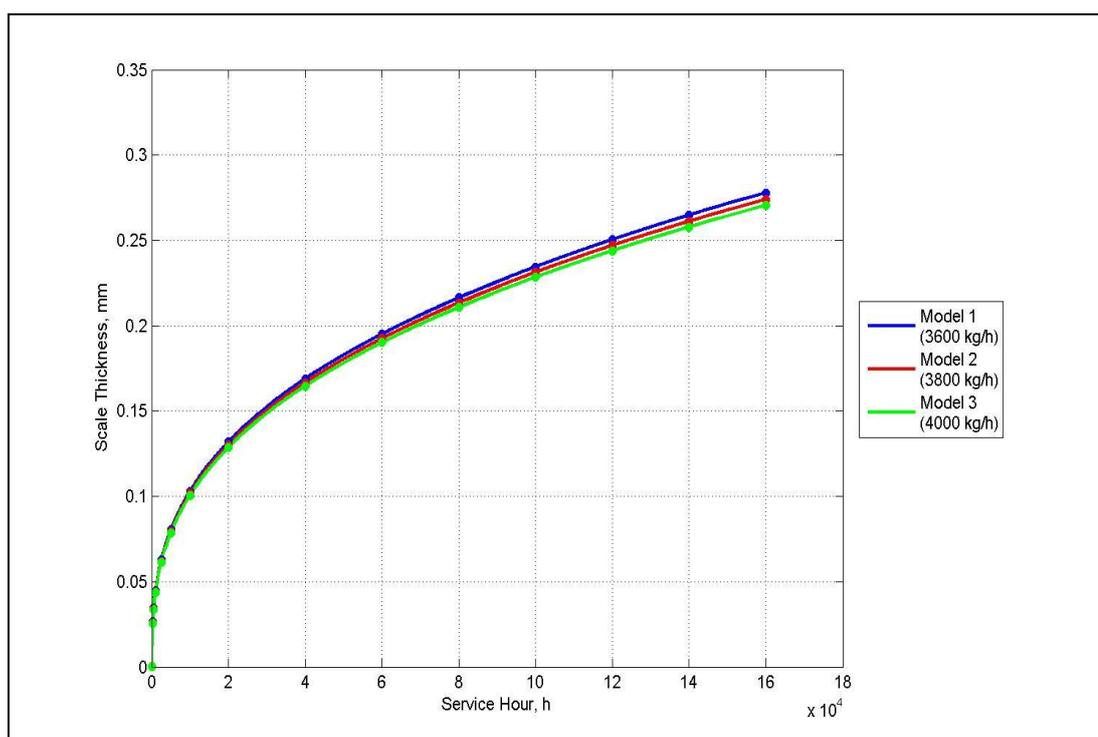
Figure 4.8: Estimated Scale Thickness with Different Steam Mass Flow Rate

4.2.3   Steam Temperature

The heat transfers parameters of models used and generated constant *B* are shown in Table 4.14 and Table 4.15. From Figure 4.9, the tube that operated at higher steam temperature causes the tube metal temperature at the beginning of operation to be higher. The decreasing value of estimated constant *B* can be seen when the design temperature rises, which indicates that the increment of tube metal temperature with higher operational temperature is lesser than the increment with lower operational temperature. In other words, the increment of temperature in the tube is getting closer (or smaller difference) to the increment of scale thickness. The increasing of the gradient of curves with higher steam temperature and lower constant *B* in Figure 4.10 is more significant than the increasing of gradient in Figure 4.9. These phenomena show that the transfer of heat from the flue gas across the tube, and to the steam is considerably impaired by the smaller temperature difference across the tube. This may result in more heat in the tube wall whereas the oxidation resistance at the inner tube wall reduces and cause greater scale formation.

In addition, Model 5 was predicted to have shorter service life than Model 1 and Model 4, which tends to fail before 160000 service hours. It can be deduced that the steam temperature is one of the factors that influence the life expectancy of boiler tube significantly.

Table 4.14: Models Used for Steam Temperature Analysis

	Model 1 (Tube 1)	Model 4 (Tube 1)	Model 5 (Tube 1)
Inner Radius (m)	0.0219	0.0219	0.0219
Outer Radius (m)	0.0254	0.0254	0.0254
Steam Temperature, T_s (°C)	540	560	580
Flue Gas Temperature, T_g (°C)	800	800	800
Calculated Convection Coefficient, h_s (W/m² °C)	2344.27	2368.79	2392.66
Calculated Convection Coefficient, h_g (W/m² °C)	121.85	121.85	121.85
Steam Mass Flow Rate, $\dot{m}_s$ (kg/h)	3600	3600	3600

Table 4.15: Generated Constant *B* and Average Percentage of Difference In Terms of Tube Metal Temperature (Model 1, 4, 5)

