HEAT TRANSFER COMPUTATION FOR CRUDE OIL FLOW ALONG PIPELINE

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ABSTRACT

The waxes that present in most crude oils include n-alkanes, iso-alkanes, alkyl cyclic compounds and alkyl aromatic. The amount of wax contained in the crude oil sample varies. The deposition of the waxes is responsible for some of the issues may result in production shutdowns and others. The wax appearance temperature (WAT) is the temperature at which, on a cooling cycle, the crude oil first precipitates solid wax. The position of the Wax Appearance Temperature (WAT) of crude oil in pipeline was determined. From the temperature of surrounds, heat conduction and convection equation are used to determine the temperature of the crude oil inside the pipeline based from different depth. It was compared with Wax Appearance Temperature (WAT) from different Crude Oil. The Crude Oils are from South China Sea, Penara and Larut Malaysia, Algeria, Libya, Iran and Venezuela. All the calculation was used FORTRAN. The Wax Appearance Temperature (WAT) of every Crude Oil was identified. Result from the calculation showed that the depth of Wax Appearance Temperature in the pipeline for every crude oil from South China Sea, Penara, Larut, Algeria, Libya, Iran and Venezuela, Angola, Syria, Gabon, Tunisia and France are 1.20253km, 2.10420km, 1.65920km, 1.35587km, 1.80920km, 1.64920km, 1.19829km, 1.98920km, 1.65587km, 1.89920km, 2.26587km and 1.67253km respectively. The depth of Wax Appearance Temperature (WAT) from Tunisia is deepest compare to other origin of Crude Oil.

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1 INTRODUCTION

1.1 *Background of Study*

The rapid growth of oil and gas industries in the world especially petroleum industries give high impact to development of economic in the certain country. Industries have developed their good pipeline transportation to have better production. The overall heat transfer coefficients of a crude oil and product pipeline are important parameters. The heat transfer is affected with the surrounding such as seawater or soil affects the temperature field inside the duct. Some domestic experts have investigated crude oil pipeline.

The pressure gradient is directly affected by the heat transfer because of the exponential variation of the liquid viscosity with temperature. In addition, as the wax deposition depends on the oil temperature. The heat transfer from the flow mixture can be avoided by proper pipe insulation, heating, and, in some cases, the addition of chemical (Azevedo et al., 2001). However, these techniques are expensive and if used, should follow an accurate estimation of the heat transfer coefficient. Consequently, the precise estimation of the flow temperature is a key factor for the correct design of exportation pipelines and an accurate calculation of the petroleum production (Fernando et al., 2008).

Crude Oils and Natural Gas consist of nearly 100% hydrocarbon. A series of natural hydrocarbon are known as n-paraffin. Most crude oils contain waxes which can precipitate during cooling and cause well-known problem such as deposition in pipelines and production equipment. Deposition of n-paraffin will usually occur along the pipe walls when the temperature of produced fluids falls below the Wax Appearance Temperature (WAT), which is the point where the first wax crystals start to precipitate. It depends on the concentration and molecular weight of the waxes and the chemical nature of the non-waxy part of the crude oil, termed the hydrocarbon matrix. Waxes are typically long, straight n-paraffin chains within the produced oil. At elevated temperatures, they usually remain dissolved within the oil. At temperature below the cloud point (providing a heat sink and concentration gradient), the n-paraffin components begin to crystallize into solid wax particles.

Therefore, this study employed the use of temperature of crude oil to predict the depth of wax appearance inside pipeline based from Wax Appearance Temperature (WAT). It is covering the determination of the well temperature due to geothermal gradient equation and the internal surface temperature inside pipeline using heat of conduction and convection equation based on the specific well depth temperature of pipeline.

1.2 Motivations

In the last quarter of 20th century, worldwide demand for crude oil had a very stable development rate averaging 1%. This has changed drastically in the first years of 21st century due to "Developing Countries" like China and India whose vigorous economies resulted in a outstanding 1.8 % global growth in demand for crude oil in 2009 (IEA,2010). Serious international studies still anticipate that in the next 20 years, at least 80 % of the world energy essential will come from petroleum, natural gas and coal (IEA, 2008). The calculation of the heat transfer computation for crude oil flow along pipeline in steady state is an issue of concern in many situations; the oil transfer in long production and transport flow-lines is a telling example. Oil exploitation is constantly moving to challenging frontiers where harsh and cold environment common. For instance, in some offshore fields, the oil may leave the reservoir at temperatures as high as 75 °C, while the surrounding water at the bottom of the sea may be as cold as 4 °C (Trevisan *et al.*, 2006).

The high molecular weight paraffins (Waxes) are known to be responsible for some of the issues that are bumped into during crude production (Kelechukwu and Abu Azam, 2008). The undesirable effect of wax deposition can cause serious production wreckage and other associated hazardous risk. While it is remedial approaches and production losses add to colossal economic destructions to the petroleum industry. The deposition process can basically lead to contraction of the internal diameter of the tubular, narrowing and complete blockage of pipeline and can boost surface roughness on the pipe wall, causing increased pumping pressure and lower throughput and also restrain or impede valves, and stop other production equipment. All of these problems may result in production shutdowns and hazardous conditions and will require extensive works, production losses and possibly irreparable damage require equipment abandonment and replacement, which can turn into millions of dollars in sales.

Once the crude oil leaves the reservoir and flows through the tubing and pipelines, its temperature begins to drop due to the ambient conditions (Kelechukwu and Abu Azam, 2008) and once a radial temperature difference is established between the crude oil and the pipe wall, it leads to concentration gradient, hence the oil temperature decreases below the Wax Appearance Temperature (WAT) of the oil, the would be high possibility of wax deposition (Creek et al., 1999; Rebbapragada, 2004) hence the solubility of paraffin in the oil is a dependent of the decreasing function of temperature of molecular weight of its constituents (Paso and Fogler, 2003).

