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Research article

Modelling of the cooling effect enhancement in drilling fluid using nanotechnology

Pham Son Tung*, Nguyen Mai Tan Dat

ABSTRACT

Drilling fluid is indispensable to assure the safety and success of a drilling operation. Besides the normal drilling fluid such as water-based mud or oil-based mud, a new kind of drilling fluid has emerged recently, which consisted of the use of nanotechnology. The aim of this paper is to study the cooling effect of nano-drilling fluid used in the petroleum industry. A dynamic model that included a reservoir formation, a well, and a drill string in the drilling process with drilling fluid circulation was built for this objective. Navier-Stoke equation was used for the fluid flow inside the well and the drill string, while Darcy's equation was used for the flow inside the formation. The rise of temperature due to friction was also accounted for in this model. Two types of drilling fluid were used in the simulation: the normal drilling fluid and the one using nanotechnology. The change of temperature in the wellbore and in the formation over time with these two types of drilling fluid was observed at various positions: at the bottom hole where the drilling bit is constantly in contact with the formation, and at other places further away from the bottom hole. The simulated results showed that, although the temperature fluctuated in the two cases but on average, the nano drilling fluid gave a better cooling effect in comparison with the normal one. This article is the first study about the application of nanoparticles in drilling fluid in Vietnam using an integrated modeling method. The approach proposed in this article can be applied efficiently in practical applications of nano drilling fluid for petroleum drilling in Vietnam. However, it is noted that this research treated typically the technical side of the application of nanotechnology in drilling fluid, while it will be necessary to asset the financial aspect in order to make this technology a real-life application.

Key words: nano drilling fluid, multi physics modeling, thermal conductivity, specific heat capacity

Faculty of Geology and Petroleum Engineering, Hochiminh City University of Technology – VNU-HCM, Vietnam

Correspondence

Pham Son Tung, Faculty of Geology and Petroleum Engineering, Hochiminh City University of Technology – VNU-HCM, Vietnam

Email: phamsontung@hcmut.edu.vn

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INTRODUCTION

Drilling fluids play an extremely important part in the success of a drilling operation. The better drilling fluids will help to solve and to restrict problems during drilling process, especially in complex areas such as unconventional reservoirs or HPHT wells (High Pressure High Temperature). The use of nanotechnology in drilling fluids is a new development but still limited in fields due to its cost and also to its lack of research. In the past, Hoelscher et al. in 2012 [1] discussed the ability to enhance wellbore stability when using nanoparticles to minimize shale permeability through physically plugging the nanometer-sized poses, when applying water-based drilling fluids in unconventional shale formation. Zisis Vryzas and Vassilios Kelessidis in 2017 [2] provided an overview for the use of nanoparticles to improve the drilling fluid's properties. Subodh Singh and Ramadan Ahmed in 2010 [3] indicated the applications of nanotechnology in drilling fluid as well as assessing economic and technical benefits. However, these studies only give the most general view about Nano-drilling fluid and these have not been focused on the specific applications. The advantages of cooling and heat transfer are an important matter of drilling fluids. Ponmani et al. in 2016 [4] showed that the use of CuO and ZnO nanoparticles will improve thermal conductivity, electrical conductivity for drilling fluid. Reinhard Hentschke [5] as well as Ravikanth S.Vajjha and Debendra K.Das [6] mentioned the reduction of the specific heat capacity of nanofluids consisting of silicon dioxide, zinc oxide and alumina nanoparticles, dispersed in a mixture of water and ethylene glycol compared to the base fluid. D. P.Kulkarni et al. in 2008 [7] compared the specific heat capacity for aluminum oxide nanofluid of experimental decrease more than theoretical value. In addition, Pan Baozhi et al. in 2014 [8] simulated the heat transfer process as well as the temperature wellbore and formation during drilling and shut-in well in case of lost circulation. However, these authors [8] did not use a dynamic modelling with circulation of drilling fluid, but rather with a static system.

In this paper, we built a model in COMSOL with a drill string inside the wellbore to circulate drilling

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fluid from the surface through the drill string then into the annular back to the surface. Moreover, the surrounding formation was included in this model to assess the cooling effect not only in the well but in the formation as well. In addition, we included in the model the calculation for the heat generated by the friction between the drill bit and the formation during drilling operation. Using the model, the variation of the temperature inside the wellbore and inside the formation in function of time was evaluated for two types of drilling fluids (nano drilling fluid and normal drilling fluid). The results will then be compared to assess the contribution of nano fluid regarding the cooling effect.

