Mathematical modelling of thermal profile of well drilling thermal profile in one of the Iran southern vertical wells to optimize the rheological characteristics of the digging fluid

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Abstract

The present work deals with finding thermal profile of fluid in a vertical well to determine the temperature distribution in different depths and parts of a well during digging. Since drilling fluid plays important roles in a well drilling process, therefore it is important to studies the effect of several of parameters on it. One of the main purposes of using fluid is to cool down the drill and the process. In this study the aim is to investigate the role of fluid as a heat exchanger from the bottom to the surface of the well and the surrounding area. On this base the heat can affect variation of the fluid characteristics such as rheology, density and pressure. Knowledge about thermal distribution of drilling fluid plays an important role in designing the fluid, estimating drop pressure, cementing and fencing and thermal energy in the well. This thermal profile is made by using mathematical modelling on the base of energy conservation and heat transfer auxiliary equations in the form of displacement, delivery and fluid movement in the well. The equations in the model are solved by coding in MATLAB and the results obtained are shown by thermal profiles for every part of the well. Temperature distribution of fluid in the digging pipe, lining pipe, mid lining and surface lining is specified. Thermal profile is obtained for both water base fluid and oil base fluid. In this research it is proved that thermal gradient of earth, well depth, rate of fluid flow in the well, density and thermal capacity of the fluid effect the thermal profile of the fluid and also there is a large difference between the thermal profile of the fluid in a digging well.

Keywords: thermal profile, drilling fluid, mathematical modelling, temperature distribution, thermal gradient.

1- Introduction

Usage of the drilling fluid is important in drilling industry, therefore a precise knowledge about the parameters effecting the drilling fluid for higher efficiency has been one of the priorities in the oil industry. In the present work the aim is to determine the thermal profile of the drilling fluid in a vertical well. During drilling process, while the fluid circulates in the pipe exchanges heat with the surrounding area ,it may absorb heat or may lose heat. The most important task of drilling fluid is cooling, lubricating the drill, transferring the scrapped materials to the earth surface and cleaning the bottom of the well and also transferring hydraulic power [1]. A good knowledge about the accurate temperature of fluid in every point is of particular importance because variation of temperature has direct effect on the design of fluid, its rheology, pressure and density, determining the thermal stresses of the drilling pipe and cementing [1]. In this study, using basic and heat transfer laws a mathematical model is presented. In this model the well enclosed by three linings is divided to several sections and the thermal behavior of each section is shown. Thermal distribution is determined from formation to fluid in the drilling pipe such that the temperature of each lining (surface, enteral and production) fluid temperature in annulus and inside the drilling pipe is determined. For a well with single lining and the well with open hole, the thermal profile obtained and their difference is shown [6]. In mathematical modelling, the physical and chemical behavior of the changes occurred in a system or number of systems connected to each other are verified mathematically. In thus model the problem is formulated using basic and special laws and the mathematical formulae for the variables of the system. Solving these equations, the relation between the variables is obtained and the proposed model is solved by coding in MATLAB and all the equations are solved simultaneously. Generally, the aim of the present research is information about the fluid temperature and linings in every point of the well, thermal distribution for programming the drilling fluid which is an important parameter in drilling. The mathematical model suggested is on the base of field information from Iran oil field and the results obtained are collated with field information [6].

LITERATURE REVIEW

In 1992, Peysson and Herzhaft showed that the method of determining the thermal profile of drilling fluid of a well in which the fluid is injected through drill string and continuous return from annulus faces large variation under varying temperature conditions. The temperature of fluid in the well can vary from 2^0 C to 180^0 C even for deep sea wells that can change many features of fluid like rheology and density. To anticipate the thermal profile of the circulating, one must measure the well data and fluid properties. To obtain thermal profile of fluid in a well during drilling, equipments for completing the well is needed and by fixing sensors outside the drilling string and in annulus the temperature variation can be measured in any depth. Installation a system will cause certain limitations, only local measurements done by instruments mounted on drill string allows to have the temperature of specific points of accessible fluid for further calculations. On this base the analysis of the final model can be done by expanding heat exchange equations. Complicated software makes use of numerical calculation to attain thermal profiles. Study of the history of shows that the thermal models have a similar profile in more cases that depends directly on inlet, outlet and bottom well temperature. The profile shape between these three points is shown using thermal profile curves in a drilling well by considering all physical considerations of heat exchange in the well [5]. In this research, the output of several softwares has been used, among which we can mention the software. Abaqus assists engineers to simulate complex real-world problems for a wide range of industries and rely on it for advanced engineering simulations. With an extensive library of element types, it can model nearly any geometry. Finally, by using the output of this software, it can be used as data for specialized drilling software.