The problem of interest is described as follows, the heat transfer for crude oil flow along offshore pipeline in steady state condition. To solve this problem, all heat transfer equations need to be identified, such as heat conduction and convection equation and mass conversion equation. Geothermal gradient equation is also used. To solve all equation, the software package Fortran is used.

Recently, Fortran software was used to build the new program that is to determine the heat transfer for crude oil flow along pipeline at below sea floor. The name produce from the two words “FORmula TRANslation”. It was design for scientists and engineers. Fortran has been used for such projects as the design of bridges and airplane structures, and also factory automation control, for storm drainage design, analysis of scientific data and so on. After the input of the outer diameters of pipelines and sea water level depth, the software can automatically divide the computational domain. The crude oil temperature was calculated by the program and compared it

1.3 Problem statement

The amount of wax contained in the crude oil sample varies, depending on the geographic source of the crude. Whenever the temperature decreases the dispersed paraffins begin to align together. As cooling the crude oil continues, the paraffins form a solid crystalline wax structure. Since paraffins occurs naturally in crude oil, there is potential for wax deposition at every step from oil production to refining. The problem of interest is described as follows, the heat transfer for crude oil flow along offshore pipeline in steady state condition. The depth of pipe when wax of crude oil occurs is a problem and it is important parameter to know. It will help the prediction of wax deposition present and can decrease the damaged of the production equipment.

1.4 Objectives

The following are the objectives of this research:

- To determine the temperature relationship of the well with depth
- To determine the depth of wax appearance temperature in pipeline.

1.5 Scope of this research

The following are the scope of this research:

i) Calculation of geothermal gradient equation to determine the temperature of the well.
ii) Calculation of heat conduction and heat convection equation.
iii) The depth wax occurs at pipeline are based on the Wax Appearance Temperature (WAT).
iv) FORTRAN is used for computation in this work.

2 LITERATURE REVIEW

2.1 *Overview*

This work studies the depth of vertical pipeline along the well when the wax of crude oil starts to appear based on wax appearance temperature (WAT). The depth is ranged from 0 km to 3.0km. FORTRAN was used for computation in this works. This program was used to calculate the temperature profile of the well based at different depths. The heat transfer of the crude oil is identified based from reservoir temperature as high as 75 °C (Dantas et al. 2009).

2.2 *Introduction*

This study presents a numerical study of steady flow of crude oil in a 48 inch diameter vertical pipe using computational program FORTRAN. The numerical simulations were carried out to study the thermal impact of cold product pipeline on hot crude oil pipeline of a steady state and the consequences of pipeline interval on the thermal impact was studied in detail under various circumstances (Yu et al., 2008). The heat transfer of the crude oil pipeline is composed of three components, namely, the convective heat transfer between the oil in the pipeline and the inner wall of the pipeline; the heat conduction between pipeline wall and the external surface of the pipeline wall; and the heat emission between the outermost pipeline wall and the around the pipeline (Na *et al.*, 2012).

The heat transfer is normally from high temperature object to lower temperature object. Heat transfer mechanism can be grouped into three board categories that is heat conduction, heat convection and radiation. The heat loss is dependent on a number of factors, such as the temperature variation of the mixture as it flows through different sections of the pipeline, different sea water temperature to which the pipeline is exposed, pipe location (above or below ground) and so on. In designing an offshore buried pipeline, either in steady-state or transient working condition, important parameters that must be considered are the burying depth of the duct and the depth of the sea. Indeed, a distinction between deep water pipelines and shallow water pipelines is made. For the case of deep water, one can assume that the sea and the soil have the same undisturbed temperature and that this temperature is a constant both in time and space; on the other hand, for shallow water, the temperature of the sea undergoes significant seasonal changes and, as a consequence, the temperature of the soil changes as well (Barletta *et al*., 2008).

The heat transfer driven by this large temperature gradient cools down the produced mixture and alters the in situ properties. In this connection, the pressure gradient is directly affected by the heat transfer because of the exponential variation of liquid viscosity with temperature. The heat transfer from the flow mixture can be avoided by proper pipe insulation, heating, and in some cases, the addition of chemicals (Azevado *et al*., 2001). These techniques are expensive and if used should follow an accurate estimation of heat transfer coefficient. The precise estimation of the flow temperature is a key factor of the correct design of exportation pipelines and accurate calculation of the petroleum production (Franca *et al*., 2008).

The heat transmission model was improved by providing a detailed method for calculating the overall heat transfer coefficient (U) for the completion in terms of natural convection and conduction. This coefficient is critical for estimating the temperature profile in the well. A steady state equation has been developed for calculating temperature in pipeline flow. This steady state equation will be applied in computing well flow temperature to see if that will yield satisfying results (Willhite., 1967).

Crude oil is a complex mixture consisting of paraffins, aromatics, naphthenics, resins, asphaltenes and other impurities. The solubility of high-molecular-weight paraffins in crude oil decreases drastically with decreasing temperature (Ramachandran *et al*., 2004). A simple temperature gradient chart was presented, that can be used to predict crude oil lift valve temperatures at the injection depth (Kirkpatrick., 1959). Much of the classic work in this area was developed. Approximate methods was presented for predicting the temperature of a single-phase crude oil flow in injection and production wells (Ramey., 1962). The crude oil temperature increases from the top to the bottom of the pipe. At the same depth of the pipe, if the ground thermal conductivity parameter increases, then crude oil temperature will decrease. The crude oil temperature increases from the top to the bottom of the pipe. At the same depth of the pipe, if crude oil output increases, temperature will increase (Wu *et al*., 2011). The heat transfer solution also assumes to the earth will be unsteady radial convection and it also considers the effect of thermal resistance in the well bore. The solution permits estimation of the temperature of fluids, tubing and casing as a function of depth and time (Ramey., 1962).