Model	Constant *B*	Average Percentage of Difference (%)
1	1.29	0.0162
4	1.16	0.0338
5	1.03	0.0549
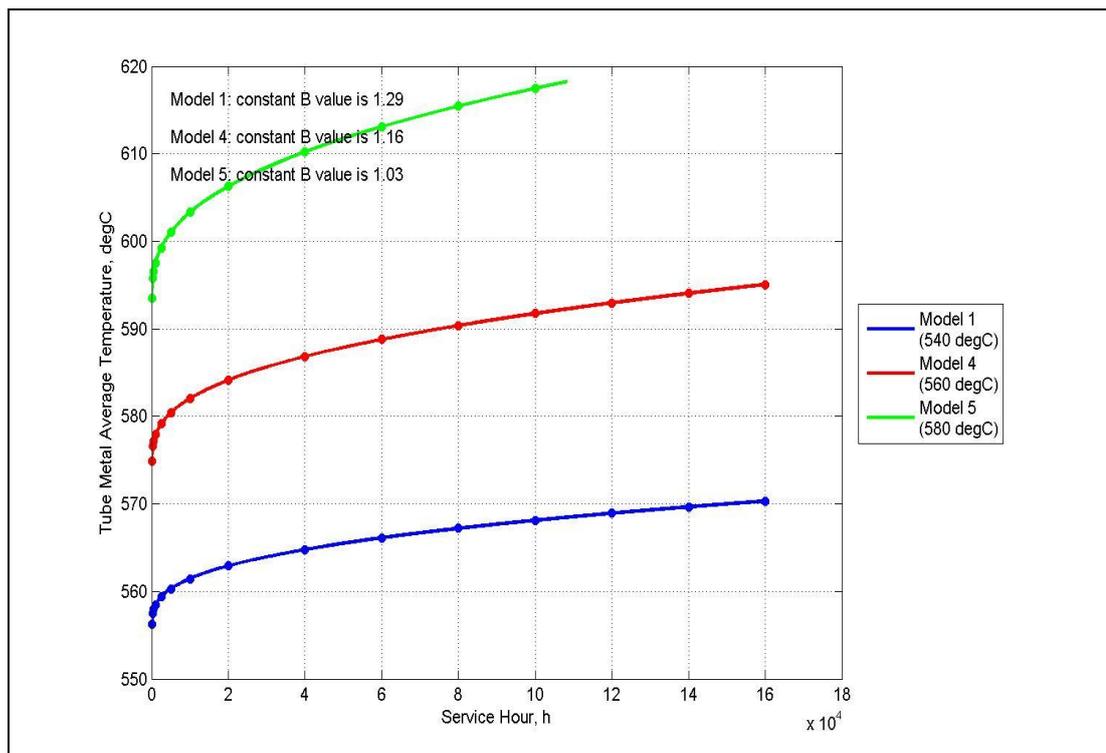
Figure 4.9: Estimated Tube Metal Temperature with Different Steam Temperature by Constant Estimation
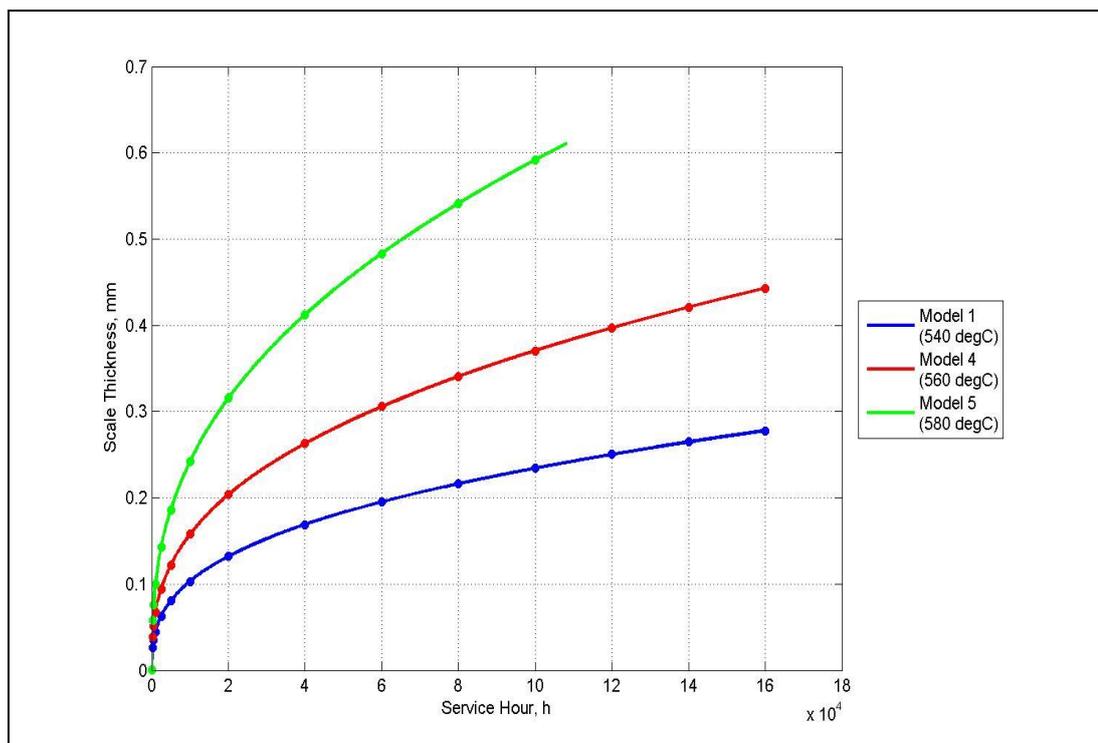
Figure 4.10: Estimated Scale Thickness with Different Steam Temperature

4.2.4   Flue Gas Temperature

The change of flue gas temperature will affect the convection coefficient of flue gas as shown in Table 4.16. It can be deduced from Figure 4.11 and Figure 4.12 that the combination of temperature and convection coefficient of flue gas has drastic effect to the temperature increase and oxide scale growth.

Table 4.17 also shows a significant increase in constant B, which implies higher flue gas temperature leads to a greater increment of both the tube metal temperature and the scale thickness, whereby the increment value for temperature is approximately 83 % more in Model 6 and 138 % more in Model 7 than the incremental scale thickness every 250 h. This may be explained as greater heat transfer from the flue gas into the tube and increase the temperature in the tube metal more swiftly than the growing of oxide layer. The vast changes in temperature are critical as it may lead to potential failure of the tube.

Table 4.16: Models Used for Flue Gas Temperature Analysis

	Model 1 (Tube 1)	Model 6 (Tube 1)	Model 7 (Tube 1)
Inner Radius (m)	0.0219	0.0219	0.0219
Outer Radius (m)	0.0254	0.0254	0.0254
Steam Temperature, T_s (°C)	540	540	540
Flue Gas Temperature, T_g (°C)	800	900	1000
Calculated Convection Coefficient, h_s (W/m² °C)	2344.27	2344.27	2344.27
Calculated Convection Coefficient, h_g (W/m² °C)	121.85	127.19	132.41
Steam Mass Flow Rate, $\dot{m}_s$ (kg/h)	3600	3600	3600

Table 4.17: Generated Constant B and Average Percentage of Difference In Terms of Tube Metal Temperature (Model 1, 6, 7)

