

HEAT TRANSFER MODEL FOR THE PREDICTION OF BOTTOM HOLE CIRCULATING  
TEMPERATURE WHILE DRILLING

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บทคัดย่อและแฟ้มข้อมูลฉบับเต็มของวิทยานิพนธ์ตั้งแต่ปีการศึกษา 2554 ที่ให้บริการในคลังปัญญาจุฬาฯ (CUIR)  
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แบบจำลองการถ่ายเทความร้อนสำหรับการพยากรณ์อุณหภูมิหมุนเวียนกันหลุมขณะขุดเจาะ



วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต

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ลิขสิทธิ์ของจุฬาลงกรณ์มหาวิทยาลัย



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 BOTTOM HOLE CIRCULATING TEMPERATURE WHILE DRILLING) อ.ที่ปรึกษา  
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อุณหภูมิหมุนเวียนกันหลุม(BHCT) เป็นหนึ่งในตัวแปรสำคัญในการดำเนินการขุดเจาะ  
 โดยทั่วไป ความคาดเคลื่อนของการวัดค่าอุณหภูมิกันหลุมสามารถนำมาซึ่งความผิดพลาดรวมถึง  
 ปัญหาต่างๆมากมาย งานวิจัยนี้ได้ทำการศึกษาค้นคว้าการขุดเจาะหลุมน้ำมันนอกชายฝั่ง ซึ่งเป็นหลุมที่มี  
 ความลาดเอียงและอยู่ในสภาวะที่ก่อให้เกิดปัญหาเกี่ยวกับเครื่องมือในการปฏิบัติงาน โดยปัญหาที่พบมาก  
 คือการที่อุณหภูมิหมุนเวียนกันหลุมในขณะขุดเจาะมีค่าสูงเกินระดับความทนทานความร้อนของ  
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 อย่างมาก เพื่อที่จะหลีกเลี่ยงปัญหาดังกล่าวเราจึงต้องการเครื่องมือบางอย่างที่สามารถพยากรณ์  
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 สามารถหาได้จากการปฏิบัติงานจริง ผลของการเปรียบเทียบค่า BHCT ที่ได้มาจากการพยากรณ์จาก  
 แบบจำลอง และค่า BHCT ที่วัดมาได้จริงมีความใกล้เคียงกันอย่างมีนัยยะ นอกจากนี้ยังมีการปรับ  
 ค่า BHCT ให้มีความแม่นยำมากขึ้นด้วยตัวแปรปรับค่าอุณหภูมิหมุนเวียนกันหลุม โดยแบบจำลองนี้  
 สามารถทำงานร่วมกันในพื้นที่และสภาวะการปฏิบัติงานจริง จากการวิเคราะห์ผลกระทบของตัวแปร  
 ต่างๆในการขุดเจาะที่มีผลต่ออุณหภูมิหมุนเวียนกันหลุมพบว่าความลาดชันของความร้อนใน  
 พื้นผิวโลกส่งผลกระทบต่ออุณหภูมิหมุนเวียนกันหลุมขณะขุดเจาะ

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PATT SIRILAPWORACHAI: HEAT TRANSFER MODEL FOR THE PREDICTION OF BOTTOM HOLE CIRCULATING TEMPERATURE WHILE DRILLING. ADVISOR: ASST. PROF. JIRAWAT CHEWAROUNGROAJ, Ph.D., 153 pp.

In typical drilling operation, bottom hole circulating temperature (BHCT) is one of the key parameters that control the drilling process. Therefore, the lacking of the accurate downhole temperature data can lead to many possible difficulties or even failure when performing the drilling operation or related work. This paper discusses an offshore field with directional wells where the wells encountered harsh environment for downhole drilling components. Relatively high chances of temperature related MWD/LWD failures were also observed. Such a problem generally leads to the delay in operational and financial perspectives. In order to avoid the mentioned issue, we will need an effective tool to foresee the borehole temperature while drilling. In this study, the BHCT shall be mathematically solved from the heat transfer model associated with the field data. This tool is also expected to be compatible with the working environment and to be used specifically in the exact area of work. The results demonstrated similar alignment of BHCT prediction compared to the measured data. Moreover, BHCT adjusted factor were introduced to the prediction model in order to improve model accuracy. The sensitivity analysis results showed that the geothermal gradient significantly affects the predicted BHCT.

Department: Mining and Petroleum Engineering      Student's Signature .....

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## List of Abbreviations

BHCT	Bottom hole circulating temperature
BHST	Bottom hole static temperature
MWD	Measure while drilling
LWD	Logging while drilling
BHA	Bottom hole assembly
POH	Pull out of hole
RIH	Run in hole
TD	Target Depth
°C	Degree Celsius
K	Degree Kelvin
GG	Geothermal gradient
Nu	Nusselt number
Re	Renold number
Pr	Prandtl number
uHT	Ultra-high temperature
NAF	Non-aqueous fluid
WBM	Water based mud
OBM	Oil based mud
SDF	Special drilling fluid
PV	Plastic viscosity
YP	Yield point
LSRV	Low shear rate viscosity

MD	Measured depth
TVD	True vertical depth
DDR	Daily drilling report
DMR	Daily mud report
Lpm	Liter per minute
psi	Pounds per square inch
cP	Centipoise



## List of Nomenclatures

$E$	Energy
$\dot{E}$	Energy rate
$Q$	Heat
$\dot{Q}$	Heat rate
$\dot{Q}_{\text{conv}}$	Convective heat rate
$\dot{Q}_{\text{cond}}$	Conductive heat rate
$\dot{m}$	Mass rate
$T$	Temperature
$T_s$	Surface Temperature
$T_\infty$	Temperature of the fluid sufficiently far from the surface
$T_D$	Drill pipe fluid Temperature
$T_A$	Annular fluid temperature
$k$	thermal conductivity
$A$	Cross-sectional area
$h$	Convective heat transfer coefficient
$\tau$	Shear stress
$\tau_0$	Yield point
$\gamma$	Shear rates
$\mu$	Fluid viscosity
$\mu_e$	Effective viscosity
$\mu_p$	Plastic viscosity
$V$	Average fluid velocity



$V_D$	Drill pipe fluid velocity
$V_A$	Annular fluid velocity
$D$	Pipe diameter
$D_H$	Hole diameter
$D_P$	Outer diameter of the pipe
$R_{600}$	Viscometer reading at 600 rpm
$R_{300}$	Viscometer reading at 300 rpm
$R_{200}$	Viscometer reading at 200 rpm
$R_{100}$	Viscometer reading at 100 rpm
$R_6$	Viscometer reading at 6 rpm
$R_3$	Viscometer reading at 3 rpm
$K$	Consistency index
$n$	Dimensionless flow behavior index
$\omega$	Mud viscometer rotation speed
$SF$	Solids fraction parameter
$C_p$	Specific heat capacity
$L_c$	Characteristic length
$f$	Friction factor

# CHAPTER I

## INTRODUCTION

### 1.1 Background

Bottom hole circulating temperature (BHCT) is a very important parameter that we need to focus throughout the drilling process because an accurate BHCT will lead to successful operations designing and planning. Whereas, failure to predict an accurate BHCT could cause long delays in rig operations.

Current practice, when drilling is performed, the drillers usually attaches a tool called measure while drilling unit (MWD) and/or logging while drilling unit (LWD) with bottom hole assembly (BHA) to record important information, such as location data, BHCT, bottom hole pressure, etc. With these collected data, the drillers can evaluate the drilling situation and reach the target depth smoothly.

However, the BHCT of wells in the interested area generally exceeds the normal temperature tolerance of MWD/LWD electronics which is typically 302°F (150°C) [1]. In order to deal with this problem, higher temperature tools rated at 347°F (175°C) are required. Even with higher temperature resistance MWD/LWD, the evidence reveals that many wells drilling operations still face higher temperature than 175°C which leads to unplanned trip. In this situation, the operators have to pull the BHA out of the hole (POH), then make up another BHA without MWD/LWD and run it in the hole (RIH) again. At this point, without other supporting technologies, the drillers have to perform a blind run which the bit location or the well trajectory remains unknown until they reach the target depth.

The increasing BHCT in drilling operation may be caused by geothermal gradient, drilling fluid properties, adjustable drilling parameters and etc. This study is aimed specifically to predict the thermal behavior of the directional wells based on data from an offshore field. Heat transfer model will be established for each categorized major rig activity with various drilling parameters to predict BHCT for any given steps of the drilling operation but the speed of the model calculation will be

limited to make it feasible in real-time interpretation. The prediction method will be validated by checking against recent field data of temperature measured down hole during drilling. The sensitivity analysis shall be performed in order to overcome the better understanding about how drilling parameters affect the BHCTs.

## **1.2 Objective**

1.2.1 To establish wellbore heat transfer models to predict the bottom hole circulation temperature.

1.2.2 To investigate the sensitivity of bottom hole circulating temperature to choices of drilling parameters based on Thailand field data.

## **1.3 Outline of Methodology**

1.3.1 Analyze the field data

1.3.2 Construct the wellbore heat transfer model associated to available field data.

1.3.3 Simulate and record the BHCT in the drilling operation for each well.

1.3.4 All simulation results are compared with the recorded BHCT, and then BHCT adjustment factors are calculated.

1.3.5 The prediction model shall be validated by the other sets of available operational data.

1.3.6 Study the effect of the drilling parameters on BHCT via the wellbore heat transfer model.

## **1.4 Outline of Thesis**

This thesis is divided into six parts as mentioned below.

Chapter I introduces background, problem statement, objectives and methodology of this study.

Chapter II describes previous studies, researches related to BHCT prediction in various aspects and schemes.

Chapter III summarizes significant theories and concepts of heat transferring, transport and thermophysical properties of drilling fluids, and the estimation of heat transfer coefficients.

Chapter IV explains the drilling wellbore heat transfer model construction and application.

Chapter V discusses results obtained from BHCT prediction model. The error assessment, adjustment factor calculation and sensitivity study shall be performed in this chapter.

Chapter VI concludes findings from the study and provides several recommendations for further study.



## CHAPTER II

### LITERATURE REVIEW

This chapter presents some of the previous researches associated to the prediction of temperature distribution around wellbore.

#### 2.1 Wellbore Temperature Prediction Model

Farris [2] was the one who firstly endeavored to study of the static and stabilized circulating of five oil wells in the Gulf coast in 1941. He also develops the correlation chart of BHTs and the depth of five shallow wells. American Petroleum Institute (API) awarded the usage of the chart to determine the cement slurries' setting schedules, without detecting the inaccuracy, oversimplification as well as their restrictive application. However, these defects later on lead to the development of more precise mathematical model of circulation temperature determination.

In 1962, Edwardson et al. [3] conducted a heat transfer model for explanation of changes involving in the formation temperature occurred by the drilling fluid circulation before and after drilling. This model has a foundation of differential equation of heat conduction under radial coordinates. The results of the equation represented formation temperature impact at various recorded radii of arbitrary drilling fluid circulation in the graphical form, while temperature distribution inside the wellbore was neglected. Edwardson et al. summarized their studies by explaining that the formation temperature near the wellbore was strongly disturbed by drilling fluid circulation.

Raymond [4] well predicted the fluid temperature during drilling or cement circulation. Effective models were created to forecast the temperatures at both transient and pseudo-steady state conditions. Raymond expanded the application the use of principle of superposition to provide a numerical solution for unsteady conditions. He, however, satisfied that the pseudo-steady state condition provides sufficient accuracy for all purposes practically. Mentioned models allow the estimation

of the drilling fluid temperature as a function of position and time. These calculations also expressed that the circulation lowers significantly the temperatures of the bottom hole fluid as well as the rock itself, also that the maximum circulating fluid temperature occurs one-fourth to one-third of the way up to the annulus.

He additionally found that all of the temperatures in the circulating fluid system are changing with time and that a true steady state is never achieved. He, however, observed that the temperatures do not appreciably change after one or two drilling fluid circulations. It was then concluded that the temperature of the formation 3.0 meters from the wellbore is fundamentally undisturbed during the drilling process. This was explained from the time during the trips, where drilling fluid tends quite quickly towards the geothermal gradient and its temperature distribution as a function of depth is within 10% of the geothermal gradient after 16 hours of trip time (shut-in time).

In 1970, Holmes and Swift [5] built up a simple numerical model to predict logged bottom hole drilling fluid temperatures. This means was also used to provide initial temperature in predicting temperature buildup of drilling fluid column after stopping the circulation. The model assumes that the heat transfer between the annular fluid and the formation can be estimated by steady state linear heat transfer. Temperatures were computed as a function of well depth, drilling fluid circulation rate, circulating fluid characteristics, reservoir properties and drill pipe size. The model as a benefit of being simple and more accurate than previous methods, though the critical assumption of steady state heat flow only suited after unrealistically long circulation times.

Keller et al. (1973) [6] conducted a further research from Raymond's method and develop a model in explaining two-dimensional transient heat transfer in and around a wellbore. The model combined with the existence of various casing strings, also the effects of energy sources in the drilling system which may have been overlooked by the method of Raymond's as well as the drilling fluid flowing down a drill pipe and returning up the annulus have been well considered. The result from the analysis confirms that in order to give the good estimation of the circulating drilling

fluid, steady-state solutions should be used. Moreover, this transient solution is better compatible to the matching temperature logs. Keller et al. summarized that the viscous flow energy, rotational energy and drill bit energy have a main impact on the overall energy balance of the drilling system. These types of energy contributed to the drill pipe, the annulus and the drill bite were estimated respectively as 37.3kW, 72kW and 168kW.

Wooley [7] established the first transient computer model called GEOTEMP to foresee BHCTs with application to either the oil well drilling industry or the geothermal. The model was calculated to determine the transient BHCTs in: 1) the wellbore (under flowing or shut-in conditions), 2) the casing and cement regions and 3) the surrounding formation. Some of the drilling processes those had been neglected by the Raymond model were well considered by GEOTEMP. The features consist of the effects related to well depth change with time, discontinuity in the drilling fluid circulation, variation of the drilling fluid properties with depth and lastly, the complexity of the completion. Both of the physical and mathematical assumptions analyzed by this model were authorized with some additional solutions exactly generated from. With the application of this model, Wooley appraised the effect of inlet temperature and the flow rate of drilling fluid on the BHCTs. It was indicated that at lower flow rates of drilling fluid, the BHCT are strongly affected. He also showed that the transient response in the flowing stream is very critical for short period of time. For example, drilling and cementing operations or production and injection start-up.

Thompson and Burgess [8] also proposed a method to perform a down hole mud temperature prediction in an accurate yet rapid manner which was different from all previous methods used at that time in all likely operational conditions where the prediction was accommodated. Their models were set up from the concepts of heat conduction and heat convection, then a series of validation and approximation processes which were applied in order to obtain stable numerical solutions. Eventually, they were able to compile the temperature prediction program in a small computer. This program could show results of short term transient behavior during a long term drilling.

Arnold [9] pointed out that when a fluid is circulated in a wellbore, the transfer of heat from surrounding formations to the fluid can help to determine the temperature profile. He also developed a solution of the differential equations describing the heat transfer process. In this solution, it was assumed to have a steady flow of heat in the wellbore and a transient conduction of heat in the formation. The solution was verified by comparing the BHT measurements from the literature. He carried out the sensitivity study parametrically to evaluate the impact of operating conditions on bottom hole circulating temperatures. During the studies, the factors analyzed were the formation properties, the rate of circulation and the surface temperature of the fluid entering the drill pipe. He concluded his own studies by demonstrating that a steady state in the wellbore can be assumed quite apparent. BHTs and annular surface temperature under circulating condition can be observed to change very quickly during the first hours of circulation. Later on, the circulating temperatures continue to change at a decreasing rate. During the circulation period, it was also observed that the maximum temperature in the circulation fluid happens at a point above the bottom of a wellbore. More application of this model were founded and reported by Garcia et al. (1997) [10] who actually applied the theory of Arnold's solution to develop a new thermal simulator called TEMLOPI to be used for the estimation of the drilling fluid and formation temperatures during the drilling of geothermal wells. The data used in the validation, application and derivation came from the literature and from some wells drilled in the geothermal field around Loz Aufres Mexican.

Later in 1996, Kabir et al. [11] developed a mathematical model to determine circulating fluid temperature in drilling, workover and well-control operations. Similar to Holmes and Swift's model in 1970, it was assumed that steady-state heat transfer occurred in the wellbore while transient heat transfer occurred in the formation. The model solution both forward and reverse circulation for rapid implementation has been developed by applying simple algebraic equations and various formation temperature distribution functions, TD from other researchers. In the calculation, the second order differential equation was solved, and then the final solution was



obtained as the fluid temperature which is a function of depth, flow rate, fluid properties, formation properties and formation temperature distribution function. They also found that the maximum temperature occurs at some distance higher from the bottom for forward circulation. As well as Holmes and Swift (1970), the solution of Kabir et al. is on the assumption that heat generating by drilling bit is negligible.

In 1997, Santoyo et al. [12] investigated the unsteady state of Heat Transfer Process of Drilling and Completions Operation and continued to develop Computer Simulator "WELLTHER" using to predict transient temperature within and around the wellbore by integrating the result of Loss Circulation as well.

From the validation test, WELLTHER is able to have the profile of the transient temperature predicted quite precisely.

- (i) Flow rate is the crucial parameter for all flowing conditions. Low flowrate is considered to be ineffective when cooling the wellbore while the higher trend will be able to yield the greater and even greatest cooling results.
- (ii) Fluid inlet temperature is one of the important criteria in identifying the BHT for well with higher rates. The deeper of the wellbores, the reduction of the inlet temperature.
- (iii) Within some circulation conditions, the bottom hole temperature will be decreasing faster with light-weight fluids. This can be understood that in some point, the drilling fluid density affects the bottom hole temperatures.
- (iv) The viscosity of the drilling also is essential on the impact on temperature in bottom hole wellbore. Generally, the non-newtonian drilling fluids is supposed to be cooler than water (Newtonian fluid).
- (v) On the contrary, specific heat capacity of drilling fluid has only minor impacts on temperature of bottom hole wellbore. As the result, cool drilling fluid will not exchange energy as quickly as with formation.

- (vi) Drilling fluid thermal conductivity also has some impact on the bottom hole wellbore temperature. The profile of cooler fluid will be in alignment to fluid with low thermal conductivities. In addition to this, the formation thermal conductivity shows the behavior to be closed to the effect producing by the fluid thermal conductivity.
- (vii) Another factor that has a major effect on the bottom hole temperatures is the shape of the geothermal gradient or profile of static formation temperature. Higher initial gradients tend to warm the fluid on the direction downwards and then reducing the amount of cooling further down along the wellbore.

As the down hole temperature data become very important, numerical methods have been used in many circumstances. For example, Romero et al. (1998) [13] developed a temperature prediction solution for deepwater wells. Other than heat transfer in the wellbore, the heat transfer in the sea was taken into account for the model development.

Besides, Keith and John (2011) [1] applied temperature simulations to a case study in (based on) Haynesville for better understanding and managing BHCT behavior in horizontal high temperature wells. The simulated temperatures were compared and calibrated to actual down hole temperature measurements taken while drilling. Then, a series of simulations were conducted to investigate the sensitivity of bottom hole circulating temperature to choices of well design and drilling parameters.

## **2.2 Fluid Properties and Correlations to Estimate Convective Heat Transfer Coefficient**

Incropera and Dewitt (1990) [14] conducted the laboratory to confirm the relationship between a fluid and a solid surface for heat transfer. These measurements, whether they are natural or forced convection processes, can be correlated as these following groups.

- (i) The ratio of total to conductive heat transfer rate or “The Nusselt Number”

- (ii) The ratio of Inertia to viscous forces or “The Reynolds Number”
- (iii) The dimensionless Prandtl number is providing a measure of the relative effectiveness of momentum and transportation of energy by diffusing the velocity and thermal boundary layers accordingly.
- (iv) The Peclet number
- (v) The friction factor is a dimensionless pressure (f) is a pressure drop (dimensionless) for internal flow. It is a factor that depends on the flow regime that preponderates the flow system.

Incropera and Dewitt also studied the problem of the convection heat transfer in a circulate pipe for laminar flow. The study shows that the Nusselt number is a constant ( $Nu=4.36$ ) independent of the  $Re$ ,  $Pr$  and axial condition in a circular pipe, characterized of a uniform surface heat flux and laminar (fully-developed condition). This value is to be used to predict the drilling fluid convection coefficients in drill pipe under conditions of laminar flow ( $Re < 2000$ )

Herzhaft et al. [15] mentioned that, It is normal that temperature of around  $20^{\circ}C$  and the pressure up to 400Bars at the mud line can be found in the conditions of deep offshore. Drilling fluid in these wells will be stabilized at the temperature during  $0-150^{\circ}C$ . They had experimented in the lab as well as had tried the mathematical approach to know more about the drilling mud rheological properties, which changed over temperature and pressure. They also discovered the correlation between the rheological properties of the base oil and the mud properties. The viscosity of the drilling mud that has been reduced will not be depending on the temperature and thus expresses that the behavior of drilling mud and its base oil is the same as temperature. On the other hand, we will be able to determine the viscosity dependency on shear rate by the complex formulation.

Kerati et al. [16] mentioned about an extreme well condition in the Gulf Of Thailand, which has been classified as ultra-high temperature (uHT) and has BHST up to  $450^{\circ}F$  ( $230^{\circ}C$ ). The drilling mud required for this category should be stabled up to  $520^{\circ}F$  ( $270^{\circ}C$ ) for exploration wells

For the drilling well in the Gulf Of Thailand, similar condition will be the 6-1/8” hole for primary target, inclination, slimness as well as high acidic gas contamination – thus leading to the difficulties in operations. He and the team explained about the development and stability of drilling fluid which fit the operation in those wells by introducing new additives which provide a thermally stable non-aqueous fluid (NAF)

From the test in lab and field, it is discovered that novel NAF can be used successfully by reducing non-productive time and also has met the objective of exploration well more than the conventional type of NAF. The study shows that the drilling fluid has continue to be developing all the time and also has adjusted its characteristics to be compatible with area and working condition – as it will have same character in the same working area.



## CHAPTER III

### THEORY AND CONCEPT

The significant theories and concepts of heat transfer and thermos-physical properties of drilling fluids related to heat transfer model construction are described in this chapter.

#### 3.1 Energy Transfer and Heat Transfer

The conservation of energy principle or typically known as the first law of thermos-dynamics explains that energy can neither be created nor destroyed during a process but can change only forms. Hence, every bit of energy must be counted during every part of the process.

Following simplification presents the conservation of energy principle for any system undergoing in any processes, which is the net change in the total energy of the system during a process is equal to the difference between the total energy entering and the total energy leaving the system during the process.

$$\left( \begin{array}{c} \text{Total energy} \\ \text{entering} \\ \text{the system} \end{array} \right) - \left( \begin{array}{c} \text{Total energy} \\ \text{leaving} \\ \text{the system} \end{array} \right) = \left( \begin{array}{c} \text{Change in the} \\ \text{total energy} \\ \text{of the system} \end{array} \right) \quad \text{--- (3.1)}$$

In aspect of the energy which can be transferred to or even from the system by heat, work, and mass flow as well as the total energy of a simple compressible system consists of internal kinetic, and potential energies, energy balance equation for any system undergoing any process can be presented as:

$$E_{in} - E_{out} = \Delta E_{system} \quad \text{--- (3.2)}$$

The expression in terms of rate can also be generated as follow:

$$\dot{E}_{in} - \dot{E}_{out} = dE_{system}/dt \quad \text{--- (3.3)}$$

The reason why energy change of any system is zero ( $\Delta E_{system} = 0$ ) is because of the fact that it is a property and the value of any property does not change unless the state of the system is changed. If the state does not change during the process that means the process is steady.

The form of energy that has been interested in heat transfer analysis is only the one that can be transferred as a result of temperature difference or so called heat or thermal energy. In this perspective, it is quite convenient to write a heat balance as well as to treat the nuclear, chemical, mechanical and electrical energies conversion into thermal energy as heat generation. Heat balance in such cases can be defined as the equation below:

$$Q_{in} - Q_{out} + E_{gen} = \Delta E_{thermal,system} \quad \text{--- (3.4)}$$

or in the rate form as:

$$\dot{Q}_{in} - \dot{Q}_{out} + \dot{E}_{gen} = dE_{system}/dt \quad \text{--- (3.5)}$$

### 3.2 Heat Transfer Mechanisms

Typically, heat can be transferred and categorized in three different modes which are conduction, convection and radiation. All of these heat transfer modes need the presence of temperature difference and modes are sequenced from high-temperature medium to a lower-temperature one. This study emphasizes specifically on conduction and convection heat transfer which are the main mechanism for the drilling operation. Radiation heat transfer which results relatively small effect compare to other mechanisms shall be neglected.

### 3.2.1 Heat Conduction

Conduction is defined as the transfer of energy from more energetic particles of a substance to the adjacent less energetic ones as a result of interaction between the particles. They can occur in solids, liquids or even gases. Considering the steady heat conduction through a large plane wall of thickness  $\Delta x = L$  and area  $A$ , temperature difference across the wall is  $\Delta T = T_2 - T_1$ , whereas the rate of heat conduction can be expressed by:

$$\dot{Q}_{cond} = kA \frac{T_1 - T_2}{\Delta x} = -kA \frac{\Delta T}{\Delta x} \quad \text{--- (3.6)}$$

By having the constant of proportionality  $k$  is the thermal conductivity of the material which is a measurement of material to conduct heat's ability. In the limiting case of  $\Delta x \rightarrow 0$ , the equation above reduces to the differential form as:

$$\dot{Q}_{cond} = -kA \frac{dT}{dx} \quad \text{--- (3.7)}$$

Specific heat capacity ( $C_p$ ) is defined as a measure of a material's ability to store thermal energy since different materials store heat differently. Similarly, thermal conductivity value ( $k$ ) is a measurement of a material's ability to conduct heat.

Thermal conductivity of a material can be represented as the rate of heat transfer through a unit thickness of the material per unit area per unit temperature difference. As the thermal conductivity of a material changes with temperature, the temperature dependence of thermal conductivity causes considerable complexity in conduction analysis. Thus, it is commonly practiced to have the thermal conductivity ( $k$ ) evaluated at the average temperature and have it treated as a constant in calculations. A material is normally assumed to be isotropic in heat transfer analysis.

In this study, conduction heat transfer equations are applied to the model when drilling fluids stay in the borehole without any movement. Heat transfers from

adjacent formation raise drilling fluid temperature. The longer the fluids were left in the borehole the higher the fluids temperature.

### 3.2.2 Heat Convection

The mode of energy transfer between a solid surface and the adjacent liquid or gas that is in motion is called convection. It engages with the combined effects of conduction and fluid motion. The faster the fluid motion goes, the greater the convection of heat transfers. In the lack of any bulk fluid motion, heat transfer between a solid surface and the nearby fluid is by pure conduction.

Convection is called “forced convection” if the fluid is forced to flow over the surface by external means such as a fan, pump or the wind. In contrast, convection is called natural convection if the fluid is motion is caused by buoyancy forces that are induced by density differences due to the variation of temperature in the fluid. The rate of convection heat transfer is experienced to be proportional to the temperature difference, and conveniently expressed by Newton’s law of cooling as:

$$Q_{\text{conv}} = hA_s(T_s - T_{\infty}) \quad \text{--- (3.8)}$$

Where  $h$  is the convective heat transfer coefficient in  $\text{W/m}^2\cdot\text{K}$ ,  $A_s$  is the surface area through which convection heat transfer take place,  $T_s$  is the surface temperature, and  $T_{\infty}$  is the temperature of the fluid sufficiently far from the surface.

While circulating, drilling fluids flow with a certain flow rate, convection heat transfer occurs between drilling fluids and adjacent formation. Then heat transfer rate can be calculated from the Eq. 3.8.

### 3.3 Transport and Thermophysical Properties of Drilling Fluids

Heat transfer in a wellbore is strongly affected by the transport and thermophysical properties of drilling fluids. In general, the drilling fluid properties that



are involved in the heat transfer mechanisms of a drilling process are the dynamic viscosity, the density, the specific heat capacity and the thermal conductivity. The convection heat transfer is affected by dynamic viscosity while the density and the specific heat capacity control the heat accumulation. The thermal conductivity also affects the transfer of heat through the drilling fluid. Noting that, these properties of drilling fluids are temperature dependent, and other properties that yields just small effect, such as the thermal expansion coefficient, is always neglected [7].

### 3.3.1 Rheological Models of Drilling Fluids

The heat exchange between the wellbore and the formation is magnificently affected by the transport properties of the drilling fluids [12]. Thus, these properties can be described by the rheological models. In this study, the drilling fluid used in the drilling operation can be categorized into two main types, water based mud (WBM) and Special drilling fluid (SDF) which can be categorized as synthetic based fluid. The transport properties of WBM and OBM shall be justified by the following fluid models and correlations associated to their type.

- (i) Newtonian model
- (ii) Bingham plastic model
- (iii) Power law model
- (iv) Modified Power Law model

#### 3.3.1.1 Newtonian model

Newtonian is the simplest class of fluids. The base fluids, including fresh water, seawater and mineral oils, of the most drilling fluids are Newtonian. The WBMs in this study were prepared using seawater thermophysical properties [17]. So they will be classified as Newtonian fluids and they will be described by Newtonian fluid model. The equation that describes the rheological behavior of Newtonian fluids is given by viscosity law equation [18]:

$$\tau = \mu \gamma \quad \text{--- (3.9)}$$

where  $\tau$  is shear stress,  $\gamma$  is shear rates, and  $\mu$  is fluid viscosity.

When applying to drill pipe and annular flow, the shear rate in the unit of  $\text{sec}^{-1}$  at the wall of the cylindrical pipe and its annulus can be determined by the Eq. 3.10 and Eq. 3.11, respectively.

$$\gamma = 8V/D \quad \text{--- (3.10)}$$

$$\gamma = 12V/(D_H - D_P) \quad \text{--- (3.11)}$$

where  $V$  is average fluid velocity(ft./sec),  $D$  is pipe diameter(ft.),  $D_H$  is hole diameter(ft.) and  $D_P$  is OD of the pipe(ft.).

For Newtonian fluids the relationship between shear stress and shear rate could be described as shown in Figure 3.1

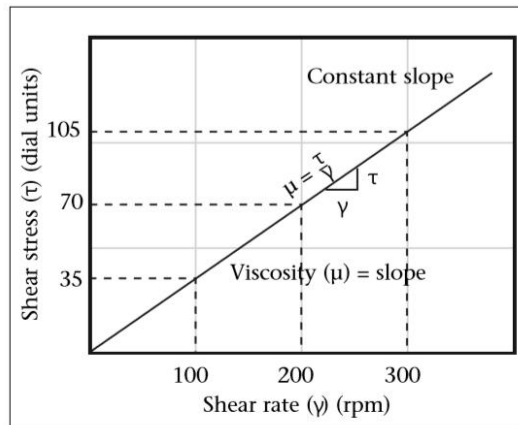


Figure 3.1 Newtonian Fluid's shear stress and shear relationship [18]

### 3.3.1.2 Bingham plastic model

This model describes a fluid that needs a finite force to start the flow. At higher shear rates it is quite fluid, but stops flowing when the shear is fallen below a value. This value is called yield point ( $\tau_0$ ). The behavior of Bingham Plastic fluids can be described as shown in Figure 3.2. The Bingham fluid behaves like Newtonian fluid at shear rate above yield point. So, the change in shear stress ( $\tau$ ) as a result from changing of shear rate ( $\dot{\gamma}$ ) shall be described by the Bingham model through the following general equation,

$$\tau = \tau_0 + \mu_p \dot{\gamma} \quad \text{--- (3.12)}$$

where  $\mu_p$  is plastic viscosity.

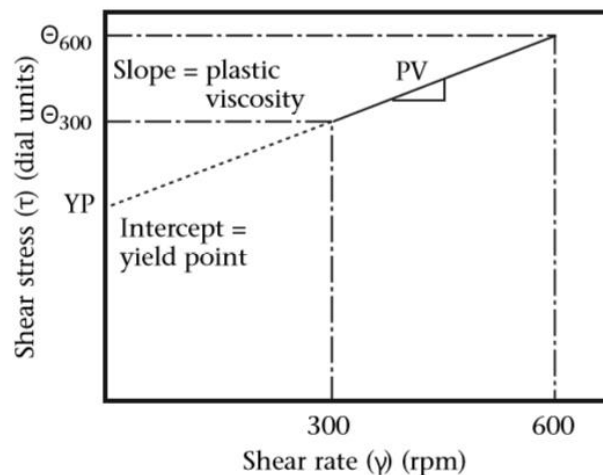


Figure 3.2 Bingham Plastic Fluid's shear stress and shear relationship [18]

Most drilling fluids are not true Bingham Plastic fluids. However, this model has become widely used in drilling fluid properties evaluation since the yield point ( $\tau_0$ ) and the plastic viscosity ( $\mu_p$ ) are probably two of the best known properties of drilling fluids [12]. Noting that the value  $\mu_p$  and  $\tau_0$  can be obtained from the following empirical formula,

$$\mu_p = R_{600} - R_{300} \quad \text{--- (3.13)}$$

and,

$$\tau_0 = R_{300} - \mu_p \quad \text{--- (3.14)}$$

where  $R_{600}$  and  $R_{300}$  are viscometer reading (R) at 600 rpm and 300 rpm respectively.

Unfortunately, for laminar flow in drill pipe, the effective viscosity ( $\mu_e$ ) of the drilling fluid shall be obtained by the following relationship:

$$\mu_e = \mu_p + \frac{\tau_0}{8(v/D)} \quad \text{--- (3.15)}$$

and, for laminar flow in annulus case:

$$\mu_e = \mu_p + \frac{\tau_0}{12v(D_o - D_i)} \quad \text{--- (3.16)}$$

where,  $v$  is fluid velocity,  $D_o$  is outer pipe's inner diameter, and  $D_i$  is inner pipe's outer diameter.

In the case of turbulent flow, the yield point ( $\tau_0$ ) of the drilling fluid can be neglected for both in the drill pipe and annulus section, then the effective viscosity ( $\mu_e$ ) is assumed to be equal to the plastic viscosity ( $\mu_p$ ). Even though, the Bingham model is simple and gained widespread acceptance in the industry, the model's accuracy is in concern at very low and very high shear rates as happening in annulus and the drilling bit, respectively.

### 3.3.1.3 Power law model

Unlike the Newtonian fluids, the shear stress of Power law fluids is not proportional to the shear rate, but it's  $n^{\text{th}}$  powered. The equation of the power flow model is expressed as:

$$\tau = K \cdot \gamma^n \quad \text{--- (3.17)}$$

where  $K$  = Consistency index, and  $n$  = Dimensionless flow behavior index.