Ambient temperature in a well increases with depth. This increase is dependent on the geothermal temperature gradient, α, expressed in °C/km. A Typical value for α in the North Sea is 30°C/km. This geothermal gradient will be assumed independent of density and other parameters, and will therefore be the same all the way from sea bed to bottom hole. Given this geothermal gradient in a 3000 meter deep well, the ambient temperature in the bottom hole is about 90°C while at the wellhead it will be around 4°C, the typical sea temperature at the sea bed. This equation is dependent upon the overall heat transfer coefficient (U), which in the pipeline flow calculations will be considered constant. This is not necessarily true for well temperature calculations, but will, for this case, be considered correct. The equation is further dependent on the temperature of the fluid flowing into the pipe or the well; the mass flow rate; the diameter of the pipe; and the heat capacity of the fluid flowing in the pipe. The temperature of the fluid flowing out of the well will also be affected by pipe length or well depth. Even if temperature in the fluid is decreasing on the way up, the increasing difference in temperature between formation and fluid gives rise to an increasing heat transfer. This increase in heat transfer can be described by an increase in the overall heat transfer coefficient (U) (Valberg.T.,2005).

The thermal energy that drives metamorphism is ultimately related to the processes of heat loss from the interior of the earth. Such as, metamorphism must be seen as a consequence of the conductive and heat transfer phenomena associated with lithospheric processes such as deformation, erosion and magma transport. Metamorphism at gradients in excess of about 40˚C /km results in intermediate to high-temperature, low-pressure metamorphism in the middle crust (Sandiford et al.,1998). The geothermal gradient is commonly expressed as degree Fahrenheit per hundred feet or degrees centigrade per centimetre or kilometre. This gradient due to dissipation of subsurface heat, which is not everywhere the same and gradients vary from place to place because of differences both in rock and in regional and local heat sources (Lovering,T.S. & Goode,H.D., 1963).

The temperature history during the 113-meter measurement shows warming of the probe; the temperatures do not describe a straight line on the 1/time plot but appear to equilibrate more rapidly than expected. We think that is due to the superposition of two transient phenomena: (1) the equilibration of the initially cold probe to the surrounding warmer sediments and (2) the flow heat upward along the 10-cm long probe body to the massive 6-cm diameter lance on which the probe is mounted. The final gradient values are as follows: from the sea floor to 52.5 meters, 0.0764±0.0004˚Cm^{-1} and from 52.5 to 113 meters, 0.072±0.0008˚Cm^{-1}. The difference is apparently real and attributable to an increase in mean conductivity from the upper to lower interval. Eastern Falkland Plateau successful bottom hole temperature measurements were made at 52.5 and 113 meters below the seafloor. The result show a regular increase of temperature with depth of 0.074˚Cm^{-1} (Langseth,M.G. & Ludwig,W.J.,1979).

The ocean is cold enough in a depth range from say 500 meters down (200 meters in the Artic). Below the sea floor, the temperature increases with depth, along the geothermal gradient (David.,2005).

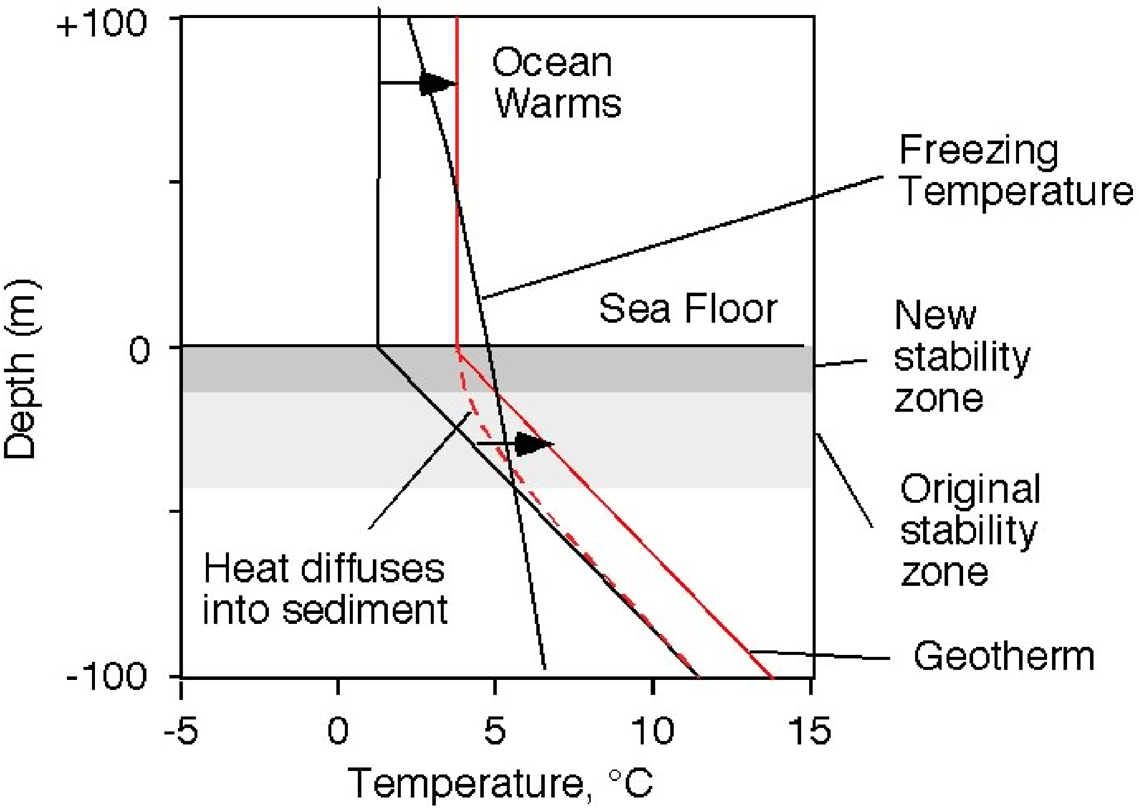

Figure 2.1: relation between depth and temperature (David.,2005)