Model	Constant B	Average Percentage of Difference (%)
1	1.29	0.0162
6	1.83	0.0343
7	2.38	0.0719
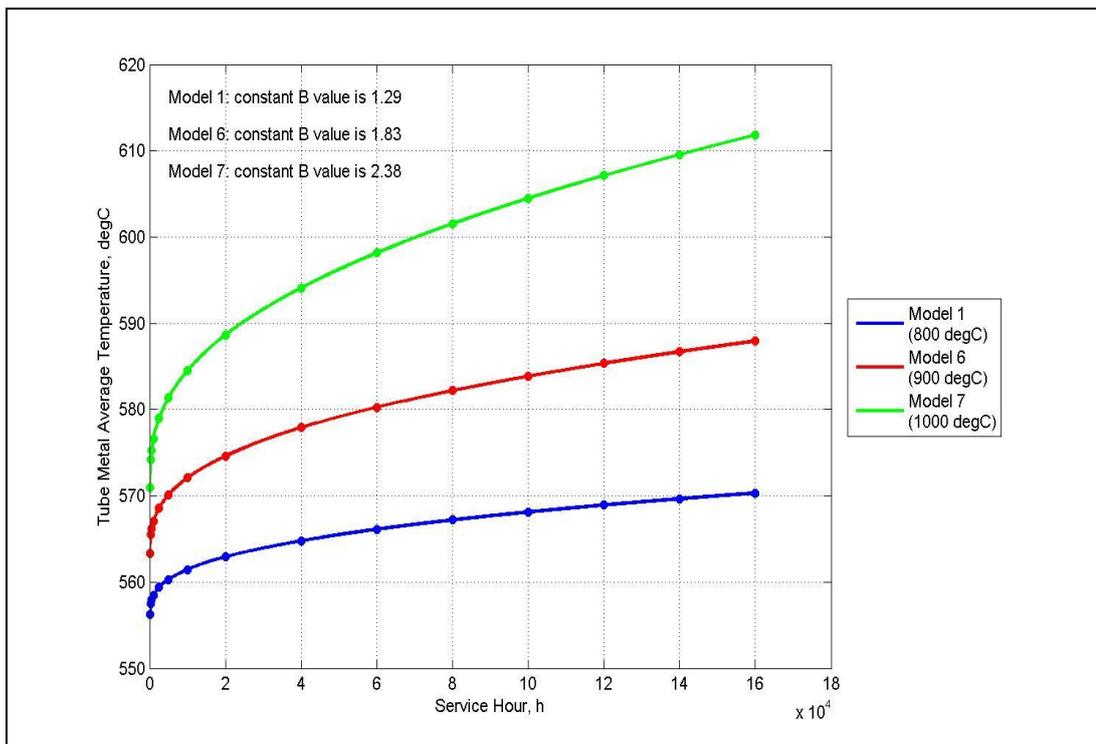
Figure 4.11: Estimated Tube Metal Temperature with Different Flue Gas Temperature by Constant Estimation
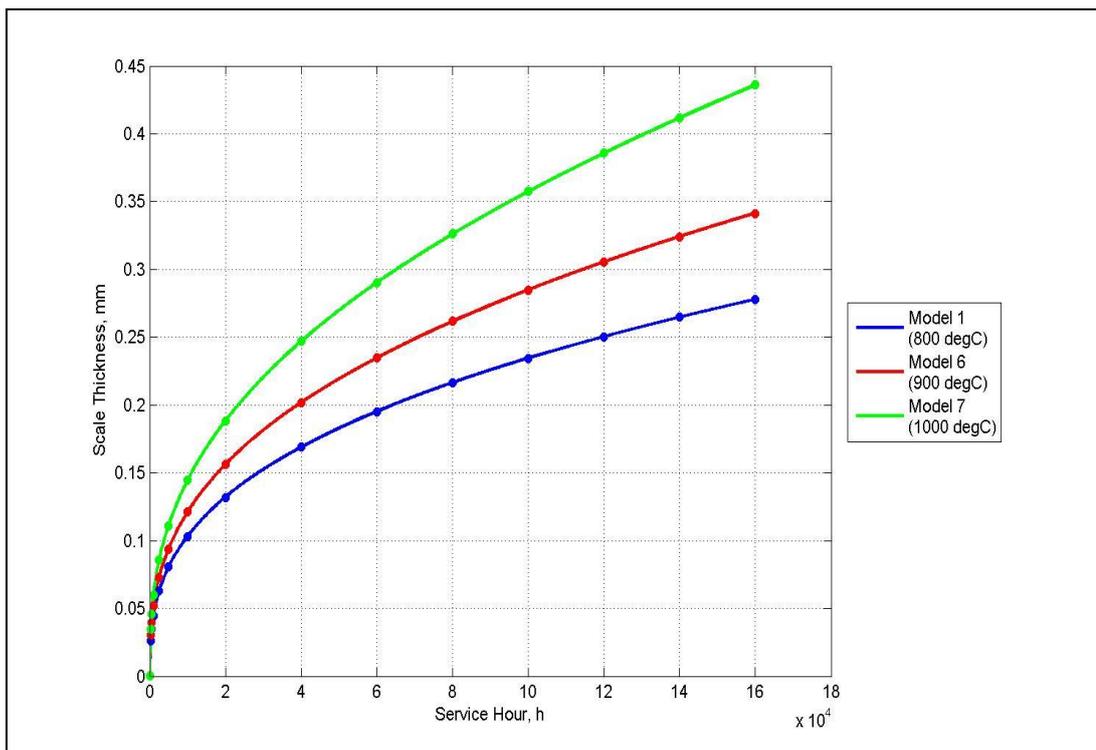
Figure 4.12: Estimated Scale Thickness with Different Flue Gas Temperature

4.2.5 Summary

A constant value *B* that is greater than one indicates the incremental tube metal temperature is more than the incremental scale thickness, while a constant value that is smaller than one indicates the other way round. The incremental value will be the same for both the tube metal temperature and scale thickness if the constant *B* is exactly one. From the four analyses discussed earlier, all the estimated *B* constants were found to be greater than one. By increasing the tube geometry, steam mass flow rate and flue gas temperature, the constant *B* was found to be increased accordingly, which signified more impact to the increment of tube metal temperature. However, the constant *B* decreased with the rose of steam temperature. It denoted less effect of the change of particular parameter to the tube metal temperature.

It was found that all the estimated tube metal temperatures by using the generated constant *B* have less than 0.1 % difference compared to the temperature predicted by iterative procedure. Therefore, the estimation using constant *B* is reliable and has very similar temperature curve with the result from MATLAB program.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

An iterative analytical procedure used for boiler tube analysis has been proposed and implemented in MATLAB. This technique was proved to be a reliable tool in estimating the service life of boiler tubes associated with various temperature dependent parameters such as oxide scale growth, wall thinning, hoop stress, heat flux, hardness, and creep damage of the tubes.

The implementation of the iterative analytical procedure coupled with the comparisons with data of failed boiler tubes reported at Kapar Power Station Malaysia and the results from other authors were presented. The estimated service life of tube in terms of cumulative creep damage was found to have less than 3 % of difference with the actual data. In order to implement the proposed iterative method with conservative estimations, a suggested time range of the service hours is ± 10 % of the estimated service life. The accuracy of the iterative analytical procedure in life prediction of tube was satisfied. The prediction of scale thickness was accurate, with a difference of less than 6.5 % and has better estimation than other authors. In general, the results obtained from the MATLAB program were shown to be in good conformity with the actual data and work from other authors.

The tube metal temperature is one of the crucial factors in affecting the scale growth on the inner surface of the tube. The formation of oxide layer was found to be the root cause of many tube failure cases by mechanical and corrosion. A proposed constant estimation technique with appropriate methodology aids the prediction of increased temperature in tube metal and scale thickness in line with the failure analysis of the tube. A constant B correlating the tube metal temperature increase and scale thickness growth was found to be useful in estimating the significant effect in either the incremental temperature or incremental scale thickness at an operation condition.

Based on the study, the value of constant B may signal a warning of the possible excessive tube metal temperature increase or scale thickness increase prior to occurrence of failure tube. A value of constant closed to one denoted the increasing rates of both the temperature and scale thickness are similar. When the constant B was greater than one, the temperature of tube increased more than scale thickness and vice versa if the constant B was smaller than one. An increase of constant B was interpreted as more rises of tube temperature in relation to the scale thickness, which could encourage greater formation of oxide scale and lead to early tube rupture. On the other hand, a decreased constant B showed a more rapid growth rate of oxide scale that tends to inhibit the heat transfer across the tube. A haste of scale growth rate can weaken the tube wall.