For pseudoplastic fluids, the dimensionless flow behavior index ( $n$ ) will be less than or equal to 1. If it is equal to 1, then Eq. 3.17 becomes the equation of flow of a Newtonian fluid that has the viscosity value of  $K$ . Then, after applying logarithmic to the Eq. 3.17, this yields Eq. 3.18, which presents a straight line on log-log coordinate  $\tau$  vs  $\gamma$  plot.  $K$  and  $n$  represent the intercept and slope of the straight line, respectively. Figure 3.3 presents the relationship between shear rate and shear stress of Power Law fluid.

$$\log \tau = \log K + n \log \gamma \quad \text{--- (3.18)}$$

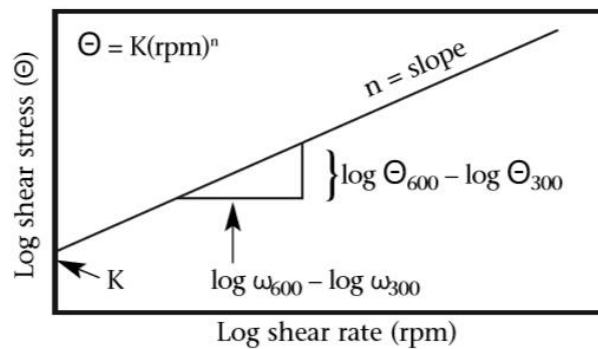


Figure 3.3 Power Law Fluid's shear stress and shear relationship in log-log scale [18]

Consequently, the effective viscosity ( $\mu_e$ ) of a Power law fluid flowing in the drill pipe shall be approximated by the following equation, regardless the flow regime:

$$\mu_e = K \left( \frac{8v}{D} \cdot \frac{3n+1}{4n} \right)^{n-1} \quad \text{--- (3.19)}$$

where, the effective viscosity of flowing in annulus can be approximated as:

$$\mu_e = K \left( \frac{8v}{D} \cdot \frac{3n+1}{4n} \right)^{n-1} \quad \text{--- (3.20)}$$

Lately, the Power law model has gained popularity in the industry because it provides a better rheological description of the drilling fluids than Bingham model[12]. On the other hand, there are several drawbacks, for example, it provides more information in the low shear rate condition than for high shear rate.

### 3.3.1.4 Modified Power law model

The Modified Power Law model can approximate more accurately the true rheological behavior of most drilling fluids. It has the advantages over Power Law Model, because it takes Low Shear Rate Viscosity (LSRV) and Yield Stress in account [18]. The comparison plot between models are shown in Figure 3.4 and Figure 3.5

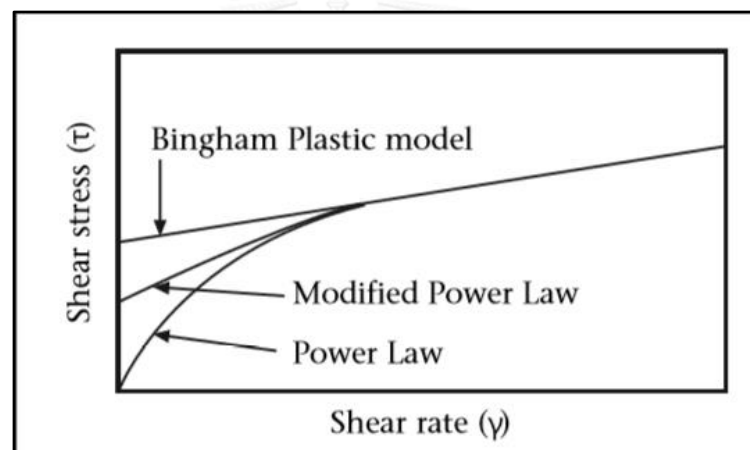


Figure 3.4 Shear rate VS Shear stress Rheological model comparison [18]

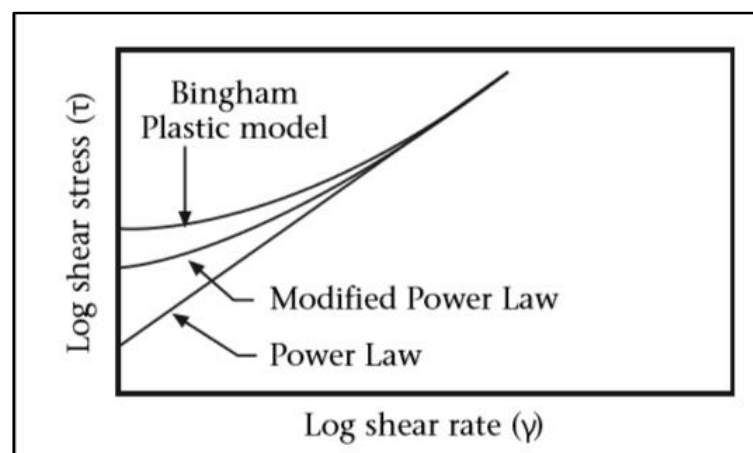


Figure 3.5 Shear rate VS Shear stress rheological model comparison in log-log scale [18]

The equation for Modified Power Law model is,

$$\tau = \tau_0 + K \cdot \gamma^n \quad \text{--- (3.21)}$$

where  $\tau$  is shear stress,

$\tau_0$  is yield point, or yield stress,

$K$  is consistency index,

$\gamma$  is shear rate, and

$n$  is Power Law index.

In practice, the yield point has been accepted to be the 3-RPM viscometer reading value. Other values of  $n$  and  $K$  shall be obtained from the empirical formulas in Eq. 3.22 and Eq. 3.23.

$$n = \log\left(\frac{R_2 - R_0}{R_1 - R_0}\right) / \log\left(\frac{\omega_2}{\omega_1}\right) \quad \text{--- (3.22)}$$

$$K = R_1 - R_0 / \omega_1^n \quad \text{--- (3.23)}$$

where  $R_0$  = 3-RPM reading or zero gel,

$R_1$  = Mud viscometer reading at lower shear rate,

$R_2$  = Mud viscometer reading at higher shear rate,

$\omega_1$  = Mud viscometer rotation speed (RPM) at lower shear rate, and

$\omega_2$  = Mud viscometer rotation speed (RPM) at higher shear rate.

### 3.3.2 Thermophysical Properties of Drilling Fluids

The thermophysical properties of the drilling fluids such as specific heat capacity and thermal conductivity play important part in wellbore heat transfer process. Heat capacity is a measurable physical quantity equal to the ratio of the heat added to (or from) an object to the resulting temperature change, while thermal conductivity could be described as the property of a material to conduct heat. So these two terms could indicate how good a material store or transfer heat.

Normally, these properties were assumed to be the same as of water. But, for the sake of accuracy, authors have proposed the importance of measuring these properties in order to evaluate their effect on the downhole temperature.

For example, Wooley [7] presented correlations for estimating the specific heat capacity ( $C_p$ ) and the thermal conduction ( $k$ ) of drilling fluids as a function of density and solids fraction parameter (SF). The solid fraction parameter (SF) is a term defined by empirical correlations in order to estimate specific heat capacity and heat conductivity of drilling fluids from a specific drilling mud density.

$$SF = 0.0798(\rho - 8.33) \quad \text{--- (3.24)}$$

for  $8.33 < \rho < 10.3$ , and

$$SF = 0.0318(\rho - 10.3) + 0.162 \quad \text{--- (3.25)}$$

for  $\rho > 10.3$

where,  $\rho$  = Fluid density in ppg.

Then,  $C_p$  and  $k$  shall be calculated from the following equations:

$$C_p = 1.0 - 0.777SF \quad \text{--- (3.26)}$$

and,

$$k = 0.399 + 9.60SF \quad \text{--- (3.27)}$$

Corre et al. [19] also proposed a set of general empirical equations which are able to estimate such thermophysical properties for water-based drilling fluids: KCl – polymer mixed with  $1100 \text{ kg/m}^3$  density as shown below:

$$C_p = 3440 + 2.72T \quad \text{--- (3.28)}$$



and,

$$k = 0.585 + 0.0023T \quad \text{--- (3.29)}$$

where T is drilling fluid temperature.

### 3.4 Estimation of Convective Heat Transfer Coefficients

Consider a circulating wellbore, the rate of heat transfer between surrounding formation and the annulus, and between the drill pipe and the annulus are caused by the convective effect of flowing drilling fluid. As can be seen in Eq. 3.8, the rate of convection heat transfer is significantly influenced by convective heat transfer coefficient ( $h$ ). The procedures to estimate the convective heat transfer coefficient is lying on numerical correlations based on dimensionless flow parameters which will be described below.

#### 3.4.1 Dimensionless Terms Related to Estimation of Convective Heat Transfer Coefficients

(i.) Nusselt number ( $Nu$ )

It is a common practice in convection studies to nondimensionalize the governing equations and combines the variables, which group together into dimensionless numbers in order to reduce the number of total variables. It is also a common practice to nondimensionalize the heat transfer coefficient  $h$  with the Nusselt number, which can be defined as:

$$Nu = \frac{hL_c}{k} \quad \text{--- (3.30)}$$

where  $L_c$  = Characteristic length.

Nusselt number is seen as the dimensionless convection heat transfer coefficient. Heat flux in either case can be describes as below equations:

$$\dot{q}_{conv} = h\Delta T \quad \text{--- (3.31)}$$

and,

$$\dot{q}_{cond} = k\Delta T/L \quad \text{--- (3.32)}$$

by having the above 2 equations taking ratio, we therefore get;

$$\frac{\dot{q}_{conv}}{\dot{q}_{cond}} = \frac{h\Delta T}{k\Delta T/L} = \frac{hL}{k} = Nu \quad \text{--- (3.33)}$$

The Nusselt number hence, represents the development of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer. The larger the Nusselt number gets, the more effective the convection can be. A Nusselt number of  $Nu = 1$  for a fluid layer shows heat transfer across the layer by pure conduction.

In case of laminar flow, flowing in circular tube yields the Nusselt number to be equal to 3.66. For a concentric annulus, the Nusselt numbers are represented as:

$$Nu_i = \frac{h_i D_h}{k} \quad \text{and} \quad Nu_o = \frac{h_o D_h}{k} \quad \text{--- (3.34)}$$

whereas hydraulic diameter can be defined as  $D_h = D_o - D_i$

(ii.) Reynolds number ( $Re$ )

Heat transfer rates are different among flow regimes. Heat transfer rate of a turbulent flow is normally higher than heat transfer rate laminar flow due to fluctuation of flow. Hence, Reynolds number is a very important value for heat transfer calculation since it classifies the flow regimes.

Flow regime majorly depends on the ratio of the inertia forces to viscous forces in the fluid. Such ratio is then called “Reynolds Number”, which is a dimensionless quantity, and is defined for internal circular tube flow as:

$$Re = \frac{\text{inertia force}}{\text{viscous force}} = \frac{v_{avg} D}{\nu} = \frac{\rho v_{avg} D}{\mu} \quad \text{--- (3.35)}$$

where  $v_{avg}$  = Average flow velocity,

$D$  = Diameter of the tube, and

$\nu$  = Kinematic viscosity of the fluid.

The flow in a tube is laminar for  $Re < 2,300$  and  $Re > 10,000$  for turbulent one and transitional flow in between.

(iii.) Prandtl number ( $Pr$ )

This dimensionless value provides a measure of the relative effectiveness of momentum and energy transport by diffusion in the velocity and thermal boundary layers, respectively. The Prandtl number can be obtained from the equation below:

$$Pr = \frac{\mu C_p}{k} \quad \text{--- (3.36)}$$

(iv.) Stanton number ( $St$ )

Stanton number was modified from the Nusselt number. Stanton number is shown as the following equation:

$$St = \frac{Nu}{Pe} \quad \text{--- (3.37)}$$

where  $Pe$  is Peclet number which is the product of  $Re$  multiply by  $Pr$ .

(v.) Friction factor ( $f$ )

Friction factor is a dimensionless pressure drop from internal flow. The value of friction factor depends on the flow regime that overcomes the flow system. The friction factor of a drill pipe laminar flow shall be obtained from the following equation:

$$f = \frac{64}{Re} \quad \text{--- (3.38)}$$

For the transition flow region, there are two approximations have been widely used to define friction factor:

$$f = \frac{64 + 0.007735(Re - 2000)}{2000} \quad \text{--- (3.39)}$$

for  $2000 < Re < 4000$ , and,

$$f = \frac{0.316}{Re^{0.25}} \quad \text{--- (3.40)}$$

For fully turbulent flow ( $Re > 4000$ ), the friction factor assumed to be equal to 0.013

### 3.4.2 Summary of the Forced Convection Correlations for Drill Pipe and Annulus Fluids under Wellbore Conditions

From Eq. 3.30, with known thermal conduction ( $k$ ) and characteristic length ( $L_c$ ), the convective heat transfer coefficient ( $h$ ) associated with a condition shall be solved explicitly from a value of Nusselt number. The forced convection correlations for the wellbore conditions are expressed in Table 3.1.

Table 3.1 Forced convection correlations for circulating wellbore conditions.

Correlations	Conditions	Note
(i) Circular pipe – Laminar flow		
$Nu = 4.36$	Constant heat flux	Incropera and DeWitt [14]
$Nu = 3.66$	Constant surface temperature	Incropera and DeWitt [14]
(ii) Circular pipe – Turbulent flow		
$Nu = \frac{(f/8)Re \cdot Pr}{1.07 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$	$0.5 < Pr < 2000$ $10^4 < Re < 5 \times 10^6$	Petukhov [20]
$Nu = \frac{(f/8)(Re - 1000) \cdot Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)}$	$0.5 < Pr < 2000$ $2300 < Re < 10^4$	Incropera and DeWitt [14]

Correlations	Conditions	Note
(iii) Circular pipe annulus– Laminar flow		
$Nu = 1.86 \left( \frac{Re \cdot Pr}{L/D} \right)^{1/3} \cdot \left( \frac{\mu}{\mu_s} \right)^{0.14}$	$T_s = \text{constant}$ $0.48 < Pr < 16700$ $0.0044 < \left( \frac{\mu}{\mu_s} \right) < 0.75$	Seider and Tate [21]
(iv) Circular pipe annulus– Turbulent flow		
$Nu_o = Nu_i = 0.027 Re^{4/5} \cdot Pr^{1/3} \cdot \left( \frac{\mu}{\mu_s} \right)^{0.14}$	$D_h = D_o - D_i$	Seider and Tate [21]

When being able to specify the appropriate dimensionless groupings, the next step is to obtain the numerical correlations to predict the Nusselt numbers in drilling wells. The selection process must be proceeded separately for drill pipe and geometry of annulus. The consideration of the flow regime and the convection processes that occur in these regions during well drilling activities will also need to be taken into account.

### 3.4.3 Double-Pipe Heat Exchanger and Overall Heat Transfer Coefficient

In case of double-pipe heat exchanger, one type of fluid flows through the pipe located inside the exchanger while other fluid flows in parallel through the annulus between two pipes. Flow types can be categorized to be two flow arrangements in a double-pipe heat exchanger which are parallel and counter flow.

When being circulated, heat transfers between drill pipe and annulus behaves the same way as counter-flow double-pipe heat exchanger which the fluids enter the heat exchanger at opposite ends and flow in the opposite directions. Illustration of double-pipe heat exchanger with counter-flow type is shown in Figure 3.6.

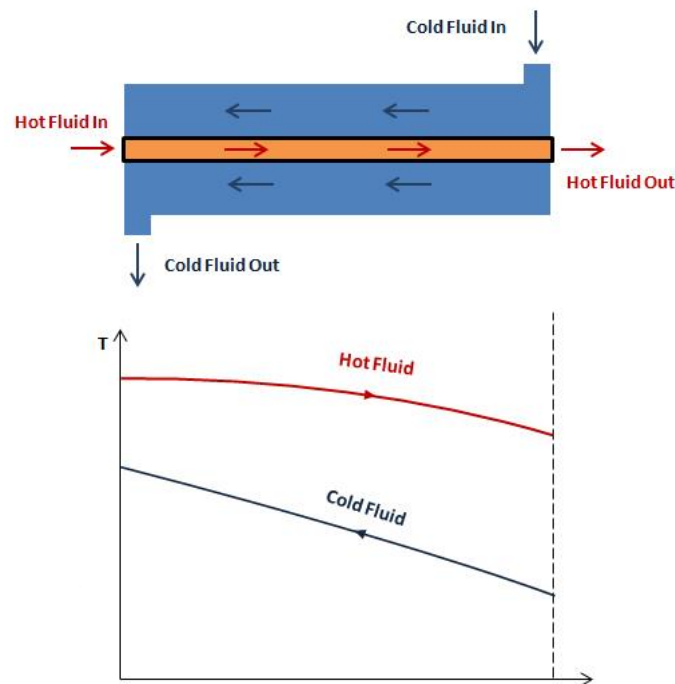


Figure 3.6 Counter-flow double-pipe heat exchanger's scheme.

When considering a double-pipe heat exchanger as two flowing fluids separated by a pipe wall, thermal resistance network in this heat transfer process consists of one conduction and two convection resistances. Heat is transferred from fluid to the pipe wall by convection, through the wall by conduction, then the pipe wall to fluid again by convection. The thermal resistance of the pipe wall is:

$$R_{wall} = \frac{\ln(D_o/D_i)}{2\pi kL} \quad \text{--- (3.41)}$$

where  $k$  is the thermal conductivity of the pipe wall,  $L$  is the length of the pipe,  $D_o$  and  $D_i$  are outer diameter and inner diameter of the inner tube, respectively. Then the overall thermal resistance becomes:

$$R_{total} = R_o + R_{wall} + R_i = \frac{1}{h_i A_i} + \frac{\ln(D_o/D_i)}{2\pi k L} + \frac{1}{h_o A_o} \quad \text{--- (3.42)}$$

where  $A_i = \pi D_i L$  and  $A_o = \pi D_o L$ .

In the analysis of heat exchangers, all thermal resistances along the heat transfer path are combined in to a single resistance  $R_{total}$  and the rate of heat transfer between the two fluids is expressed as:

$$\dot{Q} = \frac{\Delta T}{R_{total}} = U A_s \Delta T = U_i A_i \Delta T = U_o A_o \Delta T \quad \text{--- (3.43)}$$

where  $U$  is overall heat transfer coefficient, whose unit is  $W/m^2 \cdot K$ , which is identical to the unit of ordinary convection heat transfer coefficient,  $h$ . Then  $\Delta T$  is cancelled out.

$$\frac{1}{U A_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + R + \frac{1}{h_o A_o} \quad \text{--- (3.44)}$$

Note that  $U_i A_i = U_o A_o$ , since the heat transfer between the two fluid is equal, but  $U_i$  is not equal to  $U_o$  unless  $A_i = A_o$ . When the pipe wall thickness is small and the thermal conductivity of the pipe material is high, in this case, the thermal resistance of the pipe is negligible ( $R_{wall} \approx 0$ ) and  $A_i \approx A_o \approx A_s$ . Then the simplified overall heat transfer coefficient is:

$$\frac{1}{U} \approx \frac{1}{h_i} + \frac{1}{h_o} \quad \text{--- (3.45)}$$

where  $U_i \approx U_o \approx U$ .

These heat-transferred related theory and equations will be considered using in the model development section.

## CHAPTER IV

### WELLBORE HEAT TRANSFER MODEL

This chapter describes the wellbore heat transfer components and construction based on available field data, relevant theories and correlations. The main components of the well bore heat transfer model are hole geometry, geothermal gradient, well intervention, well components, drilling fluids and well operational records. Flow diagram, of methodology of this study is presented in Figure 4.1. All of the components will be assembled through numerical simulator in order to obtain the BHCTs while drilling. The data and equation evaluation process and the complete description of the model components will be presented in this section.

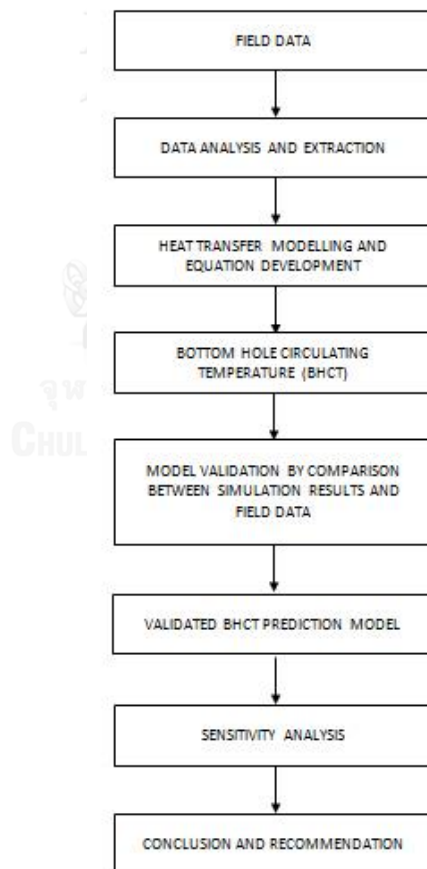


Figure 4.1 Flow diagram of methodology



#### 4.1 Model Assumptions

In order to develop the equations to explain the heat flow behavior of the well bore circulation system, certain assumptions and simplifications about the flow behavior, drilling fluid properties and heat transfer mechanisms need to be applied to the model. The assumptions of the model are as follows:

1.) Assumptions regarding fluid – heat characteristics:

1.1 Axial conduction of heat in the fluid is negligible compared with axial convection.

1.2 There are no radial temperature gradients in the fluid in either the drill pipe or the annulus.

1.3 The drilling fluid's inlet temperature shall be equal to the drill pipe fluid temperature at the top the hole.

1.4 The drilling fluid's return temperature shall be equal to annulus fluid temperature at the top the hole

2.) Assumptions regarding element in the wellbore system:

2.1 Drill pipe, casing and cement thickness are negligible.

2.2 The formation temperatures are constant in each depth.

2.3 Sea depth and air layer under the rotary table are not in consideration.

2.4 All the drilling fluid flows are fully developed steady-state flow.

3.) Assumptions regarding constant parameter:

3.1 The fluid's properties, such as heat capacity density and thermal conductivity, do not change significantly with temperature.

3.2 Heat generation by viscous dissipation in the fluid is negligible.

3.3 The velocities of drilling fluid shall be assumed to be uniform.

3.4 The other unknown information or environments are the same between wells.

3.5 Seawater thermophysical properties will be applied as drilling fluid thermophysical properties used in top section drilling. The thermophysical properties of sea water used in this study can be calculated by correlations summarized by Sharqawy et al. [17]. The sea water properties using in this study were calculated based on average seawater salinity in Gulf of Thailand which is 35,000 ppm salinity

#### 4.2 Well Flow Schematic

During a fluid circulation, one fluid enters the drill pipe with an inlet temperature,  $T_{D0}$ . As the fluid flows down the drill pipe, the fluid temperature is obtained by the rate of heat convection down the drill pipe, the rate of heat exchange between the fluid in the annulus and the drill pipe, and the rate of heat accumulation in that circulation period. At the bottom hole, the fluid left the drill pipe and then enters the annulus with the same temperature, that is  $T_D(L, t) = T_A(L, t)$ . Then the fluid flows up the annulus, the fluid temperature is determined by the rate of convection up the annulus, the rate of heat exchange across the drill pipe, and the rate of heat exchange between the surrounding formation and the annular fluid. The simple scheme of a circulation process is shown in Figure 4.2.

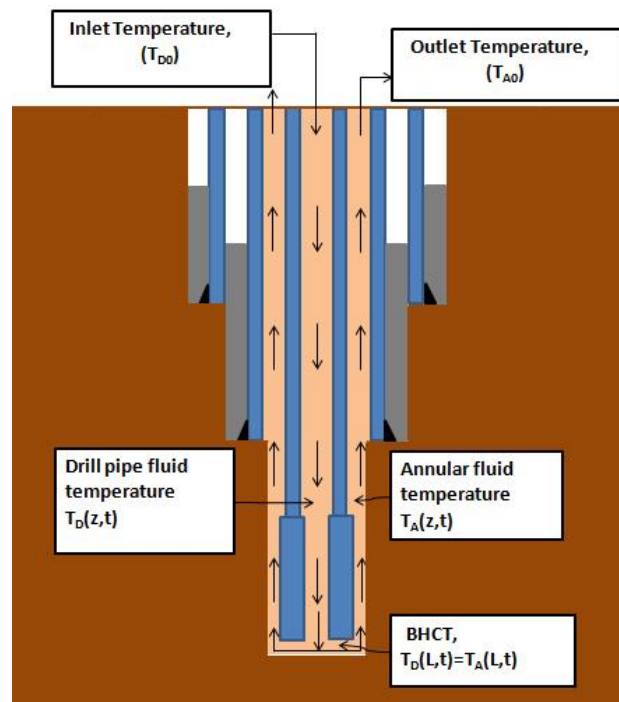


Figure 4.2 Drilling fluid temperature and flow schematic

In order to analyze the heat flow while circulating, the schematic of heat balance for a volume consists of a wellbore cross-section with a small thickness,  $dz$ , was set up as shown in Figure 4.3, where  $\dot{Q}_a$  is the heat transfer rate along the annulus at the depth  $z$ ,  $\dot{Q}_d$  is the heat transfer rate along the drill pipe,  $\dot{Q}_F$  is the transfer rate between annulus and the formation and  $\dot{Q}_{ap}$  is the heat transfer rate across the drill pipe.

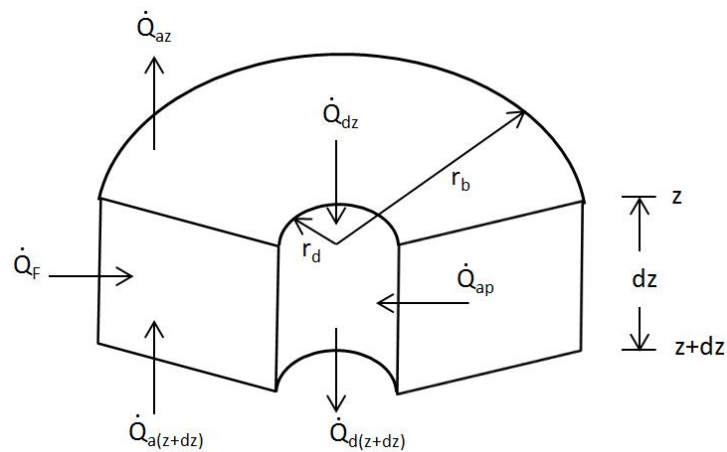


Figure 4.3 Schematic of heat balance between drill pipe, annulus and the formation

### 4.3 Field Data Evaluation

Information obtained from the field is essential to this study. It needs the application which can work by using the limited factual information in order to get the simulation result that has the closet reflection to reality. We, therefore, have to analyze the field information in choosing and framing the data to be in alignment with numerical simulation as below.

#### 4.3.1 Available Field Data

The field data were obtained from 9 wells on the same drilling platform in Gulf of Thailand. In order to confirm the model assumption as the wells were drilled closely, not only the information in this section shows the similar procedure as well as parameter, but also the field data obtained can be generated in these following outlines.

##### (i) Daily drilling report (DDR)

DDR is a summary report of drilling operation in a day. It contains important information as the list below:

- Drill bit usage information
- The interval depth
- ROP
- Drilling duration
- Drill string assembly
- Time log activity
- Survey data
- Drilling Fluid type, composition, testing results, and stocks

- Well status
- Accidents report and safety drill
- Planned Operation
- Supply boats and personnel
- Weather conditions

The DDRs are used to match up and try-in the data from other sources. The activity records are also help for better understanding about drilling operations, and rig time spending. Before the simulation input, it's better to check whether the input data match the data in DDR or not.

(ii) ASCii drilling parameter record along depth (ASCii)

While drilling, some important parameters were recorded with increasing depth. In this case, the drilling parameters were recorded every 0.5 m. (MD) penetration. The recorded parameters are including:

- MD and TVD
- Hook load
- Rate of penetration
- Rotation speed and torque
- Pump pressure
- Flow rate
- Mud weight
- Mud temperature in and out
- Bit time
- CO<sub>2</sub> and H<sub>2</sub>S concentration

The data in ASCII will be evaluated and input into the numerical simulation as important operation information.

(iii) Daily mud report (DMR)

The drilling fluid properties and compositions will be recorded into DMR in daily basis. The DMR usually contains:

- Date and location
- Drilling fluid type
- Active pit and depth
- Mud weight
- Mud sample testing results: Funnel viscosity, plastic viscosity, yield point, low shear yield point, gel strength, ES and solid proportion.
- Chemical additive and stock

The data contained in DMR play an important part for the fluid data input in the numerical simulation.

(iv) MWD-recorded BHCT

The BHCT was recorded real time for almost every stand in drilling operation using MWD tools attached at the end of drill strings. From the field data, temperature sensors were placed 10 – 22 m. away from the bottom hole.

(v) MWD survey data

MWD tools also record the location of the BHA throughout the drilling process (if attached). These tools deliver high-efficiency and enable possibility to the directional drilling now a day. The data reflect the picture of the well that allows us

to know how much the actual well path deviate from the planned well path, and also how to reach the target depth effectively. The MWD survey data is including:

- Measure depth (MD)
- True vertical depth (TVD)
- Length of each connecting point of measurement
- True vertical depth – Subsea (TVss or TVDss)
- UTM coordinates
- Dogleg Severity

The well paths in the numerical simulation were generated from MWD survey data.

#### (vi) Pressure and temperature prediction

The predicted pressure and predicted temperature are also available. The temperature gradient will be applied as formation temperature in the numerical simulation. However, noting that, they are approximated value, not the recorded value.

#### (vii) BHA specification

BHA specification sheets are consist of the BHA component data, including:

- The type of components
- OD, ID, weight, connection and length of each component
- Drill bit specification

The specification provides the information about the flow area and restriction neat bottom hole, and the location of the temperature sensor.

### 4.3.2 Data Analysis and Application

#### 4.3.2.1 Temperature Limitation of Downhole Tools

Observed from DDR, The temperature limitations of MWD were clearly seen in 5 wells before target depths were reached. These caused pull out of hole (POH) which are very unfavorable in the drilling operation, especially in the deep section. The wells operation details presented in Table 4.1 shows that, the POH occurred almost 50% of drilling wells.

Table 4.1 Observed POH in daily drilling report

Well	RPT#	Period	Interval	BHCT	Note	POH&RIH(hr.)
G	8	00:00-08:45	3453-3690.9mMD	173°C	Pump pressure drop and wash out - POH then RIH w/o MWD	17
H	9	08:45-23:15	3193.9-3654.5mMD	173°C	POH - MWD Temp. limitation	21.75
J	N/A	N/A	N/A	N/A	No trace of temp. limitation	-
K	6	00:00-12:00	3416-3662.7mMD	171°C	Low ROP - POH then RIH w/o MWD	19
L	7	00:00-04:00	3443-3378.1mMD	175°C	POH - MWD Temp. limitation	14.5
M	7	00:00-07:30	3453-3654mMD	173°C	POH - MWD Temp. limitation	59.75
P	6	00:00-00:00	3123.5-3683mMD	166°C	blind run, after 166oC	-
Q	10	00:00-09:30	4189-4404.3mMD	173°C	POH - MWD Temp. limitation	19.25
R	6	00:00-20:00	3221-3873mMD	175°C	POH - MWD Temp. limitation	14.75

The POH caused the temperature built up in the wells because heat from surrounding formation continually transfers into the wellbore risen the total heat in the system. This effect caused the drilling fluid temperature of overall system significantly increased as can be seen as BHCT difference between before and after the POH.

#### 4.3.2.2 Drilling Section Analogy

This study has included the factor of drilling condition into the model. From the raw data, we brought the drilling information and summarized it in Table 4.2 below. It can be seen that the drilling characteristics and trend of the hole temperature are similar. In addition, drilling operations can be classified in two groups which are the one that has one stop of main drilling and another one which has more than one stop. The classification greatly helps in getting the data set in the model simulation. For the information that hasn't been used in calculation, they will be used in evaluating the model accuracy.