Laderian [1998] showed that information about the heat transfer in the opening of the well is important. This needs analysis of numerical variables for controlling the bottom well behavior. Raymond [1968], Peysson. et.al [1992], Kabir C.S. et.al, [1992] and Laderian [1998] defined the function of drill fluid during drilling the well as shown in fig.1.They defined the circulating of the fluid in three different phases:

* Fluid that enters the drill string on the surface and runs longitudinal.

* Fluid that runs out of the drill pipe and drill nozzle and enters the annular space and bottom of the well.

* Fluid that rises up from annular space and leaves the well on the surface.

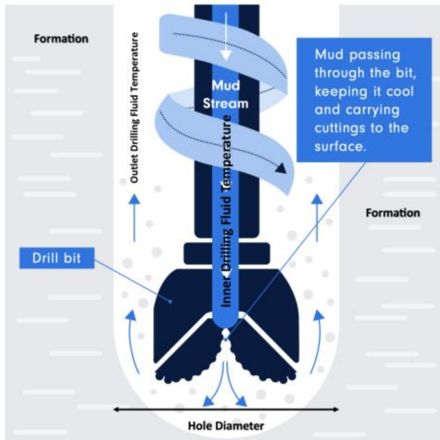

Fig.1 schmatic of drilling fluid circulation

When the fluid runs up in the annular space its stands between thermal convection rate, heat exchange rate between the annular space and drill string, heat exchange rate between annular space adjacent formation and fluid and time. These heat exchange rate and time which depend on time are identified by thermal equations of the wells. Temperature profile in annular space and formation are determined by solving the equations 1 and 2 by considering boundary conditions in equation4 [3].

$$\mathrm{A_D} p v_D c_p \frac{\partial \mathrm{T_D(Z,t)}}{\partial Z} + 2\pi r_D U[T_D(z,t) - T_A(z,t)] = -pA_D C_p \frac{\partial \mathrm{T_D(Z,t)}}{\partial t} \quad (1)$$

$$2\pi r_B h_f\left[T_f(rw,z,t) - T_A(z,t)\right] + \mathrm{A_A} p v_A c_p + 2\pi r_D U[T_D(z,t) - T_A(z,t)] = pA_A C_p \frac{\partial \mathrm{T_A(Z,t)}}{\partial t} \quad (2)$$

$$\frac{\partial \mathrm{T_f(r_w,z,t)}}{\partial \mathrm{t}} = \frac{\mathrm{k_1}}{\mathrm{p_f C_p}} \frac{1}{\mathrm{r}} \frac{\partial}{\partial \mathrm{r}} [r \frac{\partial T_f(r_w,z,t)}{\partial t}] \quad (3)$$

$$2\pi \mathrm{r_B h_f}[T_f(z,t) - T_a(z,t) = 2\pi r_B k_f [\frac{\partial T_f(z,t)}{\partial r}] \quad (4)$$

Fluid heat exchange rate in annulus depends on temperature of both formation and tubing. The temperature of the fluid entering the annular space in head of the well (T_a) is little more or less than the formation temperature on the surface. Although the temperature in bottom of the well is much more than the fluid temperature in annulus. Therefore, when the fluid moves down the annulus and comes up from the tubing it absorbs the formation's heat. High fluid temperature of annulus shows that heat loss occurs by central tubing. To obtain a relation for defining the temperature of the running fluid in annulus and central tubing we need an energy balance, an energy balance for a partial element of annulus fluid with length dz has been offered [2].

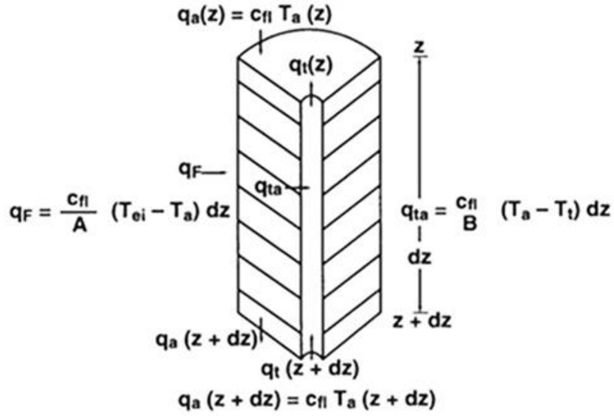

Fig.2 schmatic of heat balance in formation and centeral tube[2]

When the fluid enters down the central tube and comes up through annulus the direction of flow is reverse of the previous one. The method is the same as energy balance for partial element, only minor variation should be done to formulize the problem. For the heat flow from formation to annulus we use equation 5 and for heat flow from annulus to central tube we use equation7, because in these cases the force causing temperature difference clearly shows the direction of heat flow. The fluid energy exchanged when entering the partial element is q_a (z+dz) and when leaving is q_a (z). equations 1,2 are changing as below:

$$q_a(z) - q_a(z + dz) = q_{ta} - q_f \quad (5)$$

$$c_{fl}[T_a(z) - T_a(z + dz) = q_{ta} - q_f \quad (6)$$

$$q_F = \frac{2\pi K_e}{wT_D}(T_{ei} - T_{wb})dz \quad (1) \quad (7)$$

During drilling process fluid is pumped into the drill string and after passing through the drill and annulus it comes up from drilling tube. Fluid has different functions such as cooling the drill, lubricating drill teeth and drill string, transferring the clog to the surface , performing hydrostatic pressure and so on[4].