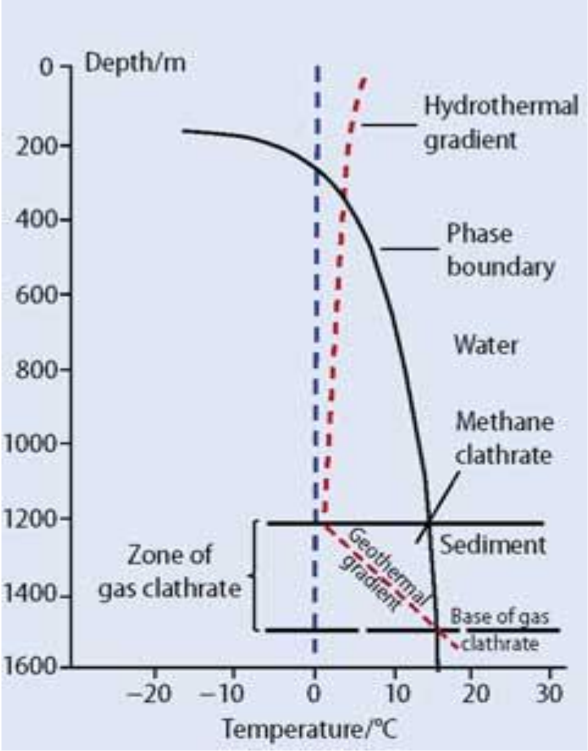

Figure 2.2: shows a plot of depth against temperature for a typical temperate-water coastal shelf (Rayner-Canhem,G., & Way.T., 2009).

The red-dashed water temperature curve (the hydrothermal gradient) shows how the temperature decreases with increasing depth to close to 0˚C at the sea floor. Descending through the sediment, the mud and gravel increase in temperature (the geothermal gradient) as a result of the heat emanating from the Earth’s core (Rayner-Canhem,G., & Way.T., 2009).

Crude oils with high paraffin content are generally classified as a waxy crudes. The temperature at which wax begins to precipitate out from the crude oil is called the Wax Appearance Temperature (WAT). Wax precipitation may potentially give rise to various transportation and production related problems. Wax deposition on cold surface causing a reduced flow and increased pressure drop, high apparent viscosity that may lead to an increased pressure drop, oil gelation resulting in a high restart pressure of a shut-down pipeline (Karan *et al.*, 2000). Concerns about wax deposition, wax gelatin and hydrate formation play a significant role in concept selection for deep water and ultra-deep water development projects. Water depth, long distances from the reservoir to the host facility via subsea tiebacks, dry tree risers and extended export pipelines in cold ambient water temperatures all pose risks for operators to consider when planning their development scenarios (Golczynski.T.S & Kempton.E.C., 2006).

Wax deposition and wax gelation are two potentially catastrophic issues in crude oil and gas/condensate systems that can render a pipeline unusable. The deposition of n-paraffin will usually occur along the pipe walls when the temperature of produced fluids falls below the Wax Appearance Temperature (WAT) or cloud point. When a waxy crude oil is cooled, at the WAT the wax begins to separate out as solid crystals when the solubility limit is exceeded. A distinction must be made between the thermodynamic WAT and experimentally measured WAT. The thermodynamic WAT defines the true solid-liquid phase boundary temperature, i.e. the maximum temperature at which the solid and liquid phases exist in equilibrium at a fixed pressure. The experimental WAT presents the temperature at which the first crystals are detected and, consequently, depends on the sensitivity of the measurement technique. Normally, the experimaental WAT would be well within the thermodynamic Solid-Liquid phase envelope (Karan.K *et al.*, 2000).

Wax gelation is less common in steady-state than is wax deposition, but it can have even greater impact if, during production system shutdowns, fluids temperatures cool below the fluid pour point, allowing the formation of a “candle” or solid wax column. Solid deposition from waxy crude oils is a complex engineering problem, which involves the consideration of thermodynamics, solid-liquid multiphase equilibria, crystallization kinetics, fluid dynamics, heat transfer, mass transfer, rheology, and thermophysical and transport properties. Modeling of solids deposition has been attempted via molecular diffusion and mass transfer, shear dispersion, Brownian motion, and heat transfer (Mehrotra.K.A and Bidmus.H.O., 2006).

2.3 Previous work

A total of 175,000 km (108,740 mi.) or 4.4 times of the earth’s circumference of subsea pipelines have been installed by 2006. The deepest water depth that pipelines have been installed is 2,414 m (7,918 ft) in the Gulf of Mexico (GOM) by Anadarko for the Independence Hub project in 2007. The record is broken by Petrobras Cascade flowlines which are installed in 2,689 m (8,820 ft) of water in GOM in 2009 [10]. The longest oil subsea tieback flowline length is 43.4 miles (69.8 km) from the Shell’s

Penguin A-E and the longest gas subsea tieback flowline length is 74.6 miles (120 km) of Norsk Hydro’s Ormen Lange, by 2006. The deepwater flowlines are getting high pressures and high temperatures (HP/HT). Currently, subsea systems of 15,000 psi and 350 °F (177 °C) have been developed (SUT., 2007). By the year 2005, Statoil’s Kristin Field in Norway holds the HP/HT record of 13,212 psi (911 bar) and 333 °F (167 °C), in 1,066 ft of water. The deepwater exploration and production (E&P) is currently very active in West Africa which occupies approximately 40% of the world E&P (SUT.,2007) (see Figure 2.1).