Table 4.2 Drilling Operation Characteristics

SLOT Code		first drill		second drill		third drill		slope section (°C/m)		
		start	stop	start	stop	start	stop	first	second	third
G	m.TVD	441	1415	1415	2917	-	-	0.022587	0.056591	-
	BHCT(°C)	31	53	86	171	-	-			
H	m.TVD	414	1587	1587	2377	2377	2897	0.029	0.035	0.052
	BHCT(°C)	31	65	98	126	141	168			
J	m.TVD	415	1639	1639	2614	-	-	0.026144	0.065641	-
	BHCT(°C)	31	63	106	170	-	-			
K	m.TVD	414	1527	1527	2954	-	-	0.023	0.054	-
	BHCT(°C)	31	57	92	169	-	-			
L	m.TVD	427	1401	1401	2020	2020	3166	0.016	0.040	0.051
	BHCT(°C)	31	47	77	102	114	173			
M	m.TVD	432	1417	1417	2873	-	-	0.022335	0.059753	-
	BHCT(°C)	31	53	86	173	-	-			
P	m.TVD	408	1741	1741	2790	-	-	0.022506	0.053384	-
	BHCT(°C)	31	61	110	166	-	-			
Q	m.TVD	406	1606	1606	2200	2200	2746	0.037	0.030	0.059
	BHCT(°C)	31	75	108	126	141	173			
R	m.TVD	413	1563	1563	2899	-	-	0.026087	0.060629	-
	BHCT(°C)	31	61	94	175	-	-			

Figure 4.4 to Figure 4.9 shows that the wells in the area have the similar drilling characteristic. Thus, we apply the same simulation model for these wells

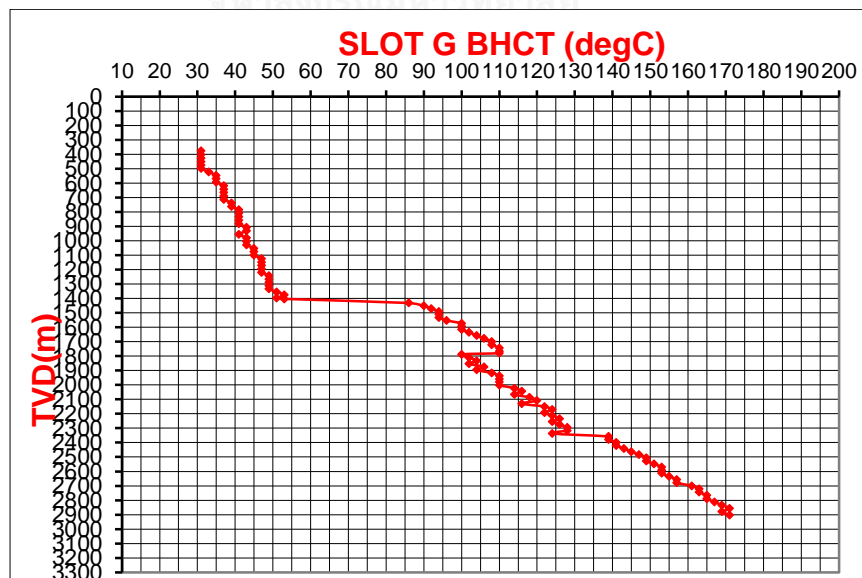


Figure 4.4 MWD-Measured BHCT of Slot G

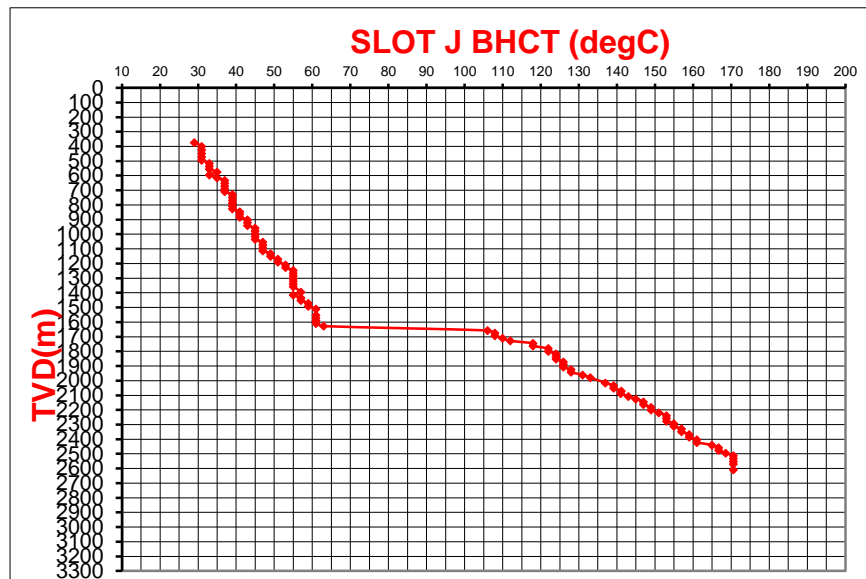


Figure 4.5 MWD-Measured BHCT of Slot J

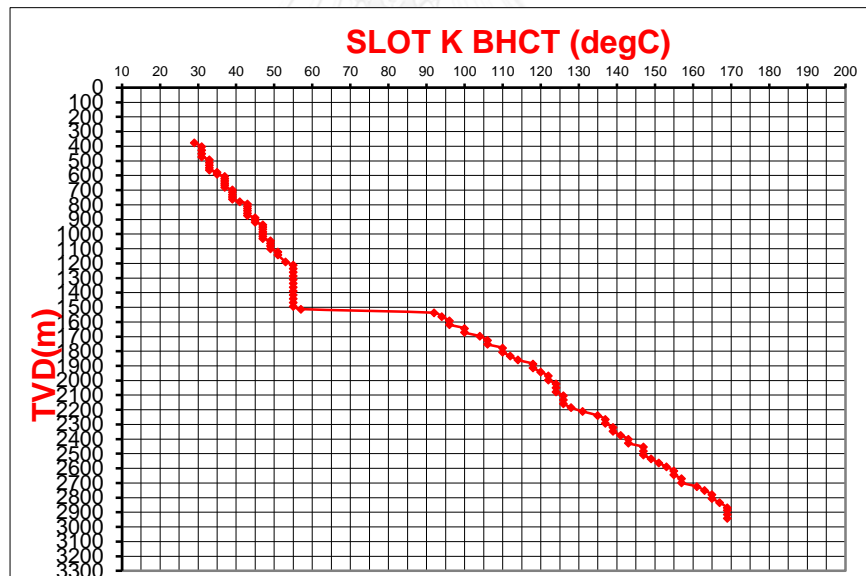


Figure 4.6 MWD-Measured BHCT of Slot K

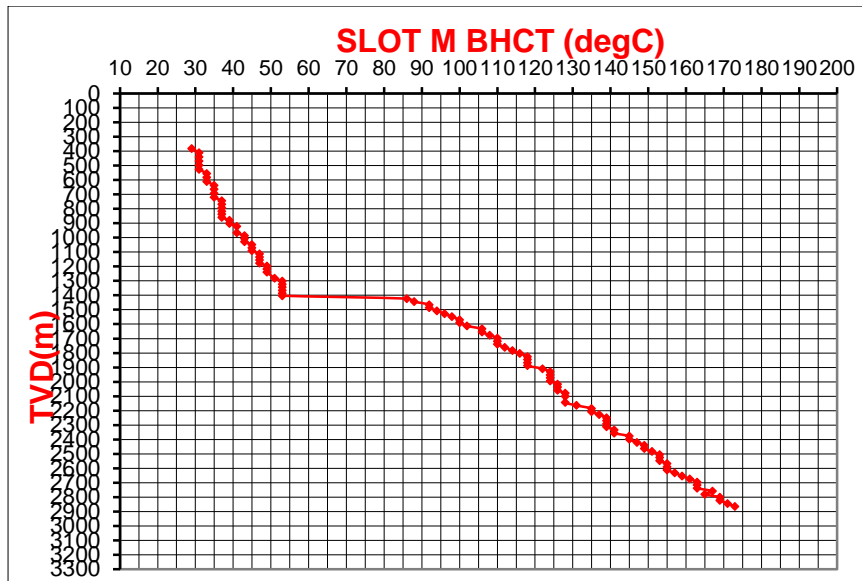


Figure 4.7 MWD-Measured BHCT of Slot M

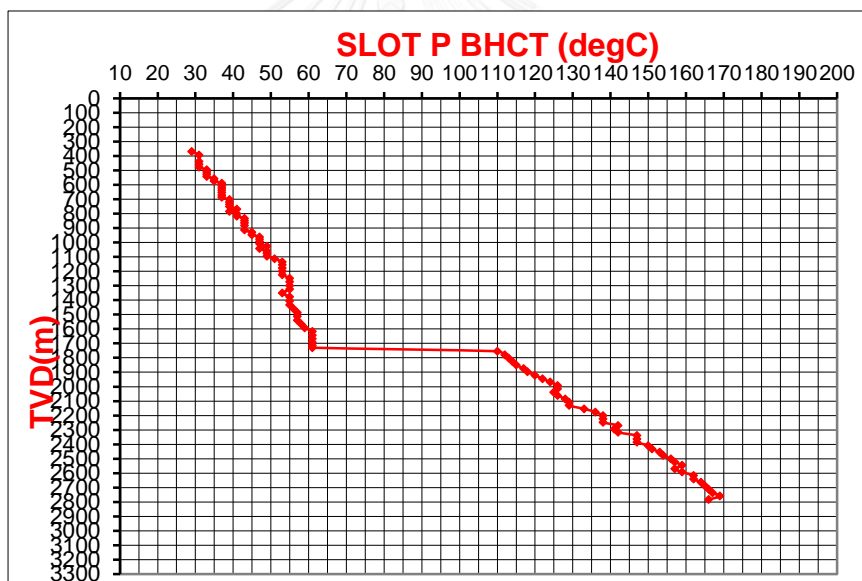


Figure 4.8 MWD-Measured BHCT of Slot P

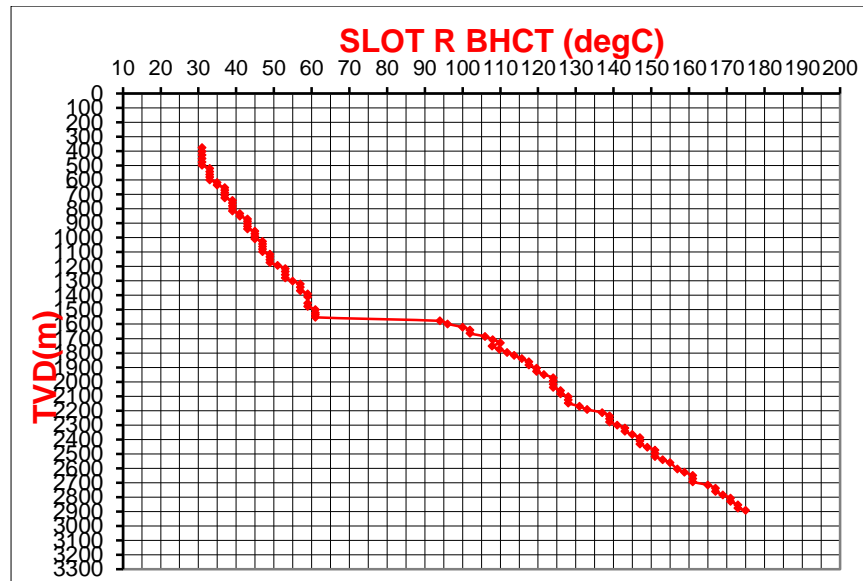


Figure 4.9 MWD-Measured BHCT of Slot R

From the drilling information, we see that the drilling operation can be categorized to Top and Bottom section, as there are significant differences in each of the drilling parameters along with other physical characteristics of each phase.

Top section of the drilled well has a size of 8-1/2", drilled with seawater and has quite high flowrate (>2000 lpm), while the bottom section of the drilled well has a size of 6-1/8", drilled with SDF and has lower flow rate than the top section ( $\approx$ 1000 lpm).

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#### 4.3.3 Data Input Summary

The input data extracted from raw data were transformed their unit into model unit for the purpose of calculation. The input data with their unit and sources are summarized in Table 4.3.

Table 4.3 Data unit and their dimensions

Parameters	Input unit	Model unit	Unit dimension	Source(s)
Fluid density ( $\rho$ )	SG.	kg/m <sup>3</sup>	$\frac{[M]}{[L^3]}$	ASCii, DMR
Cross sectional area (A)	in <sup>2</sup>	m <sup>2</sup>	$[L^2]$	DDR, BHA
Flow rate ( $q$ )	LPM	m <sup>3</sup> /hr.	$\frac{[L^3]}{[t]}$	ASCii
Inlet Temperature ( $T_{in}$ )	°C	°C	$[T]$	ASCii
Outlet Temperature ( $T_{out}$ )	°C	°C	$[T]$	ASCii
BHCT	°C	°C	$[T]$	MWD-BHCT
Duration (t)	hr.	hr.	$[t]$	ASCii
Depth (z)	m.	m.	$[L]$	MWD-Survey
Radius (r)	in.	in.	$[L]$	DDR
Geothermal gradient (GG)	°C/100m	°C/100m	$\frac{[T]}{[L]}$	Drilling program
ROP	m./hr.	m./hr.	$\frac{[L]}{[t]}$	ASCii
Yield Point (YP)	lb/100ft <sup>2</sup>	lb/100ft <sup>2</sup>	$\frac{[M]}{[L^2]}$	DMR,DDR
Plastic viscosity (PV)	Centipoise	Centipoise	$\frac{[M]}{[L][t]}$	DMR,DDR

Parameters	Input unit	Model unit	Unit dimension	Source(s)
Low shear yield point (LSYP)	lb/100ft <sup>2</sup>	lb/100ft <sup>2</sup>	$\frac{[M]}{[L^2]}$	DMR,DDR
Effective viscosity ( $\mu_e$ )	Centipoise	Centipoise	$\frac{[M]}{[L][t]}$	DMR,DDR

#### 4.4 Numerical Heat Transfer Model Development for a Circulating Wellbore

##### 4.4.1 Wellbore Heat Transfer Equations Development

Since the recorded BHCT data from MWD were measured at down hole in the annulus, the prediction model will focus mainly on the annular temperature. The final outcome of the model will be the annular temperature at the end of each interval for the purpose of the temperatures comparison and model validation. Noting that, the heat transfer equations for drill pipe fluid can be developed in the same manner as of the annulus, but in the opposite direction due to the opposite in the direction of flowing fluid. The heat transfer equation to predict annular fluid temperature shall be developed as shown in this section.

The heat balance in a general control volume shall be expressed as:

$$\left( \begin{array}{l} \text{Rate of heat} \\ \text{transfer into} \\ \text{the system} \end{array} \right) - \left( \begin{array}{l} \text{Rate of heat} \\ \text{transfer out of} \\ \text{the system} \end{array} \right) + \left( \begin{array}{l} \text{Rate of heat} \\ \text{generation} \end{array} \right) = \left( \begin{array}{l} \text{Rate of heat} \\ \text{accumulation} \end{array} \right) \quad \text{--- (4.1)}$$

For a given depth in a circulating borehole system, by the absence of work done by other operation rather than fluid circulation in the wellbore, the rate of heat generation term shall be cancelled out.

$$\left( \begin{array}{c} \text{Rate of heat} \\ \text{transfer into} \\ \text{the system} \end{array} \right) - \left( \begin{array}{c} \text{Rate of heat} \\ \text{transfer out of} \\ \text{the system} \end{array} \right) = \left( \begin{array}{c} \text{Rate of heat} \\ \text{accumulation} \end{array} \right) \quad \text{--- (4.2)}$$

A fluid flows through an annulus shall be assumed to be one-dimensional. The properties can be assumed to change only in the direction of flow. So, all properties are approximated to be uniform at any cross section, and the properties are assumed to have bulk average volumes over the entire cross section. Under the approximated one-directional flow, the mass flow rate flowing in the pipe as well as in the wellbore can be expressed as:

$$\dot{m} = \rho v A_c \quad \text{--- (4.3)}$$

where  $\dot{m}$  is mass rate,  $\rho$  is fluid density with the average velocity  $v$  in the flow direction, and  $A_c$  is the cross-sectional area of the annulus.

For a steady-flow system, the rate of mass flow into the control volume must be equal to the rate of outlet mass flow. That is  $\dot{m}_{\text{in}} = \dot{m}_{\text{out}} = \dot{m}$ . When the changes in kinetic and potential energies are negligible, which is usually the case, and there is no work interaction, the energy balance for such steady-flow systems reduce to:

$$\dot{Q} = \dot{m} C_p \Delta T \quad \text{--- (4.4)}$$

From Figure 4.3, consider the heat that transfer in the annulus, since the fluid flows up the annulus, the rate of heat transfer changes up the annulus shall be expressed as:

$$\begin{aligned} \dot{Q}_A &= \dot{m} C_p (T_{A(z+dz)} - T_{A(z-dz)}) \\ &= \rho A_A v_A C_p (T_{A(z+dz)} - T_{A(z-dz)}) \end{aligned} \quad \text{--- (4.5)}$$

where,  $v_A$  is the flow velocity of annular fluid.

Besides, there is also the heat that transfers across drill pipe as a result of the temperature different between the flowing drill pipe and annular fluid. The heat exchange across the drill pipe can be compared to the function of double-pipe heat exchanger. The rate of the heat that transfers from the flowing fluid in the annulus to the flowing fluid in the drill pipe can be approximated by the following equation:

$$\begin{aligned}\dot{Q}_{AD} &= AU(T_A - T_D) \\ &= 2\pi r_D \Delta z U (T_A - T_D)\end{aligned}\quad \text{--- (4.6)}$$

where,  $U$  is the overall heat transfer coefficient of a countered flow between the annular fluid with the temperature of  $T_A$  to the drill pipe fluid with the temperature of  $T_D$ .

There's also heat that transfers from the surrounding formation to the wellbore. In this study, the formation's temperatures can be calculated using the expected geothermal gradient from the field survey. Then, the rate of heat transfer from the surrounding formation to the flowing annular shall be calculated from the convection heat transfer equation as:

$$\begin{aligned}\dot{Q}_F &= Ah_f(T_F - T_A) \\ &= 2\pi r_B \Delta z h_f (T_F - T_A)\end{aligned}\quad \text{--- (4.7)}$$

The last term in the heat balance equation which is the rate of heat accumulation for a control volume is expressed as:

$$\begin{aligned}\dot{Q} &= \frac{mC_p \Delta T}{\Delta t} \\ &= \rho A \Delta z C_p \frac{\Delta T}{\Delta t}\end{aligned}\quad \text{--- (4.8)}$$

Unfortunately, according to Eq. 4.2, heat transfer of a control volume in the circulating annulus can be written as:

$$\rho A_A v_A C_p \Delta T_A + 2\pi r_D \Delta z U \Delta T_{DA} + 2\pi r_B \Delta z h_f \Delta T_{AF} = \rho A_A \Delta z C_p \frac{\Delta T_A}{\Delta t}\quad \text{--- (4.9)}$$



where,  $\Delta T_A$  is the temperature difference in the annulus,

$\Delta T_{DA}$  is the temperature difference across the drill pipe, and

$\Delta T_{AF}$  is the temperature difference between the surrounding formation and the annulus fluid

Rearrange the equation, then:

$$\rho A_A v_A C_p \frac{\Delta T_A}{\Delta Z} + 2\pi r_D U \Delta T + 2\pi r_B h_f \Delta T_{AF} = \rho A_A C_p \frac{\Delta T_A}{\Delta t} \quad \text{--- (4.10)}$$

and the differential form can be expressed as:

$$\rho A_A v_A C_p \frac{\partial T_A}{\partial Z} + 2\pi r_D U (T_D - T_A) + 2\pi r_B h_f (T_F - T_A) = \rho A_A C_p \frac{\partial T_A}{\partial t} \quad \text{--- (4.11)}$$

Using the same process of heat transferring in the annulus equation derivation, the heat transfer equation for the drill pipe will be obtained as shown below. Noting that the effect of formation temperature will be cancelled out this time.

$$\rho A_D v_D C_p \frac{\partial T_D}{\partial Z} + 2\pi r_D U (T_A - T_D) = \rho A_D C_p \frac{\partial T_D}{\partial t} \quad \text{--- (4.12)}$$

The Eq. 4.11 and Eq. 4.12 is going to be used to calculate the wellbore fluid temperature for a given circulating condition. In the next section, the numerical method to solve the down hole temperature will be introduced.

#### 4.4.2 Numerical Procedure and Simulation Output

In order to solve for the BHCT during circulations, the wellbore will be divided into small thickness of  $dz$  along the depth. The heat balance equation (Eq. 4.11 and Eq. 4.12) associated to each depth will be applied, and then the temperature for all depths will be calculated mathematically at the same time.

The heat transfer in a circulating system from the last section can be visualized as shown in Figure 4.10. Thus, the heat balance equations associated to any given depth,  $i$ , and duration,  $t$ , shall be discretized as shown in Eq. 4.14 and Eq. 4.15.

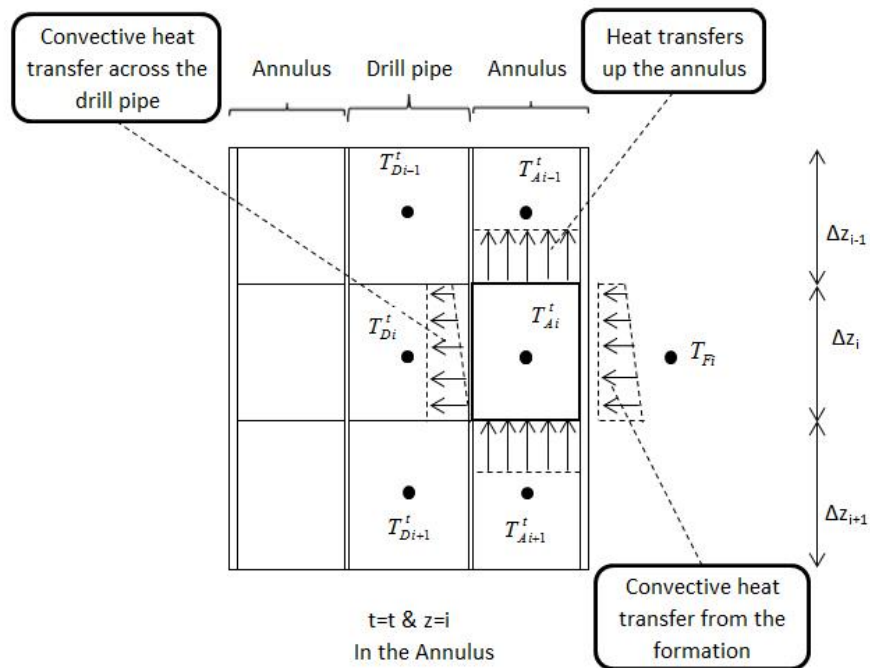


Figure 4.10 Heat transfer of an annulus at the depth  $z = i$  and at time  $t$

From Eq. 4.11, at  $z = i$ , considering an annulus, the heat balance equation can be expressed as:

$$\rho C_p \bar{A}_{Ai} \bar{v}_{Ai} \frac{(T_{Ai+1}^t - T_{Ai-1}^t)}{\Delta z_i} + 2\pi \bar{r}_{Di} \bar{U}_i (T_{Di}^t - T_{Ai}^t) + 2\pi \bar{r}_{Bi} \bar{h}_{fi} (T_{Fi} - T_{Ai}^t) = \rho A_{Ai} C_p \frac{(T_{Ai}^{t+1} - T_{Ai}^t)}{\Delta t} \quad \text{--- (4.13)}$$

Rearrange the equation:

$$T_{Ai}^{t+1} = T_{Ai}^t + \frac{\bar{v}_{Ai}\Delta t}{\Delta z_i} (T_{Ai+1}^t - T_{Ai-1}^t) + \frac{2\pi\bar{r}_{Di}\bar{U}_i\Delta t}{\rho A_{Ai}C_p} (T_{Di}^t - T_{Ai}^t) + \frac{2\pi\bar{r}_{Bi}\bar{h}_{fi}\Delta t}{\rho A_{Ai}C_p} (T_{Fi} - T_{Ai}^t) \quad \text{--- (4.14)}$$

The same process will be applied to the equation of the drill pipe. Then the solution to solve the drill pipe will be obtained as shown below.

$$T_{Di}^{t+1} = T_{Di}^t + \frac{\bar{v}_{Di}\Delta t}{\Delta z_i} (T_{Di-1}^t - T_{Di+1}^t) + \frac{2\pi\bar{r}_{Di}\bar{U}_i\Delta t}{\rho A_{Di}C_p} (T_{Ai}^t - T_{Di}^t) \quad \text{--- (4.15)}$$

The equations of heat transfer in the drill pipe and annulus (Eq. 4.14 and 4.15) will be applied to each wellbore grid block along well depth and each time step. Subsequently, fluid temperature of a circulating system shall be explicitly solved. The simulated BHCT of each interval will be presented as the fluid temperature of the last grid block of annulus.

#### 4.4.3 BHCT Simulator Components

After studying the data set and being able to develop the equations that can help predicting BHCT from available data, this section will cover the working steps as well as the simulator component. This mentioned simulator is comprised of 5 modules which separately work but have continuous sequences, which are Well Path Generator Module, Well Detail Module, Initialization Module, Fluid Properties module and Explicit Operation Module.

This simulator is written by VBA program on Microsoft Excel version 2013, which can be opened and compiled in Excel format for the user's convenience, edit or even further developed. It also responded the real-time interface, since the data is limited in the input process and the system has the short drilling interval calculation, we therefore are able to save some time in processing the input data and simulation compiling.

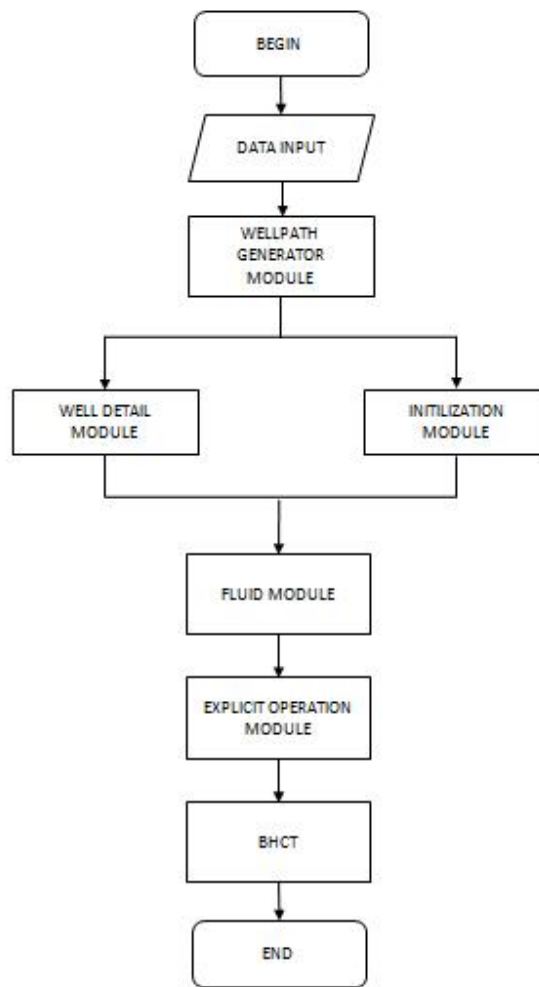


Figure 4.11 BHCT simulator flow diagram

(i) Well path generator module

Firstly, the Well Path Generator Module will create the well path from MWD survey data that we have input before separating the well to be equal-sizing grid block based on its measured depth (MD).

Later on, the system will put the formation temperature ( $T_f$ ) which associated with True Vertical depth (TVD) in each block so that other modules can utilize the information. Flow diagram of well path generator module is shown in Figure 4.12 and Figure 4.13.

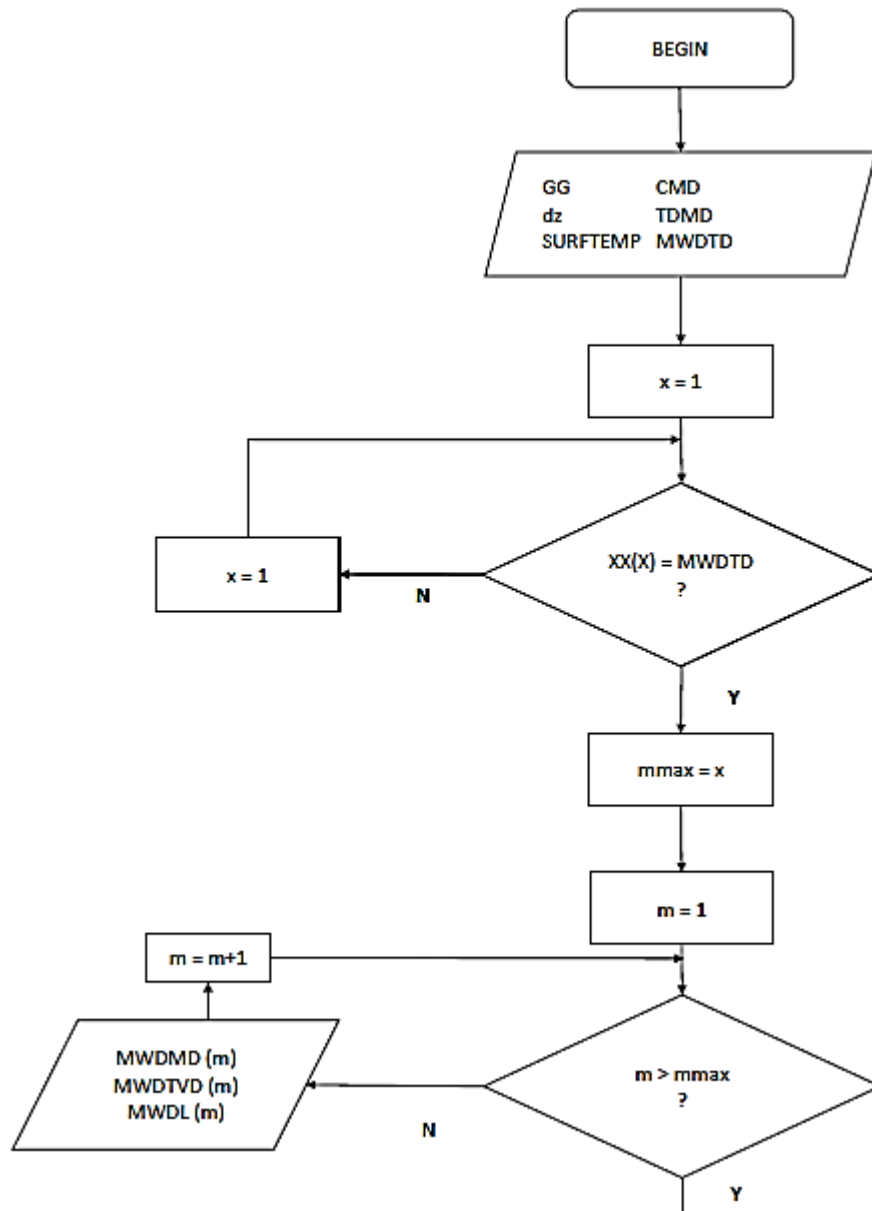


Figure 4.12 Flow diagram of Well path generator module (1/2)

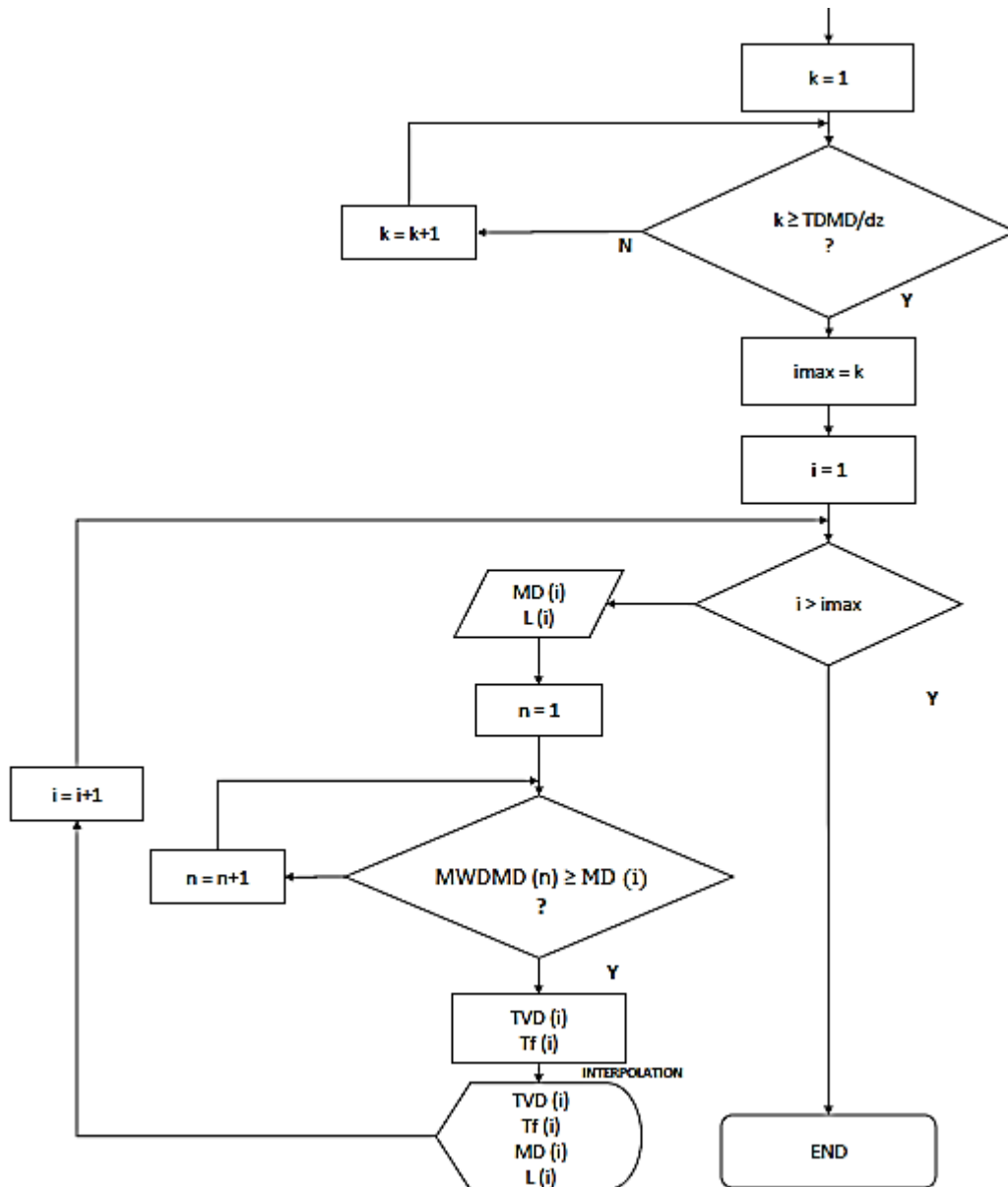


Figure 4.13 Flow diagram of Well path generator module (2/2)

(ii) Well details module

Well detail module is the section which identifies the size and location of the components in well bore. The program stores the depth of each grid block calculated in well path generator, which later on calculating the detailed specification of drill pipe, casing as well as BHA in each of the block. The data which obtains from the

module is the important part in determining the flow restriction and flow regime of fluid circulation during the drilling operation.