Drilling fluid is the base of every heat transfer model for drilling a well opening and has important effect on the drilling process. Moreover, for studying the rheological model in hydrodynamic condition of fluid in the well is required. This model consists of a clear strategy for deciding a rheological and various parameter. It shows the nature of fluid flow, velocity distribution in the fluid and fluid properties. The drilling fluid can be classified as water, oil and gas base. In fluid mechanic, drilling fluid follows a more complicated formula and does not obey Newtonian rule and fluid and should be considered as a non-Newtonian one [4].

In the field state, the temperature of fluid entering the drill string can be measured directly. When circulating starts the temperature of fluid in the opening hole approaches the earth temperature of the formation. In this study thermal gradient of the earth is assumed to be a+bz, a is formation temperature and b is thermal gradient. Primary distribution of fluid temperature in formation and circular space is estimated as below using the earth temperature [3].

$$T_D(z,t) = T_A(z,t) = a + bz \tag{8}$$

Initial temperature of the formation in a specific depth is assumed to be uniform. For one of boundary conditions, we have to assume the outlet thermal rate equal the one entering the annulus, because in very large radius the earth thermal temperature remains unchanged. The second boundary condition is $T_{f(r-\infty)}(z,t) = a + bz,$ applying boundary conditions the thermal profile of the circulating fluid can be obtained numerically. Results obtained have dimensions of depth, time and temp. which ultimately have different conclusion for computations [4].

During the flow of fluid in the well heat exchange occurs in various places, boundaries of drill string, formation and annulus. This exchange depends on nature of fluid, gradient, speed and fluid properties, steel cement and stone. Equations of fluid energy in different places of well can be determined by computation of thermodynamic of radial thermal convection and vertical thermal conduction. As a form of energy, heat can be transferred due to temperature difference in the form of displacement, radiation and conduction or a sum of them. Making model in heat transfer leads to the formation of differential equations in which temperature is estimated as a function of one or several variable. According to the type of system, the differential equation can be obtained in cartesian or spherical coordinates and will be solved using analytically or numerically using proper boundary conditions [7].

Dividing a drilling well into different sections, for every section differential equation can be obtained using laws of conversation of energy and auxiliary equation that shows heat distribution in every section separately. During drilling a well, the fluid runs down the drilling tube getting out of the drill nozzles comes up through annulus and exchange heat with the surrounding area that cause the fluid gains or lose heat. In the present research the behavior of the fluid is assumed to be partially stable in suggested rheological model and Bingham fluid is assumed which is independent of time [5].

3- Research methodology and modelling

The model made in this research is based on the modelling methods. To make the model the system is assumed to be semi stable and because the rheological behavior of the fluid is assumed to be Bingham therefore heat transfer in the well is assumed to be stable. The model is made on the base of second law of thermodynamics and laws of conservation energy. To show heat distribution in the well, auxiliary conductive heat transfer equations and, displacement and fluid motion are used. To estimate the heat throughout the well the model suggested should be solved numerically. Solving the model needs nodding the equation in coupling form throughout the well. Because solving the equations are laborious and time consuming, numerical solution of the model is done using MATLAB according to the algorithm shown in figure3.

Fig.3- Numerical method solving of the model using MATLAB coding

Accessing to the research goals, the equations must be solved numerically. After coding in MATLAB, the equations are solved using implicit numerical methods with the least error and the results are shown in the form of charts. MATLAB is written according to algorithm shown in fig.2. Generally, method of solving equation of model using algorithm in fig.4 is to obtain the data from the surface down to every one meter in the well considering thermal gradient of the earth in every node in couple form according to final equation from 0 to 67.7-meter depth of the well which is covered by three walls. Total heat transfer factors and heat conduction are considered for every wall, annulus and cement taking into account the thermal gradient of the earth and the equations are solved for that section. From the depth of 67.7 to 1298 of the wells is covered with two walls and heat transfer, heat conduction factor is considered separately solving the nodded equations for it. From the depth1298 to 3640meter of the well is covered with on lining and one wall and again heat transfer and heat conduction factor are considered separately in that section. Because there is no wall from the depth 3640 to 4738 and the well is completed in opening mouth form therefore conduction factor is considered along with thermal gradient of the earth.