METHODOLOGY

Nano-drilling fluid is created by adding nanoparticles (10-9 m) in a base fluid to improve the properties of drilling fluid which can solve more effectively the common problems encountered during drilling operation. The addition of nanoparticles will change rheology, mechanics, thermal properties and other properties of drilling fluids.

Nano-drilling fluid has outstanding features such as heat transfer, gel formation, drag and torque reduction, formation consolidation, corrosive control[2]. The applications of nanotechnology in drilling fluids bring a lot of expected results. Nanoparticles regulate the rheology and many other properties of drilling fluid quickly and easily through adjusting the shape, type, size and concentration of nanoparticles in drilling fluids[9]. In addition, nanoparticles enhance the drilling fluid's stability when drilling into a complex stratigraphy. A smart drilling fluid that has optimal properties with a wide range of application and better performance is hence created. Nanoparticles in drilling fluid improve wellbore stability, reduce fluid loss and formation damage, increase cutting lifting capacity and cutting suspension, improve wellbore strengthening and thermal stability to protect the equipment's span life especially in drilling HPHT wells[2].

Some outstanding applications of nano-drilling fluid can be listed as follows:

- Control loss fluid and wellbore stability especially when drilling into shale formation.
- Improve cutting lifting capacity to reduce the problem of being stuck.
- Reduce torque and drag force.
- Cooling and thermal stability when drilling in an HPHT environment.

This article will be focused on the cooling effect and heat transfer of the nano-drilling fluid and compare with normal drilling fluid to highlight the potential superiority of nano drilling fluid. The addition of CuO and ZnO nanoparticles in drilling fluids helps to increase thermal conductivity hence the heat transfer is faster. According to the experiments, CuO nanoparticles help to increase the thermal conductivity in range from 28% to 53% and ZnO nanoparticles help to enhance thermal conductivity by 12% to 23%[2], depending on concentration and size of particles.

At the same time, CuO and ZnO nanoparticles help to decrease specific heat capacity of drilling fluids which contributes to a faster heat exchange as well as a better cooling effect. After these nanoparticles are added into the drilling fluid, the drilling fluid's specific heat capacity can be changed according to Equation 1[6]:

$$C_{pnf} = \phi C_{pn} + (1-\phi) C_{pf} \tag{1}$$

Where C_{pnf}, C_{pn} and C_{pf} are respectively specific heat capacity of nano fluid, nanoparticles and base fluid, kJ/kg.^{o}C; ϕ is the particle volumetric concentration.

In addition, Equation 2 is used to determine the nanofluids specific heat capacity when nanoparticles are added[6]:

$$C_{pnf} = \frac{\phi \rho_n C_{pn} + (1-\phi) \rho_f C_{pf}}{\rho_{nf}} \tag{2}$$

Where ρ_{nf}, ρ_n, ρ_f are respectively the density of nanofluid, nanoparticles and base fluid, kg/m^3. The particle volumetric concentration is determined:

$$\phi = \frac{\frac{y}{\rho_n}}{\frac{y}{\rho_n} + \frac{y}{\rho_f}};\ y = \frac{M_n}{M_f}$$

Where y is the mass ratio, Mf is the mass of the base fluid, M_n is the total mass of the nanoparticles.

Equation 3 presents variation of heat transfer in the formation in the process of drilling fluid invasion:

$$\begin{aligned} \{ (\rho C)_{eq} \frac{\partial T}{\partial t} + \rho C u.\nabla T = \nabla.\left(k_{eq} \nabla T\right) + Q k_{eq} \\ = \varphi k + (1-\varphi) k_m (\rho C)_{eq} = \varphi \rho C + (1-\varphi) \rho_m C_m \end{aligned} \tag{3}$$

Where k and k_m are thermal conductivity coefficients of the fluid and the matrix, W/m.^{o}C; C and C_m are the specific heat capacity of the fluid and the matrix, kJ/kg.^{o}C; ρ and ρm are the density of the fluid and the matrix, kg/m^3; Q is the heat source, W/m^3; φ is the formation porosity; u is the velocity vector, m/s.