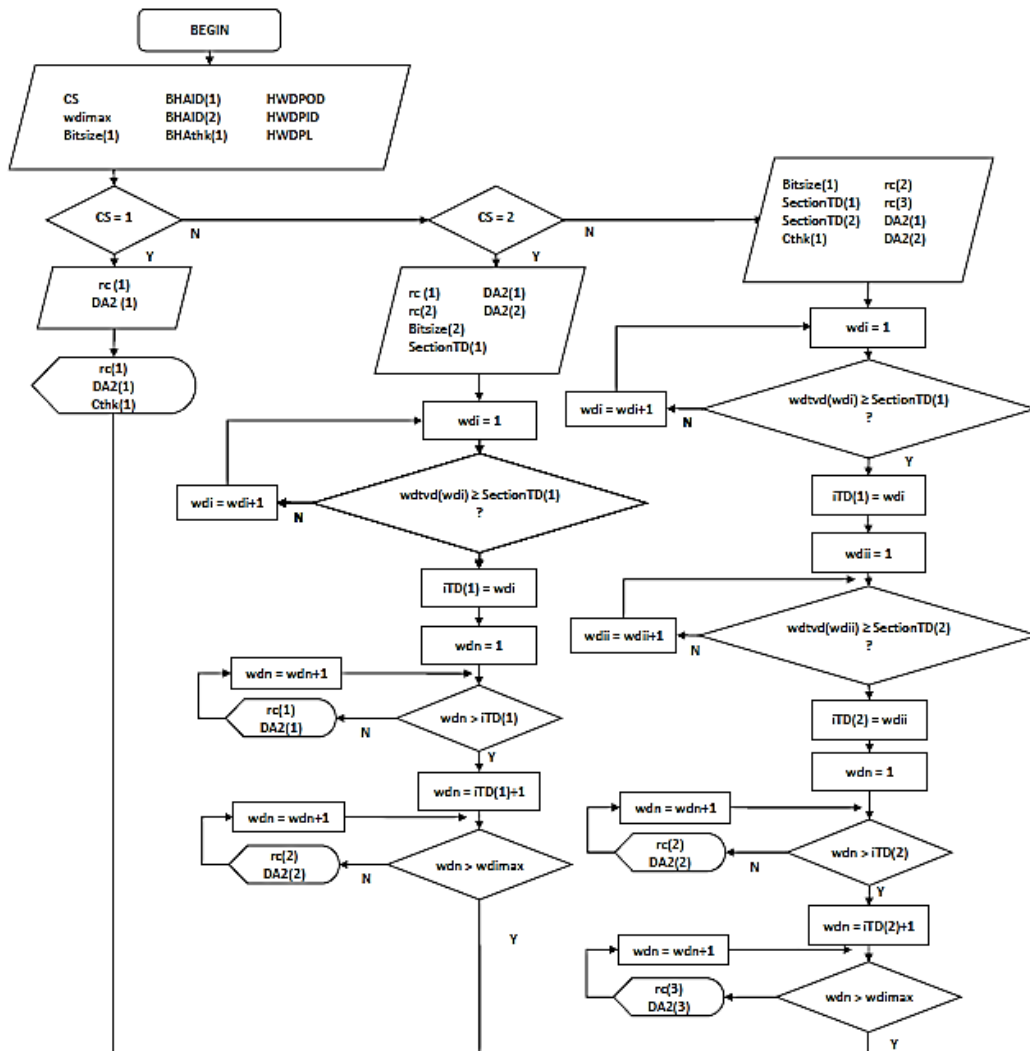


Figure 4.14 Flow diagram of Well detail module (1/2)

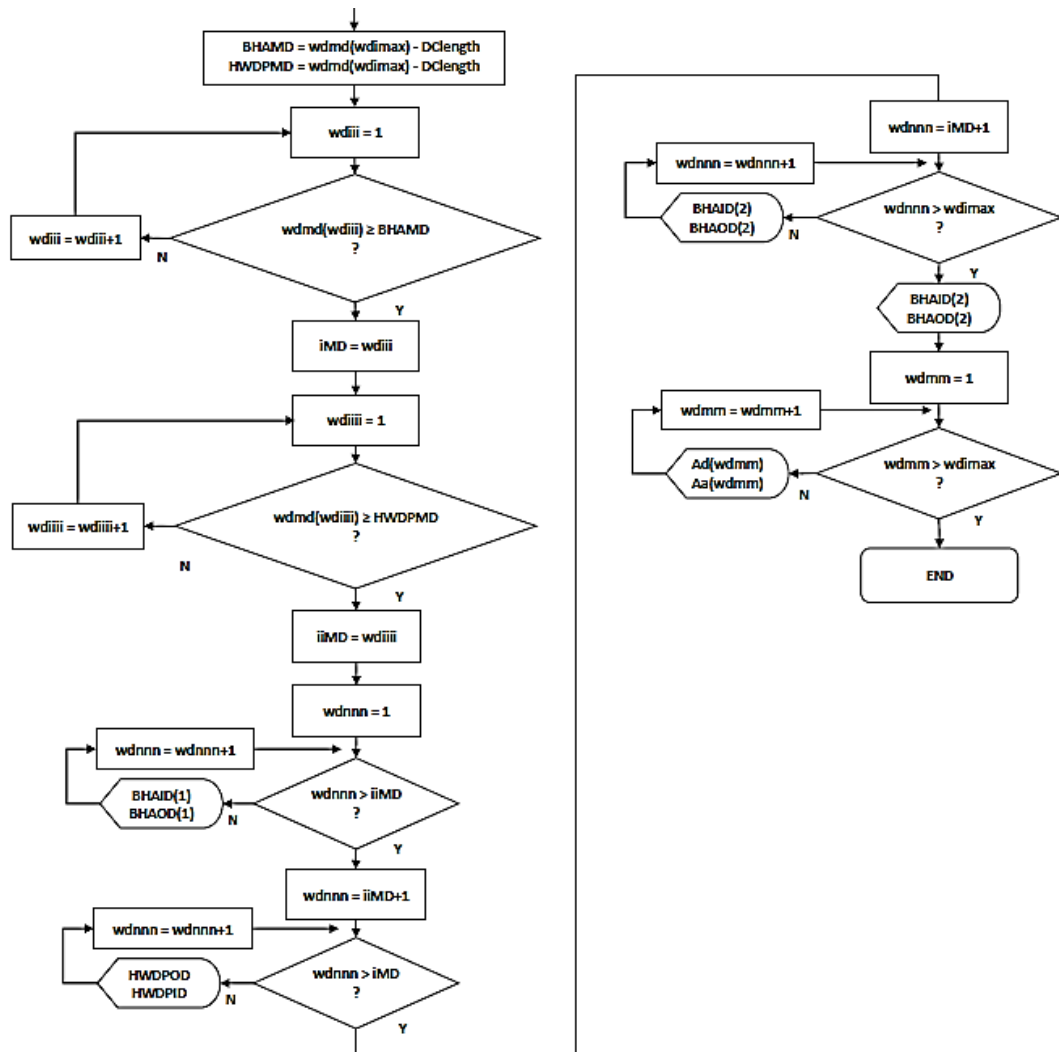


Figure 4.15 Flow diagram of Well detail module (2/2)

(iii) Initialization module

Initialization Module is the part which works as temperature profile collector of the previous interval and helps to generate Initial Fluid temperature of drill pipe ( $T_D^0$ ) as well as annulus ( $T_A^0$ ) of each well. Flow diagram of Initialization can be shown in Figure 4.16.



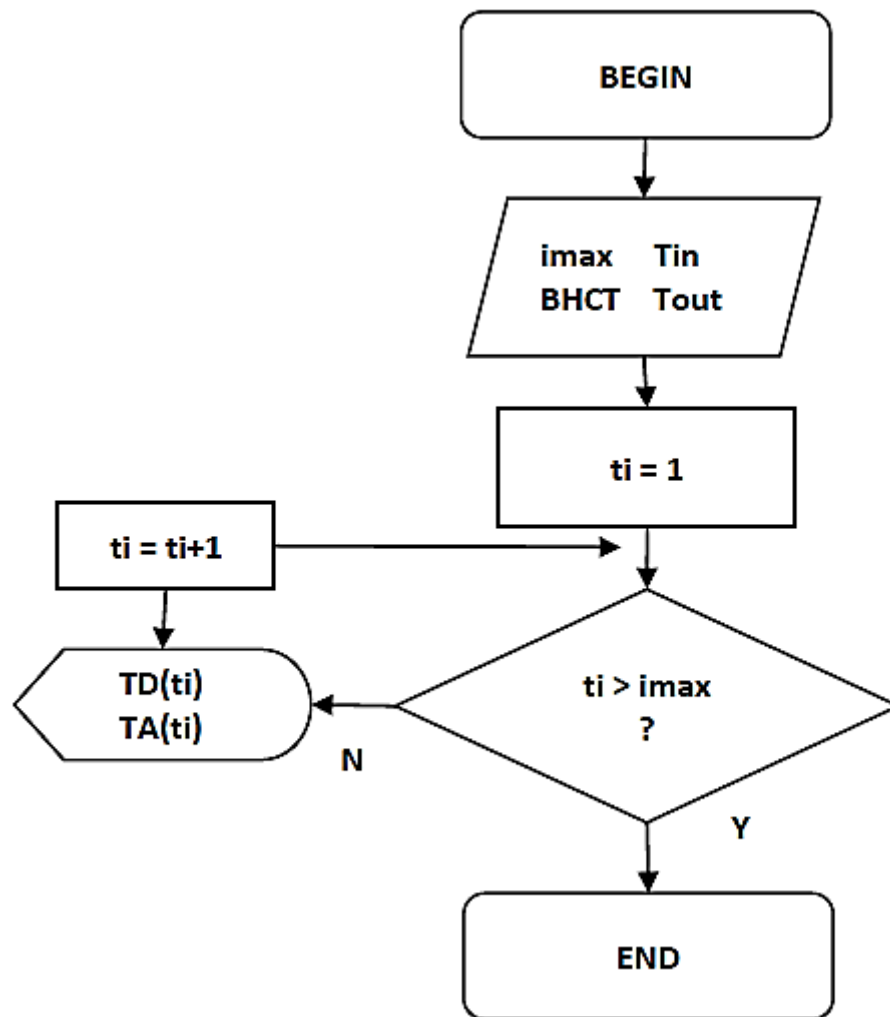


Figure 4.16 Flow diagram of Initialization module

(iv) Fluid properties module

Fluid properties module plays the main role in finding the Convective Heat Transfer Coefficient (CHTC), in which varies by Flow regime and flow geometry of the flow. Data of cross sectional flow area calculating from the well detail module can be interpreted that the depth of each area will be different by the various flow restrictions. This thus makes the CHTC in each depth and flow region vary. The information used as the section input are mud weight and mud's rheological properties. Flow diagram of Fluid Properties Module is displayed in Figure 4.17 and Figure 4.18.

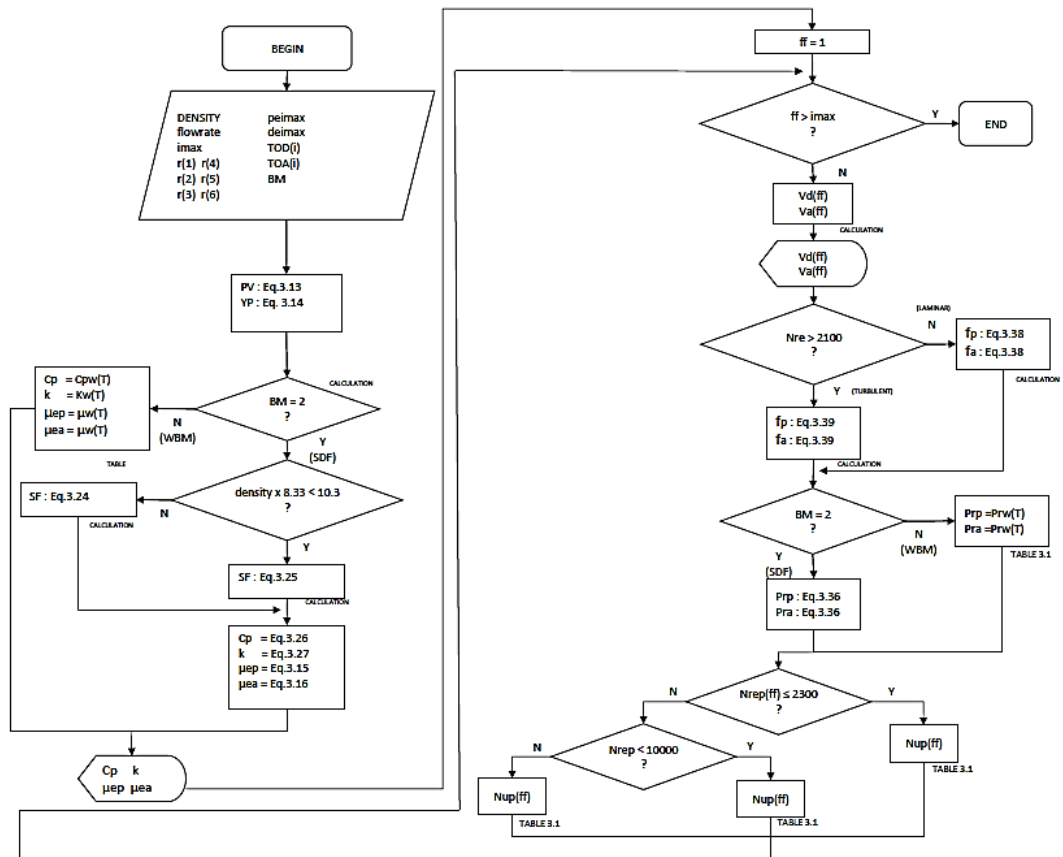
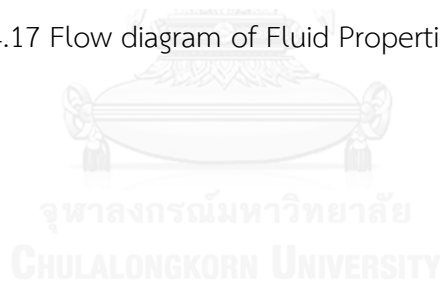


Figure 4.17 Flow diagram of Fluid Properties module (1/2)



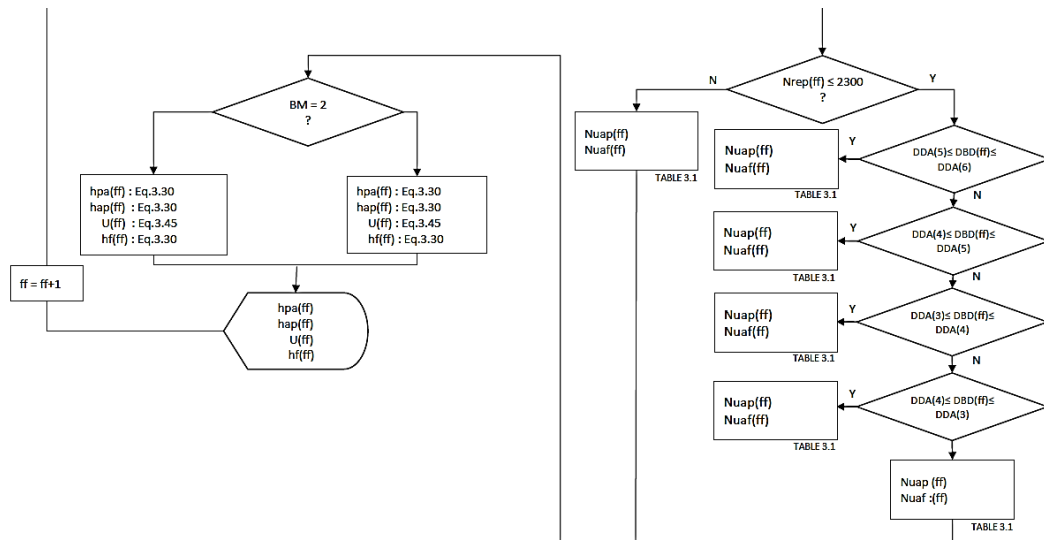


Figure 4.18 Flow diagram of Fluid Properties module (2/2)

(v) Explicit operation module

Explicit operation module is the main calculation part of this simulator. The mentioned module will bring the value of each calculated parameters from the prior modules, recalculate them to be the drilling fluid temperature for every grid block in drill pipe and annulus – by having the fluid temperature continuously align horizontally in each time step. When finishing each time step, each value will be stored as the calculation based for the next other time steps. Flow diagram of Explicit Operation Module is shown in Figure 4.19.

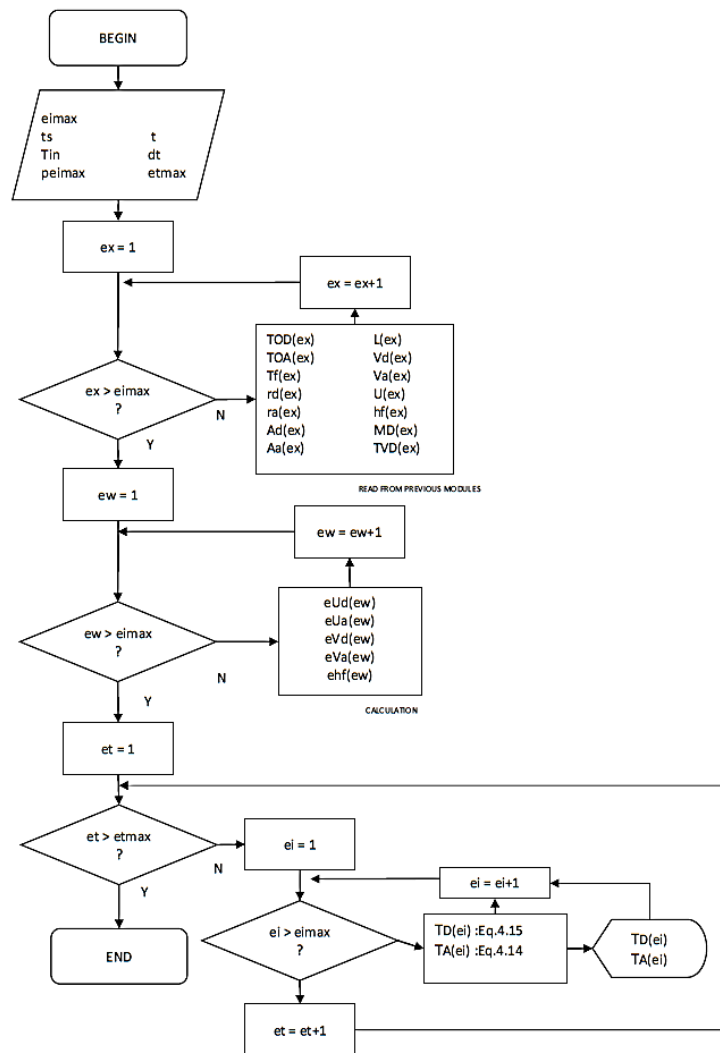


Figure 4.19 Flow diagram of Explicit Operation Module

#### 4.4.4 Time Step Size and Numerical Grid

The explicit method is not unconditionally stable, and the largest allowable time step ( $\Delta t$ ) value is limited by stability criterion. The solutions obtained by the explicit method may oscillate uncontrollably and diverge from the actual solution. To prevent the solution from that stability, the value of  $\Delta T$  must be kept below a limit under stability criterion. Pertaining to the second law of Thermodynamics, we can rely on either the mathematical or physical assumption that the stability criterion is satisfied if the coefficients of all  $T_i^t$  in the  $T_i^{t+1}$  expressions are greater than or equal to zero for all nodes  $i$  [22]. In this study, for example, the coefficient of  $T_{Di}^t$  in the  $T_{Di}^{t+1}$

expression is  $\left(1 - \frac{2\pi\bar{r}_{Di}\bar{U}_i\Delta t}{\rho A_{Di}C_p}\right)$  (From Eq. 4.15), the stability criterion for all nodes in this case is:

$$\left(1 - \frac{2\pi\bar{r}_{Di}\bar{U}_i\Delta t}{\rho A_{Di}C_p}\right) \geq 0 \quad \text{--- (4.16)}$$

or,

$$\Delta t \leq \frac{\rho A_{Di}C_p}{2\pi\bar{r}_{Di}\bar{U}_i} \quad \text{--- (4.17)}$$

That is, the largest value of time step which allows the stability for the drill pipe fluid temperature simulation is  $\frac{\rho A_{Di}C_p}{2\pi\bar{r}_{Di}\bar{U}_i}$

Grid block thickness should be small enough to deliver acceptable grid refinement to efficiently reflect a wellbore condition. However, the grid block size shouldn't be too fine, for the purpose of computation time spending. In this study, the grid block thickness shall be normally set to be 25m each, in order to ensure that the MWD temperature measurement tool was located in the deepest block of the well.

#### 4.4.5 BHCT Simulator limitation

The starting point of the simulation is a limitation of the program. Since wellbore conditions and wellbore temperature profile are unknown before RIH. So the starting point BHCT is needed to be set as high as the measured BHCT before the first interval BHCT calculation. This may affect the simulated BHCT results in the early intervals to be deviated from the deeper intervals in the same section.

## CHAPTER V

### RESULTS AND DISCUSSION

This chapter exhibits the result and explanation of BHCT simulation by using the model which has been constructed from the previous chapter. When getting the simulation result, there will be an adjustment to more accurately calculate the prediction model. Afterwards, some part of the field data will be obtained to validate the prediction model.

By the end of this chapter, sensitivity analysis will be conducted to see the effect that will happen to the BHCT, from the changes in each parameter. This is purposely making the clearer picture about the behavioral changes of the temperature while drilling, which will later on leads to the operational improvement, in order to avoid the heat problem as well.

#### 5.1 BHCT Simulation Results

From Previous chapter, BHCTs of six wells will be calculated using BHCT simulator. The simulation results are shown as BHCT vs TVD comparison plot between simulated BHCT and measured BHCT.

##### 5.1.1 Simulation Results of Top Sections

The simulation results of top sections of selected wells are presented in Figure 5.1.

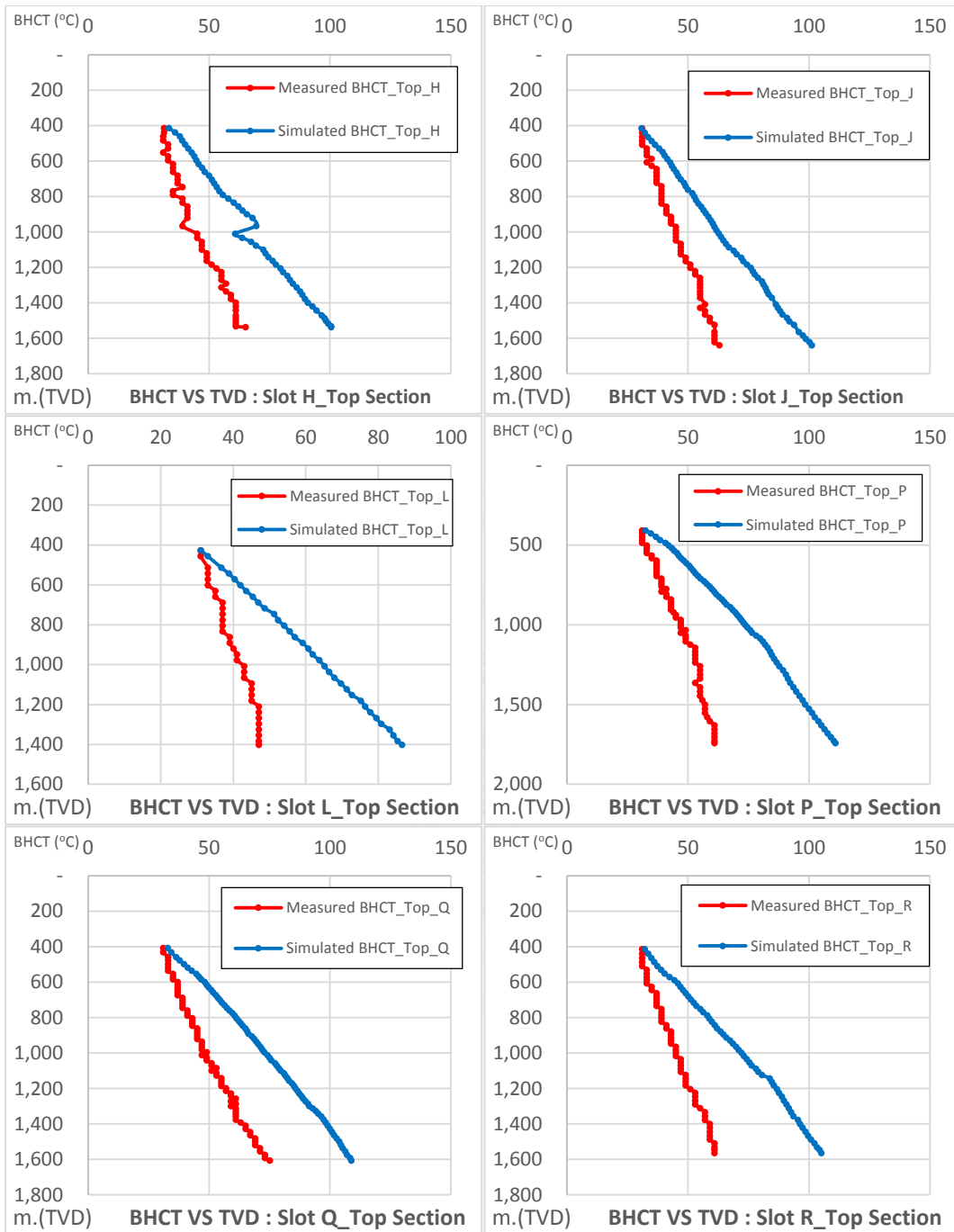


Figure 5.1 Comparison plot between simulated BHCT and measured BHCT of top section of well H, J, L, P, Q and R

### 5.1.2 Simulation Results of Bottom Sections

The simulation results of top sections of selected wells are presented in Figure 5.2.

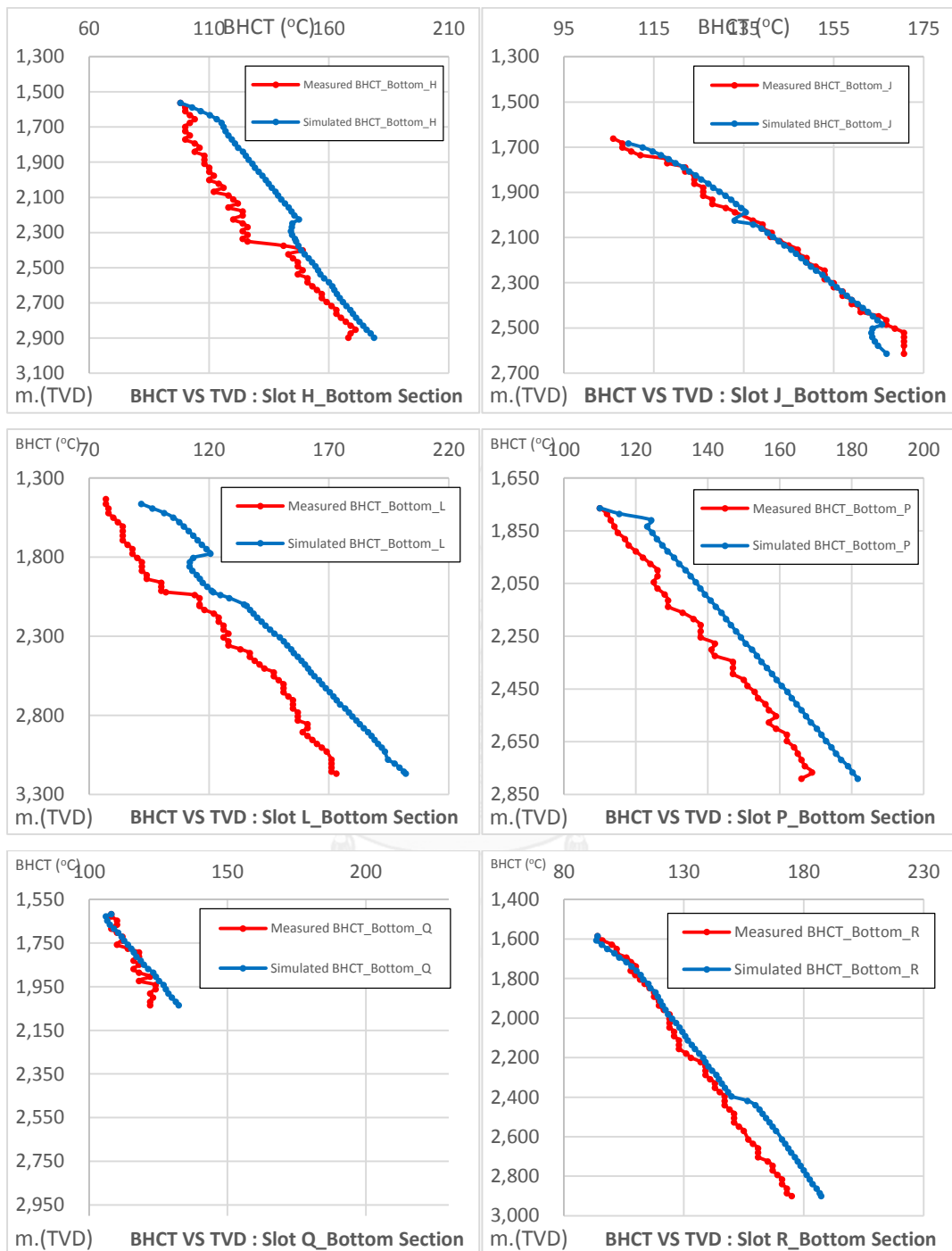


Figure 5.2 Simulation result plot between simulated BHCT and measured BHCT of bottom section of well H, J, L, P, Q and R



It can be seen that the result from simulation is similar to BHCT value in some stage, though it can also be observed that there is a difference between two curves due to several uncertainties which are yet to be identified in the model. This, the model needs to be adjusted in order to be able to predict the BHCT more precisely, which will be mentioned in the next section.

## 5.2 BHCT Adjusted Factor for BHCT Prediction Model

In order to adjust the simulated BHCT to be more accurate, the study will adjust BHCT value with the parameter called BHCT adjusted factor.

Observing from the simulation output, the results show differences between simulated BHCT and measured BHCT in each depth. So The BHCT adjusted factor will be calculated as a function of depth. That is BHCT adjusting function.

From the assumption that wells used in calculating by this model are located in the same area, they have the similar location, nearby environment as well as the similar drilling procedure. These wells are considered to be sharing the same BHCT adjusting function.

### 5.2.1 BHCT Adjusted Factor Calculation

Based on the above information as well as the simulated result which was shown in Figure 5.1 to Figure 5.12, BHCT adjusted factor ( $\Delta T_{adj}$ ) of each part will need to be found so that BHCT in each part can also be aligned.

Since we desire to have the predicted BHCT be very close to measured BHCT, the calculation concept of how to obtain the value of  $\Delta T_{adj}$  can be shown as per below equations.

$$BHCT_s + \Delta T_{adj} = BHCT_m \quad \text{--- (5.1)}$$

or

$$\Delta T_{adj} = BHCT_m - BHCT_s \quad \text{--- (5.2)}$$

where  $BHCT_s$  is simulated BHCT,

$\Delta T_{adj}$  is BHCT adjusted factor, and

$BHCT_m$  is measured BHCT.

By having the value of  $BHCT_s$  and  $BHCT_m$  located in the trend line equation by acting as the function of TVD. Calculation example can be shown in terms of  $\Delta T_{adj}$  from Figure 5.3 which exhibits the trend line of  $BHCT_s$  and  $BHCT_m$  on the top section of well R based on Eq. 5.3 and Eq. 5.4 respectively.

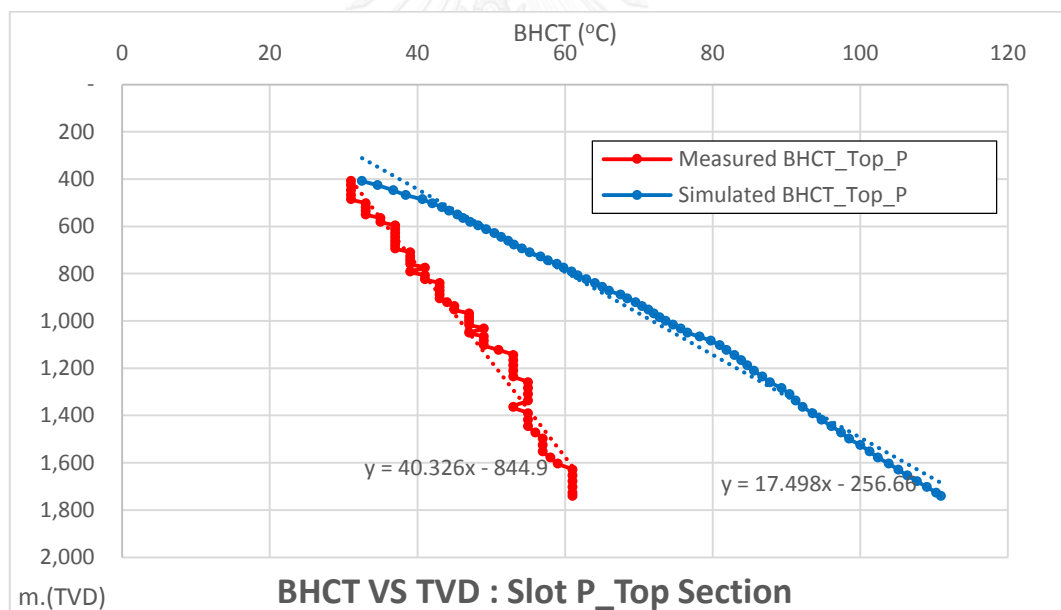


Figure 5.3 Trend lines of BHCT vs TVD comparison plot of top section of well P

$$BHCT(TVD)_{s\_top\_P} = \frac{(TVD + 256.66)}{17.498} \quad \text{--- (5.3)}$$

$$BHCT(TVD)_{m\_top\_P} = \frac{(TVD + 844.9)}{40.326} \quad \text{--- (5.4)}$$

From Eq. 5.2,  $\Delta T_{adj}$  can be found from the deduction of Eq.5.3 out of Eq. 5.4 as per Eq. 5.5, then the BHCT adjusting function of top section of well P can be obtained.

$$\Delta T(TVD)_{adj\_top\_P} = 8.38976 - 0.03706TVD \quad \text{--- (5.5)}$$

### 5.2.2 BHCT Adjusted Factor For Prediction Model

From six wells those are simulated in section 5.1, they are searched out for BHCT adjusting function for each well by formatting in general equation form (Eq. 5.6) and lined out in Table 5.1., which summarizes coefficients(a) and constants(b) for BHCT adjusted functions.

$$\Delta T(TVD)_{adj} = aTVD + b \quad \text{--- (5.6)}$$

Table 5.1 Summary of BHCT adjusting function of the selected wells

Well	$\Delta T_{adj}$			
	Top		Bottom	
	a	b	a	b
H	-0.026	4.12	N/A	N/A
J	-0.036	14.57	-0.006	17.56
L	N/A	N/A	-0.008	8.07
P	-0.037	8.39	-0.004	-1.68
Q	-0.029	23.65	-0.002	10.18
R	-0.036	10.81	-0.006	24.74
Avg.	-0.033	12.31	-0.006	2.91

From Table 5.1, the coefficients of TVD and constants of each equation will be averaged out, and then they will be used as the representative of BHCT adjusting function of this area. Noting that the coefficient (a) and constant (b) of top section of well L were subtracted out of this calculation, because the values were far different among wells. This could yield inaccuracy in the normal drilling BHCT prediction. Besides, the coefficient (a) and constant (b) of bottom section of well H were also subtracted out, since the operation difficulties affect the BHCT profile of it. This will lead to BHCT adjusting function of the top and bottom section which are shown in Eq. 5.7 and Eq. 5.8 respectively.

$$\Delta T(TVD)_{adj\_Top} = 12.31 - 0.033TVD \quad \text{--- (5.7)}$$

$$\Delta T(TVD)_{adj\_Bottom} = 2.91 - 0.006TVD \quad \text{--- (5.8)}$$

The additional well data might help improving the deviation of data set and make it more compatible using the mean as the representative value for the adjusting function. After obtaining BHCT adjusting function of each section, we would be able to calculate the predicted BHCT from Eq. 5.9

$$\text{Predicted BHCT} = \Delta T_{adj} + \text{Simulated BHCT} \quad \text{--- (5.9)}$$

By testing the value of  $\Delta T_{adj}$  from top and bottom section to be applied with simulator well P, we found that BHCT from prediction model (predicted BHT) is likely more similar to measurement than the one obtaining from simulator from the first place (Simulated BHCT). Figure 5.4 and Figure 5.5 present the results of BHCT adjusted factors after applying to the prediction model.