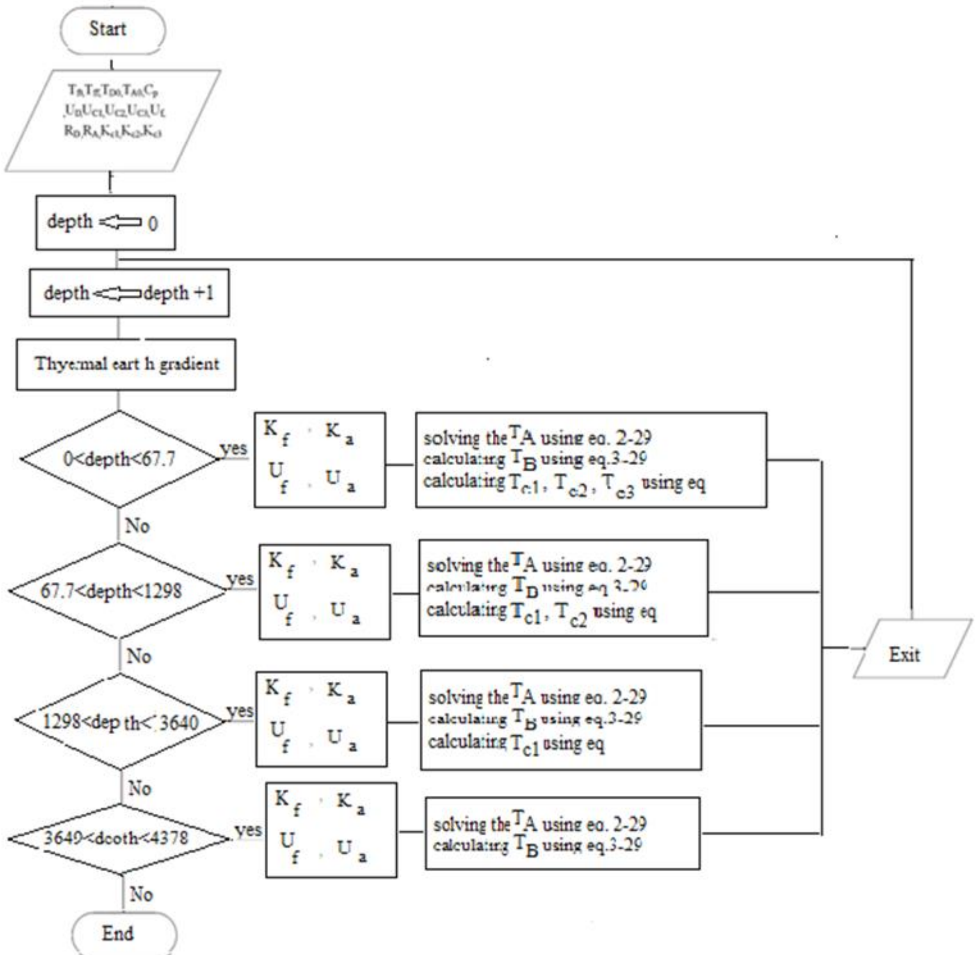

Fig.4- Matlab coding algorithm

4- Analysis

4.1- Data used

In this research, field data from one of the wells in Ahwaz are used for verification. These data related to drill fluid information, structure of the well, petrophysical information of the field layers, thermodynamic properties of fluid, formation and annulus that have been extracted from type of fluid, type of well logging, drilling reports, test and reports about the fluid, wall specification and earth thermal information. The information extracted for well information in table (1), water-based drilling fluid table (2) and oil-based drilling fluid table (3) is given in table below:

depth	Radius r	Type of tube wall/drilling	No.
67.7 m	0.2366 m	Surface wall18 5/8"	١
1298 m	0.1699m	Mid 13⅜"	٢
2608 m	0.1223 m	production wall 9⅝"	٣
2481-3640 m	0.0889 m	lining 7"	۴

3640-4378 m	0.0889 m	Open Hole	۵

Table 1- information of well geometry and walls

Oil based drill fluid		Water based drill fluid	
58.3 PCF	(ρ) Fluid weigh	140 PCF	(ρ) Fluid weigh
255.4 gpm	(Q) Rate of flow	512 gpm	(Q)Rate of flow
3.26kj/(kg°C)	(C_p) Thermal capacity	3.26kj/(kg°C)	(C_p) Thermal capacity
46.6℃	Inlet temperature into tube	57.6°C	Inlet temperature into tube
60.2℃	Outlet temperature from annulus	71.42 °C	Outlet temperature from annulus
55 ℃	Formation temperature on the earth surface	55 °C	Formation temperature on the earth surface

Table2- Information of water- based and oil-based fluid

4.2- Thermal profile of drilling fluid for the section with three walls

As in figure 5 during circulation of fluid through drilling tube to annulus enclosed in a section with three walls undergoes variations which depends on the type of fluid and its properties, diameter of the well and sizes of the walls. For every fluid these variations will be given.