Therefore, the iterative analytical procedure and the correlation function between the tube metal temperature change and scale growth may be utilised in assisting the predictive maintenance in power plant such as condition monitoring system. These two proposed techniques are capable to provide an estimation of boiler tube life and other useful information without incurring high cost and much time consumption.

5.2   Limitation of Developed MATLAB Program

The current development of MATLAB program is only capable to perform analysis on the boiler tube using the material of Alloy Steel Seamless Tube SA213-T12 and SA213-T22. The maximum allowable stresses used in MATLAB are referred to these two materials. Raw data of maximum allowable stress is required if other tube material is to be used to carry out an analysis. Those values of maximum allowable stress can be obtained from ASME Table 1A Section II Part D.

The number of models to be analysed is limited to maximum of six models in a single simulation. This limitation helps to improve the visibility and clarity of the plotted graph. Apart from that, certain graphs from the separated function files can only plot one model at once due to the different types of comparison. For instance, a graph of heat flux distribution contains four curves that representing four regions of the tube wall (inner surface, scale layer, tube metal, and outer surface). It is not recommended to compare with other models to avoid unnecessary confusion.

5.3   Recommendations

The boiler tube analysis can be improved by incorporating the proposed iterative analytical procedure with other commercial software such as ANSYS. The iterative analytical method is a numerical estimation using a regular time step and can only perform analysis for one dimensional geometry. ANSYS is capable to demonstrate and simulate the temperature distribution of complicated geometry that involves two or more dimensions such as finned tube. Thus, a programming language that can export the results obtained from the ANSYS to the MATLAB for further numerical analysis is recommended. The tube metal temperature increase estimated by ANSYS can be used in conjunction with the constant estimation method in which only required a set of data for scale thickness and tube metal temperature over period of time.

The scope of the research can be extended by considering the thermal strain experienced in the tube. The development of thermal stress and thermal strain as a function of temperature, pressure and time can also lead to boiler tube failure. The thermal strain generated can be studied in relation to the thermal expansion and temperature and pressure loading of the boiler tube.