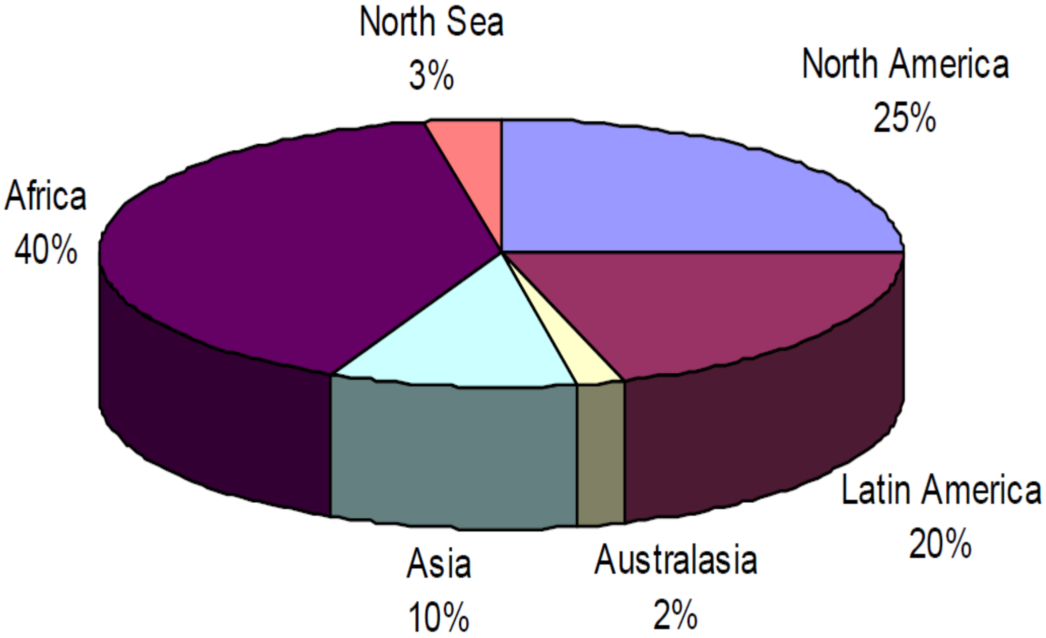

Figure 2.3: worldwide Deepwater Exploration and Production. (SUT., 2007)

The influence of convection and related flow effects in conduction heat transfer included investigation of heat exchanges in heterogeneous flows, conjugate forced convection-conduction analysis, transient heat transfer due to conduction and internal sources in a slab and conjugate problems dealing with conduction and free convection. The heat conduction problem can be considered as the fundamental problem in the solution of partial differential equation for scalar variables. It provides a convenient testing ground for the development and evaluation of numerical methods. A number of papers deal with direct heat conduction problems. Both finite-difference and finiteelement methods have been developed. Attention is given to the accuracy and efficiency of methods. Nonlinear heat conduction problems are now being handled in an inverse manner (Eckert *et al.,* 1996).

The majority of marine geothermal heat flow measurements have been made using instruments little different from the two basic designs employed for the first few measurements; the solid Bullard probe (Bullard., 1954). The Ewing design with outrigger temperature sensor on a corebarrel (Gerard et al., 1962). The temperature dependence of thermal conductivity was studied on dry samples for temperatures ranging from 0 to 500 °C using a divided bar device. Due to the increased inter-granular contact resistance within the dry rock samples, thermal conductivity at ambient conditions for these measurements is usually lower than that determined by the needle probe on the water- saturated rocks (Vosteen, Schellschmidt., 2003).