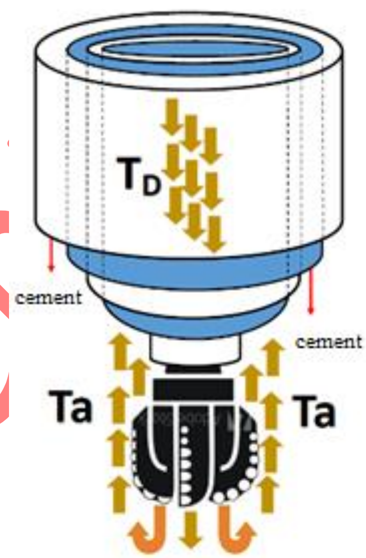

Fig.5- well section enclosed with three walls[5]

4.3- Fluid temperature difference for water-based fluid in drilling tube and annulus

From fig.6 the thermal profile of the water-based fluid is shown by continuous line which differs from the thermal profile of the fluid shown by dashed line. Temperature in different deaths of the well is different. In the primary depths this difference is about 7–12-degree cent., and in depth of 500 -700 m it is 3–5degree cent. And in depths more than 1500m it is about 8–11degree cent. In the depth (more than 3640) of an open hole well this difference is more. As shown in fig. inside annulus the heat exchange of fluid in formation and lining tubes is more, friction and swinging of the drilling increase the temperature that can be observed from the fluid inside the annulus. The maximum temperature of the fluid will be in annulus and bottom of the well. Temperature difference of fluid in the bottom of the between drilling tube and annulus is about 13 -15-degree cent.

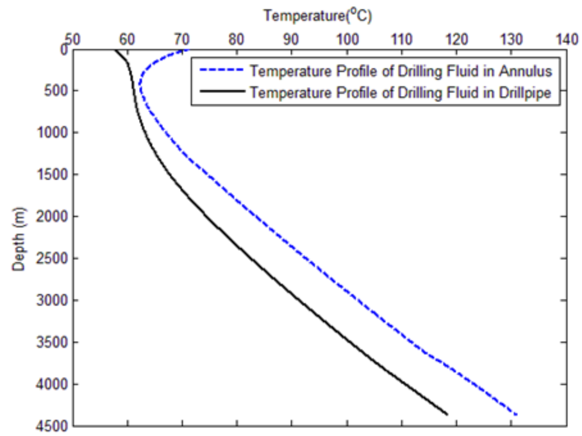

Fig.6- temperature differnce of fluid imside the drilling tube and annulus for water based fluid

4.4- Temperature difference of oil-based fluid in annulus and drilling tube

In fig.7 there is not much difference between the thermal profile of the oil-based fluid shown by dashed line and thermal profile of the annulus fluid shown by continuous line. Temperature difference between the thermal profile of the fluid inside annulus and drilling tube is about 4–5-degree cent. This shows for oil based-fluid that temperature difference of the thermal profile of annulus and drilling tube is almost constant. The figure shows that temperature of the oil-based fluid in annulus and drilling well in different depth of the well is more than that of water-based fluid. Maximum temperature of the oil -based fluid in annulus is about 140-degree cent.

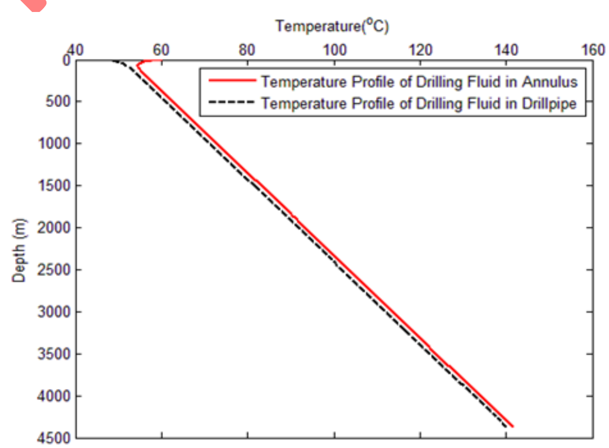

Fig.7- temperature difference of fluid in drilling tube snd snnulud for oil-based fluid

4.5- Comparison of thermal profile of water-based fluid with oil-based fluid in drilling tube

Fig.8 shows the thermal profile of the water based fluid shown by dashed line with that of oil-based fluid shown by contiuos line inside the driling tube. As clear from the figure in both case in the primary depths the temoerature is increasing relatively .In water based fluid upto the depth of 800m temperature is almost constant while in oil-based fluid temperaure increases. Due to different properties and different thermal capacity of the two fluid the minimum temperautre of water based fluid is 48 degree and that of oilbased fluid is 48 degree cent. In final depth the temperautre of oil based fluid is more than water-based fluid