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APPENDICES

APPENDIX A: MATLAB Program Codes (Main Program)

```
% ------------------------------------------------------------------------
% Complete script for Creep Analysis
% Filename    : creepanalysis.m
% Done by     : Ang Wei Bing & Edwin Lim
% Date        : 27 June 2012
% Mod. Date   : 7 April 2013
% ------------------------------------------------------------------------


% List of variables to be key-ed in as input (input CONV sequence.txt):
% hs          = Convection coefficient of steam [W/m^2-degC]
% hg          = Convection coefficient of flue gas [W/m^2-degC]
% T_s         = Steam temperature [degC]
% pressure    = Steam pressure [MPa]
% T_g         = Flue gas temperature [degC]
% l           = Length of boiler tube [m]
% LMP         = Larson-Miller parameter (w.r.t. hoop stress) [x 10^3]
% k_o         = Thermal conductivity of oxide scale [W/m-degC]
% k_m         = Thermal conductivity of metal boiler tube [W/m-degC]
% R0          = Inner radius of the tube (up to steam side wall) [m]
% R2          = Outer radius of the tube (up to gas side wall) [m]
% thickness   = Scale thickness [m]
% thinrate    = Thin rate [mm/h]


% List of variables to be key-ed in to calculate hs (input RAW sequence.txt)
% m_dot_s     = Mass flow rate of steam [kg/h]
% di          = Inner diameter of tube [m]


% List of variables to be key-ed in to calculate hg (input RAW sequence.txt)
% y_CO2       = Volume fraction of CO2 (%/100)
% y_H2O       = Volume fraction of H2O (%/100)
% y_N2        = Volume fraction of N2 (%/100)
% y_O2        = Volume fraction of O2 (%/100)
% y_SO2       = Volume fraction of SO2 (%/100)
% y_HCl       = Volume fraction of HCl (%/100)
% w_g         = Gas flow [kg/h]
% n_w         = Number of tube wide
% s_t         = Transverse pitch [m]
% do          = Outer diameter of tube [m]


% List of important variables in program:
% T1          = Service hour 1 [h]
% T2          = Service hour 2 [h]
% CCDMG1      = Cumulative creep damage 1
% CCDMG2      = Cumulative creep damage 2
% X1          = Initial scale thickness [mils] (1 mils = 0.0254 mm)
% X2          = New scale thickness [mils] (1 mils = 0.0254 mm)
% R1          = Oxide radius of the tube (up to scale/metal interface) [m]
% R_steam     = Thermal resistance of steam [degC/W]
% R_oxide     = Thermal resistance of oxide scale [degC/W]
% R_metal     = Thermal resistance of metal boiler tube [degC/W]
```

```
% R_gas        = Thermal resistance of flue gas [degC/W]
% q_radial     = Heat transfer rate in radial direction [W]
% hoop         = Hoop stress [MPa]
% Ts0          = Temperature of inner surface of boiler tube [degC]
% Ts1          = Temperature of scale/metal interface [degC]
% Ts2          = Temperature of outer surface of boiler tube [degC]
% Tave_o       = Average temperature of oxide scale [degC]
% Tave_m       = Average temperature of metal boiler tube [degC]
% DTave_m      = Increment of average temperature of metal boiler tube [degC]
% Tave_o_rank  = Average temperature of oxide scale [degRankine]
% Tave_m_rank  = Average temperature of metal boiler tube [degRankine]
% q_flux_0     = Heat flux at inner surface of boiler tube [W/m^2]
% q_flux_o     = Heat flux at oxide scale of boiler tube [W/m^2]
% q_flux_m     = Heat flux at tube metal of boiler tube [W/m^2]
% q_flux_2     = Heat flux at outer surface of boiler tube [W/m^2]
% q_flux_ave   = Average of heat fluxes at tube metal and outer surface [W/m^2]
% LMPX1        = Larson-Miller parameter for service hour 1 (w.r.t. scale thickness)
% LMPX2        = Larson-Miller parameter for service hour 2 (w.r.t. scale thickness)
% X1A          = Scale thickness for service hour 1 [mils] (1 mils = 0.0254 mm)
% X1B          = Scale thickness for service hour 2 [mils] (1 mils = 0.0254 mm)
% DX1          = Increment of scale thickness [mils] (1 mils = 0.0254 mm)
% LMPH1        = Larson-Miller parameter for service hour 1 (w.r.t. Vickers hardness)
% LMPH2        = Larson-Miller parameter for service hour 2 (w.r.t. Vickers hardness)
% HV1A         = Vickers hardness for service hour 1
% HV1B         = Vickers hardness for service hour 2
% HV           = Vickers hardness
% thin         = Thinned thickness [m]
% T_rup        = Rupture time [h]
% DTave_m_pred = Increment of predicted average tube metal temperature [degC]
% Tave_m_pred  = Predicted average tube metal temperature [degC]
% DX1_pred     = Increment of predicted scale thickness [mils] (1 mils = 0.0254 mm)
% X1_pred      = Predicted scale thickness [mils] (1 mils = 0.0254 mm)
% p_diff       = Percentage of difference for predicted result [%]
% avg_p_diff   = Average percentage of difference [%]
% min_avg_diff = Minimum average percentage of difference obtained [%]
% constB       = Selected constant B


% List of general variables in program for special purposes:
% I                    = Iteration
% data_sets            = Number of data set/model
% inputvalue           = List of input values from text document
% outputdata_input     = Option for output file overwritten
% user_input           = Option for text document (input) selection
% loop_outputdata_input = Loop of output file overwritten
% loop_user_input      = Loop of text document selection
% loop_data_sets       = Loop of main program
% a                    = Number of input variables in text document
% b                    = Number of data set/model in text document
% J                    = Indication of column (set/model number) in "inputvalue"
%                         variable
% setnum               = Indication of row (set/model number) in each variable
% col                  = Indication of column (varying values) in each variable
% t_step               = Predetermined time step
% tstep_count          = Count of time step
% Z                    = Iteration at predetermined time step (vector quantity)
% max_thin             = Maximum allowable thinning [m]
% allow_str_limit      = Allowable stress switch control w.r.t. hoop stress
%                         (0-above limit, 1-below limit)
% time_str             = Time where hoop stress exceeds allowable stress
% time_str_disp        = Stress time switch control (0-no record time, 1-record time)
% allow_str_Temp_C     = Temperature set for allowable stress [degC]
% allow_str_MPa        = Allowable stress w.r.t. tube metal temperature [MPa]
% interp_allow_str     = Interpolated allowable stress [MPa]
% test                 = Number of loop to test constant B
% test_constB          = Test constant B
% W                    = Iteration for test constant
% W_switch             = Test constant switch control [0-no record 'V' , 1-record
'V']
% V                    = Iteration at selected test constant B
% U                    = Iteration for scale thickness prediction