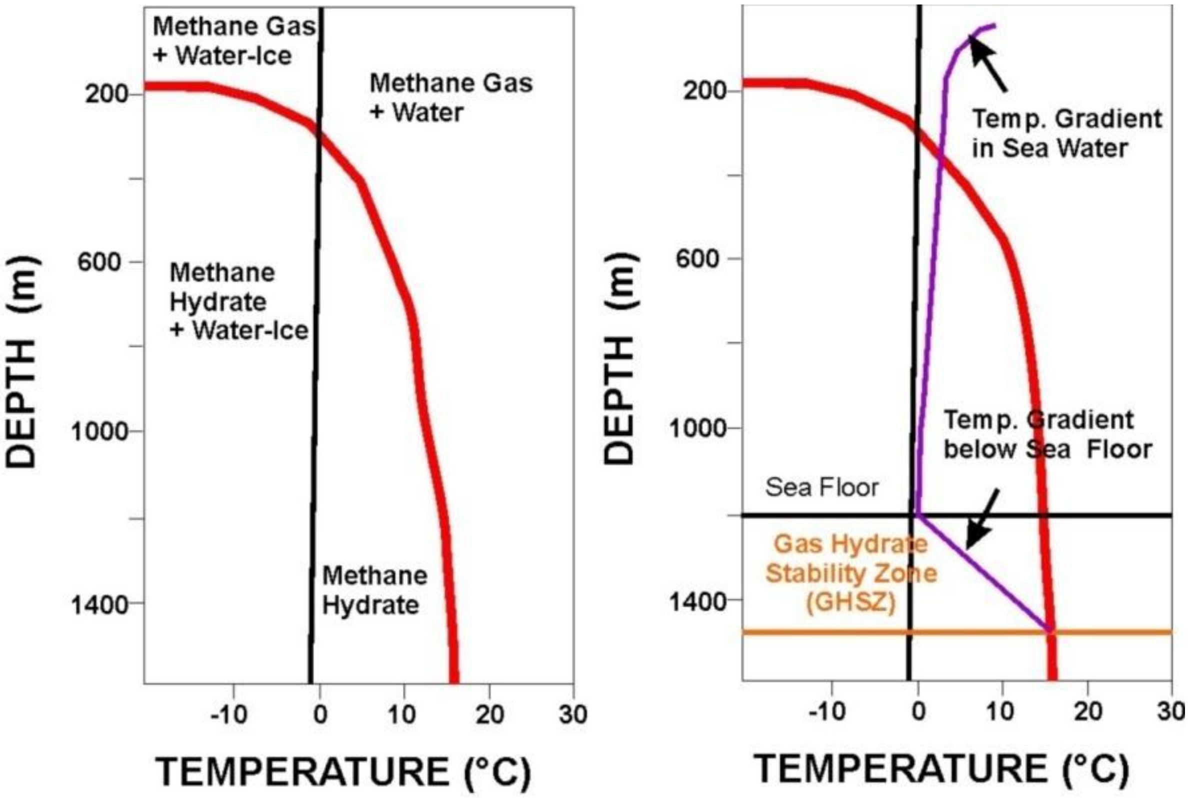

Figure 2.4: effect of seawater temperature at several of depth
(Tinivella.U & Giustiniani.M.,(2013).

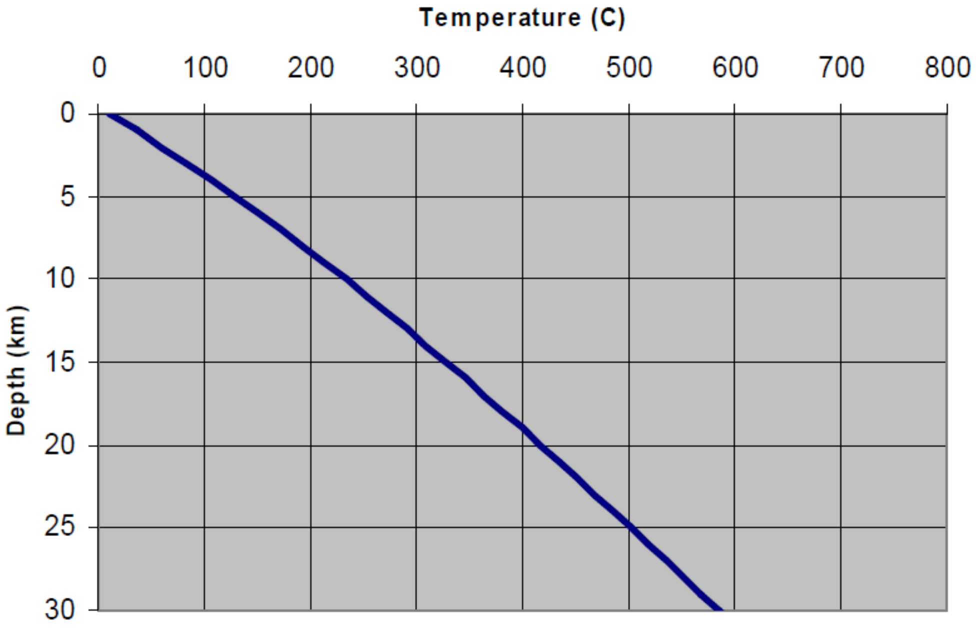

Figure 2.5: effect of temperature at various of depth below sea floor, (selley,1997)

From figure 2.2, the viola line represents the geothermal. A water depth of the sea floor of 1200m is assumed, temperature steadily decreases with water depth and minimum value near 0˚C is reached at the ocean bottom (Tinivella.U & Giustiniani.M.,2013). From figure 2.3, the temperature varies to every depth. In air, the temperature increased 25°C per kilometre (continental average). It is shows the temperature increase as the depth increase or the temperature is steadily increase. It varies with tectonic setting (selley,1997).