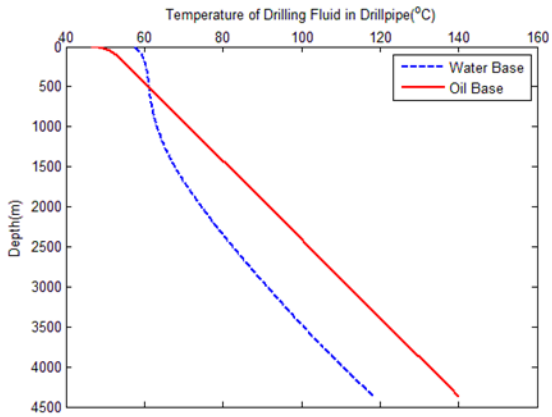

Fig.8- comparison of thermal profile of the water-based fluid with oil-based fluid in drilling tube

4.6- Comparison of thermal profile of the water-based fluid with oil-based fluid in annulus

Fig.9 shows the thermal profile of the water based fluid shown by dashed line with that of oil-based fluid shown by contiuos line inside the annulus. As clear from the figure in both case in the primary depths the temoerature is decreasing relatively.In water-based fluid decrease of temperature occure in lowe depths more than 200m while in case of oil-based fluid it occurs in lesser depths. In water based fluid in the depth of 3680m a break is observed in the figure and the slope of increasing temperaure becomes more which does not happen for oil-based fluid. Because of different properties and thermal capacities of the two fluids ,in ultimate depth temperature of oil-based fluid is more rthan that of water based fluid.In side formations of the lower sections of well hole large thermal gradient occurs during swinging.Durin drilling the temperature of the formations of more than 10ft from the opening remains unchanged [١١].

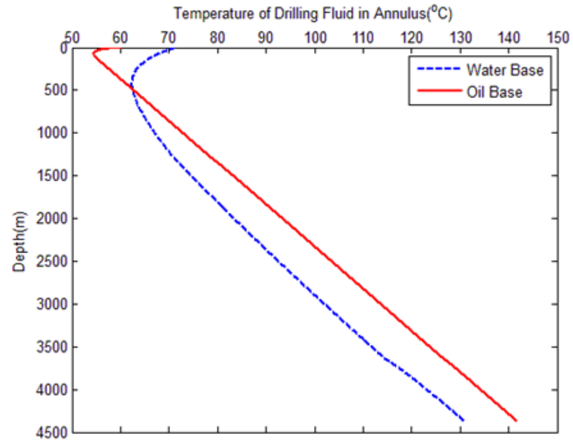

Fig.9- comparison of thermal profile of water-based and oil-based fluids inside the annulus

4.7- Comparison of thermal profile of production side tube for water-based and oil-based fluid

Thermal profile of of production side tube for water-based fluid is shown in figure 10 by dashed line and that of oil-based fluid by continuous line comparing them .As it is clear the temperature of both profiles as is constant in primary depth upto 70 m.Temperature of production side tube for oil-based fluid is less than water based one,but ultimately the wall temperature in oil-based fluid is more than water based one . In depth1298, the end of mid wall where the annulus is in contact woth formation both profiles will break and their slope increase,while thermal profile change is more with water based fluid. In final depth, the production wall or annulus is more for oil- based fluid than the water based one.

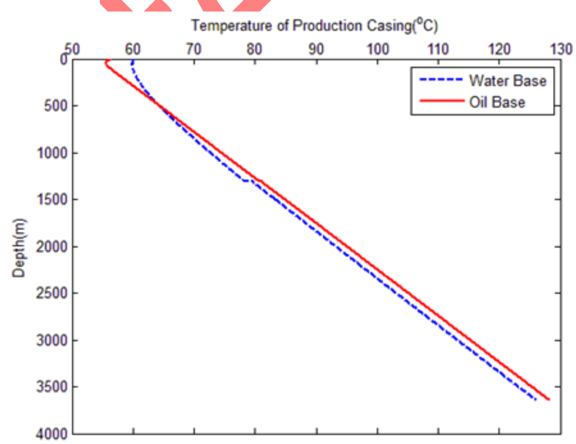

Fig10- Comparison of thermal profile of production side tube for water and oil-based fluids

4.8- Effect of different flow rates on thermal profile of fluid in drilling tube

Fig.11 shows thermal profile of a water-based fluid for different rates of flow. Up to depth of 700m the profiles of three rates are same and for further depth there is considerable difference while the fluid flow rate is having least amount (256 gallon/min) out of flow rates. It has the most temperature increase and in most flow rate (768 gallon/min)it earns least fluid temperature comparing the other two profiles. In the bottom of the well maximum fluid temperature i.e.,130-

degree cent.is for minimum rate of flow and minimum fluid temperature in the bottom of the well is for maximum flow rate