% ite                  = Last iteration of each data set/model
% time                 = Last service hour of each data set/model
% n_sets               = Loop of data set/model (for summary of results)
% R                    = Loop of data set/model w.r.t. predetermined time step
% S                    = Loop of time step
% zi                   = Iteration at predetermined time step (scalar quantity)
```

```matlab
clear   % clear workspace
clc     % clear command window
clf     % clear figure window

loop_outputdata_input = 0;

while (loop_outputdata_input == 0)  % Overwriting output data file

    disp(' ');
    disp(' ');
    disp('Do you want to overwrite the output data file?');
    outputdata_input = input('Please enter 1 to overwrite or 2 to continue append at
the end : ');

    switch (outputdata_input)
        case (1)
            fileID = fopen('creepanalysis_result.txt','w');
            disp(' ');
            loop_outputdata_input = 1;
        case (2)
            fileID = fopen('creepanalysis_result.txt','a');
            disp(' ');
            loop_outputdata_input = 1;
        otherwise
            disp('Wrong input. Please key in again.');
    end
end

loop_user_input = 0;

while (loop_user_input == 0)  % text document (input file) selection

    user_input = input('Please enter 1 to read input_raw_values.txt OR 2 to read
input_conv_values.txt: ');

        switch (user_input)
        case (1)
            fileID1 = fopen('input_raw_values.txt');
            inputvalue  = fscanf(fileID1, '%g %g %g %g %g %g', [23 6]);
            fclose(fileID1);
            [a,b] = size(inputvalue);
            data_sets = b;

            loop_user_input = loop_user_input + 1;

         case (2)
            fileID1 = fopen('input_conv_values.txt');
            inputvalue  = fscanf(fileID1, '%g %g %g %g %g %g', [13 6]);
            fclose(fileID1);
            [a,b] = size(inputvalue);
            data_sets = b;

            loop_user_input = loop_user_input + 1;

        otherwise
            disp('Wrong input. Please key in again.');
        end
end

J = 1;
col = 1;  % for all input variables in scalar quantity

while (J <= data_sets)  % import input values from text document

    setnum = J;

    switch (user_input)
        case (1)

            [hs] = calc_hs(inputvalue,data_sets);
            [hg] = calc_hg(inputvalue,data_sets);

            T_s(setnum,col) = inputvalue(3,J);
            pressure(setnum,col) = inputvalue(4,J);
            l(setnum,col) = inputvalue(15,J);
```

```matlab
                    T_g(setnum,col) = inputvalue(5,J);
                    LMP(setnum,col) = inputvalue(17,J);
                    k_o(setnum,col) = inputvalue(18,J);
                    k_m(setnum,col) = inputvalue(19,J);
                    R0(setnum,col) = inputvalue(20,J);
                    R2(setnum,col) = inputvalue(21,J);
                    thickness(setnum,col) = inputvalue(22,J);
                    thinrate(setnum,col) = inputvalue(23,J);

                    J = J + 1;

                case (2)

                    hs(setnum,col) = inputvalue(1,J);
                    hg(setnum,col) = inputvalue(2,J);
                    T_s(setnum,col) = inputvalue(3,J);
                    pressure(setnum,col) = inputvalue(4,J);
                    T_g(setnum,col) = inputvalue(5,J);
                    l(setnum,col) = inputvalue(6,J);
                    LMP(setnum,col) = inputvalue(7,J);
                    k_o(setnum,col) = inputvalue(8,J);
                    k_m(setnum,col) = inputvalue(9,J);
                    R0(setnum,col) = inputvalue(10,J);
                    R2(setnum,col) = inputvalue(11,J);
                    thickness(setnum,col) = inputvalue(12,J);
                    thinrate(setnum,col) = inputvalue(13,J);

                    J = J + 1;

        end
end

loop_data_sets = 1;

while (loop_data_sets <= data_sets)  % start of main program

    setnum = loop_data_sets;
    t_step(1,:) = [1, 250, 500, 1000, 2500, 5000, 10000, 20000, 40000, 60000, ...
        80000, 100000, 120000, 140000, 160000];   % predetermined time step
    tstep_count = 1;

    I = 1;
    T1 = 1;
    T2 = 250;
    CCDMG1 = 0;
    CCDMG2(setnum,1) = 0;
    thin(setnum,1) = 0;
    max_thin(setnum,1) = 0;
    allow_str_limit(setnum,1) = 0;
    time_str(setnum,1) = 160250;
    time_str_disp = 0;

    X1(setnum,1) = (thickness(setnum,col)/0.0000254); % conversion from metre
                                                      %    to mils for thickness
    R1 = thickness(setnum,col) + R0(setnum,col); % unit in metre

    % Reference from Fundamentals of Heat and Mass Transfer (6th ed.); ...
    %     F. P. Incropera et al.
    % Equation 3.9; Page 99
    R_steam = 1/(2*hs(setnum,col)*pi*R0(setnum,col)*l(setnum,col));
    % Equation 3.28; Page 117
    R_oxide = (log(R1/R0(setnum,col)))/(2*pi*k_o(setnum,col)*l(setnum,col));
    % Equation 3.28; Page 117
    R_metal = (log(R2(setnum,col)/R1))/(2*pi*k_m(setnum,col)*l(setnum,col));
    % Equation 3.9; Page 99
    R_gas = 1/(hg(setnum,col)*2*pi*R2(setnum,col)*l(setnum,col));

    % Equation 3.29; Page 118
    q_radial = (T_g(setnum,col) - T_s(setnum,col))/(R_steam + R_oxide + ...
        R_metal + R_gas);

    % Equation 3 from M. M. Rahman et al. journal - Root cause failure analysis ...
    %     of a division wall superheater tube of a coal-fired power station
    hoop(setnum,1) = pressure(setnum,col)*(R0(setnum,col) + (R2(setnum,col)- ...
        R0(setnum,col))/2)/(R2(setnum,col)-R0(setnum,col));
```

```matlab
        Ts2(setnum,1) = T_g(setnum,col) - (R_gas*q_radial);
        Ts1(setnum,1) = Ts2(setnum,1) - (R_metal*q_radial);
        Ts0(setnum,1) = Ts1(setnum,1) - (R_oxide*q_radial);

        Tave_o(setnum,1) = Ts0(setnum,1); % or Tave_o = (Ts0 + Ts1)/2; where Ts0 = Ts1
        Tave_m(setnum,1) = (Ts1(setnum,1) + Ts2(setnum,1))/2;


        % Reference from Fundamentals of Heat and Mass Transfer (6th ed.); ...
        %       F. P. Incropera et al.
        % Equation 3.8; Page 99
        q_flux_0(setnum,1) = hs(setnum,col)*(Ts0(setnum,1) - T_s(setnum,col));
        % Table 3.3; Page 126
        q_flux_o(setnum,1) = k_o(setnum,col)*(Ts1(setnum,1) - Ts0(setnum,1))/ ...
            (R1*log(R1/R0(setnum,col)));
        % Table 3.3; Page 126
        q_flux_m(setnum,1) = k_m(setnum,col)*(Ts2(setnum,1) - Ts1(setnum,1))/ ...
            (R1*log(R2(setnum,col)/R1));
        % Equation 3.8; Page 99
        q_flux_2(setnum,1) = hg(setnum,col)*(T_g(setnum,col) - Ts2(setnum,1));
        q_flux_ave(setnum,1) = (q_flux_m(setnum,1) + q_flux_2(setnum,1))/2;

        Tave_o_rank = Tave_o(setnum,1)*1.8 + 32 + 460;
        Tave_m_rank = Tave_m(setnum,1)*1.8 + 32 + 460;
        % deg Fahrenheit = deg Celsius * 1.8 + 32
        % deg Rankine = deg Fahrenheit + 460