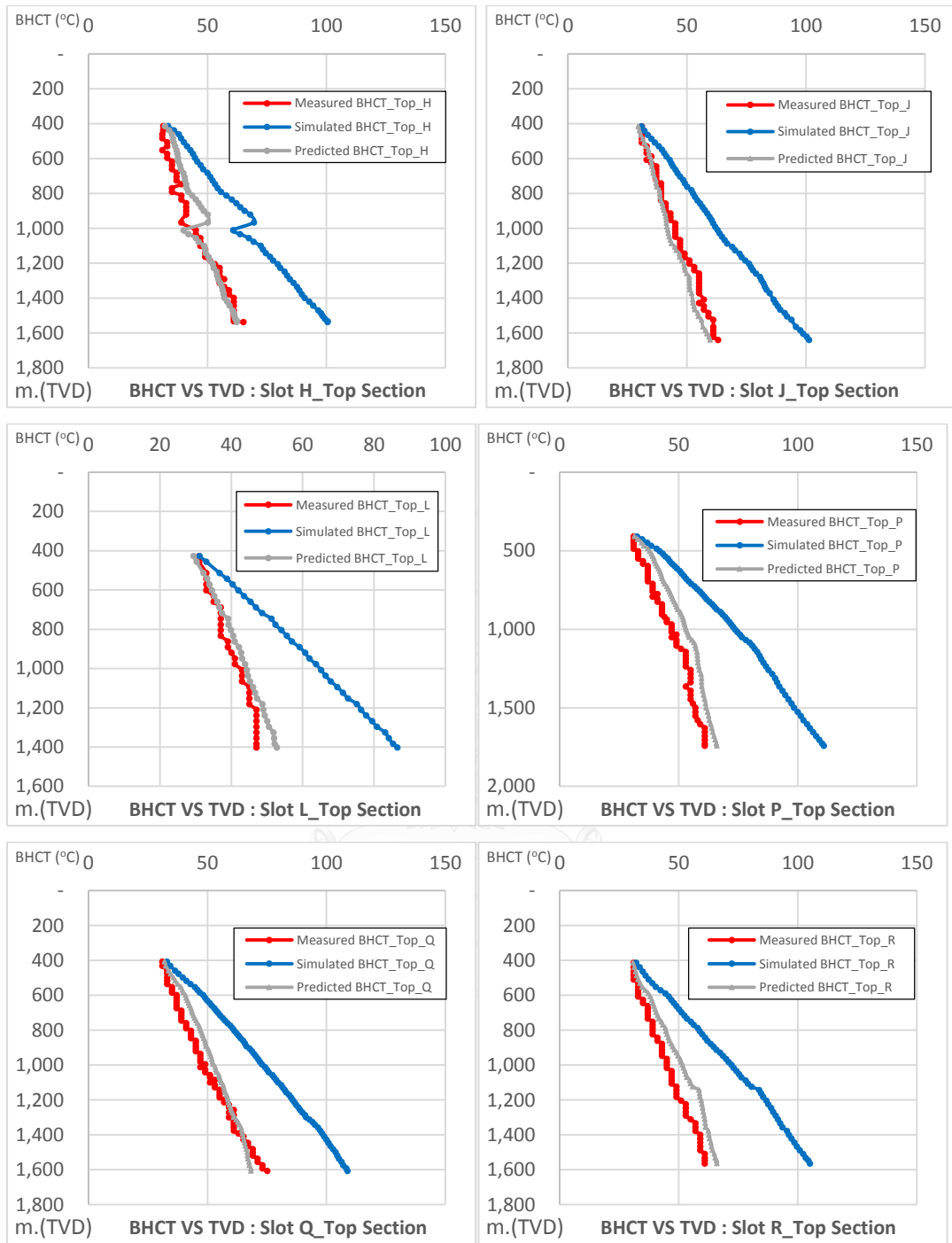


Figure 5.4 Comparison plot of Measured BHCT, Simulated BHCT, and Predicted BHCT of top section of well H, J, L, P, Q and R

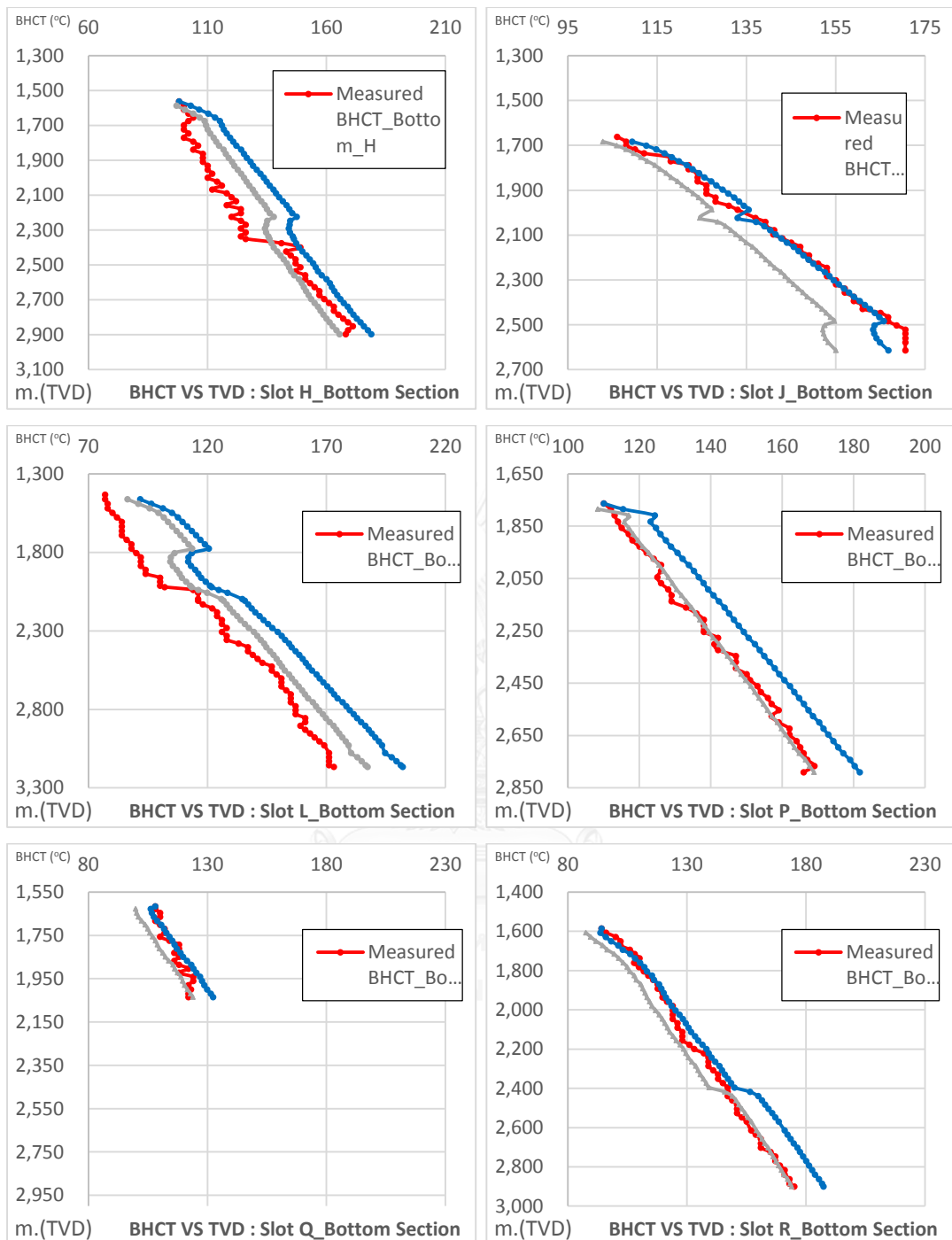


Figure 5.5 Comparison plot of Measured BHCT, Simulated BHCT, and Predicted BHCT of top section of well H, J, L, P, Q and R

When considering the predicted BHCT of the selected six wells, the average temperature differences between predicted BHCT and measured BHCT of top section is 2.55°C with standard deviation of 3.52. The percentage error is 14%. For the bottom

section, the average is 2.7°C with standard deviation of 8.19. The percentage error of the bottom section is 37%. As can be seen, the average errors of both top and bottom sections are not quite high, since the measured BHCT in this case vary between 29°C to 175°C. However, the percentage of error of both sections are higher than 5%, especially in bottom section. The deviation of the temperature different might be caused by differences in well activities between wells, for example, shut in duration, well control process, ROP improvement and etc. The additional well data might help improving the deviation and also mitigation of error.

### 5.3 Model Validation

After obtaining the prediction model, this section will be outlining the method of model validation. Prediction model will be validated from the field data of three wells which are not utilized in prediction model construction.

Well G, K and M are located in the same area as six previously mentioned wells which have been used in simulation, with the same size, parameter as well as closed procedure. Therefore the nearby BHCT adjusted factor function shall be applied.

The information of these wells will be utilized for simulation and finally found out for their predicted BHCT, and later on have their results compared to the actual BHCT.

The comparison plots between predicted BHCT and measured BHCT of well G, K and M are shown in Figure 5.6 and Figure 5.7 for top sections and bottom section, respectively.

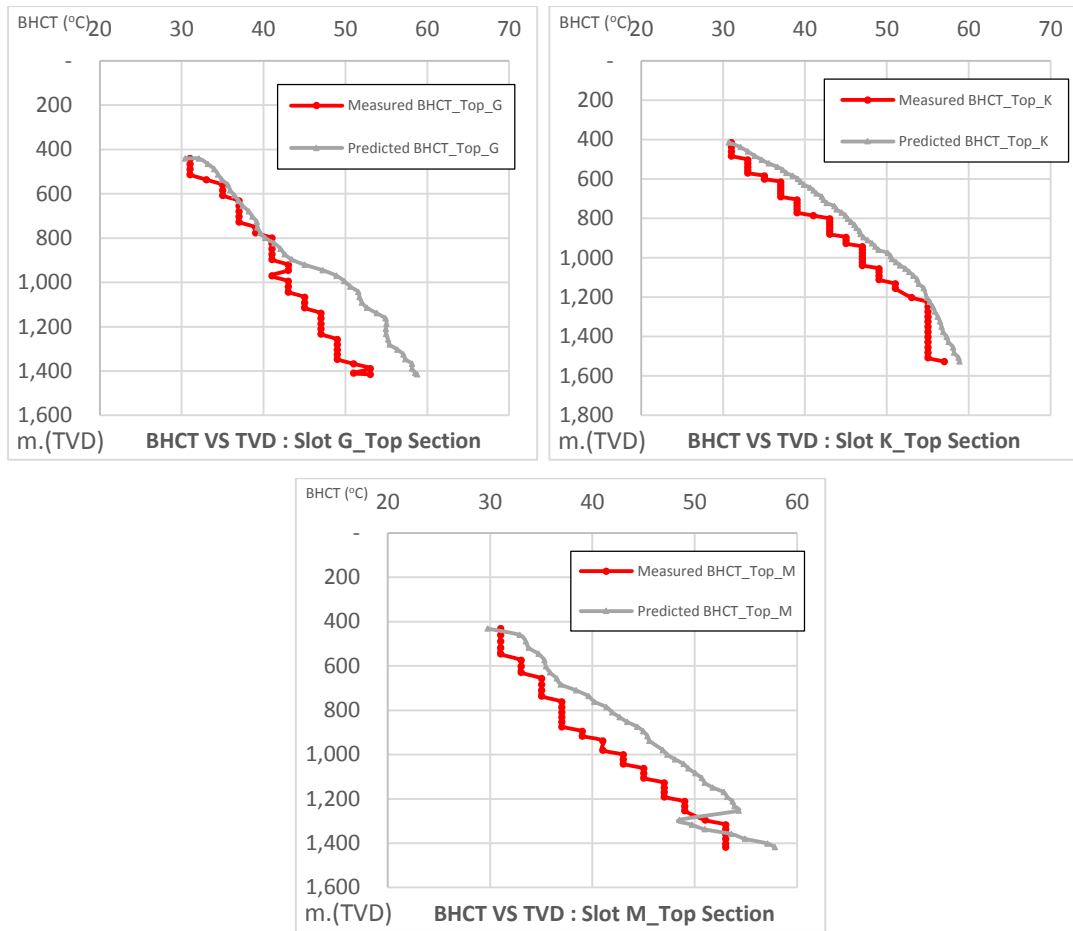


Figure 5.6 Comparison plot between Measured BHCT and Predicted BHCT of top section of well G, K, and M



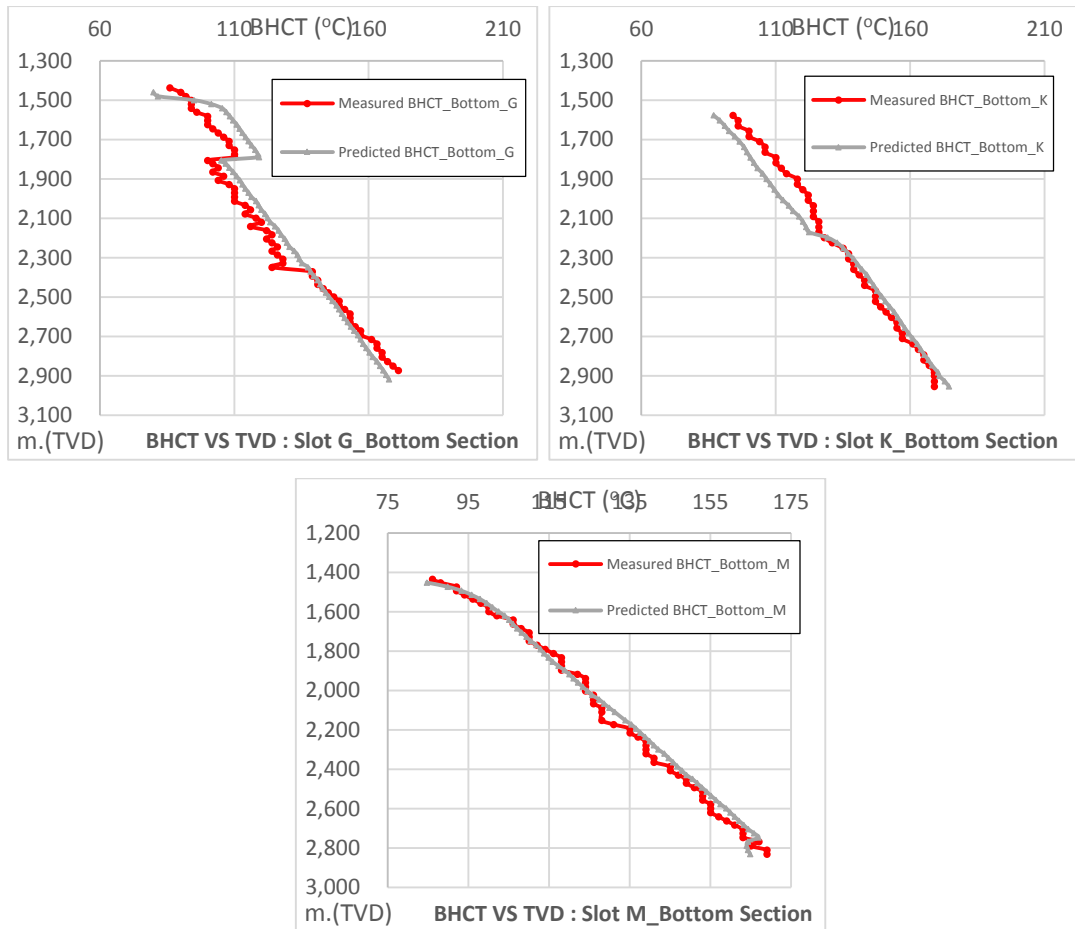


Figure 5.7 Comparison plot between Measured BHCT, Simulated BHCT and Predicted BHCT of Bottom section of well G, K, and M

There are value differences between measured BHCT and predicted BHCT at each depth. These BHCT errors of the three validating wells were collected, then plotted on a chart to see the distribution of error. The percentage of data amount and BHCT error intervals are summarized in Table 5.2 , Figure 5.8 and Figure 5.9

Table 5.2 Summary of percentage of data with BHCT error intervals

<b>Top Section</b>			
<b>BHCT diff (°C)</b>	<b>Well G (%data)</b>	<b>Well K (%data)</b>	<b>Well M (%data)</b>
(-5) to (-0)°C	6.82	1.69	9.52
(0) to (5)°C	45.45	94.92	59.52
(5) to (10)°C	47.73	3.39	30.95
<b>Bottom Section</b>			
<b>BHCT diff (°C)</b>	<b>Well G (%data)</b>	<b>Well K (%data)</b>	<b>Well M (%data)</b>
(-15) to (-10)°C	2.86	5.77	0.0
(-10) to (-5)°C	2.86	32.69	0.0
(-5) to (0)°C	30.0	7.69	32.31
(0) to (5)°C	20.0	51.92	66.15
(5) to (10)°C	38.57	1.92	1.54
(10) to (15)°C	5.71	0.0	0.0

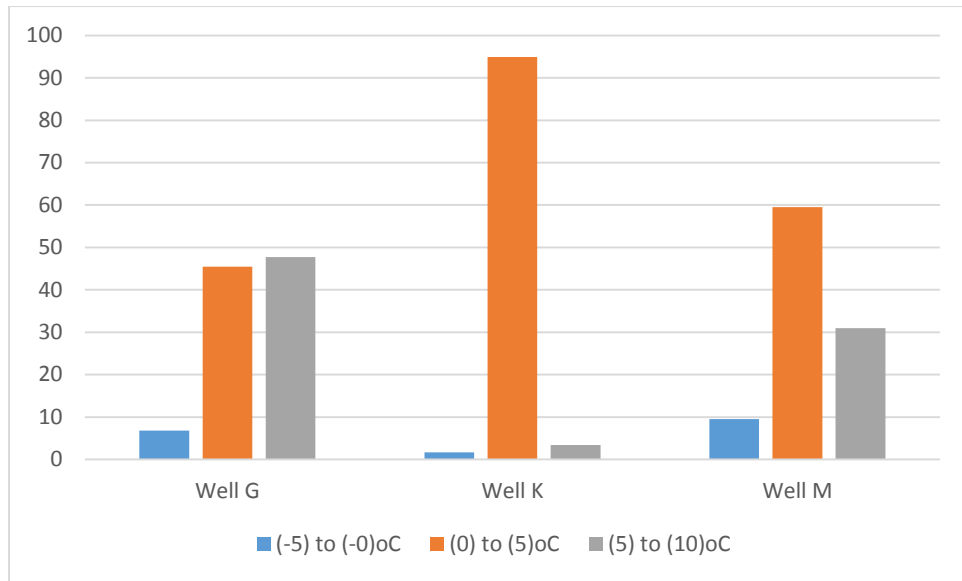


Figure 5.8 Error distribution of BHCT prediction for top section

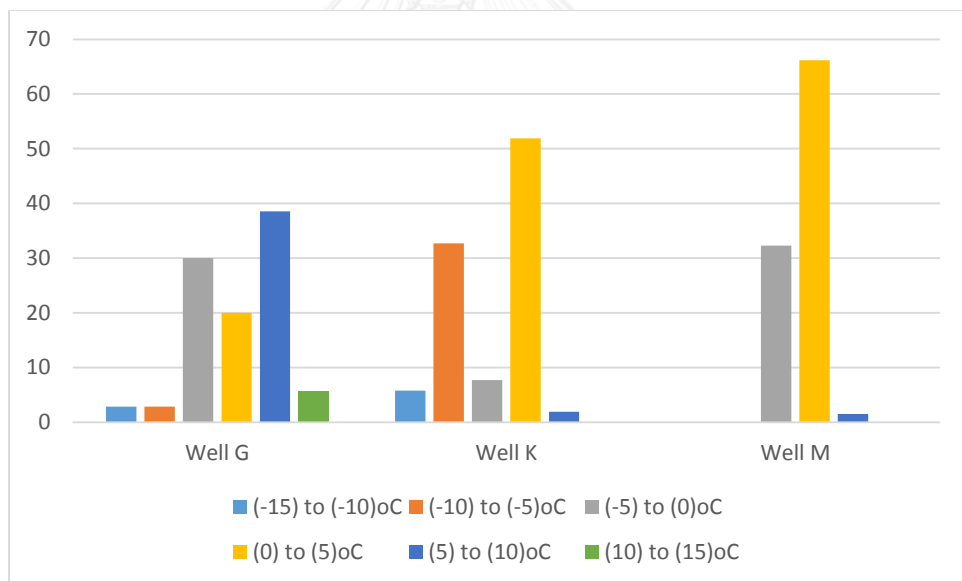


Figure 5.9 Error distribution of BHCT prediction for bottom section

### 5.3.1 Error Distribution of BHCT Prediction for Top Section

From the consideration in error of top section of well G, K, and M, the model validation could be summarized as:

- All of errors of three wells located in the acceptable range of  $-10^{\circ}\text{C}$  to  $10^{\circ}\text{C}$ , especially more than 70% of all data fall under  $-5^{\circ}\text{C}$  to  $5^{\circ}\text{C}$  range.
- More than 90% of error for all three wells stays between 0 to 10% over prediction
- It might be concluded that the prediction model is deviated in level of  $\pm 10\%$  and also that most of the deviation can be categorized as over prediction.

### 5.3.2 Error Distribution of BHCT Prediction for Bottom Section

From the consideration in error of bottom section of well G, K, and M, the model validation could be summarized as:

- Most of the error which is 69% of data located in the range of  $-5\%$  to  $5\%$ , and as high as 95.2% of data falls under the scope of  $-10^{\circ}\text{C}$  to  $10^{\circ}\text{C}$
- Well G has the scattering pattern of error more than well K and M, as same as top section
- More than 85% of error for all three wells stays between 0 to 10% over prediction
- It might be concluded that the prediction model is deviated in level of  $\pm 10\%$  and also that most of the deviation can be categorized as over prediction.

### 5.4 Effect of Drilling Parameters on BHCT

Several parameters are applied in the BHCT prediction model to evaluate their sensitivity and effects on BHCT. The interested drilling parameters include:

- Penetration rate
- Geothermal gradient
- Circulation rate
- Drilling mud property

- Drilling fluid inlet temperature

BHCTs are predicted under the same field data set. In this case well P was selected to be the sensitivity base case.

#### 5.4.1 Sensitivity Base Case

The simulation base case was constructed using the well trajectory, drilling section, BHA, drilling mud and well components of well P. The geothermal gradient of  $6^{\circ}\text{C}/100$  was the standard expected geothermal gradient of this area. The drilling inlet temperature of  $34^{\circ}\text{C}$  was normally kept as constant in the operation. Observing the operation log, flowrate of the top section and bottom section usually as high as 3000lpm and 900lpm, respectively.

The sensitivity base case specifications can be summarized as shown in Table 5.3.

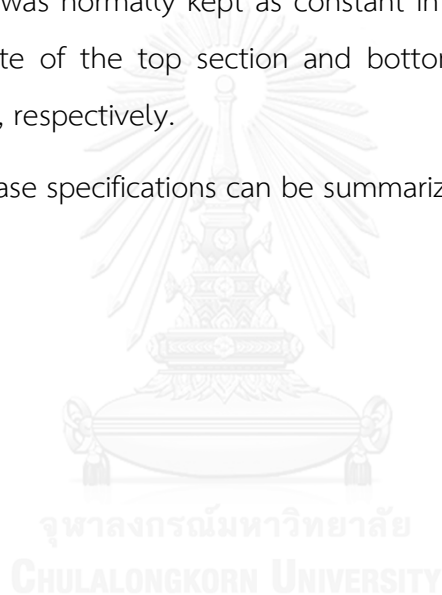


Table 5.3 Base case model specification

<b>Base case model specification</b>	
Well trajectory	Trajectory of well P
Drilling Section	Drilling section of well P
Well Components	Well components of well P
Geothermal Gradient	6°C/100m.
BHA Specification	BHA specification of well P
<b>Top Section</b>	
Drilling Fluid inlet temperature	34°C - constant
Section TD (m.TVD)	1006
Length (m.TVD)	339.3793764
SG.	1.04
Plastic Viscosity (cp)	12
Yield Point (lb/100ft <sup>2</sup> )	19
ROP (m/hr)	600
Drilling Fluid	Seawater
Flowrate (lpm)	3000
<b>Bottom Section</b>	
Drilling Fluid inlet temperature	34°C - constant
Section TD (m.TVD)	3018.5
Length (m.TVD)	468.6557863
SG.	1.2
Plastic Viscosity (cp)	19
Yield Point (lb/100ft <sup>2</sup> )	14
ROP (m/hr)	60
Drilling Fluid	SDF
Flowrate (lpm)	900

In this study, the sensitivity analysis was conducted to see the effects of drilling parameters including, ROP, flowrate, drilling fluid properties, geothermal gradients and drilling fluid inlet temperature on predicted BHCT. The results were concluded in the section below.

#### **5.4.2 Effect of Penetration Rate**

Penetration rate is the speed at which the drill bit can break the rock beneath it and then deepen the well bore. The higher ROP value means the shorter time spent to drill through an interval. Normally, high rate of penetration is favorable for drilling operation. Drillers design the operations to optimize penetration rate, for example, they use the proper type of drill bit to be matched with the formation lithology, they use the proper drilling fluid properties, and if low ROP is observed, the drillers change the drilling plan to make it better.

This study is conducted to evaluate the effects of penetration rates (ROP) on BHCT profile. The penetration rates are varies -20% to +20% of the actual ROP data. ROP values will be elevated by shorten or extend the time spent for each drilling interval.

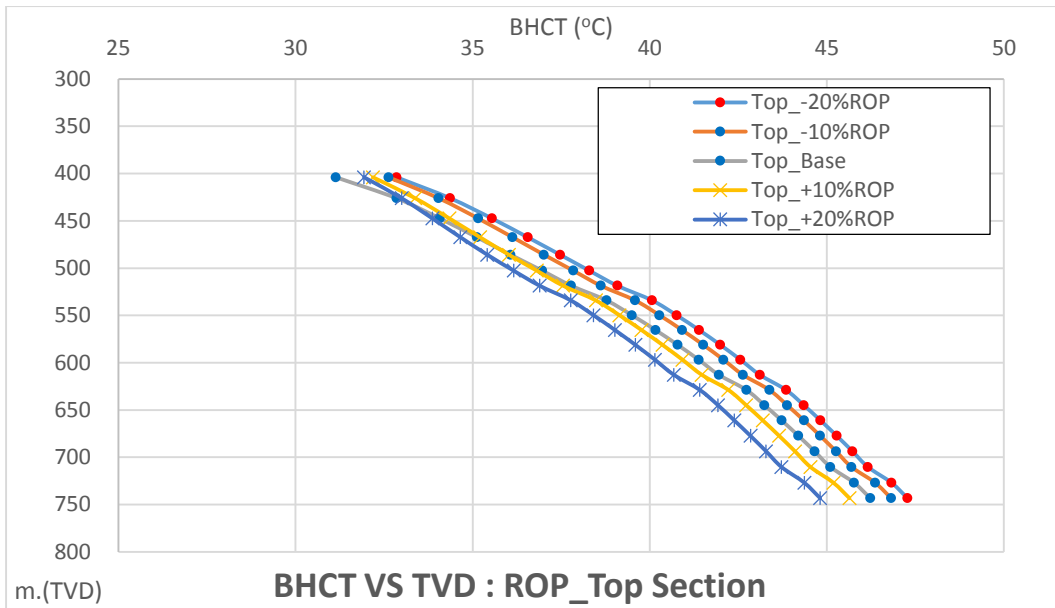


Figure 5.10 Effect of various ROP on BHCT for top section.

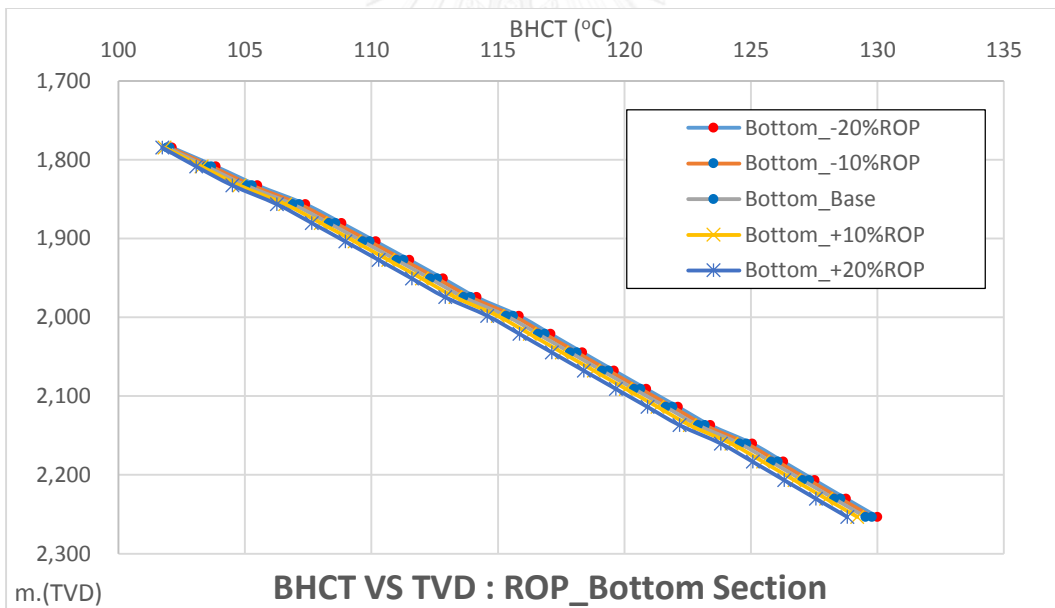


Figure 5.11 Effect of various ROP on BHCT for bottom section.

The higher ROP means less drilling time spent, which also means less amount of heat can be transferred from formation into the wellbore.



As can be seen in Figure 5.10 and Figure 5.11, ROP slightly affects BHCT for Both sections. When ROP increases, predicted BHCT decreases.

### 5.4.3 Effect of Geothermal Gradient

Geothermal gradient (GG) presents increase of temperatures with depths. In this study, geothermal gradient is defined as an estimated value for one well. All the wells have the same geothermal gradient, as high as 6°C/100m.

In this study, the geothermal gradients of 4 °C/100m. to 8°C/100m will be applied to the BHCT prediction model in order to evaluate the effects of geothermal gradients on BHCT profile.

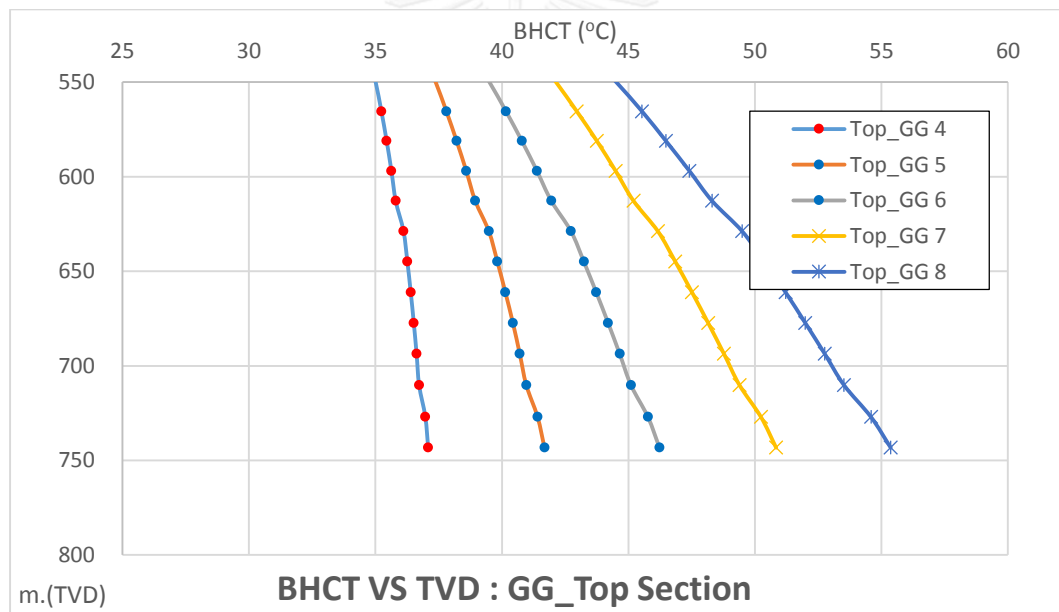


Figure 5.12 Effect of various geothermal gradient on BHCT for top section.

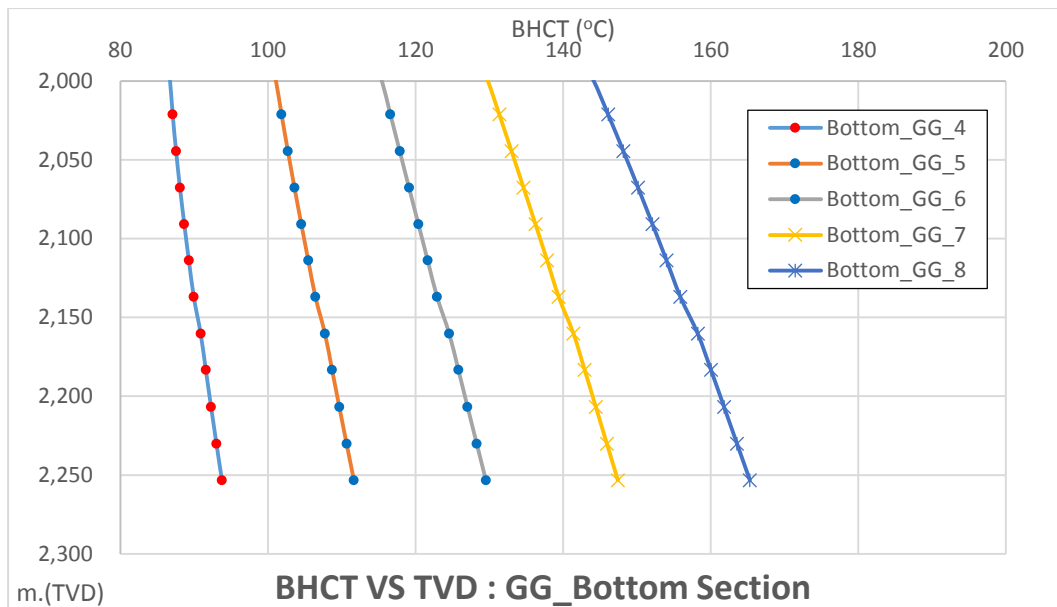


Figure 5.13 Effect of various geothermal gradient on BHCT for bottom section.

From the field data of each well observed, it can be understood that lithology of formation around the specific area are classified as inter-bedded, sandstone, mudstone and very thin clay layer which lays in their complexities. Each type of rock has the different thermophysical properties and fluid storage inside the matrix. This can potentially occurred from the increase in geothermal gradient of each well as the temperature is increased in straight line as per each TVD. This, however, is the estimated value which isn't the literal reflection of the real formation.

From Figure 5.12 and Figure 5.13, geothermal gradients magnificently affect predicted BHCT since they are the main heat supplier to the wellbore circulation system. When geothermal gradient increases, the formation temperature increases. This increases the rate of heat transfer between formation and annulus.

#### 5.4.4 Effect of circulation rate

Since circulation rate plays the important role in the convective heat transfer coefficient calculation, so changing of circulation rate may directly affect the BHCT. From the given data, the circulation rate seems to be similar among well sections. The

bottom sections have higher circulation rate than top sections. Besides, it looks like the driller try to keep the circulation rate at a constant value through the operation. Other than during drilling, the circulation rate will be varied with various drilling activities. Circulate hole clean, displace hole and well control process might need different required circulation rates.

In this study, the circulation rates will be varied between -20% and +20% to the actual circulation rate value. The effects of varying circulation rate on BHCT are presented in Figure 5.14 and Figure 5.15.