The heat transfer of drilling fluid in the well is described in Equation 4:

$$\{ \rho C_{df} \frac{\partial T}{\partial t} + \rho C_{df} u.\nabla T + \nabla.q = Qq = -k \nabla T \tag{4}$$

Where ρ is the density of drilling fluid, kg/m^3; Cdf is the specific heat capacity of drilling fluid, kJ/kg.^{o}C; u is the velocity vector, m/s.

Drilling fluid is circulated from the surface through drill string to the bottom hole and then follows the annular back to the surface. The flow in the wellbore is described by Navier-Stokes in Equation 5:

$$\{\rho\frac{\partial u}{\partial t}+\rho\,(u.\nabla)\,u=\nabla.\left[-p2I+\mu\left(\nabla u+(\nabla u)^T\right)\right] \\ +F\rho\nabla.(u)=0\left(F_x,F_y,F_z\right) \\ =\left(-\frac{\partial P}{\partial x}+\rho g_x,-\frac{\partial P}{\partial y}+\rho g_y,-\frac{\partial P}{\partial z}+\rho g_z\right) \tag{5}$$

Where ρ is the density of drilling fluid, kg/m^3; P is hydraulic pressure (the drilling fluid pressure), Pa; F represents the external stress, N/m^3; g is gravity acceleration, m/s^2; u is the velocity vector, m/s.

We use Darcy's law in Equation 6 to describe the fluid flow in porous medium in the reservoir:

$$\{\frac{\partial}{\partial t}\left(\rho_f\varphi\right)+\nabla\left(\rho_f u\right)=Q_m\frac{\partial}{\partial t}\left(\rho_f\varphi\right) \\ =\rho_f\left[\varphi_f+(1-\varphi)_m\right]\frac{\partial P_r}{\partial t}u=-\frac{K_m}{\mu_f}\nabla P_r \tag{6}$$

Where ρ_f is the density of the reservoir fluid, kg/m^3; P$_r$ is the reservoir pressure, Pa; K$_m$ is the reservoir permeability, $10^{-3}\mu$m^2; μ_f is the formation fluid viscosity, Pa.s.

The convection heat transfer is determined in Equation 7:

$$-k\frac{\partial T}{\partial n}|_\Gamma=\alpha\left(T_1-T_2\right)|_\Gamma \tag{7}$$

Where α is the convection heat transfer coefficient, W/(m^2.^{o}C); T$_1$ and T$_2$ are respectively the temperature of hot source and warm source.

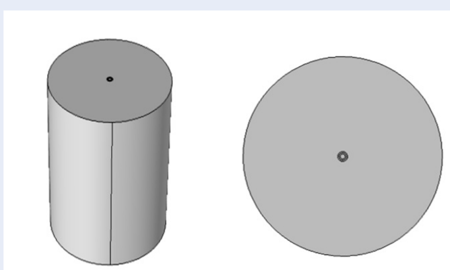

Figure 1: The modeling of the wellbore and the formation around the wellbore.

To evaluate the cooling effect brought by two types of drilling fluid, a dynamic model (Figure 1) that included wellbore and formation with a height of 10 m, wellbore and formation around the wells with radius of 0.2 m and 4 m, respectively. In the wellbore, a drill string is built to simulate the drilling fluid circulation. Assuming that the flow inside the well is a free flow so the Navier-Stokes (Equation 5) can be used, while the flow in the formation is governed by Darcy's equation (Equation 6). The heat transfer process in the formation and in the well are described in Equations 3 and 4, respectively. The software COMSOL was used to implement the model. The model was validated using data extracted from literature review [8].

RESULTS AND DISCUSSIONS

The cooling effect in the annular during drilling operation

We firstly consider the process of heat transfer in the annular during drilling operation. The temperature of the drilling fluid varies in annular during this process due to friction between the drill bits and the formation. That generated heat can damage and reduce the span life of the drill bits, especially in HPHT wells. A good drilling fluid with good thermal conductivity can deal with this problem efficiently. To find out how the nano drilling fluid can help in this case, we made a modelling of the drilling process with a circulation of drilling fluid in a wellbore with a radius of 0.2 m, and in a drill string with an internal diameter of 0.1 m and 0.05 m in thickness. We drill into a formation with porosity of 15%, permeability of 20 mD. In the model, the initial temperatures of the drilling fluid and the formation are 126^{o}C and 50^{o}C, respectively. In the drilling process, the extra heat generated by friction is considered to be 16^{o}K according to Xiu Chang et al. [10]. Changes in thermal conductivity of the drilling fluid were modelled using results from literature review. CuO nanoparticles added can increase the thermal conductivity with a range from 28% to 53%, and ZnO nanoparticles enhance thermal conductivity by 12% to 23% [2]. In addition, CuO and ZnO nanoparticles will make the specific heat capacity of drilling fluid to decrease so that the specific heat capacity of nano-drilling fluid is lower than normal drilling fluid.