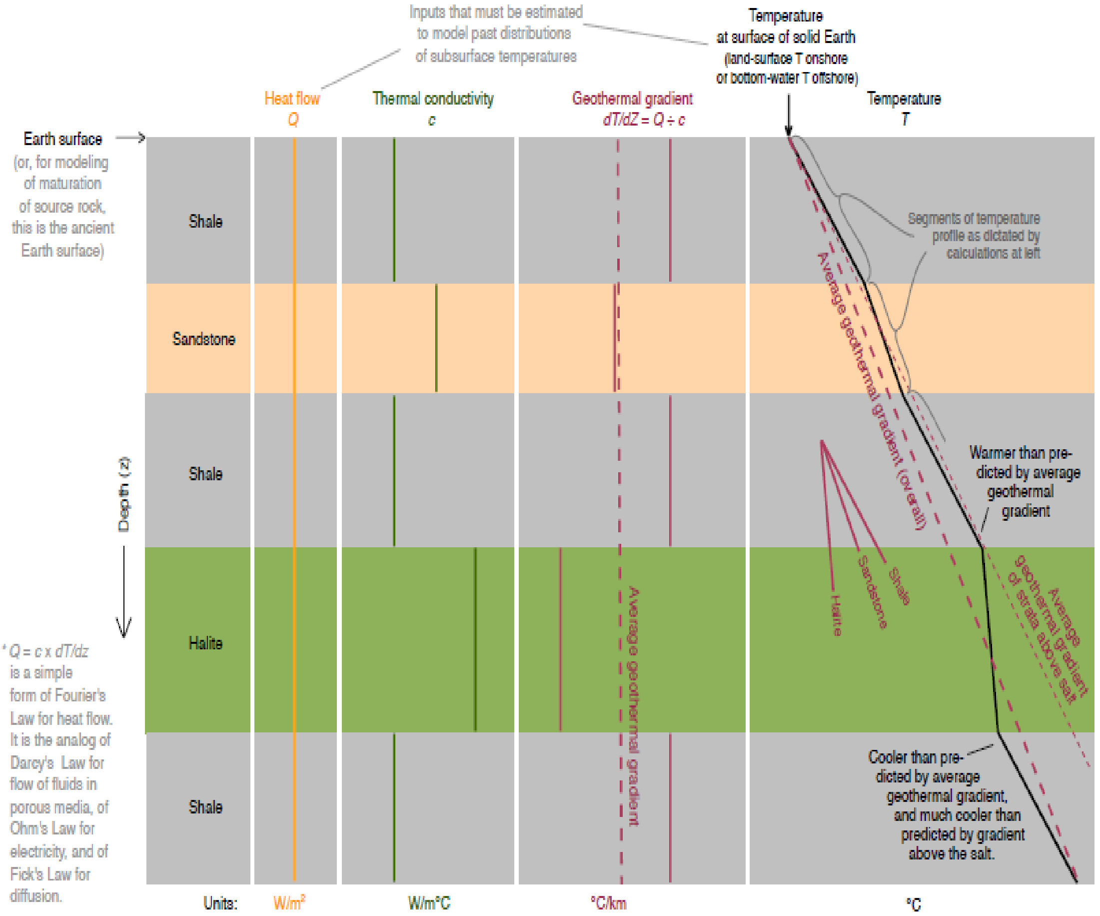

Figure2.6: Heat flow, thermal conductivity, geothermal gradient, and subsurface temperatures, (BjØlykke, 2010)

Understanding the time and place of maturation of source rocks for petroleum requires an understanding of past geothermal gradients. Attempts to estimate past geothermal gradients commonly involve modelling of the flow of heat through layers of sedimentary rock, as shown at figure 2.4. If one can make a reasonable assumption about the past heat flow in sedimentary basin, one can use the thermal conductivity of the strata in the basin to calculate the geothermal gradient at any time and thus estimate the past distribution of subsurface temperatures. The figure 2.4 above works from left to the right to show these relationships (BjØlykke, 2010).

3 MATERIALS AND METHODS

3.1 Overview

To determine the position of the Wax Appearance Temperature or crude oil in pipeline, the temperature of the sea water was determined from geothermal gradient equation. From that temperature, heat conduction and convection equation are used to determine the temperature of the crude oil inside the pipeline based from different depth. It was compared with Wax Appearance Temperature (WAT) from different Crude Oil. All the calculation is programmed under FORTRAN.

3.2 Introduction

This paper present a numerical study of crude oil flow in API 5L – ERW X52, NPS 28-0.45 inch.

3.3 Discretization of the computational domain (FORTRAN)

FORTRAN software is used to build the new program that is to determine the heat transfer for crude oil flow along pipeline at sea water. The name produce from the two words FORmula TRANslation. It is design for scientists and engineers. FORTRAN has been used for such projects as the design of bridges and aeroplane structures, and also factory automation control, for storm drainage design, analysis of scientific data and so on. After the input of the outer diameters of pipelines and sea water level depth, the software can automatically divide the computational domain. The crude oil temperature was calculated by the program and compared it with different measured parameters. The deep pipeline in sea water, the more it will be affected by the crude oil pipeline meanwhile the more the temperature gradient will be.