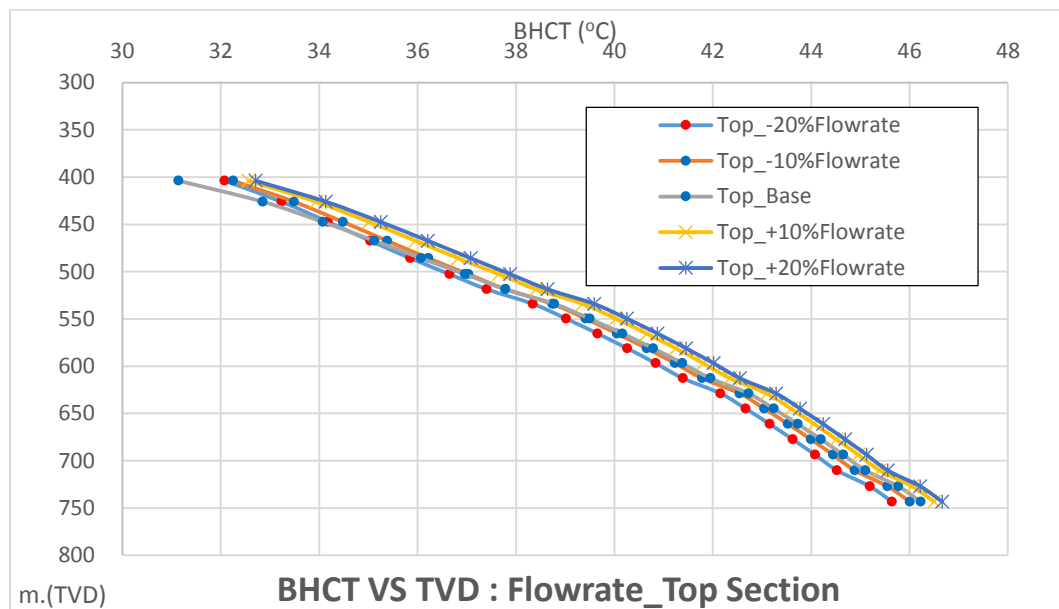


Figure 5.14 Effect of various circulation rate on BHCT for top section.

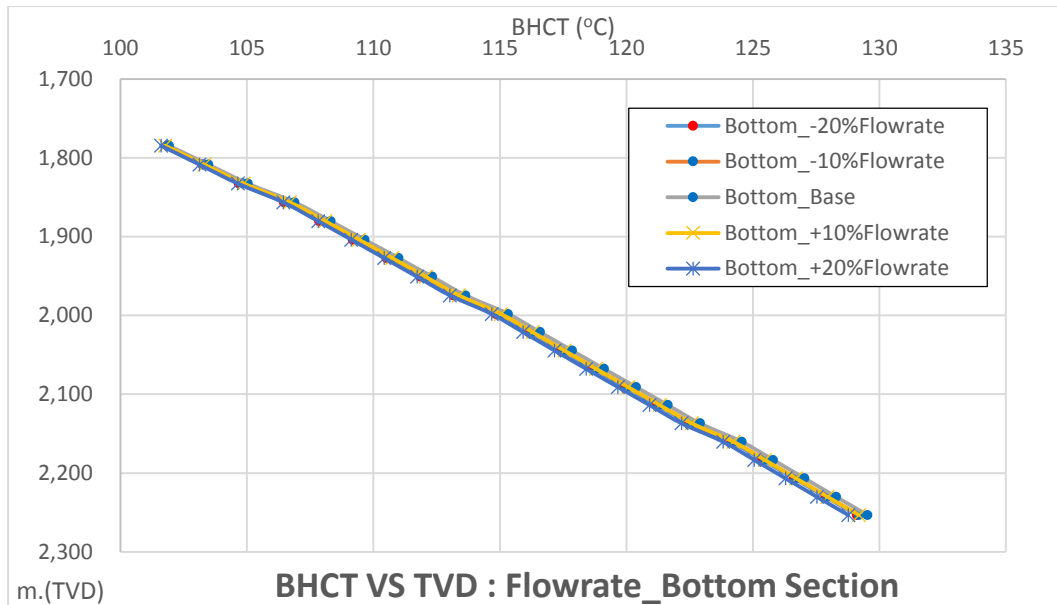


Figure 5.15 Effect of various circulation rate on BHCT for bottom section.

The effects of flowrate to predicted BHCT are different between top and bottom section. This may be caused by the differences in drilling mud properties and typical flowrate used in the drilling operations. In top section, seawater is circulated at high flow rate. Besides, surrounding formation temperature is not too high compared to annular fluid. This may cause the heat transfer coefficient of the higher flowrate case to be lower.

#### 5.4.5 Effect of drilling mud properties

Drilling fluid properties are the main critical determination of thermophysical properties of prediction model. Mainly, the drilling mud properties will be changed in order to keep the well pressure in control and to enable the cutting transport. Mud density will be increased along the depth to maintain the wellbore stability. Plastic viscosity and yield point will be calculate in order to have the suitable drilling mud for specific hole conditions.

In this study, sensitivity analysis of main parameters will be conducted on drilling fluid properties which are composed of drilling mud density, plastic

viscosity(PV), and yield point(YP) where as these variables are directly input into the model.

These drilling fluid properties have shown great effect in calculating the effective viscosity, in which considered as important factor in obtaining dimensionless parameter such as Nusselt number, Reynold number and Prandtl number.

Effect of these drilling parameter are shown below.

#### 5.4.5.1 Effect of drilling mud density

The effect of elevated drilling mud density can be seen in Figure 5.16 for Top section and in Figure 5.17 for bottom section.

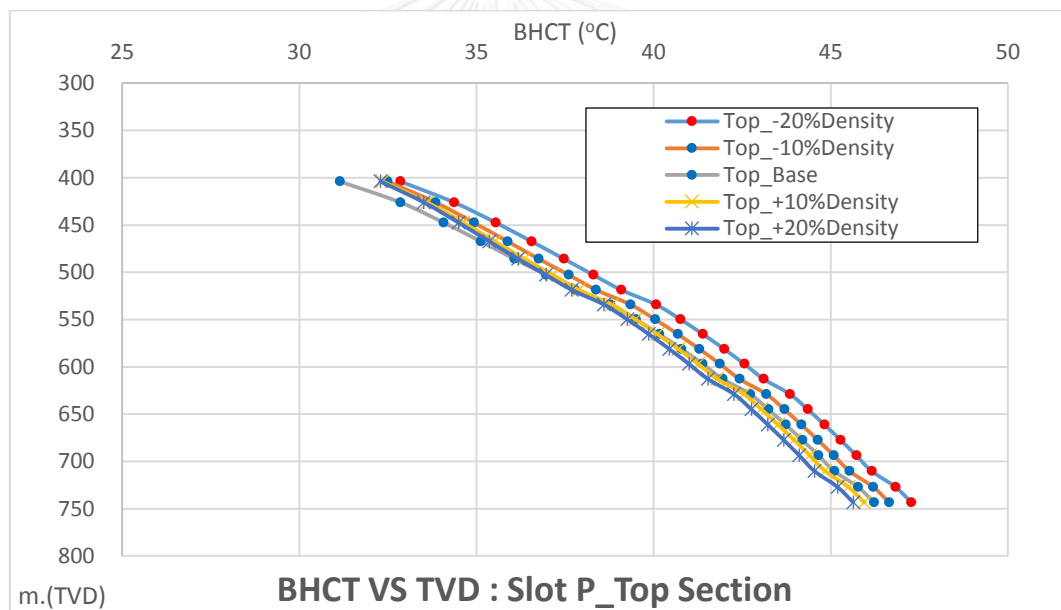


Figure 5.16 Effect of drilling mud density on BHCT for top section.

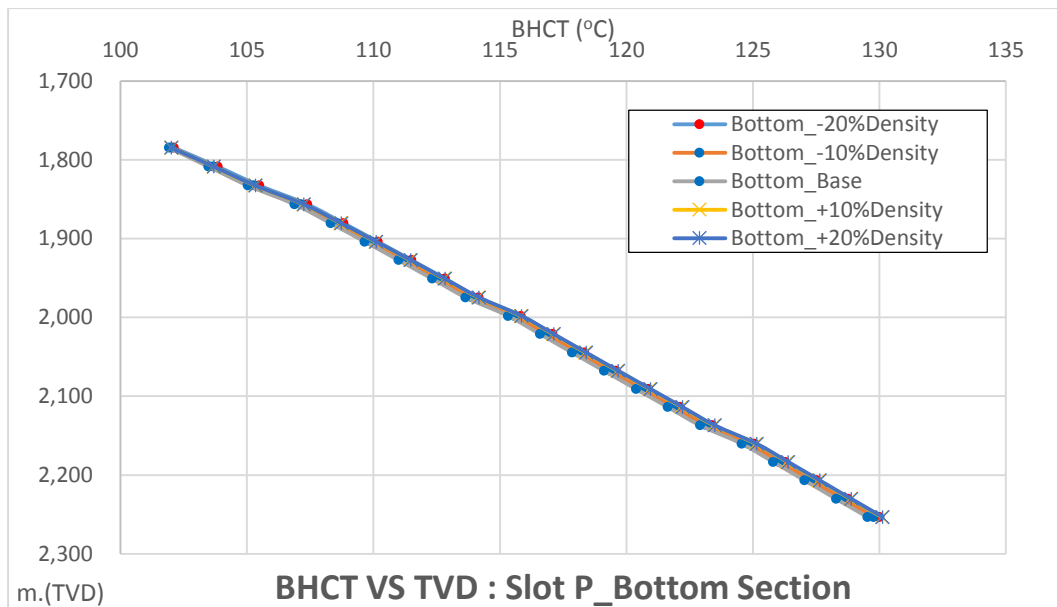


Figure 5.17 Effect of drilling mud density on BHCT for bottom section.

From the above figures, changing of mud density yield just small effects to predicted BHCT. When the mud weight increases, the predicted BHCT increases. In this study, the salinity and temperature effects mud density, then resulting in the change of thermal conductivity ( $k$ ) and specific heat capacity ( $C_p$ ). These parameters relate in many terms of the main calculating components, so the trend of the BHCT could not be explain by changing of fluid density alone.

#### 5.4.5.2 Effect of Drilling Mud Plastic Viscosity

The effect of elevated drilling mud plastic viscosity can be seen in Figure 5.18 for bottom section. The top section has different fluid property system, so the effect of plastic viscosity can be described in bottom section only.

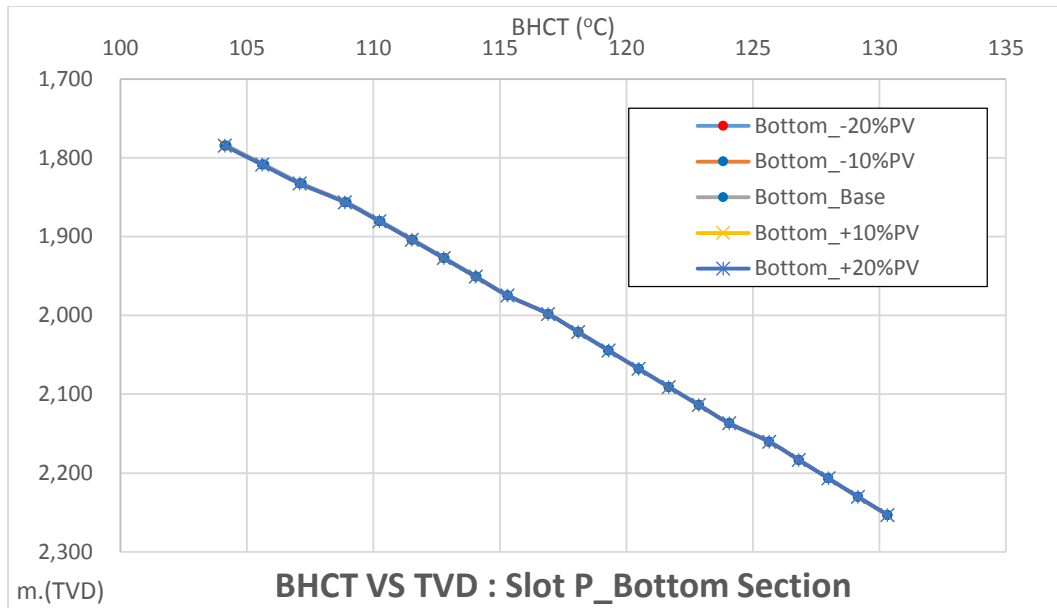


Figure 5.18 Effect of various drilling fluid plastic viscosity on BHCT for bottom section.

In this case, we fixed yield point and elevated the plastic viscosity. Changing of plastic viscosity leaves just small effect on predicted BHCT for both top and bottom section. It can be seen that, when the plastic viscosity increases, the predicted BHCT decreases.

#### 5.4.5.3 Effect of Drilling Mud Yield Point

The effect of elevated drilling mud yield point can be seen in Figure 5.19 for bottom section. The top section has different fluid property system, so the effect of plastic viscosity can be described in bottom section only.

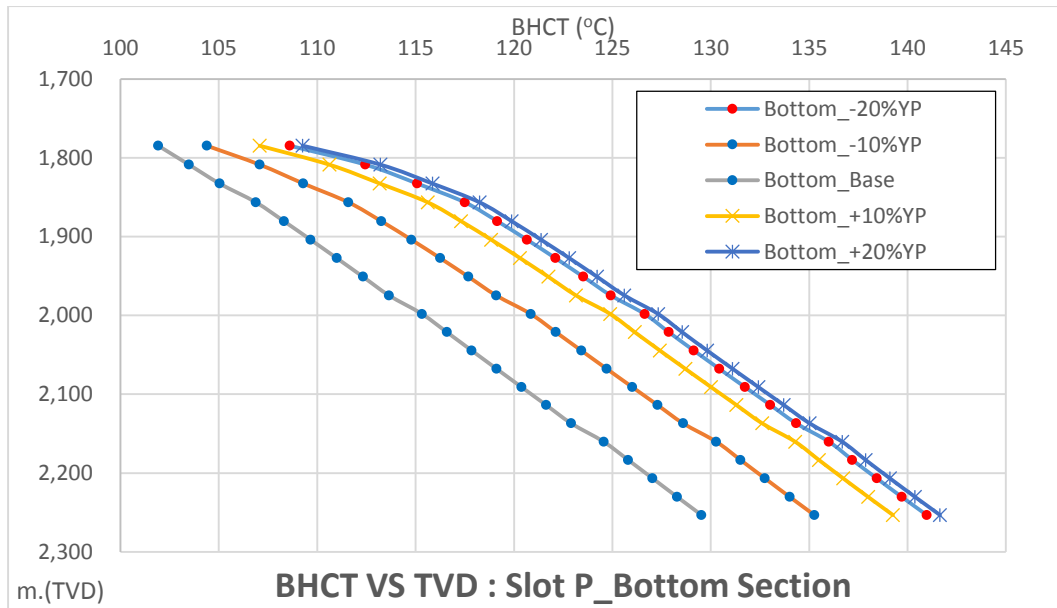


Figure 5.19 Effect of various drilling fluid yield point on BHCT for bottom section.

As can be seen in Figure 5.19, yield point significantly affects predicted BHCT. Besides, increasing of yield point doesn't confirm increasing or decreasing of predicted BHCT. This may be caused by the heat transfer coefficient changes significantly by the changing proportion of yield point to plastic viscosity which influence dynamic viscosity and flow regime.

#### 5.4.5.4 Effect of Inlet Temperature

From the field data, it seems that the driller tried to keep the inlet temperature constant through the operation. In addition to this, information from the field questionnaire led to the event that these wells have the mud cooling system, which assists in down hole temperature control. Before also introducing the drilling mud into the well which is another means of transferring the heat out of the system. The experiment had adjusted the inlet temperature to be between -20% to +20% to see the effect of BHCT changing.



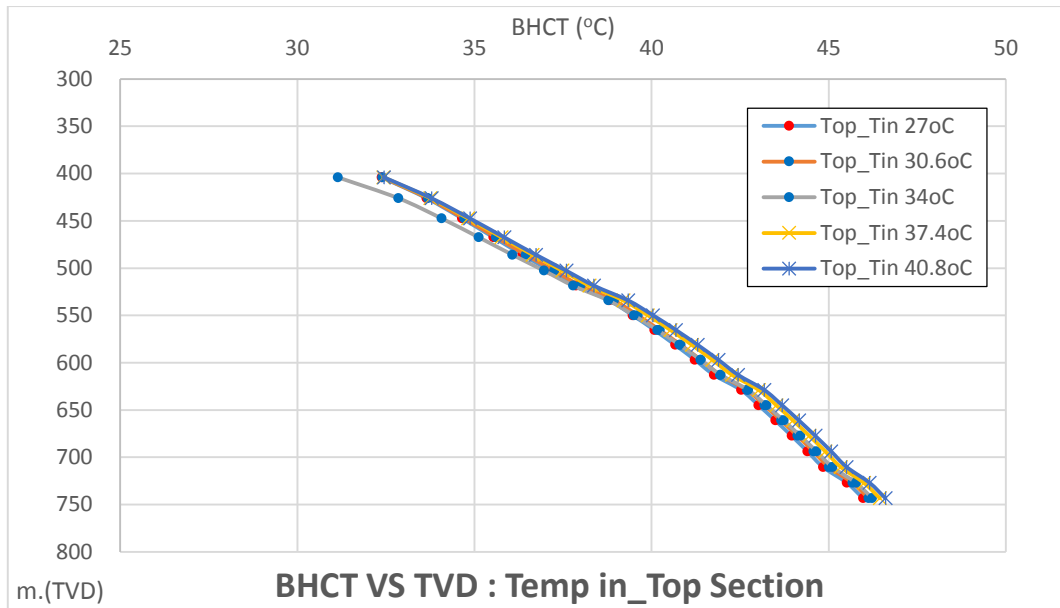


Figure 5.20 Effect of various inlet temperature on BHCT for top section.

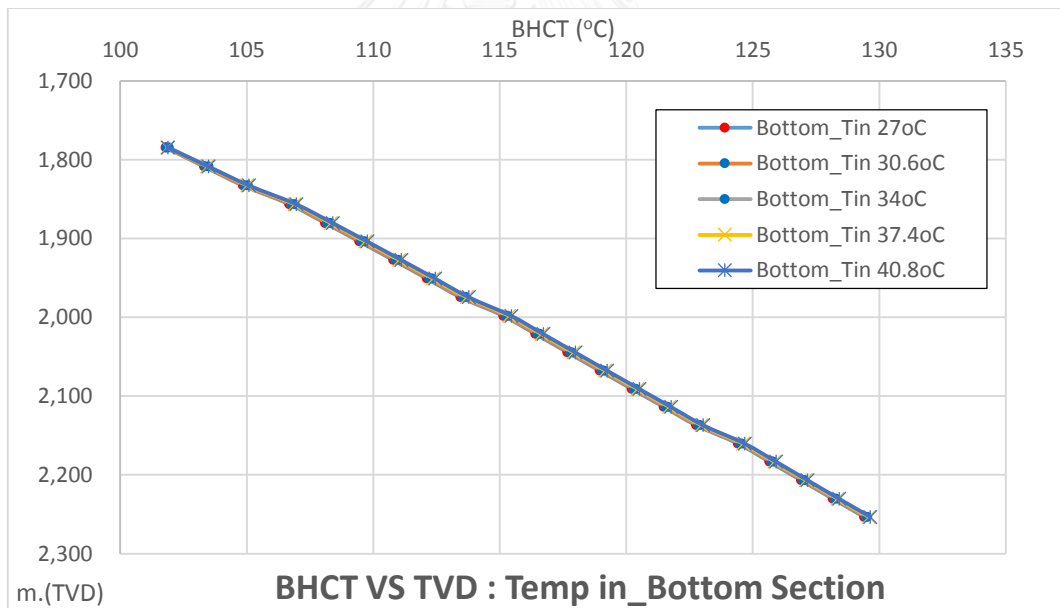


Figure 5.21 Effect of various inlet temperature on BHCT for bottom section.

As can be seen in Figure 5.20 and Figure 5.21 the increasing of drilling fluid inlet temperature, the increasing of predicted BHCT. However, just slightly effects can be observed. The result may imply that controlling inlet temperature might not help reducing BHCT that much.

### 5.5 Summary of Effects of Drilling Parameter on Predicted BHCT

From all studied parameters, geothermal gradient is the most influenced parameter. By changing 1 degree Celsius geothermal gradient (16.67%), the end point predicted BHCT changes its value more than 13°C (10%) for bottom section and around 10°C (17%) for top section. Others parameters yield slightly effect on predicted BHCT. The effects of various parameters on BHCT could be summarized as shown in Table 5.

4



Table 5. 4 Effects of various drilling parameters on BHCTs (%diff from base case  
BHCT)

	Top Section			
	-20%	-10%	10%	20%
<b>Tin</b>	0.81	1.39	-0.38	-0.96
<b>Flowrate</b>	-2.17	-0.83	1.01	1.62
<b>ROP</b>	3.91	2.19	-2.19	-5.27
<b>Density</b>	3.91	1.58	-1.04	-2.20
<b>GG</b>	-19.7	-9.9	9.9	19.7
	Bottom Section			
	-20%	-10%	10%	20%
<b>Tin</b>	0.03	0.07	-0.04	-0.07
<b>Flowrate</b>	-0.23	-0.19	-0.19	-0.42
<b>ROP</b>	0.27	0.15	-0.18	-0.40
<b>Density</b>	0.27	0.13	0.32	0.34
<b>PV</b>	0.00	0.00	0.00	0.00
<b>YP</b>	6.39	3.20	5.43	6.77
<b>GG</b>	-16	-6.9	6.9	16

## CHAPTER VI

### CONCLUSION AND RECOMMENDATION

#### 6.1 Conclusion

The objectives of this study are to develop a heat transfer model for the prediction of BHCT and to see the effect of drilling parameter on it. The results can be summarized as follows:

- (i) The heat transfer model to predict the BHCT was constructed by the development of heat transfer equations. The field data were used for the simulator designing stage, for the BHCT adjusting function and for the model validation.
- (ii) From data analysis, the wellbores were totally separated into two sections which are top section and bottom section. The BHCT were simulated using the same simulator, but different in input condition and BHCT adjusting function.
- (iii) The simulation results showed similar alignment with the measured values, however there are differences of BHCT values along the depth. In order to improve the accuracy of the prediction model, the BHCT adjusted function was introduced as an accuracy assessment.

After applying BHCT adjusting function to simulator, BHCT prediction model was obtained. The results showed that the accuracy of the prediction model has improved.

- (iv) The prediction model was validated by field data. The results showed the temperature deviation between the prediction model and measurement around  $\pm 10^{\circ}\text{C}$
- (v) From sensitivity study, geothermal gradient is the most dominated parameter that control BHCT. By changing 1 degree Celsius per 100 meter of geothermal gradient, the end point predicted BHCT changes

its value around 13°C for bottom section and around 10°C for top section. Other parameters yield slightly effect on predicted BHCT. These may imply that the actual geothermal gradient could be varied with depth and/or with the areal lithology.

## 6.2 Recommendation

The following issues are suggestions for the further study of BHCT prediction while drilling.

1. To get the model with more solidity, additional information from more numbers of well should be obtained in order to have reliable data pool. This will be beneficial to different scenarios of drilling operation and would be able to apply as other options in the prediction model
2. In order to improve model accuracy and adjust the model to be closer to actual wellbore conditions, the following improvements are recommended to be applied to the model,
  - a. Well components:
    - Heat transfer above the mud line should take the actual flow seawater condition into account
    - Material of well components such as drill pipe, casing and cement should be factors of attention. This is based on the fact that these components affect the rate of heat transfer between flow regions.
  - b. Drilling fluid properties:
    - Consideration on fluid properties which changes upon the temperature and pressure based on the condition of the well will make the model be more realistic.
  - c. Drilling operations:

- Conductive heat transfer model could help estimating the downhole temperature while the wellbore is shut-in, i.e. no circulation.



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APPENDIX

จุฬาลงกรณ์มหาวิทยาลัย  
CHULALONGKORN UNIVERSITY

## Program Coding

### A-1 Well Path Module

```
'=====WELL PATH GENERATOR START=====
```

```
Sub Button1_Click()
```

```
Dim SurfTemp As Double    'surface temperature
Dim gg As Double          'Geothermal Gradient
Dim dz As Double          'input grid block thickness
Dim ox As Double          'origin UTM x-coordinate
Dim oy As Double          'origin UTM y-coordinate
Dim CMD As Double         'Current position MD'
Dim TDMD As Double        'Drilling target MD
Dim MWDTD As Double       'Targer depth (MD) from MWD survey
Dim z(0 To 500) As Double 'vertical depth from the prevoius MWD section
Dim MWDMD(0 To 500) As Double 'MD from MWD
Dim MWDTVD(0 To 500) As Double 'TVD from MWD
Dim MWDL(0 To 500) As Double 'Length from MWD
Dim MD(0 To 500) As Double 'model's MD for grid block(i)
Dim TVD(0 To 500) As Double 'model's TVD for grid block(i)
Dim L(0 To 500) As Double  'model's gridblock length for grid block(i)
Dim Tf(0 To 500) As Double 'model's formation temp for grid block(i)
Dim xx(1 To 500) As Double
Dim i As Integer          'order of grid block
Dim imax As Integer       'maximum number of grid block
Dim n As Integer
```

Dim m As Integer

Dim k As Integer

Dim r As Integer

'Read Value'

gg = Worksheets("2.Wellpath").Cells(4, 6).Value

SurfTemp = Worksheets("2.Wellpath").Cells(6, 6).Value

dz = Worksheets("2.Wellpath").Cells(5, 6).Value

ox = Worksheets("2.Wellpath").Cells(3, 6).Value

oy = Worksheets("2.Wellpath").Cells(3, 10).Value

CMD = Worksheets("2.Wellpath").Cells(13, 6).Value

TDMD = Worksheets("2.Wellpath").Cells(14, 6).Value

MWDTD = Worksheets("2.Wellpath").Cells(8, 6).Value

MWDMD(0) = Worksheets("1.Survey data").Cells(4, 1).Value

MWDTV(0) = Worksheets("1.Survey data").Cells(4, 5).Value

MWDL(0) = Worksheets("1.Survey data").Cells(4, 4).Value

MD(0) = MWDMD(0)

TVD(0) = MWDTV(0)

L(0) = 0

Tf(0) = SurfTemp

'Obtain mmax

For x = 1 To 500

    xx(x) = Worksheets("1.Survey data").Cells(x + 4, 1).Value

    If xx(x) = MWDTD Then mmax = x

    Worksheets("2.Wellpath").Cells(8, 10).Value = mmax

Next x

'Read value MWDMD(m), MWDTVD(m) and MWDL(m)

For m = 1 To mmax

MWDMD(m) = Worksheets("1.Survey data").Cells(m + 4, 1).Value

MWDTVD(m) = Worksheets("1.Survey data").Cells(m + 4, 5).Value

MWDL(m) = Worksheets("1.Survey data").Cells(m + 4, 4).Value

Next m

Do While k <= TDMD / dz

k = k + 1

Loop

imax = k

Worksheets("2.Wellpath").Cells(5, 10).Value = imax

Worksheets("2.Wellpath").Cells(1, 14).Value = "i"

Worksheets("2.Wellpath").Cells(3, 14).Value = 0

Worksheets("2.Wellpath").Cells(1, 15).Value = "MD"

Worksheets("2.Wellpath").Cells(2, 15).Value = "m."

Worksheets("2.Wellpath").Cells(3, 15).Value = MD(0)

Worksheets("2.Wellpath").Cells(1, 16).Value = "TVD"

Worksheets("2.Wellpath").Cells(2, 16).Value = "m."

Worksheets("2.Wellpath").Cells(3, 16).Value = TVD(0)

Worksheets("2.Wellpath").Cells(1, 17).Value = "L"

Worksheets("2.Wellpath").Cells(2, 17).Value = "m."

Worksheets("2.Wellpath").Cells(3, 17).Value = L(0)

Worksheets("2.Wellpath").Cells(1, 18).Value = "Tf"

Worksheets("2.Wellpath").Cells(2, 18).Value = "oC"

Worksheets("2.Wellpath").Cells(3, 18).Value = Tf(0)

For i = 1 To imax

Worksheets("2.Wellpath").Cells(i + 3, 14).Value = i

MD(imax) = TDMD

Select Case i

Case 1

MD(i) = MD(imax) - (dz \* (imax - 1))

L(i) = MD(i)

Case imax

L(i) = dz

Case Else

MD(i) = MD(1) + (dz \* (i - 1))

L(i) = dz

End Select

Worksheets("2.Wellpath").Cells(i + 3, 15).Value = MD(i)

Worksheets("2.Wellpath").Cells(i + 3, 17).Value = L(i)

For n = 1 To mmax

If MWDMD(n) >= MD(i) Then

TVD(i) = MWDTV(n - 1) + ((MD(i) - MWDMD(n - 1)) \* (MWDTV(n) - MWDTV(n - 1)) / (MWDMD(n) - MWDMD(n - 1)))

Worksheets("2.Wellpath").Cells(i + 3, 16).Value = TVD(i)

Exit For

End If

Next n

$Tf(i) = SurfTemp + (TVD(i) * gg / 100)$

Worksheets("2.Wellpath").Cells(i + 3, 18).Value = Tf(i)

Next i

Worksheets("4.Initialization").Cells(5, 4).Value = Worksheets("2.Wellpath").Cells(13, 4)

Worksheets("4.Initialization").Cells(5, 5).Value = Worksheets("2.Wellpath").Cells(13, 5)

Worksheets("4.Initialization").Cells(5, 6).Value = Worksheets("2.Wellpath").Cells(13, 6)

Worksheets("4.Initialization").Cells(5, 7).Value = Worksheets("2.Wellpath").Cells(13, 7)

Worksheets("4.Initialization").Cells(6, 4).Value = Worksheets("2.Wellpath").Cells(14, 4)

Worksheets("4.Initialization").Cells(6, 5).Value = Worksheets("2.Wellpath").Cells(14, 5)

Worksheets("4.Initialization").Cells(6, 6).Value = Worksheets("2.Wellpath").Cells(14, 6)

Worksheets("4.Initialization").Cells(6, 7).Value = Worksheets("2.Wellpath").Cells(14, 7)

End Sub

'=====WELL PATH GENERATOR END=====

## A-2 Well Detail Module

'=====Well Details Module Starts=====

Sub Welldetail\_Button1\_Click()

Dim CS As Integer 'Current section

Dim section(1 To 3) As Integer 'at which section

Dim sectionTD(1 To 3) As Double 'Section TD

Dim bitsize(1 To 3) As Double 'Bitsize

Dim Installation(1 To 3) As Integer 'Casing installed or not

Dim COD(1 To 3) As Double	'Casing OD
Dim CID(1 To 3) As Double	'Casing ID
Dim Cthk(1 To 3) As Double	'Casing Thickness
Dim Dp(1 To 5) As Double	'Drillpipe ID(ft.)
Dim DA2(1 To 5) As Double	'Outer annulus diameter(ft.)
Dim DA1(1 To 5) As Double	'Inner annulus diameter(ft.)
Dim BHAOD(1 To 2) As Double	
Dim BHAID(1 To 2) As Double	
Dim BHAthk(1 To 2) As Double	
Dim DClength As Double	'Drill collar length
Dim BHAMD As Double	'Top of drill collar MD
Dim HWDPOD As Double	'HWDP outer diameter
Dim HWDPID As Double	'HWDP inner diameter
Dim HWDPL As Double	'HWDP length
Dim HWDPMMD As Double	'MD of top of HWDP
Dim wdiiii As Integer	
Dim iiMD As Integer	
Dim rc(1 To 3) As Double	
Dim iTD(1 To 3) As Double	
Dim iMD As Double	
Dim rfa As Double	
Dim wdn As Integer	
Dim wdn As Integer	
Dim wdn As Integer	



```
Dim wdimax As Integer
```

```
Dim wdi As Integer
```

```
Dim wdii As Integer
```

```
Dim wdiii As Integer
```

```
Dim wdtvd(1 To 500) As Double
```

```
Dim wdmd(1 To 500) As Double
```

```
Dim wdm As Integer
```

```
Dim wdmn As Integer
```

```
'read value
```

```
CS = Worksheets("3.Welldetail").Cells(3, 6).Value
```

```
wdimax = Worksheets("2.Wellpath").Cells(5, 10).Value
```

```
Worksheets("2.Wellpath").Cells(1, 19).Value = "rc1"
```

```
Worksheets("2.Wellpath").Cells(2, 19).Value = "m."
```

```
Worksheets("2.Wellpath").Cells(3, 19).Value = 0
```

```
Worksheets("2.Wellpath").Cells(1, 20).Value = "rfa"
```

```
Worksheets("2.Wellpath").Cells(2, 20).Value = "m."
```

```
Worksheets("2.Wellpath").Cells(3, 20).Value = 0
```

```
Worksheets("2.Wellpath").Cells(1, 21).Value = "rd"
```

```
Worksheets("2.Wellpath").Cells(2, 21).Value = "m."
```

```
Worksheets("2.Wellpath").Cells(3, 21).Value = 0
```

```
Worksheets("2.Wellpath").Cells(1, 22).Value = "DP-OR"
```

```
Worksheets("2.Wellpath").Cells(2, 22).Value = "m."
```

```
Worksheets("2.Wellpath").Cells(3, 22).Value = 0
```

```
Worksheets("2.Wellpath").Cells(1, 23).Value = "Ad"
```

Worksheets("2.Wellpath").Cells(2, 23).Value = "sqm."  
Worksheets("2.Wellpath").Cells(3, 23).Value = 0  
Worksheets("2.Wellpath").Cells(1, 24).Value = "Aa"  
Worksheets("2.Wellpath").Cells(2, 24).Value = "sqm."  
Worksheets("2.Wellpath").Cells(3, 24).Value = 0  
Worksheets("2.Wellpath").Cells(1, 30).Value = "DA2"  
Worksheets("2.Wellpath").Cells(2, 30).Value = "ft"  
Worksheets("2.Wellpath").Cells(3, 30).Value = 0  
Worksheets("2.Wellpath").Cells(1, 31).Value = "DA1"  
Worksheets("2.Wellpath").Cells(2, 31).Value = "ft"  
Worksheets("2.Wellpath").Cells(3, 31).Value = 0  
Worksheets("2.Wellpath").Cells(1, 32).Value = "DP"  
Worksheets("2.Wellpath").Cells(2, 32).Value = "ft"  
Worksheets("2.Wellpath").Cells(3, 32).Value = 0  
bitsize(1) = Worksheets("3.Welldetail").Cells(7, 6).Value  
wdimax = Worksheets("2.Wellpath").Cells(5, 10).Value  
BHAOD(1) = Worksheets("3.Welldetail").Cells(34, 6).Value  
BHAOD(2) = Worksheets("3.Welldetail").Cells(40, 6).Value  
BHAID(1) = Worksheets("3.Welldetail").Cells(35, 6).Value  
BHAID(2) = Worksheets("3.Welldetail").Cells(41, 6).Value  
BHAtk(1) = Worksheets("3.Welldetail").Cells(36, 6).Value  
BHAtk(2) = Worksheets("3.Welldetail").Cells(42, 6).Value  
DClength = Worksheets("3.Welldetail").Cells(43, 6).Value  
HWDDPOD = Worksheets("3.Welldetail").Cells(47, 6).Value