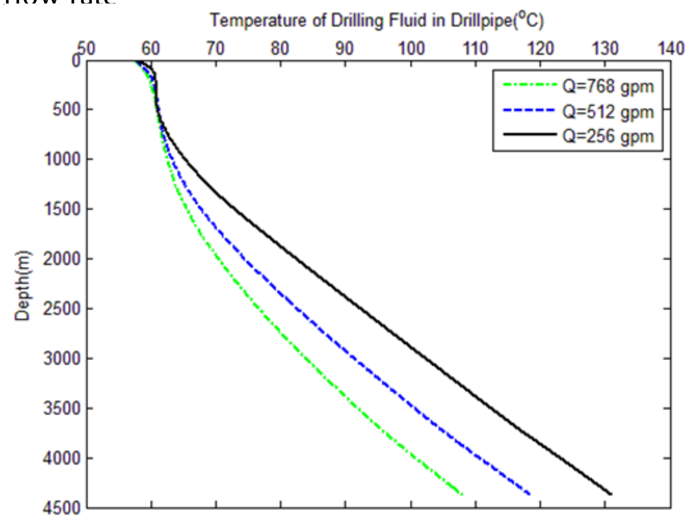

Fig.11-Comparison of thermal profile of fluid for different flow rates in drilling tube for water-based fluid

4.9- Effect of different flow rates on thermal profile of fluid in annulus

Fig.12 shows thermal profile of a water-based fluid for three different rates of flow. It is clear that the maximum temperature is related to the fluid with the least flow rate (256gallon/min, When the fluid rises up through the annulus the temperature decrease in the fluid with least flow rate is more. the figure shows heat in fluid is inversely proportional to fluid flow rate.

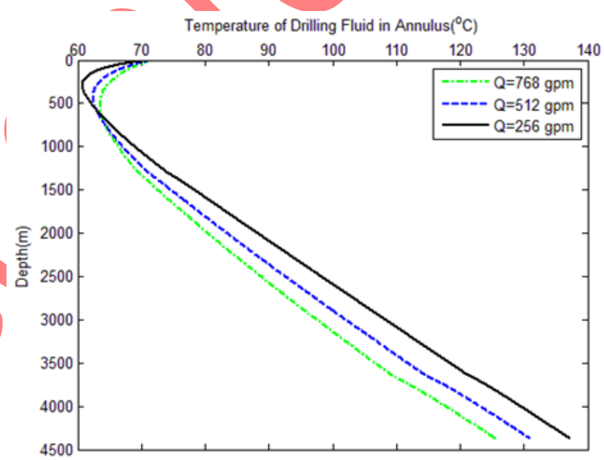

Fig.12-Comparison of thermal profile of fluid in annulus for different flow rates for water-based fluid

4.10- Comparison of the results obtained from suggested model with those of others

Different authors like Raymon, Payson , and so on have given different models for obtaining thermal profile of drilling fluid which were pointed in chapter 2.The results obtained in this work are compared with the earlier ones ,certain common case and also differences are observed. Fig.13 shows thermal profile of fluid in drilling tube and thermal profile of oil-based fluid in annulus are compared for different models and the results are verified. In continuation new items are studied which are not considered in previous works.

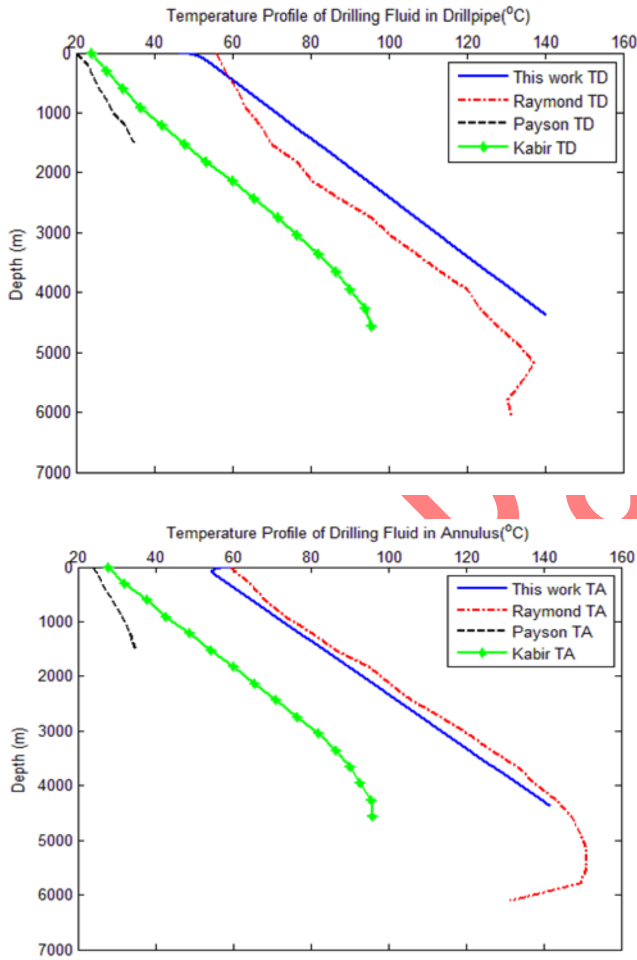

Fig.14- Comparison of thermal profiles of the fluid in annulus in the present research with the previous ones