        T_rup(setnum,1) = 10^((LMP(setnum,col)*1000)/(Tave_m_rank*1.0)-20);

        LMPX1 = Tave_o_rank*(20 + log10(T1*1));
        X1A = (10^(0.00022*LMPX1-7.25));
        LMPX2 = Tave_o_rank*(20 + log10(T2*1));
        X1B = (10^(0.00022*LMPX2-7.25));

        DX1(setnum,1) = X1B - X1A;
        X2(setnum,1) = X1(setnum,1) + DX1(setnum,1); % X1A,X1B,DX1,X1,X2 are in unit ...
                                                     %     'mils' (1/1000 inches) or ...
                                                     %     (0.0254 mm)

        % Reference from Damage Mechanisms and Life Assessment of High-Temperature ...
        %       Components; R. Viswanathan
        LMPH1 = Tave_m_rank*(20 + log10(T1*1));
        HV1A = 961.713 - (0.020669*LMPH1); % Equation 5.27; Page 237
        HV(setnum,1) = HV1A;

        LMPH2 = Tave_m_rank*(20 + log10(T2*1));
        HV1B = 961.713 - (0.020669*LMPH2);  % Equation 5.27; Page 237

        % For T22 material: (from ASME Table 1A Metric Section II Part D)
        allow_str_Temp_C = [65, 100, 125, 150, 200, 250, 300, 325, 350, 375, 400, ...
            425, 450, 475, 500, 525, 550, 575, 600, 625, 650];
        allow_str_MPa = [118,   118, 116, 114, 114, 114, 114, 114, 114, 114, 114, ...
            114, 114, 100, 80.9, 64, 47.7, 34.5, 23.5, 15.5, 9.39];

        % For T12 material: (from ASME Table 1A Metric Section II Part D)
%       allow_str_Temp_C = [65, 100, 125, 150, 200, 250, 300, 325, 350, 375, 400, ...
%           425, 450, 475, 500, 525, 550, 575, 600, 625, 650];
%       allow_str_MPa = [117, 116, 114, 114, 114, 114, 113, 112, 110, 109, 107, ...
%           106, 103, 101, 88.3, 61.9, 40.3, 26.4, 17.3, 11.7, 7.4];

        interp_allow_str(setnum,1) = interp1(allow_str_Temp_C,allow_str_MPa, ...
            Tave_m(setnum,1));

        % indication of data set with thinning or without thinning
        switch (thinrate(setnum,col))
            case (0)
                fprintf(fileID,'CREEP ANALYSIS RESULT WITHOUT THINNING: (DATA
MODEL %d)\r\n\r\n',loop_data_sets);
            otherwise
                fprintf(fileID,'CREEP ANALYSIS RESULT WITH THINNING: (DATA
MODEL %d)\r\n\r\n',loop_data_sets);
        end


fprintf(fileID,'%6s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s
%12s %12s %12s\r\n','I','T1','Tave_o','Tave_m','hoop','X1*0.0254','CCDMG2','thin','Ts
0','Ts1','Ts2','HV','q_flux_0','q_flux_o','q_flux_m','q_flux_2','q_flux_ave');
```

```matlab
        % conditions to be fulfilled to continue looping
        while (CCDMG2(setnum,I)<=1 && T1<=160000 && max_thin(setnum,1)<=0.0018 ...
                && allow_str_limit(setnum,1)~=1)

            result = [I T1 Tave_o(setnum,I) Tave_m(setnum,I) hoop(setnum,I) ...
                X1(setnum,I)*0.0254 CCDMG2(setnum,I) thin(setnum,I) Ts0(setnum,I) ...
                Ts1(setnum,I) Ts2(setnum,I) HV(setnum,I) q_flux_0(setnum,I) ...
                q_flux_o(setnum,I) q_flux_m(setnum,I) q_flux_2(setnum,I) ...
                q_flux_ave(setnum,I)];

fprintf(fileID,'\r\n%6d %12d %12.3f %12.3f %12.3f %12.4f %12.4f %12.5f %12.3f %12.3f
%12.3f %12.3f %12.3f %12.3f %12.3f %12.3f %12.3f\r\n',result);

            % record the particular iteration when predetermined time step reached
            while (T1 == t_step(tstep_count))
                Z(setnum,tstep_count) = I;

                if tstep_count <= (numel(t_step)-1)
                    tstep_count = tstep_count + 1;
                else
                    tstep_count = 1;  % reset the count before the time step exceeds ...
                                      %     15th value
                end

            end

            % thickness control (limit maximum thinning)
            max_thin(setnum,1) = (thin(setnum,I)-thin(setnum,1)) + (R1-R0(setnum,col));

            I = I + 1;

            thickness(setnum,col) = X2(setnum,I-1)*0.0000254;
            R1 = thickness(setnum,col) + R0(setnum,col);
            thin(setnum,I) = (thinrate(setnum,col)*T1)/1000;


            R_steam = 1/(2*hs(setnum,col)*pi*R0(setnum,col)*l(setnum,col));
            R_oxide = (log(R1/R0(setnum,col)))/(2*pi*k_o(setnum,col)*l(setnum,col));
            R_metal = (log((R2(setnum,col)-thin(setnum,I))/R1))/(2*pi*k_m(setnum,col) ...
                *l(setnum,col));
            R_gas = 1/(hg(setnum,col)*2*pi*(R2(setnum,col)-thin(setnum,I))*l(setnum,col));

            q_radial = (T_g(setnum,col) - T_s(setnum,col))/(R_steam + R_oxide + ...
                R_metal + R_gas);
            hoop(setnum,I) = pressure(setnum,col)*(R0(setnum,col) + (R2(setnum,col)- ...
                R0(setnum,col)-thin(setnum,I))/2)/(R2(setnum,col)-R0(setnum,col)- ...
                thin(setnum,I));

            Ts2(setnum,I) = T_g(setnum,col) - (R_gas*q_radial);
            Ts1(setnum,I) = Ts2(setnum,I) - (R_metal*q_radial);
            Ts0(setnum,I) = Ts1(setnum,I) - (R_oxide*q_radial);


            T1 = T2;
            T2 = T2 + 250;
            X1(setnum,I) = X2(setnum,I-1);

            Tave_o(setnum,I) = (Ts0(setnum,I) + Ts1(setnum,I))/2;
            Tave_m(setnum,I) = (Ts1(setnum,I) + Ts2(setnum,I))/2;
            CCDMG1 = CCDMG2(setnum,I-1);


            q_flux_0(setnum,I) = hs(setnum,col)*(Ts0(setnum,I) - T_s(setnum,col));
            q_flux_o(setnum,I) = k_o(setnum,col)*(Ts1(setnum,I) - Ts0(setnum,I))/ ...
                (R1*log(R1/R0(setnum,col)));
            q_flux_m(setnum,I) = k_m(setnum,col)*(Ts2(setnum,I) - Ts1(setnum,I))/ ...
                (R1*log(R2(setnum,col)/R1));
            q_flux_2(setnum,I) = hg(setnum,col)*(T_g(setnum,col) - Ts2(setnum,I));
            q_flux_ave(setnum,I) = (q_flux_m(setnum,I) + q_flux_2(setnum,I))/2;


            Tave_m_rank = Tave_m(setnum,I)*1.8 + 32 + 460;
            % deg Fahrenheit = deg Celsius * 1.8 + 32
            % deg Rankine = deg Fahrenheit + 460
```

```matlab
        T_rup(setnum,I) = 10^((LMP(setnum,col)*1000)/(Tave_m_rank*1.0)-20);
        CCDMG2(setnum,I) = (250.0/T_rup(setnum,I)) + CCDMG1;

        Tave_o_rank = Tave_o(setnum,I)*1.8 + 32 + 460;
        LMPX1 = Tave_o_rank*(20 + log10(T1*1));
        X1A = (10^(0.00022*LMPX1-7.25));
        LMPX2 = Tave_o_rank*(20 + log10(T2*1));
        X1B = (10^(0.00022*LMPX2-7.25));

        DX1(setnum,I) = X1B - X1A;
        X2(setnum,I) = X1(setnum,I) + DX1(setnum,I);

        LMPH1 = Tave_m_rank*(20 + log10(T1*1));
        HV1A = 961.713 - (0.020669*LMPH1);
        LMPH2 = Tave_m_rank*(20 + log10(T2*1));
        HV1B = 961.713 - (0.020669*LMPH2);

        HV(setnum,I) = (HV1A + HV1B)/2;

        interp_allow_str(setnum,I) = interp1(allow_str_Temp_C,allow_str_MPa, ...
            Tave_m(setnum,I));

        if I >= 2   % check whether the allowable stress drops below hoop stress
            if interp_allow_str(setnum,I) <= hoop(setnum,I)
                allow_str_limit(setnum,1) = 1;

                if time_str_disp == 0;