HWDPID = Worksheets("3.Welldetail").Cells(48, 6).Value

HWDPDPL = Worksheets("3.Welldetail").Cells(50, 6).Value

For wdm = 1 To wdimax

wdtvd(wdm) = Worksheets("2.Wellpath").Cells(wdm + 3, 16).Value

wmdm(wdm) = Worksheets("2.Wellpath").Cells(wdm + 3, 15).Value

Next wdm

'to obtain rc and rfa

Select Case CS

Case 1

rc(1) = bitsize(1) \* 0.5 \* 2.541 \* 0.01

DA2(1) = bitsize(1)

Cthk(1) = 0

For wdn = 1 To wdimax

Worksheets("2.Wellpath").Cells(wdn + 3, 19).Value = rc(1)

Worksheets("2.Wellpath").Cells(wdn + 3, 30).Value = DA2(1)

Next wdn

Case 2

bitsize(2) = Worksheets("3.Welldetail").Cells(15, 6).Value

sectionTD(1) = Worksheets("3.Welldetail").Cells(6, 6).Value

Cthk(1) = Worksheets("3.Welldetail").Cells(11, 6).Value \* 2.541 \* 0.01

rc(1) = Worksheets("3.Welldetail").Cells(10, 6).Value \* 0.5 \* 2.541 \* 0.01

rc(2) = bitsize(2) \* 0.5 \* 2.541 \* 0.01

DA2(1) = Worksheets("3.Welldetail").Cells(10, 6).Value

DA2(2) = bitsize(2)

For wdi = 1 To wdimax

    If wdtvd(wdi) >= sectionTD(1) Then

        Exit For

    End If

    iTD(1) = wdi

Next wdi

For wdn = 1 To iTD(1)

    Worksheets("2.Wellpath").Cells(wdn + 3, 19).Value = rc(1)

    Worksheets("2.Wellpath").Cells(wdn + 3, 30).Value = DA2(1)

Next wdn

For wdn = iTD(1) + 1 To wdimax

    Worksheets("2.Wellpath").Cells(wdn + 3, 19).Value = rc(2)

    Worksheets("2.Wellpath").Cells(wdn + 3, 30).Value = DA2(2)

Next wdn

Case 3

bitsize(3) = Worksheets("3.Welldetail").Cells(23, 6).Value

sectionTD(1) = Worksheets("3.Welldetail").Cells(6, 6).Value

sectionTD(2) = Worksheets("3.Welldetail").Cells(14, 6).Value

Cthk(1) = Worksheets("3.Welldetail").Cells(11, 6).Value \* 2.541 \* 0.01

Cthk(2) = Worksheets("3.Welldetail").Cells(19, 6).Value \* 2.541 \* 0.01

rc(1) = Worksheets("3.Welldetail").Cells(10, 6).Value \* 0.5 \* 2.541 \* 0.01

DA2(1) = Worksheets("3.Welldetail").Cells(10, 6).Value

rc(2) = Worksheets("3.Welldetail").Cells(18, 6).Value \* 0.5 \* 2.541 \* 0.01

DA2(2) = Worksheets("3.Welldetail").Cells(18, 6).Value

```

rc(3) = bitsize(3) * 0.5 * 2.541 * 0.01

DA2(3) = bitsize(3)

rfa = rc(1) + Cthk(1) - rc(2) - Cthk(2)

For wdi = 1 To wdimax

    If wdtvd(wdi) >= sectionTD(1) Then

        Exit For

    End If

    iTD(1) = wdi

Next wdi

For wdii = 1 To wdimax

    If wdtvd(wdii) >= sectionTD(2) Then

        Exit For

    End If

    iTD(2) = wdii

Next wdii

For wdn = 1 To iTD(1)

    Worksheets("2.Wellpath").Cells(wdn + 3, 20).Value = rfa

Next wdn

For wdn = 1 To iTD(2)

    Worksheets("2.Wellpath").Cells(wdn + 3, 19).Value = rc(2)

    Worksheets("2.Wellpath").Cells(wdn + 3, 30).Value = DA2(2)

Next wdn

For wdn = iTD(2) + 1 To wdimax

```

Worksheets("2.Wellpath").Cells(wdn + 3, 19).Value = rc(3)

Worksheets("2.Wellpath").Cells(wdn + 3, 30).Value = DA2(3)

Next wdn

End Select

'to obtain rd

BHAMD = wdmd(wdimax) - DClength

HWDPMD = wdmd(wdimax) - DClength - HWDPL

For wdiii = 1 To wdimax

If wdmd(wdiii) >= BHAMD Then

Exit For

End If

iMD = wdiii

Next wdiii

For wdiiii = 1 To wdimax

If wdmd(wdiiii) >= HWDPMD Then

Exit For

End If

iiMD = wdiiii

Next wdiiii

For wdnnn = 1 To iiMD

Worksheets("2.Wellpath").Cells(wdnnn + 3, 21).Value = BHAID(1) \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 22).Value = BHAOD(1) \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 31).Value = BHAOD(1)

Worksheets("2.Wellpath").Cells(wdnnn + 3, 32).Value = BHAID(1)

Next wdnnn

For wdnnn = iiMD + 1 To iMD

Worksheets("2.Wellpath").Cells(wdnnn + 3, 21).Value = HWDPID \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 22).Value = HWDPOD \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 31).Value = HWDPOD

Worksheets("2.Wellpath").Cells(wdnnn + 3, 32).Value = HWDPID

Next wdnnn

For wdnnn = iMD + 1 To wdimax

Worksheets("2.Wellpath").Cells(wdnnn + 3, 21).Value = BHAID(2) \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 22).Value = BHAOD(2) \* 0.5 \* 2.541 \*  
0.01

Worksheets("2.Wellpath").Cells(wdnnn + 3, 31).Value = BHAOD(2)

Worksheets("2.Wellpath").Cells(wdnnn + 3, 32).Value = BHAID(2)

Next wdnnn

'to obtain Ad and Aa

For wdmm = 1 To wdimax

Worksheets("2.Wellpath").Cells(wdmm + 3, 23).Value =  
((Worksheets("2.Wellpath").Cells(wdmm + 3, 21).Value) ^ 2) \* 3.14

```
Worksheets("2.Wellpath").Cells(wdmm + 3, 24).Value =
(((Worksheets("2.Wellpath").Cells(wdmm + 3, 19).Value) ^ 2) * 3.14) -
(((Worksheets("2.Wellpath").Cells(wdmm + 3, 22).Value) ^ 2) * 3.14)
```

```
Next wdmm
```

```
End Sub
```

```
'=====Well Details Module Ends=====
```

### A-3 Initialization Module

```
'=====Temperature Initialization Starts=====
```

```
Sub litialization_Button1_Click()
```

```
Dim imax As Integer      'Total number of gridblocks along hole
```

```
Dim Tin As Double       'Inlet temperature while measureing BHCT
```

```
Dim Tout As Double     'Outlet temperaure while measuring BHCT
```

```
Dim BHCT As Double     'Bottom hole circulating temperature from MWD
temperature log
```

```
Dim TD(1 To 500) As Double 'Assumed drill pipe fluid temperature while
measuring BHCT
```

```
Dim TA(1 To 500) As Double 'Assumed annulus fluid temperature while measuring
BHCT
```

```
Dim ti As Integer
```

```
'read value
```

```
imax = Worksheets("2.Wellpath").Cells(5, 10).Value
```

```
BHCT = Worksheets("4.Initialization").Cells(5, 7).Value
```

```
Tin = Worksheets("4.Initialization").Cells(5, 8).Value
```

```
Tout = Worksheets("4.Initialization").Cells(5, 9).Value
```



'obtain Td0 and Ta0

Worksheets("2.Wellpath").Cells(1, 25).Value = "Td0"

Worksheets("2.Wellpath").Cells(2, 25).Value = "oC"

Worksheets("2.Wellpath").Cells(3, 25).Value = Tin

Worksheets("2.Wellpath").Cells(1, 26).Value = "Ta0"

Worksheets("2.Wellpath").Cells(2, 26).Value = "oC"

Worksheets("2.Wellpath").Cells(3, 26).Value = Tout

For ti = 1 To imax

TD(ti) = Tin + (ti \* ((BHCT - Tin) / imax))

TA(ti) = Tout + (ti \* ((BHCT - Tout) / imax))

Worksheets("2.Wellpath").Cells(ti + 3, 25).Value = TD(ti)

Worksheets("2.Wellpath").Cells(ti + 3, 26).Value = TA(ti)

Next ti

End Sub

'=====Temperature Initialization Ends=====

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#### A-4 Fluid Module

'=====Fluid Properties Section Starts=====

Sub Fluid\_Button1\_Click()

Dim density As Double 'Drilling fluid density from time log in S.G.

Dim ECD As Double 'ECD from time log in S.G.

Dim flowrate As Double 'flowrate from time log in lpm.

Dim gpm As Double 'flowrate from time log in gpm.

Dim Vd(1 To 500) As Double 'Drill pipe fluid velocity along hole

Dim Va(1 To 500) As Double	'Annulus fluid velocity along hole
Dim SF As Double	'Solids fraction parameter
Dim Cp As Double	'Specific heat capacity from Wooley correlation
Dim CpSI As Double	'Specific heat capacity from Wooley correlation in SI unit
Dim k As Double	'Heat conductivity from Wooley correlation
Dim kSI As Double	'Heat conductivity from Wooley correlation in SI unit
Dim r(1 To 6) As Double	'Viscosimeter reading, R1@600rpm, R6@3rpm
Dim PV As Double	'Plastic viscosity
Dim YP As Double	'Yield point
Dim np As Double	'n exponent of drillpipe fluid
Dim kp As Double	'k consistensy index of drillpipe fluid
Dim na As Double	'n exponent of annular fluid
Dim ka As Double	'k consistancy of annular fluid
Dim uep(1 To 500) As Double	'Effective viscosity for drillpipe fluid
Dim uea(1 To 500) As Double	'Effective viscosity for annular fluid
Dim Nrep(1 To 500) As Double	'Reynolds Number of drillpipe fluid
Dim Nrea(1 To 500) As Double	'Reynolds Number of annular fluid
Dim fp(1 To 500) As Double	'friction factor of drillpipe fluid
Dim fa(1 To 500) As Double	'friction factor of annular fluid
Dim Prp(1 To 500) As Double	'Prandt number of drillpipe fluid
Dim Pra(1 To 500) As Double	'Prandt number of annular fluid
Dim Nup(1 To 500) As Double	'Nusselt number of drillpipe fluid
Dim Nuap(1 To 500) As Double	'Nusselt number of annular fluid (AN VS DP)

Dim Nuaf(1 To 500) As Double	'Nusselt number of annular fluid (AN VS Formation)
Dim DBD(1 To 500) As Double	'Di/Do
Dim DDA(1 To 6) As Double	'Di/Do Table for laminar constant surface temp. with one side isothermal, another side adiabatic
Dim DDB(1 To 8) As Double	'Di/Do Table for laminar constant surface heat flux both sides
Dim NuiA(1 To 6) As Double	'Nui Table for laminar constant surface temp. with one side isothermal, another side adiabatic
Dim NuiB(1 To 8) As Double	'Nui Table for laminar constant surface heat flux both sides
Dim NuoA(1 To 6) As Double	'Nuo Table for laminar constant surface temp. with one side isothermal, another side adiabatic
Dim NuoB(1 To 8) As Double	'Nuo Table for laminar constant surface heat flux both sides
Dim Dh(1 To 500) As Double	'Hydraulic diameter
Dim hpa(1 To 500) As Double	'Convective heat transfer coeff. of flowing drillpipe fluid to annulus
Dim hap(1 To 500) As Double	'Convective heat transfer coeff. of flowing annular fluid to drillpipe
Dim haf(1 To 500) As Double	'Convective heat transfer coeff. of flowing annular fluid to surrounding formation
Dim U(1 To 500) As Double	'overall heat transfer coeff. across the drill pipe
Dim Dp(1 To 500) As Double	'Dh of Drillpipe
Dim BM As Integer	'WBM or SDF
Dim BMP As Double	
Dim ff As Integer	

Dim imax As Integer

Dim fh As Integer

Dim fhselect As Integer

Dim fhh As Integer

Dim Tw(1 To 17) As Double

Dim Denw(1 To 17) As Double

Dim Cpw(1 To 17) As Double

Dim kw(1 To 17) As Double

Dim visw(1 To 17) As Double

Dim Prw(1 To 17) As Double

Dim eimax As Integer

eimax = Worksheets("2.Wellpath").Cells(5, 10).Value

Dim T0D(0 To 500) As Double

Dim T0A(0 To 500) As Double

Dim peimax As Integer

Dim ii As Integer

Dim deimax As Integer

Dim gg As Integer

Dim jj As Integer

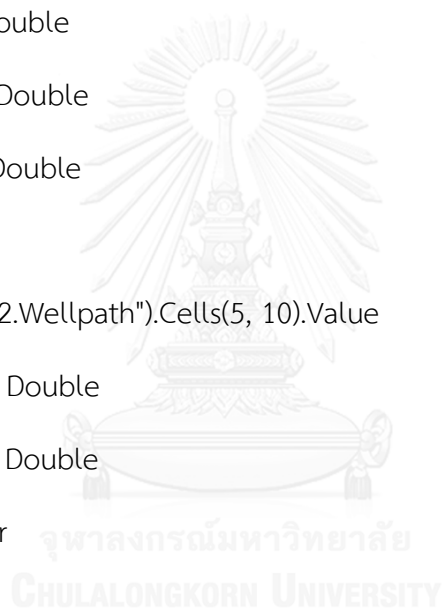
Dim mm As Integer

Dim kk As Integer

Dim Cpia(1 To 500) As Double

Dim kia(1 To 500) As Double

Dim visia(1 To 500) As Double



Dim Pria(1 To 500) As Double

Dim Cpip(1 To 500) As Double

Dim kip(1 To 500) As Double

Dim visip(1 To 500) As Double

Dim Prip(1 To 500) As Double

'read value

density = Worksheets("5.Fluid").Cells(4, 5).Value

ECD = Worksheets("5.Fluid").Cells(5, 5).Value

flowrate = Worksheets("5.Fluid").Cells(6, 5).Value

gpm = Worksheets("5.Fluid").Cells(6, 5).Value \* 0.264172

imax = Worksheets("2.Wellpath").Cells(5, 10).Value

BM = Worksheets("5.Fluid").Cells(7, 5).Value

'R(1) = Worksheets("5.Fluid").Cells(17, 5).Value

'R(2) = Worksheets("5.Fluid").Cells(17, 6).Value

r(3) = Worksheets("5.Fluid").Cells(18, 5).Value

'R(4) = Worksheets("5.Fluid").Cells(18, 6).Value

r(5) = Worksheets("5.Fluid").Cells(19, 5).Value

'R(6) = Worksheets("5.Fluid").Cells(19, 6).Value

'Annular convective heat transfer coeff. table for laminar flow

'Table for laminar constant surface temp. with one side isothermal, another side  
adiabatic

DDA(1) = 0

DDA(2) = 0.05

DDA(3) = 0.1

$$DDA(4) = 0.25$$

$$DDA(5) = 0.5$$

$$DDA(6) = 1$$

$$NuiA(1) = 17.46$$

$$NuiA(2) = 17.46$$

$$NuiA(3) = 11.56$$

$$NuiA(4) = 7.37$$

$$NuiA(5) = 5.74$$

$$NuiA(6) = 4.86$$

$$NuoA(1) = 3.66$$

$$NuoA(2) = 4.06$$

$$NuoA(3) = 4.11$$

$$NuoA(4) = 4.23$$

$$NuoA(5) = 4.43$$

$$NuoA(6) = 4.86$$



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Table for laminar constant surface heat flux both sides

$$DDB(1) = 0$$

$$DDB(2) = 0.05$$

$$DDB(3) = 0.1$$

$$DDB(4) = 0.2$$

$$DDB(5) = 0.4$$

$$DDB(6) = 0.6$$

$$DDB(7) = 0.8$$

$$DDB(8) = 1$$

$$\text{NuiB}(1) = 17.81$$

$$\text{NuiB}(2) = 17.81$$

$$\text{NuiB}(3) = 11.91$$

$$\text{NuiB}(4) = 8.499$$

$$\text{NuiB}(5) = 6.583$$

$$\text{NuiB}(6) = 5.912$$

$$\text{NuiB}(7) = 5.58$$

$$\text{NuiB}(8) = 5.385$$

$$\text{NuoB}(1) = 4.364$$

$$\text{NuoB}(2) = 4.792$$

$$\text{NuoB}(3) = 4.834$$

$$\text{NuoB}(4) = 4.833$$

$$\text{NuoB}(5) = 4.979$$

$$\text{NuoB}(6) = 5.099$$

$$\text{NuoB}(7) = 5.24$$

$$\text{NuoB}(8) = 5.385$$



‘Seawater thermophysical properties

$$T_w(1) = 0$$

$$T_w(2) = 10$$

$$T_w(3) = 20$$

$$T_w(4) = 30$$

$$T_w(5) = 40$$

$$T_w(6) = 50$$

$$T_w(7) = 60$$

$$Tw(8) = 70$$

$$Tw(9) = 80$$

$$Tw(10) = 90$$

$$Tw(11) = 100$$

$$Tw(12) = 110$$

$$Tw(13) = 120$$

$$Tw(14) = 130$$

$$Tw(15) = 140$$

$$Tw(16) = 150$$

$$Denw(1) = 1007.9$$

$$Denw(2) = 1007.4$$

$$Denw(3) = 1005.7$$

$$Denw(4) = 1003.1$$

$$Denw(5) = 999.7$$

$$Denw(6) = 995.5$$

$$Denw(7) = 990.6$$

$$Denw(8) = 985.1$$

$$Denw(9) = 979.1$$

$$Denw(10) = 972.6$$

$$Denw(11) = 965.7$$

$$Denw(12) = 958.3$$

$$Denw(13) = 950.6$$

$$Denw(14) = 942.4502$$

$$Denw(15) = 933.8797$$





$$\text{Denw}(16) = 924.8877$$

$$\text{Cpw}(1) = 4142.1$$

$$\text{Cpw}(2) = 4136.7$$

$$\text{Cpw}(3) = 4132.8$$

$$\text{Cpw}(4) = 4130.5$$

$$\text{Cpw}(5) = 4129.7$$

$$\text{Cpw}(6) = 4130.8$$

$$\text{Cpw}(7) = 4133.7$$

$$\text{Cpw}(8) = 4138.5$$

$$\text{Cpw}(9) = 4145.3$$

$$\text{Cpw}(10) = 4154.2$$

$$\text{Cpw}(11) = 4165.4$$

$$\text{Cpw}(12) = 4178.8$$

$$\text{Cpw}(13) = 4194.7$$

$$\text{Cpw}(14) = 4210.6$$

$$\text{Cpw}(15) = 4226.5$$

$$\text{Cpw}(16) = 4242.4$$

$$\text{kw}(1) = 0.571$$

$$\text{kw}(2) = 0.588$$

$$\text{kw}(3) = 0.603$$

$$\text{kw}(4) = 0.617$$

$$\text{kw}(5) = 0.629$$

$$\text{kw}(6) = 0.64$$

$$\text{kw}(7) = 0.65$$



$$kw(8) = 0.658$$

$$kw(9) = 0.665$$

$$kw(10) = 0.671$$

$$kw(11) = 0.675$$

$$kw(12) = 0.679$$

$$kw(13) = 0.681$$

$$kw(14) = 0.685$$

$$kw(15) = 0.683$$

$$kw(16) = 0.681$$

Seawater vis in centipoise

$$visw(1) = 1.82$$

$$visw(2) = 1.33$$

$$visw(3) = 1.021$$

$$visw(4) = 0.814$$

$$visw(5) = 0.667$$

$$visw(6) = 0.56$$

$$visw(7) = 0.478$$

$$visw(8) = 0.414$$

$$visw(9) = 0.364$$

$$visw(10) = 0.323$$

$$visw(11) = 0.289$$

$$visw(12) = 0.262$$

$$visw(13) = 0.238$$

$$visw(14) = 0.218$$



$$\text{visw}(15) = 0.201$$

$$\text{visw}(16) = 0.187$$

$$\text{Prw}(1) = 13.21$$

$$\text{Prw}(2) = 9.36$$

$$\text{Prw}(3) = 7$$

$$\text{Prw}(4) = 5.45$$

$$\text{Prw}(5) = 4.38$$

$$\text{Prw}(6) = 3.61$$

$$\text{Prw}(7) = 3.04$$

$$\text{Prw}(8) = 2.6$$

$$\text{Prw}(9) = 2.27$$

$$\text{Prw}(10) = 2$$

$$\text{Prw}(11) = 1.78$$

$$\text{Prw}(12) = 1.61$$

$$\text{Prw}(13) = 1.47$$

$$\text{Prw}(14) = 1.45$$

$$\text{Prw}(15) = 1.44$$

$$\text{Prw}(16) = 1.43$$

'Obtain T0D and T0A

peimax = Worksheets("4.Initialization").Cells(8, 4).Value

deimax = eimax - peimax

For ii = 0 To peimax

T0D(ii) = Worksheets("4.Initialization").Cells(12 + ii, 1).Value

T0A(ii) = Worksheets("4.Initialization").Cells(14 + ii + peimax, 1).Value



Next ii

Select Case deimax

Case 1

$$T0A(eimax) = (2 * T0A(peimax)) - T0A(peimax - 1)$$

$$T0D(eimax) = (2 * T0D(peimax)) - T0D(peimax - 1)$$

Case Else

$$T0A(eimax - 1) = (2 * T0A(peimax)) - T0A(peimax - 1)$$

$$T0A(eimax) = (2 * T0A(eimax - 1)) - T0A(peimax)$$

$$T0D(eimax - 1) = (2 * T0D(peimax)) - T0D(peimax - 1)$$

$$T0D(eimax) = (2 * T0D(eimax - 1)) - T0D(peimax)$$

End Select

'obtain PV and YP

PV = Worksheets("5.Fluid").Cells(13, 5).Value

YP = Worksheets("5.Fluid").Cells(14, 5).Value

r(2) = PV + YP

r(1) = (2 \* r(2)) - YP

r(4) = r(2) - (((2 \* r(1)) - r(2)) / 3)

If BM = 1 Then

r(6) = 5

BMP = 1

Else: r(6) = 9

BMP = 1

End If

Worksheets("5.Fluid").Cells(17, 5).Value = r(1)

Worksheets("5.Fluid").Cells(17, 6).Value = r(2)

Worksheets("5.Fluid").Cells(18, 6).Value = r(4)

Worksheets("5.Fluid").Cells(19, 6).Value = r(6)

'obtain n and k

$np = 3.32 * 0.4343 * \text{Log}(r(1) / r(2))$

$kp = 5.11 * r(1) / (1022 ^ \wedge np)$

$na = 0.657 * 0.4343 * \text{Log}(r(4) / r(6))$

If na < 0 Then na = na \* -1

$ka = 5.11 * r(6) / (5.11 ^ \wedge na)$

Worksheets("5.Fluid").Cells(21, 5).Value = np

Worksheets("5.Fluid").Cells(22, 5).Value = kp

Worksheets("5.Fluid").Cells(21, 9).Value = na

Worksheets("5.Fluid").Cells(22, 9).Value = ka

'put data in Wellpath

Worksheets("2.Wellpath").Cells(1, 27).Value = "Vd"

Worksheets("2.Wellpath").Cells(2, 27).Value = "m/s"

Worksheets("2.Wellpath").Cells(3, 27).Value = 0

Worksheets("2.Wellpath").Cells(1, 28).Value = "Va"

Worksheets("2.Wellpath").Cells(2, 28).Value = "m/s"

Worksheets("2.Wellpath").Cells(3, 28).Value = 0

Worksheets("2.Wellpath").Cells(1, 29).Value = "Density"

Worksheets("2.Wellpath").Cells(2, 29).Value = "kg/cu.m."

Worksheets("2.Wellpath").Cells(3, 29).Value = density \* 1000

'present data needed for fluid section calculation in Fluid section

Worksheets("5.Fluid").Cells(1, 12).Value = "i"

Worksheets("5.Fluid").Cells(3, 12).Value = 0

Worksheets("5.Fluid").Cells(1, 13).Value = "L"

Worksheets("5.Fluid").Cells(2, 13).Value = "ft"

Worksheets("5.Fluid").Cells(3, 13).Value = 0

Worksheets("5.Fluid").Cells(1, 14).Value = "Density"

Worksheets("5.Fluid").Cells(2, 14).Value = "ppg."

Worksheets("5.Fluid").Cells(3, 14).Value = density \* 8.345406

Worksheets("5.Fluid").Cells(1, 15).Value = "DA2"

Worksheets("5.Fluid").Cells(2, 15).Value = "in"

Worksheets("5.Fluid").Cells(3, 15).Value = 0

Worksheets("5.Fluid").Cells(1, 16).Value = "DA1"

Worksheets("5.Fluid").Cells(2, 16).Value = "in"

Worksheets("5.Fluid").Cells(3, 16).Value = 0

Worksheets("5.Fluid").Cells(1, 17).Value = "DP"

Worksheets("5.Fluid").Cells(2, 17).Value = "in"

Worksheets("5.Fluid").Cells(3, 17).Value = 0

Worksheets("5.Fluid").Cells(1, 18).Value = "Vp"

Worksheets("5.Fluid").Cells(2, 18).Value = "ft/min"

Worksheets("5.Fluid").Cells(3, 18).Value = 0

Worksheets("5.Fluid").Cells(1, 19).Value = "Va"

Worksheets("5.Fluid").Cells(2, 19).Value = "ft/min"

Worksheets("5.Fluid").Cells(3, 19).Value = 0

Worksheets("5.Fluid").Cells(1, 20).Value = "uep"

Worksheets("5.Fluid").Cells(2, 20).Value = "cP"

Worksheets("5.Fluid").Cells(3, 20).Value = 0

Worksheets("5.Fluid").Cells(1, 21).Value = "uea"

Worksheets("5.Fluid").Cells(2, 21).Value = "cP"

Worksheets("5.Fluid").Cells(3, 21).Value = 0

Worksheets("5.Fluid").Cells(1, 22).Value = "Nrep"

Worksheets("5.Fluid").Cells(3, 22).Value = 0

Worksheets("5.Fluid").Cells(1, 23).Value = "Nrea"

Worksheets("5.Fluid").Cells(3, 23).Value = 0

Worksheets("5.Fluid").Cells(1, 24).Value = "fp"

Worksheets("5.Fluid").Cells(3, 24).Value = 0

Worksheets("5.Fluid").Cells(1, 25).Value = "fa"

Worksheets("5.Fluid").Cells(3, 25).Value = 0

Worksheets("5.Fluid").Cells(1, 26).Value = "Plp"

Worksheets("5.Fluid").Cells(2, 26).Value = "psi."

Worksheets("5.Fluid").Cells(3, 26).Value = 0

Worksheets("5.Fluid").Cells(1, 27).Value = "Pla"

Worksheets("5.Fluid").Cells(2, 27).Value = "psi."

Worksheets("5.Fluid").Cells(3, 27).Value = 0

Worksheets("5.Fluid").Cells(1, 28).Value = "Prp"

Worksheets("5.Fluid").Cells(3, 28).Value = 0

Worksheets("5.Fluid").Cells(1, 29).Value = "Pra"

Worksheets("5.Fluid").Cells(3, 29).Value = 0

```

Worksheets("5.Fluid").Cells(1, 30).Value = "Nup"
Worksheets("5.Fluid").Cells(3, 30).Value = 0
Worksheets("5.Fluid").Cells(1, 31).Value = "Nuap"
Worksheets("5.Fluid").Cells(3, 31).Value = 0
Worksheets("5.Fluid").Cells(1, 32).Value = "Nuaf"
Worksheets("5.Fluid").Cells(3, 32).Value = 0
Worksheets("5.Fluid").Cells(1, 33).Value = "hpa"
Worksheets("5.Fluid").Cells(2, 33).Value = "W/m^2K"
Worksheets("5.Fluid").Cells(3, 33).Value = 0
Worksheets("5.Fluid").Cells(1, 34).Value = "hap"
Worksheets("5.Fluid").Cells(2, 34).Value = "W/m^2K"
Worksheets("5.Fluid").Cells(3, 34).Value = 0
Worksheets("5.Fluid").Cells(1, 35).Value = "U"
Worksheets("5.Fluid").Cells(2, 35).Value = "W/m^2K"
Worksheets("5.Fluid").Cells(3, 35).Value = 0
Worksheets("5.Fluid").Cells(1, 36).Value = "haf"
Worksheets("5.Fluid").Cells(2, 36).Value = "W/m^2K"
Worksheets("5.Fluid").Cells(3, 36).Value = 0

'obtain Cp and k
If BM = 2 Then
    If density * 8.33 < 10.3 Then
        SF = 0.0798 * ((density * 8.33) - 8.33)
    Else: SF = 0.0318 * ((density * 8.33) - 10.3) + 0.162
    End If

```



```

Cp = 1 - (0.777 * SF)
k = 0.399 + (9.6 * SF)
Worksheets("5.Fluid").Cells(9, 5).Value = Cp
Worksheets("5.Fluid").Cells(10, 5).Value = k
CpSI = Worksheets("5.Fluid").Cells(9, 5).Value * 4184
kSI = Worksheets("5.Fluid").Cells(10, 5).Value * 1.730734666
Worksheets("5.Fluid").Cells(9, 9).Value = CpSI
Worksheets("5.Fluid").Cells(10, 9).Value = kSI
Else
For gg = 1 To imax
  For jj = 1 To 17
    If T0A(gg) <= Tw(jj) Then
      Cpia(gg) = Cpw(jj)
      kia(gg) = kw(jj)
      visia(gg) = visw(jj)
      Pria(gg) = Prw(jj)
    Exit For
  End If
Next jj
Next gg

For mm = 1 To imax
  For kk = 1 To 17
    If TOD(mm) <= Tw(kk) Then

```

Cpip(mm) = Cpw(kk)

kip(mm) = kw(kk)

visip(mm) = visw(kk)

Prip(mm) = Prw(kk)

Exit For

End If

Next kk

Next mm

End If

'obtain Vd and Va

For ff = 1 To imax

'Create table in '2.Wellpath' as model's unit

Vd(ff) = flowrate / ((Worksheets("2.Wellpath").Cells(ff + 3, 23).Value) \* 60 \* 1000)

Va(ff) = flowrate / ((Worksheets("2.Wellpath").Cells(ff + 3, 24).Value) \* 60 \* 1000)

Worksheets("2.Wellpath").Cells(ff + 3, 27).Value = Vd(ff)

Worksheets("2.Wellpath").Cells(ff + 3, 28).Value = Va(ff)

Worksheets("2.Wellpath").Cells(ff + 3, 29).Value = density \* 1000

Worksheets("5.Fluid").Cells(ff + 3, 12).Value = Worksheets("2.Wellpath").Cells(ff + 3, 14).Value

Worksheets("5.Fluid").Cells(ff + 3, 13).Value = Worksheets("2.Wellpath").Cells(ff + 3, 17).Value \* 3.28084

Worksheets("5.Fluid").Cells(ff + 3, 14).Value = Worksheets("5.Fluid").Cells(4, 5).Value \* 8.345406

Worksheets("5.Fluid").Cells(ff + 3, 15).Value = Worksheets("2.Wellpath").Cells(ff + 3, 30).Value

Worksheets("5.Fluid").Cells(ff + 3, 16).Value = Worksheets("2.Wellpath").Cells(ff + 3, 31).Value

Worksheets("5.Fluid").Cells(ff + 3, 17).Value = Worksheets("2.Wellpath").Cells(ff + 3, 32).Value

'obtain  $V_p$  and  $V_a$

Worksheets("5.Fluid").Cells(ff + 3, 18).Value = 24.48 \* gpm /  
(Worksheets("5.Fluid").Cells(ff + 3, 17).Value ^ 2)

Worksheets("5.Fluid").Cells(ff + 3, 19).Value = 24.48 \* gpm /  
((Worksheets("5.Fluid").Cells(ff + 3, 15).Value ^ 2) - (Worksheets("5.Fluid").Cells(ff + 3, 16).Value ^ 2))

'obtain effective viscosity

If BM = 2 Then

Worksheets("5.Fluid").Cells(ff + 3, 20).Value = 100 \* (((3 \* np) + 1) / (4 \* np)) ^  
np) \* kp \* ((1.6 \* Worksheets("5.Fluid").Cells(ff + 3, 18).Value /  
Worksheets("5.Fluid").Cells(ff + 3, 17).Value) ^ (np - 1))

Worksheets("5.Fluid").Cells(ff + 3, 21).Value = 100 \* ka \* ((2.4 \*  
Worksheets("5.Fluid").Cells(ff + 3, 19).Value / (Worksheets("5.Fluid").Cells(ff + 3,  
15).Value - Worksheets("5.Fluid").Cells(ff + 3, 16).Value)) ^ (na - 1)) \* (((2 \* na) + 1) / (3  
\* na)) ^ na)

Else

Worksheets("5.Fluid").Cells(ff + 3, 20).Value = visip(ff)

Worksheets("5.Fluid").Cells(ff + 3, 21).Value = visia(ff)

```

End If

'obtain Reynolds number

Worksheets("5.Fluid").Cells(ff + 3, 22).Value = 15.467 * density * 8.33 *
Worksheets("5.Fluid").Cells(ff + 3, 18).Value * Worksheets("5.Fluid").Cells(ff + 3,
17).Value / Worksheets("5.Fluid").Cells(ff + 3, 20).Value

Worksheets("5.Fluid").Cells(ff + 3, 23).Value = 15.467 * density * 8.33 *
Worksheets("5.Fluid").Cells(ff + 3, 19).Value * (Worksheets("5.Fluid").Cells(ff + 3,
15).Value - Worksheets("5.Fluid").Cells(ff + 3, 16).Value) / Worksheets("5.Fluid").Cells(ff
+ 3, 21).Value

'Check flow regimes for drillpipe, obtain fp
If Worksheets("5.Fluid").Cells(ff + 3, 22).Value > 2100 Then

Worksheets("5.Fluid").Cells(ff + 3, 24).Value = (((0.4343 * Log(np)) + 3.93) / 50) /
(Worksheets("5.Fluid").Cells(ff + 3, 22).Value ^ ((1.75 - (0.4343 * Log(np))) / 7))

Else

Worksheets("5.Fluid").Cells(ff + 3, 24).Value = 16 / Worksheets("5.Fluid").Cells(ff
+ 3, 22).Value

End If

'Check flow regimes for annulus, obtain fa
If Worksheets("5.Fluid").Cells(ff + 3, 23).Value > 2100 Then

Worksheets("5.Fluid").Cells(ff + 3, 25).Value = (((0.4343 * Log(na)) + 3.93) / 50) /
(Worksheets("5.Fluid").Cells(ff + 3, 23).Value ^ ((1.75 - (0.4343 * Log(na))) / 7))

Else

Worksheets("5.Fluid").Cells(ff + 3, 25).Value = 24 / Worksheets("5.Fluid").Cells(ff
+ 3, 23).Value

End If

'Flowing Pressure loss