One of the obvious commonalities between the profiles obtained in drilling tube and annulus is from the model suggested and the previous researches matching the shape of thermal profiles. Without considering initial temperature and properties of the fluid it is observed that the thermal profiles are almost similar in the above figures and increase in temperature looks to be constant. The results obtained from all gradients show that by increasing depth the temperature increase which is affected by the thermal gradient of the earth. Profile analysis shows that the geometry of the well has little effect on the thermal profile [١٢]. This can be a reason for controlling the rheological properties if the drilling fluid during circulation in the well. The results show that the fluid properties such as rheological, density, and fluid flow rate effect the thermal profile of the fluid and temperature difference of fluid in annulus with drilling tube in oil-based fluid is less than the temperature difference in previous researches with oil-based fluid, this difference is due to considering the effect of the temperature radially in formation and walls and also applying the field data. In water-based fluid this difference is high in some parts of the well [١٣].

The results obtained in this study are based on the field data whereas in Reymond model simulated wells are used that can make several errors in analysis. Another difference is maximum temperature min the present work maximum temperature is in the bottom of the well and in annulus whereas in previous studies maximum temperature was higher than the bottom of the well. Knowledge about the thermal distribution in the walls is useful for cementing and building the walls. One of the most important results obtained in this work is determining the thermal distribution in the walls which is not determined in the previous works. In the present work both profile of water-based and oil-based fluid are obtained, in the previous researches the profile obtained is only for oil-based fluid [14]. The model suggested is applicable for any depth of well, in the previous work the depth of the well is assumed constant and also heat transfer in formation, annulus, walls and drilling tube is given separately for every part of the well which has not been given in earlier works. [15]

5- **Conclusion**

The results obtained from this study shows that the weight and density have direct effect on thermal profile of the fluid and by increasing depth, temperature in the well will increase., and specific thermal capacity of the fluid effects the profile. If the specific thermal capacity of the fluid is high the maximum temperature is lower than the temperature of the fluid with less the fluid with less specific thermal capacity there it can stated that the thermal profile of the fluid is directly related to the thermal gradient of the earth, in other words the thermal gradient of the fluid is a function of depth. On the base of studies in fluid mechanic engineering, the drop pressure in fluid can be estimated by using thermal profile which is an optimizing method of infiltration rate of drill. Present study shows that using fluids with low thermal capacity can use thermal earth temperature for changing to other type of energy. The fluid, whether compressible or non-compressible also effects the thermal gradient of the fluid.

Research and analysis of the thermal profile during drilling operation shows that thermal profiles can results in proper cementing and also appropriate time for proper cement covering of the walls. Field analysis shows that drilling fluid flow rate has inverse effect on the thermal profile, in this way that, in the same conditions the more the fluid flow rate the less is temperature and the well geometry and dimeter of the well opening have not much effect on thermal profile. On the type of fluid used, the analysis shows that the maximum temperature for oil-based fluid is more than that of water-based fluid in the bottom of the well and the oil-based fluid have better action in higher depths. Regarding the validation of this article, we can mention the software developed at the Gobkin University of Oil and Gas in Russia, which is used under the brand name Takeoff in this country and is most commonly used in high-temperature wells.

To simulate the thermal behavior of the fluid in the system, each of the phases of circulation must be described mathematically. In Phase 1, the fluid enters the drill pipe at a specified temperature, TDo. As the fluid passes down the pipe, its temperature is determined by the rate of heat convection down the drill pipe, the rate of heat exchange between the drill pipe and the annulus, and time. Phase 2 of the circulating process merely requires that the fluid temperature at the exit of the drill pipe be the same as the fluid temperature at the entrance of the annulus; i.e., TD (L, t) = TA (L, t). Thus, in Phase 3, the fluid enters the annulus at TD (L, t). As the fluid flows up the annulus, its temperature is determined by the rate of heat convection up the annulus, the rate of heat exchange between the annulus and the drill pipe, the rate of heat exchange between the formation adjacent to the annulus and the fluid in the annulus, and time. These rates of heat exchange and the time dependency of mud temperature are described by well-known heat-flow equations.

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