                    time_str(setnum,1) = T1;
                    time_str_disp = 1;
                end
            else
                allow_str_limit(setnum,1) = 0;
            end
        else
            allow_str_limit(setnum,1) = 0;
        end
end

%---------- This section is specially for correlation function ----------%
% Prediction of constant B
test = 1;
test_constB(setnum,1) = 0.01;

while (test <= 500) % loop until the test constant user want divided by ...
                    %      'test_constB'
    DTave_m_pred(setnum,1) = 0;
    Tave_m_pred(setnum,1) = Tave_m(setnum,1);
    p_diff(setnum,1) = (abs(Tave_m_pred(setnum,1) - Tave_m(setnum,1)))*100 ...
        / Tave_m(setnum,1);
    W = 2;

    while (W <= I)
        DTave_m_pred(setnum,W) = DX1(setnum,W-1)*test_constB(setnum,test);
        Tave_m_pred(setnum,W) = Tave_m_pred(setnum,W-1) + DTave_m_pred(setnum,W);
        p_diff(setnum,W) = (abs(Tave_m_pred(setnum,W) - Tave_m(setnum,W)))*100 ...
            / Tave_m(setnum,W);
        W = W + 1;
    end
    avg_p_diff(setnum,test) = sum(p_diff(setnum,:)) / I;
    test = test + 1;
    test_constB(setnum,test) = test_constB(setnum,test-1) + 0.01;
end

min_avg_diff(setnum,1) = min(avg_p_diff(setnum,:));
W_switch = 0;
test = 1;
while (W_switch == 0)
    if min_avg_diff(setnum,1) == avg_p_diff(setnum,test)
        V(setnum,1) = test;
        W_switch = 1;
    else
        W_switch = 0;
    end
    test = test + 1;
end

% After obtaining predicted constant B, average temperature of tube metal ...
```

```matlab
    %      Tave_m_pred can be estimated from DX1
    constB(setnum,col) = test_constB(setnum,V(setnum,1));
    DTave_m_pred(setnum,1) = 0;
    Tave_m_pred(setnum,1) = Tave_m(setnum,1);
    p_diff(setnum,1) = (abs(Tave_m_pred(setnum,1) - Tave_m(setnum,1)))*100 / ...
        Tave_m(setnum,1);

    W = 2;

    while (W <= I)
        DTave_m_pred(setnum,W) = DX1(setnum,W-1)*constB(setnum,col);
        Tave_m_pred(setnum,W) = Tave_m_pred(setnum,W-1) + DTave_m_pred(setnum,W);

        p_diff(setnum,W) = (abs(Tave_m_pred(setnum,W) - Tave_m(setnum,W)))*100 / ...
            Tave_m(setnum,W);
        W = W + 1;
    end

    avg_p_diff(setnum,1) = sum(p_diff(setnum,:)) / I;

    % Predict oxide scale growth using predicted constant B
    DTave_m(setnum,1) = 0;
    X1_pred(setnum,1) = X1(setnum,1);
    U = 2;

    while (U <= I)
        DTave_m(setnum,U) = Tave_m(setnum,U) - Tave_m(setnum,U-1);
        DX1_pred(setnum,U) = DTave_m(setnum,U)/constB(setnum,col);
        X1_pred(setnum,U) = DX1_pred(setnum,U) + X1_pred(setnum,U-1);
        U = U + 1;
    end

    %-------------------------------------------------------------------------%

    fprintf(fileID,'\r\n\r\n');

    loop_data_sets = loop_data_sets + 1;
    ite(setnum,1) = I;
    time(setnum,1) = T1;
end

n_sets = 1;
fprintf(fileID,'SUMMARY:\r\n\r\n');

while (n_sets <= data_sets)  % reason for the termination of loop
    if CCDMG2(n_sets,ite(n_sets,1)) > 1
        fprintf(fileID,'Model %d fails at %g hours due to creep damage.\r\n\r\n', ...
            n_sets,time(n_sets,1)-250);
    elseif max_thin(n_sets,1) > 0.0018
        fprintf(fileID,'Model %d is in critical state at %g hours due to tube wall
thinning more than 1.8 mm.\r\n\r\n', n_sets,time(n_sets,1)-250);
    elseif allow_str_limit(n_sets,1)== 1
        fprintf(fileID,'Model %d is in critical state at %g hours due to hoop stress
exceeds max allowable stress.\r\n\r\n', n_sets,time_str(n_sets,1)-250);
    elseif time(n_sets,1) > 160000
        fprintf(fileID,'Model %d has service life longer than %g
hours.\r\n\r\n',n_sets,time(n_sets,1)-250);
    end

    n_sets = n_sets + 1;
end

%------------ This section is specially for correlation function ------------%
% display generated constant B and average percentage of difference
n_sets = 1;
fprintf(fileID,'\r\n\r\n\r\nCORRELATION FUNCTION RESULT:\r\n\r\n');
fprintf(fileID,'%6s %12s %18s\r\n','Model','constB','min_avg_diff');

while (n_sets <= data_sets)
    result = [n_sets constB(n_sets,1) min_avg_diff(n_sets,1)];
    fprintf(fileID,'\r\n%6d %12.2f %18.4f\r\n',result);

    n_sets = n_sets + 1;
end
%-------------------------------------------------------------------------%

fprintf(fileID,'\r\n\r\n\r\n');

while
```

```matlab
fclose(fileID);
type creepanalysis_result.txt

disp('Plotting graph(s).....');

% Graph Plotting Functions %
% --Comparison between data sets:--

[X1_step]= X1_graph(time,ite,data_sets,X1,t_step);
[CCDMG2_step]= CCDMG2_graph(time,ite,data_sets,CCDMG2,t_step);
[Tave_m_step]= Tave_m_graph(time,ite,data_sets,Tave_m,t_step);
[HV_step]= HV_graph(time,ite,data_sets,HV,t_step);
[q_flux_m_step]= q_flux_m_graph(time,ite,data_sets,q_flux_m,t_step);
[q_flux_ave_step]= q_flux_ave_graph(time,ite,data_sets,q_flux_ave,t_step);
[k_value_p,k_value_p_ave]= k_value_p_graph(time,ite,data_sets,X1);
[k_value_q,k_value_q_ave]= k_value_q_graph(time,ite,data_sets,X1);
[Tave_m_pred_step]= Tavem_pred_graph(time,ite,constB,data_sets,Tave_m_pred,t_step);
[X1_pred_step]= X1_constB_graph(time,ite,constB,data_sets,X1_pred,t_step);

% --Plots of single set:--

[Tave_step_o,Tave_step_m]= Tave_graph(time,ite,Tave_o,Tave_m,t_step);
[q_flux_step_inner,q_flux_step_o,q_flux_step_m,q_flux_step_outer]= ...
    q_flux_graph(time, ite,q_flux_0, q_flux_o,q_flux_m,q_flux_2,t_step);
[Ts_inner_step,Ts_om_step,Ts_outer_step]= Ts_graph(time,ite,Ts0,Ts1,Ts2,t_step);
[interp_allow_str_step] = allowable_stress_graph(time,time_str,...
    ite,interp_allow_str, hoop,t_step);
[Tavem_step_pred,Tavem_step]= corr_fn_graph(time,ite,constB,Tave_m_pred, ...
    min_avg_diff,Tave_m,t_step);

disp('Continue displaying result(s)......');

R = 1;
fileID2 = fopen('creepanalysis_result_tstep.txt','w');

while (R <= data_sets)  % creep analysis results w.r.t. the predetermined time step

    S = 1;
    fprintf(fileID2,'\r\n\r\n');  % for spacing
    fprintf(fileID2,'CREEP ANALYSIS RESULT IN t_step: (DATA MODEL %d)\r\n\r\n',R);

fprintf(fileID2,'%6s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s %12s
 %12s %12s %12s\r\n','t_step','Tave_o','Tave_m','hoop','X1*0.0254','CCDMG2','thin','T
s0','Ts1','Ts2','HV','q_flux_0','q_flux_o','q_flux_m','q_flux_2','q_flux_ave','T_rup'
);

    while (S <= numel(Z(R,:)) && Z(R,S) ~= 0)
        zi = Z(R,S);
        result_step = [t_step(1,S) Tave_o(R,zi) Tave_m(R,zi) hoop(R,zi) ...
            X1(R,zi)*0.0254 CCDMG2(R,zi) thin(R,zi) Ts0(R,zi) Ts1(R,zi) Ts2(R,zi) ...
            HV(R,zi) q_flux_0(R,zi) q_flux_o(R,zi) q_flux_m(R,zi) q_flux_2(R,zi) ...
            q_flux_ave(R,zi) T_rup(R,zi)];

fprintf(fileID2,'\r\n%6d %12.3f %12.3f %12.3f %12.4f %12.4f %12.5f %12.3f %12.3f %12.
3f %12.3f %12.3f %12.3f %12.3f %12.3f %12g\r\n',result_step);
        S = S + 1;
    end

    R = R + 1;

end

fclose(fileID2);
type creepanalysis_result_tstep.txt
```