```

Worksheets("5.Fluid").Cells(ff + 3, 26).Value = density \* 8.33 \*  
 Worksheets("5.Fluid").Cells(ff + 3, 24).Value \* Worksheets("5.Fluid").Cells(ff + 3,  
 18).Value \* Worksheets("5.Fluid").Cells(ff + 3, 18).Value \* Worksheets("5.Fluid").Cells(ff  
 + 3, 13).Value / (92916 \* Worksheets("5.Fluid").Cells(ff + 3, 17).Value)

Worksheets("5.Fluid").Cells(ff + 3, 27).Value = density \* 8.33 \*  
 Worksheets("5.Fluid").Cells(ff + 3, 25).Value \* Worksheets("5.Fluid").Cells(ff + 3,  
 19).Value \* Worksheets("5.Fluid").Cells(ff + 3, 19).Value \* Worksheets("5.Fluid").Cells(ff  
 + 3, 13).Value / (92916 \* (Worksheets("5.Fluid").Cells(ff + 3, 15).Value -  
 Worksheets("5.Fluid").Cells(ff + 3, 16).Value))

'Prandtl number

If BM = 2 Then

Worksheets("5.Fluid").Cells(ff + 3, 28).Value = Worksheets("5.Fluid").Cells(ff + 3,  
 20).Value \* CpSI / (1000 \* kSI)

Worksheets("5.Fluid").Cells(ff + 3, 29).Value = Worksheets("5.Fluid").Cells(ff + 3,  
 21).Value \* CpSI / (1000 \* kSI)

Else

Worksheets("5.Fluid").Cells(ff + 3, 28).Value = Prip(ff)

Worksheets("5.Fluid").Cells(ff + 3, 29).Value = Pria(ff)

End If

'Read dimensionless values

uep(ff) = Worksheets("5.Fluid").Cells(ff + 3, 20).Value

uea(ff) = Worksheets("5.Fluid").Cells(ff + 3, 21).Value

Nrep(ff) = Worksheets("5.Fluid").Cells(ff + 3, 22).Value

Nrea(ff) = Worksheets("5.Fluid").Cells(ff + 3, 23).Value

fp(ff) = Worksheets("5.Fluid").Cells(ff + 3, 24).Value

fa(ff) = Worksheets("5.Fluid").Cells(ff + 3, 25).Value

```

Prp(ff) = Worksheets("5.Fluid").Cells(ff + 3, 28).Value

Pra(ff) = Worksheets("5.Fluid").Cells(ff + 3, 29).Value

DBD(ff) = Worksheets("5.Fluid").Cells(ff + 3, 16).Value / Worksheets("5.Fluid").Cells(ff
+ 3, 15).Value

Dh(ff) = Worksheets("5.Fluid").Cells(ff + 3, 15).Value - Worksheets("5.Fluid").Cells(ff +
3, 16).Value

'Obtain Nusselt Number of drillpipe fluid

Select Case Nrep(ff)

Case Is <= 2300

    Nup(ff) = 3.66

Case Is > 2300

    If Nrep(ff) < 10000 Then

        Nup(ff) = ((fp(ff) / 8) * (Nrep(ff) - 1000) * Prp(ff) / (1 + (12.7 * ((fp(ff) / 8) ^
0.5) * ((Prp(ff) ^ (2 / 3) - 1))))

        Else: Nup(ff) = ((fp(ff) / 8) * (Nrep(ff)) * Prp(ff) / (1.07 + (12.7 * ((fp(ff) / 8) ^
0.5) * ((Prp(ff) ^ (2 / 3) - 1))))

    End If

End Select

'Obtain Nusselt Number of annular fluid

Select Case Nrea(ff)

Case Is <= 2300

    If DDA(5) < DBD(ff) <= DDA(6) Then

        Nuap(ff) = NuiA(6) - (((NuiA(6) - NuiA(5)) * (DDA(6) - DBD(ff)) / (DDA(6) -
DDA(5))))

```

$$\text{Nuaf(ff)} = \text{NuoA}(6) - (((\text{NuoA}(6) - \text{NuoA}(5)) * (\text{DDA}(6) - \text{DBD}(ff)) / (\text{DDA}(6) - \text{DDA}(5))))$$

Elseif  $\text{DDA}(4) < \text{DBD}(ff) \leq \text{DDA}(5)$  Then

$$\text{Nuap(ff)} = \text{NuiA}(5) - (((\text{NuiA}(5) - \text{NuiA}(4)) * (\text{DDA}(5) - \text{DBD}(ff)) / (\text{DDA}(5) - \text{DDA}(4))))$$

$$\text{Nuaf(ff)} = \text{NuoA}(5) - (((\text{NuoA}(5) - \text{NuoA}(4)) * (\text{DDA}(5) - \text{DBD}(ff)) / (\text{DDA}(5) - \text{DDA}(4))))$$

Elseif  $\text{DDA}(3) < \text{DBD}(ff) \leq \text{DDA}(4)$  Then

$$\text{Nuap(ff)} = \text{NuiA}(4) - (((\text{NuiA}(4) - \text{NuiA}(3)) * (\text{DDA}(4) - \text{DBD}(ff)) / (\text{DDA}(4) - \text{DDA}(3))))$$

$$\text{Nuaf(ff)} = \text{NuoA}(4) - (((\text{NuoA}(4) - \text{NuoA}(3)) * (\text{DDA}(4) - \text{DBD}(ff)) / (\text{DDA}(4) - \text{DDA}(3))))$$

Elseif  $\text{DDA}(2) < \text{DBD}(ff) \leq \text{DDA}(3)$  Then

$$\text{Nuap(ff)} = \text{NuiA}(3) - (((\text{NuiA}(3) - \text{NuiA}(2)) * (\text{DDA}(3) - \text{DBD}(ff)) / (\text{DDA}(3) - \text{DDA}(2))))$$

$$\text{Nuaf(ff)} = \text{NuoA}(3) - (((\text{NuoA}(3) - \text{NuoA}(2)) * (\text{DDA}(3) - \text{DBD}(ff)) / (\text{DDA}(3) - \text{DDA}(2))))$$

Else:

$$\text{Nuap(ff)} = \text{NuiA}(1)$$

$$\text{Nuaf(ff)} = \text{NuoA}(1)$$

End If

Case  $Is > 2300$

If  $\text{Nrea}(ff) < 10000$  Then

$$\text{Nuap(ff)} = ((\text{fa}(ff) / 8) * (\text{Nrea}(ff) - 1000) * \text{Pra}(ff)) / (1 + (12.7 * ((\text{fa}(ff) / 8) ^ 0.5) * ((\text{Pra}(ff) ^ (2 / 3) - 1))))$$

Else:  $Nu_{ap}(ff) = ((f_a(ff) / 8) * (N_{rea}(ff)) * P_{ra}(ff)) / (1.07 + (12.7 * ((f_a(ff) / 8) ^{0.5} * ((P_{ra}(ff) ^{(2/3)} - 1))))))$

End If

$Nu_{af}(ff) = Nu_{ap}(ff)$

End Select

Worksheets("5.Fluid").Cells(ff + 3, 30).Value =  $Nu_p(ff)$

Worksheets("5.Fluid").Cells(ff + 3, 31).Value =  $Nu_{ap}(ff)$

Worksheets("5.Fluid").Cells(ff + 3, 32).Value =  $Nu_{af}(ff)$

$D_p(ff) =$  Worksheets("5.Fluid").Cells(ff + 3, 17).Value

'obtain h and U

If  $BM = 2$  Then

$h_{pa}(ff) = Nu_p(ff) * k_{SI} / (D_p(ff) * 0.3048)$

$h_{ap}(ff) = Nu_{ap}(ff) * k_{SI} / (D_h(ff) * 0.3048)$

$U(ff) = 1 / ((1 / h_{pa}(ff)) + (1 / h_{ap}(ff)))$

$h_{af}(ff) = BMP * Nu_{af}(ff) * k_{SI} / (D_h(ff) * 0.3048)$

Else

$h_{pa}(ff) = Nu_p(ff) * k_{ia}(ff) / (D_p(ff) * 0.3048)$

$h_{ap}(ff) = Nu_{ap}(ff) * k_{ip}(ff) / (D_h(ff) * 0.3048)$

$U(ff) = 1 / ((1 / h_{pa}(ff)) + (1 / h_{ap}(ff)))$

$h_{af}(ff) = BMP * Nu_{af}(ff) * k_{ia}(ff) / (D_h(ff) * 0.3048)$

End If

Worksheets("5.Fluid").Cells(ff + 3, 33).Value =  $h_{pa}(ff)$

Worksheets("5.Fluid").Cells(ff + 3, 34).Value =  $h_{ap}(ff)$

Worksheets("5.Fluid").Cells(ff + 3, 35).Value =  $U(ff)$



```
Worksheets("5.Fluid").Cells(ff + 3, 36).Value = haf(ff)

Next ff

End Sub

'=====Fluid Properties Section Ends=====
```

### A-5 Explicit Operation Module

```
'=====Explicit Operation Starts=====

Sub Explicit_Button1_Click()

Dim T0Dx(0 To 1000) As Double 'Initial Drillpipe fluid temperature
Dim T0Ax(0 To 1000) As Double 'Initial Annular fluid temperature
Dim Tfx(0 To 1000) As Double 'Surrounding formation temperature
Dim rdx(0 To 1000) As Double 'drillpipe radius in m.
Dim rax(0 To 1000) As Double 'annulus outter radius in m.
Dim Adx(0 To 1000) As Double 'Drillpipe flow area in sq.m.
Dim Aax(0 To 1000) As Double 'Annulus flow area in sq.m.
Dim Lx(0 To 1000) As Double 'gridblock length i m.
Dim Vdx(0 To 1000) As Double 'Drillpipe fluid flow velocity in m/s
Dim Vax(0 To 1000) As Double 'Annular fluid flow velocity in m/s
Dim Ux(0 To 1000) As Double 'Convective heat transfer coeff. across drillpipe
Dim hfx(0 To 1000) As Double 'Convective heat transfer coeff. between the
formation and annulus fluid
Dim tdim(0 To 1000) As Double 'Dimensionless time
Dim tempdim(0 To 1000) As Double 'Dimensionless temperature
Dim alfa As Double 'Thermal diffusivity of formation
```

Dim dqdz(0 To 1000) As Double	'dq/dz
Dim Twb(0 To 1000) As Double	'Wellbore surface temperature
Dim Twbk(0 To 1000) As Double	'Wellbore surface temperature loop=k+1
Dim ke As Double	
Dim imaxdiff As Integer	'number of imax different between current and previous interval
Dim MD(0 To 1000) As Double	
Dim TVD(0 To 1000) As Double	
Dim pBHCT As Double	
Dim t As Double	'Drilling duration
Dim dt As Double	'Time step size
Dim i(0 To 1000) As Double	'Gridblock order
Dim T0D(0 To 1000) As Double	'Initial Drillpipe fluid temperature
Dim T0A(0 To 1000) As Double	'Initial Annular fluid temperature
Dim TD(0 To 1000) As Double	'Drillpipe fluid temperature after a drilling period
Dim TA(0 To 1000) As Double	'Annular fluid temperature after a drilling period
Dim Tf(0 To 1000) As Double	'Surrounding formation temperature
Dim Tin As Double	'Inlet mud temp.
Dim Tout(0 To 20000) As Double	'Outlet mud temp.
Dim rd(0 To 10000) As Double	'drillpipe radius in m.
Dim ra(0 To 1000) As Double	'annulus outter radius in m.
Dim den As Double	'density in kg/cu.m.
Dim Cp As Double	'Specific heat capacity in J/kg*K
Dim Ad(0 To 1000) As Double	'Drillpipe flow area in sq.m.

Dim Aa(0 To 1000) As Double	'Annulus flow area in sq.m.
Dim L(0 To 1000) As Double	'gridblock length i m.
Dim Vd(0 To 1000) As Double	'Drillpipe fluid flow velocity in m/s
Dim Va(0 To 1000) As Double	'Annular fluid flow velocity in m/s
Dim U(0 To 1000) As Double	'Convective heat transfer coeff. across drillpipe
Dim hf(0 To 1000) As Double	'Convective heat transfer coeff. between the formation and annulus fluid
Dim ts As Double	'Surface Temp.
Dim bb(1 To 1000) As Double	'Conduction exponent
Dim eUd(0 To 1000) As Double	'Term U of DP
Dim eUa(0 To 1000) As Double	'Term U of AN
Dim evd(0 To 1000) As Double	'Term V of DP
Dim eva(0 To 1000) As Double	'Term V of AN
Dim ehf(0 To 1000) As Double	'Term hf of AN
Dim Pi As Double	
Dim peimax As Integer	'Previous point's eimax
Dim eey As Integer	
Dim eeym As Integer	
Dim eeymm As Integer	
Dim eeymmm As Integer	
Dim eex As Integer	
Dim eexm As Integer	
Dim eexmm As Integer	
Dim eexmmm As Integer	

Dim ea As Integer

Dim eaa As Integer

Dim ei As Integer

Dim eii As Integer

Dim eiiim As Integer

Dim eiip As Integer

Dim eiii As Integer

Dim eiiim As Integer

Dim eiip As Integer

Dim et As Integer

Dim ett As Integer

Dim eimax As Integer

Dim eimax As Integer

Dim eimaxmm As Integer

Dim eimaxmmm As Integer

Dim etmax As Integer

Dim ew As Integer

Dim ex As Integer

Dim ey As Integer

Dim ez As Integer

Dim eiiimax As Integer

Dim eiiimaxm As Integer

Dim x As Integer

Dim y As Integer



Dim s As Integer

Dim r As Integer

'Read Values from all previous tabs

i(0) = 0

eimax = Worksheets("2.Wellpath").Cells(5, 10).Value

ts = Worksheets("2.Wellpath").Cells(6, 6).Value

Tin = Worksheets("4.Initialization").Cells(5, 8).Value

peimax = Worksheets("4.Initialization").Cells(8, 4).Value

den = Worksheets("5.Fluid").Cells(4, 5).Value \* 1000

Cp = Worksheets("5.Fluid").Cells(9, 9).Value

t = Worksheets("5.Fluid").Cells(24, 5).Value

Pi = 3.14159265359

alfa = Worksheets("3.Welldetail").Cells(37, 12).Value

ke = Worksheets("3.Welldetail").Cells(34, 12).Value

Cells(4, 3).Value = den

Cells(5, 3).Value = Cp

dt = Worksheets("6.Explicit").Cells(6, 3).Value

etmax = t / dt

For ex = 1 To eimax

T0Dx(ex) = Worksheets("2.Wellpath").Cells(ex + 3, 25).Value

T0Ax(ex) = Worksheets("2.Wellpath").Cells(ex + 3, 26).Value

Tfx(ex) = Worksheets("2.Wellpath").Cells(ex + 3, 18).Value

rdx(ex) = Worksheets("5.Fluid").Cells(ex + 3, 17).Value \* 2.541 \* 0.5 \* 0.01

rax(ex) = Worksheets("5.Fluid").Cells(ex + 3, 15).Value \* 2.541 \* 0.5 \* 0.01

$$Adx(ex) = \text{Pi} * ((\text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 17).\text{Value} * 2.541 * 0.5 * 0.01) ^ 2)$$

$$Aax(ex) = \text{Pi} * (((\text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 15).\text{Value} * 2.541 * 0.5 * 0.01) ^ 2) - ((\text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 16).\text{Value} * 2.541 * 0.5 * 0.01) ^ 2))$$

$$Lx(ex) = \text{Worksheets}("2.Wellpath").\text{Cells}(ex + 3, 17).\text{Value}$$

$$Vdx(ex) = \text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 18).\text{Value} * 0.00508$$

$$Vax(ex) = \text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 19).\text{Value} * 0.00508$$

$$Ux(ex) = \text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 35).\text{Value}$$

$$hfx(ex) = \text{Worksheets}("5.Fluid").\text{Cells}(ex + 3, 36).\text{Value}$$

$$Twb(ex) = \text{Worksheets}("6.Explicit").\text{Cells}(ex + 6, 27).\text{Value}$$

$$bb(ex) = \text{Worksheets}("4.Initialization").\text{Cells}(ex + 4, 17).\text{Value}$$

$$MD(ex) = \text{Worksheets}("2.Wellpath").\text{Cells}(ex + 3, 15).\text{Value}$$

$$TVD(ex) = \text{Worksheets}("2.Wellpath").\text{Cells}(ex + 3, 16).\text{Value}$$

Next ex

$$Lx(0) = 0$$

$$L(0) = 0$$

$$TODx(0) = \text{Tin}$$

$$TOD(0) = TODx(0)$$

$$Tfx(0) = \text{ts}$$

$$Tf(0) = Tfx(0)$$

$$rdx(0) = rdx(1)$$

$$rd(0) = rdx(0)$$

$$rax(0) = rax(1)$$

$$ra(0) = rax(0)$$

$$\text{Adx}(0) = \text{Adx}(1)$$

$$\text{Ad}(0) = \text{Adx}(0)$$

$$\text{Aax}(0) = \text{Aax}(1)$$

$$\text{Aa}(0) = \text{Aax}(0)$$

$$\text{Vdx}(0) = \text{Vdx}(1)$$

$$\text{Vd}(0) = \text{Vdx}(0)$$

$$\text{Vax}(0) = \text{Vax}(1)$$

$$\text{Va}(0) = \text{Vax}(0)$$

$$\text{Ux}(0) = \text{Ux}(1)$$

$$\text{U}(0) = \text{Ux}(0)$$

$$\text{hfx}(0) = \text{hfx}(1)$$

$$\text{hf}(0) = \text{hfx}(0)$$

$$\text{T0A}(0) = \text{Tout}(0)$$

'Present Table in 6.Explicit

Worksheets("6.Explicit").Cells(4, 6).Value = "i"

Worksheets("6.Explicit").Cells(6, 6).Value = i(0)

Worksheets("6.Explicit").Cells(4, 7).Value = "L"

Worksheets("6.Explicit").Cells(5, 7).Value = "m."

Worksheets("6.Explicit").Cells(6, 7).Value = L(0)

Worksheets("6.Explicit").Cells(4, 8).Value = "rd"

Worksheets("6.Explicit").Cells(5, 8).Value = "m."

Worksheets("6.Explicit").Cells(6, 8).Value = rd(0)

Worksheets("6.Explicit").Cells(4, 9).Value = "ra"

Worksheets("6.Explicit").Cells(5, 9).Value = "m."

Worksheets("6.Explicit").Cells(6, 9).Value = ra(0)  
Worksheets("6.Explicit").Cells(4, 10).Value = "Ad"  
Worksheets("6.Explicit").Cells(5, 10).Value = "sq.m."  
Worksheets("6.Explicit").Cells(6, 10).Value = Ad(0)  
Worksheets("6.Explicit").Cells(4, 11).Value = "Aa"  
Worksheets("6.Explicit").Cells(5, 11).Value = "sq.m."  
Worksheets("6.Explicit").Cells(6, 11).Value = Aa(0)  
Worksheets("6.Explicit").Cells(4, 12).Value = "Vd"  
Worksheets("6.Explicit").Cells(5, 12).Value = "m/s"  
Worksheets("6.Explicit").Cells(6, 12).Value = Vd(0)  
Worksheets("6.Explicit").Cells(4, 13).Value = "Va"  
Worksheets("6.Explicit").Cells(5, 13).Value = "m/s"  
Worksheets("6.Explicit").Cells(6, 13).Value = Va(0)  
Worksheets("6.Explicit").Cells(4, 14).Value = "Tf"  
Worksheets("6.Explicit").Cells(5, 14).Value = "oC"  
Worksheets("6.Explicit").Cells(6, 14).Value = ts  
Worksheets("6.Explicit").Cells(4, 15).Value = "U"  
Worksheets("6.Explicit").Cells(5, 15).Value = "W/m2K"  
Worksheets("6.Explicit").Cells(6, 15).Value = U(0)  
Worksheets("6.Explicit").Cells(4, 16).Value = "hf"  
Worksheets("6.Explicit").Cells(5, 16).Value = "W/m2K"  
Worksheets("6.Explicit").Cells(6, 16).Value = hf(0)  
Worksheets("6.Explicit").Cells(4, 17).Value = "TERM"  
Worksheets("6.Explicit").Cells(5, 17).Value = "U(d)"



```

Worksheets("6.Explicit").Cells(6, 17).Value = 0
Worksheets("6.Explicit").Cells(4, 18).Value = "TERM"
Worksheets("6.Explicit").Cells(5, 18).Value = "U(a)"
Worksheets("6.Explicit").Cells(6, 18).Value = 0
Worksheets("6.Explicit").Cells(4, 19).Value = "TERM"
Worksheets("6.Explicit").Cells(5, 19).Value = "v(d)"
Worksheets("6.Explicit").Cells(6, 19).Value = 0
Worksheets("6.Explicit").Cells(4, 20).Value = "TERM"
Worksheets("6.Explicit").Cells(5, 20).Value = "v(a)"
Worksheets("6.Explicit").Cells(6, 20).Value = 0
Worksheets("6.Explicit").Cells(4, 21).Value = "TERM"
Worksheets("6.Explicit").Cells(5, 21).Value = "hf"
Worksheets("6.Explicit").Cells(6, 21).Value = 0
Worksheets("6.Explicit").Cells(4, 22).Value = "t=0"
Worksheets("6.Explicit").Cells(5, 22).Value = "DP"
Worksheets("6.Explicit").Cells(6, 22).Value = Tin
Worksheets("6.Explicit").Cells(eimax + 7, 22).Value = "AN"
Worksheets("6.Explicit").Cells(eimax + 8, 22).Value = T0A(0)

'Define required values

For ey = 1 To eimax

    i(ey) = ey

    Worksheets("6.Explicit").Cells(ey + 6, 6).Value = i(ey)

    rd(ey) = rdx(ey)

    ra(ey) = rax(ey)

```

$$Ad(ey) = Adx(ey)$$

$$Aa(ey) = Aax(ey)$$

$$Vd(ey) = Vdx(ey)$$

$$Va(ey) = Vax(ey)$$

$$Tf(ey) = Tfx(ey)$$

$$U(ey) = Ux(ey)$$

$$hf(ey) = hfx(ey)$$

$$L(ey) = Worksheets("2.Wellpath").Cells(ey + 3, 17).Value$$

$$Worksheets("6.Explicit").Cells(ey + 6, 7).Value = L(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 8).Value = rd(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 9).Value = ra(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 10).Value = Ad(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 11).Value = Aa(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 12).Value = Vd(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 13).Value = Va(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 14).Value = Tf(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 15).Value = U(ey)$$

$$Worksheets("6.Explicit").Cells(ey + 6, 16).Value = hf(ey)$$

Next ey

'Define T0A

imaxdiff = eimax - peimax

T0D(0) = Tin

T0D(1) = Tin

Worksheets("6.Explicit").Cells(7, 22).Value = TOD(1)

For x = 2 To eimax

eeey = x + 14 + peimax

eeeym = eeey - 1

eeeymm = eeey - 2

eeeymmm = eeey - 3

eex = 12 + peimax

eexm = eex - 1

eexmm = eex - 2

Select Case imaxdiff

Case 1

pBHCT = Worksheets("4.Initialization").Cells(eeey, 1).Value

If x < eimax Then

T0A(x) = Worksheets("4.Initialization").Cells(eeey, 1).Value

T0D(x) = Worksheets("4.Initialization").Cells(x + 12, 1).Value

Else

T0A(x) = Worksheets("4.Initialization").Cells(eeeym, 1).Value +  
 ((Worksheets("4.Initialization").Cells(eeeym, 1).Value) -  
 (Worksheets("4.Initialization").Cells(eeeymm, 1).Value))

T0D(x) = Worksheets("4.Initialization").Cells(x + 11, 1).Value +  
 ((Worksheets("4.Initialization").Cells(x + 11, 1).Value) -  
 (Worksheets("4.Initialization").Cells(x + 10, 1).Value))

End If

Case Else

If x <= peimax Then

T0A(x) = Worksheets("4.Initialization").Cells(eey, 1).Value

T0D(x) = Worksheets("4.Initialization").Cells(x + 12, 1).Value

Elseif x = eimax - 1 Then

T0A(x) = Worksheets("4.Initialization").Cells(eeym, 1).Value +  
 ((Worksheets("4.Initialization").Cells(eeym, 1).Value) -  
 (Worksheets("4.Initialization").Cells(eeymm, 1).Value))

T0D(x) = Worksheets("4.Initialization").Cells(eex, 1).Value +  
 ((Worksheets("4.Initialization").Cells(eex, 1).Value) -  
 (Worksheets("4.Initialization").Cells(eexm, 1).Value))

Else

T0A(x) = Worksheets("4.Initialization").Cells(eeymm, 1).Value + 2 \*  
 (((Worksheets("4.Initialization").Cells(eeymm, 1).Value) -  
 (Worksheets("4.Initialization").Cells(eeymmm, 1).Value)))

T0D(x) = Worksheets("4.Initialization").Cells(eex, 1).Value +  
 ((Worksheets("4.Initialization").Cells(eex, 1).Value) +  
 ((Worksheets("4.Initialization").Cells(eex, 1).Value) -  
 (Worksheets("4.Initialization").Cells(eexm, 1).Value)) -  
 (Worksheets("4.Initialization").Cells(eexm, 1).Value))

End If

End Select

T0A(1) = T0A(2) - (T0A(3) - T0A(2))

Worksheets("6.Explicit").Cells(eimax + x + 8, 22).Value = T0A(x)

Worksheets("6.Explicit").Cells(x + 6, 22).Value = T0D(x)

Next x

pBHCT = Worksheets("4.Initialization").Cells(14 + peimax + peimax, 1).Value

$$T0A(1) = T0A(2) - (T0A(3) - T0A(2))$$

$$T0A(0) = T0A(1) - (T0A(3) - T0A(2))$$

Worksheets("6.Explicit").Cells(eimax + 9, 22).Value = T0A(1)

Worksheets("6.Explicit").Cells(eimax + 8, 22).Value = T0A(0)

'define all coefficient terms

For ew = 1 To eimax

$$eUd(ew) = (2 * Pi * U(ew) * rd(ew) * dt) / (den * Ad(ew) * Cp)$$

$$eUa(ew) = (2 * Pi * U(ew) * rd(ew) * dt) / (den * Aa(ew) * Cp)$$

$$evd(ew) = (Vd(ew) * dt) / (L(ew))$$

$$eva(ew) = (Va(ew) * dt) / (L(ew))$$

$$ehf(ew) = (2 * Pi * ra(ew) * hf(ew) * dt) / (den * Aa(ew) * Cp)$$

Worksheets("6.Explicit").Cells(ew + 6, 17).Value = eUd(ew)

Worksheets("6.Explicit").Cells(ew + 6, 18).Value = eUa(ew)

Worksheets("6.Explicit").Cells(ew + 6, 19).Value = evd(ew)

Worksheets("6.Explicit").Cells(ew + 6, 20).Value = eva(ew)

Worksheets("6.Explicit").Cells(ew + 6, 21).Value = ehf(ew)

Next ew

'Initialization Moving

For s = 1 To 500

Worksheets("4.Initialization").Cells(s + 9, 2).Value = Worksheets("4.Initialization").Cells(s + 9, 1).Value

Next s

'Explicit operation

For et = 1 To etmax

ett = et + 21

ettp = ett + 1

eimaxp = eimax + 7

Worksheets("6.Explicit").Cells(4, ettp).Value = et

Worksheets("6.Explicit").Cells(5, ettp).Value = "DP"

Worksheets("6.Explicit").Cells(4, etppp).Value = et \*\*\*\*

Worksheets("6.Explicit").Cells(eimaxp, ettp).Value = "AN"

For ei = eimax To 2 Step -1

eii = ei + 6

eiiip = eii + 1

eiiim = eii - 1

eiiimax = eimax + 8

eiiimaxmm = eimax + 6

eiiimaxmmm = eimax + 5

eiiiii = eiiimax + ei

eiiiiiip = eiiiii + 1

eiiiiiim = eiiiii - 1

eiiiiiimax = eiiiiiim + eimax

eiiiiiimaxm = eiiiiiimax - 1

Select Case ei

Case eimax

TD(eimax) = (Cells(eiiimaxmm, ett).Value) + ((eUd(eimax)) \* ((Cells(eiiiiiimax, ett).Value) - (Cells(eiiimaxmm, ett).Value))) - ((evd(eimax)) \* ((Cells(eiiimaxmm,

ett).Value) - (Cells(eiimaxmmm, ett).Value))) + ((Vd(eimax) \* dt / ((0.5 \* L(eimax)) + (0.5 \* ra(eimax)))) \* (((Cells(eiiimax, ett).Value) - ((Cells(eiimaxmm, ett).Value))))

TA(eimax) = (Cells(eiiimax, ett).Value) + ((ehf(eimax)) \* (Tf(eimax) - (Cells(eiiimax, ett).Value))) - ((eUa(eimax)) \* ((Cells(eiiimax, ett).Value) - (Cells(eiimaxmm, ett).Value))) - ((eva(eimax)) \* ((Cells(eiiimax, ett).Value) - (Cells(eiiimaxm, ett).Value)))

Worksheets("6.Explicit").Cells(eiimaxmm, ettp).Value = TD(eimax)

Worksheets("6.Explicit").Cells(eiiimax, ettp).Value = TA(eimax)

Case Else

TD(ei) = (Cells(eii, ett).Value) + ((eUd(ei)) \* ((Cells(eiii, ett).Value) - (Cells(eii, ett).Value))) + ((evd(ei)) \* ((Cells(eiip, ett).Value) - (2 \* (Cells(eii, ett).Value)) + (Cells(eiim, ett).Value)))

TA(ei) = (Cells(eiii, ett).Value) + ((ehf(ei)) \* (Tf(ei) - (Cells(eiii, ett).Value))) + ((eva(ei)) \* ((Cells(eiiip, ett).Value) - (2 \* (Cells(eiii, ett).Value)) + (Cells(eiiim, ett).Value))) - ((eUa(ei)) \* ((Cells(eiii, ett).Value) - (Cells(eii, ett).Value)))

Worksheets("6.Explicit").Cells(eii, ettp).Value = TD(ei)

Worksheets("6.Explicit").Cells(eiii, ettp).Value = TA(ei)

End Select

Next ei

TD(0) = Tin

TA(1) = TA(2) - (TA(3) - TA(2))

TA(0) = TA(1) - (TA(3) - TA(2))

TD(1) = Tin

Worksheets("6.Explicit").Cells(6, ettp).Value = TD(0)

Worksheets("6.Explicit").Cells(7, ettp).Value = TD(1)

Worksheets("6.Explicit").Cells(eiimax, ettp).Value = TA(0)

Worksheets("6.Explicit").Cells(eimax + 1, ettp).Value = TA(1)

Next et

Worksheets("6.Explicit").Cells(8, 1).Value = TA(5)

Worksheets("6.Explicit").Cells(9, 1).Value = alfa

Worksheets("6.Explicit").Cells(10, 1).Value = rax(75)

Worksheets("6.Explicit").Cells(11, 1).Value = dt

Worksheets("6.Explicit").Cells(15, 1).Value = "TVD"

Worksheets("6.Explicit").Cells(16, 1).Value = TVD(eimax)

Worksheets("6.Explicit").Cells(18, 2).Value = "TD"

Worksheets("6.Explicit").Cells(19, 2).Value = TD(eimax)

Worksheets("6.Explicit").Cells(18, 3).Value = "TA"

Worksheets("6.Explicit").Cells(19, 3).Value = TA(eimax)

Worksheets("6.Explicit").Cells(18, 4).Value = "Tin"

Worksheets("6.Explicit").Cells(19, 4).Value = Tin

Worksheets("6.Explicit").Cells(18, 5).Value = "Tout"

Worksheets("6.Explicit").Cells(19, 5).Value = TA(0)

Worksheets("6.Explicit").Cells(18, 1).Value = "Tf"

Worksheets("6.Explicit").Cells(19, 1).Value = Tf(eimax)

Worksheets("6.Explicit").Cells(1, 14).Value = "Section"

Worksheets("6.Explicit").Cells(2, 14).Value = Worksheets("3.Welldetail").Cells(3, 6).Value

Worksheets("6.Explicit").Cells(21, 1).Value = "Q"

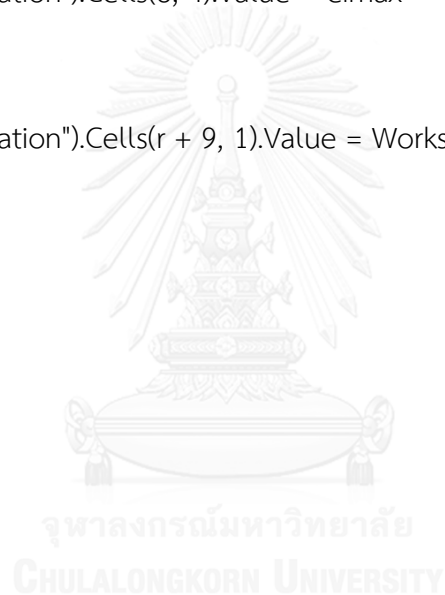
Worksheets("6.Explicit").Cells(22, 1).Value = Worksheets("5.Fluid").Cells(6, 5).Value

Worksheets("6.Explicit").Cells(21, 2).Value = "SG"

Worksheets("6.Explicit").Cells(22, 2).Value = Worksheets("5.Fluid").Cells(4, 5).Value



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Worksheets("6.Explicit").Cells(21, 3).Value = "Bittime"  
Worksheets("6.Explicit").Cells(22, 3).Value = Worksheets("5.Fluid").Cells(24, 5).Value  
Worksheets("6.Explicit").Cells(21, 4).Value = "ROP"  
Worksheets("6.Explicit").Cells(22, 4).Value = Worksheets("DataInput").Cells(7, 2).Value  
'Initialization preparation for next interval  
Worksheets("4.Initialization").Cells(8, 5).Value = Worksheets("4.Initialization").Cells(8,  
4).Value  
Worksheets("4.Initialization").Cells(8, 4).Value = eimax  
For r = 1 To 1000  
Worksheets("4.Initialization").Cells(r + 9, 1).Value = Worksheets("6.Explicit").Cells(r + 3,  
etmax + 22).Value  
Next r  
End Sub
```



## VITA

Patt Sirilapworachai was born on July 24th, 1982 in Bangkok, Thailand. He received his Bachelor's degree in Civil Engineering from Faculty of Engineering, Chulalongkorn University in 2004. Afterwards, he joined Warnes Associates as a structural engineer for five years and six months. Then, he moved to CTCI Thailand working as a civil engineer for one year and six months. After that, he continued his study in Master's Degree of Petroleum Engineering at graduate school of the Department of Mining and Petroleum Engineering, Chulalongkorn University since 2011