3.4 Discretization of the governing equations

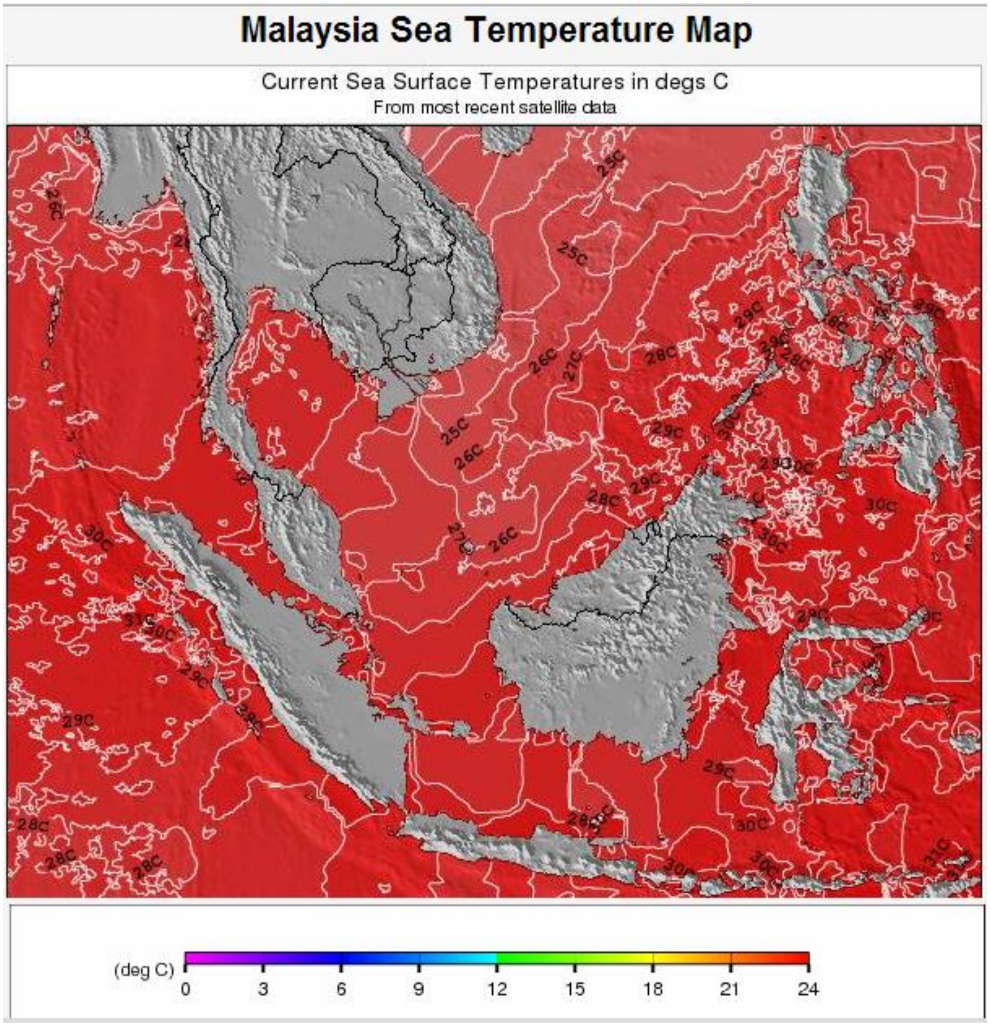

Figure 3.1: Malaysia sea temperature map, (Surf-forecast,2013)

A finite different method is applied to discretize the oil flow equation while control volume integration method was employed. Geothermal gradient equation is shown in equation (1), where it is the change of temperature with depth. The seabed temperature is 4˚C and a kilometer down, the temperature is increased to 30˚C (Valberg,T.,2005).. So, the geothermal gradient equation as below:

$$T_2(K) = Depth \times 34 + 273.15 \qquad (1)$$

Where, T_2 is below sea floor temperature.

Heat conduction at the surface at selected direction = heat convection at the surface at the same direction. r_1 and r_2 are shown in the figure 3.2. For determination of internal surface of pipe is used Heat conduction equation based on the temperature of the sea water of specific depth. The heat conduction and convection equation are shown below:

$$Q_{cylinder} = 2\pi kL\frac{T_1 - T_2}{\ln(r_2/r_1)} \tag{2}$$

Where:

$Q_{cylinder}$ is the heat flow in W/m^2

k is the thermal conductivity of the pipe W/mK

L is the thickness of the pipe (m)

T_1 is the outside temperature (K)

T_2 is the outside temperature (K)

r_2 is the outside diameter of pipe (m)

r_1 is the inside diameter of pipe (m)

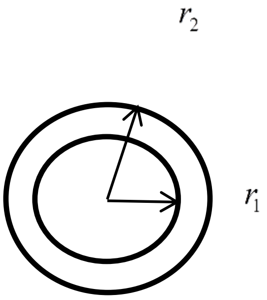

Figure 3.2

For the natural convection heat transfer, Newton's Law of Cooling involved. Newton's Law of Cooling is an equation that is widely used for both forced convection and natural convection calculations. This Law are used to determine the temperature of the liquid (crude oil) at various depths. The equation for Newton's Law of Cooling is:

$$Q = hA(T_2 - T_1) \tag{3}$$

Where:

Q is the rate of heat transfer (W)

A is the area of the surface (m^2)

T_1 is the solid surface temperature (K)

T_2 is the fluid (crude oil) temperature (K)

h is the convective heat transfer coefficient (W/m^2K)

Estimating values for convection heat transfer coefficients is not an exact science. The value of a convection heat transfer coefficient depends on the physical configuration. Empirical correlations are available to estimate heat transfer coefficients.

Prandtl number (Pr)

$$\mathrm{Pr} = \frac{\mu C_P}{k} \tag{4}$$

Grashof number (Gr)

$$Gr = \frac{D^3 \rho^2 g \Delta T \beta}{\mu^2} \tag{5}$$

Film Temperature (K)

$$T_f = (T_1 + T_2)/2 \tag{6}$$

Thermal expansion coefficient (K^{-1})

$$\beta = 1/T_f \tag{7}$$

Convective heat transfer coefficient (W/m^2K)

$$h = \frac{kNu}{D} \tag{8}$$

Rayleigh number

$$Ra = Gr\,\mathrm{Pr} \tag{9}$$

Nusselt number

$$Nu = \left[2 + \frac{0.859 Ra^{1/4}}{\left[1 + \left(0.469/\mathrm{Pr}\right)^{9/16}\right]^{4/9}} \right] \qquad (10)$$

Where:

h is the convective heat transfer coefficient $\left(W/m^2 K\right)$

D is the inside diameter of pipe (m)

k is the thermal conductivity (W/mK)

μ is the viscosity of the fluid (kg/ms)

C_P is the heat capacity of the fluid (J/kgK)

ρ is the density of crude oil $\left(kg/m^3\right)$

T_1 is the temperature of sea water (K)

T_2 is the temperature of wall of pipe (K)

(Bengtson,2010)

Table 3.1: Data and average properties used in the calculation

Properties	Value
Crude oil	
Flow rate F	$0.0184 m^3/s$
Specific-heat capacity C_p	$2400 J/kgK$
Thermal conductivity k	$0.15 W/mK$
Viscosity μ	$0.01 kg/ms$
Density ρ	$750 kg/m^3$
Pipeline	
Inside diameter $D = r_1$	$0.689m$
Outside diameter r_2	$0.711m$
Thickness of the pipe L	$0.0111m$
Thermal conductivity k	$20.0 W/mK$

(Bidmus, 2006)