We conducted successively the simulation with normal drilling fluid and nano-drilling fluid. Figure 2 illustrates the three representative points from bottom hole to surface inside the annular which were chosen so that the cooling effect caused by normal fluid and nanofluid could be compared. The coordinates of these points are: A(0.125; 0.125; 0.1), B(0.125; 0.125; 3.5), C(0.125; 0.125;7). In addition, the modelling of the circulation of drilling fluid in drill string and annular is shown in Figure 3. A more detailed illustration of the drill string and the annular is presented in

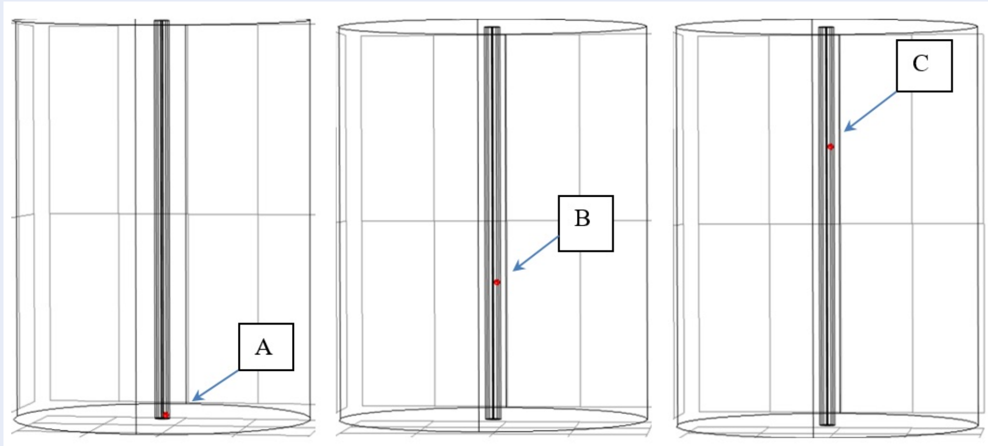

Figure 2: The three points A, B and C inside the annular where cooling effect caused by nanofluid and normal fluid will be compared.

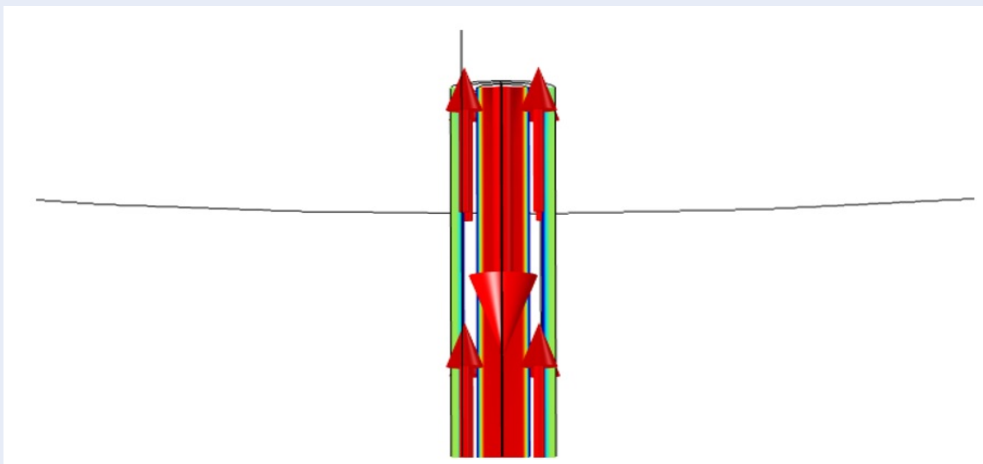

Figure 3: The modelling of the circulation of drilling fluid in drill string and annular.

Figure 4.

Figure 5 showed the temperature inside the annular during drilling operation. It is deduced from the result that nano-drilling fluid has a better cooling effect and a more efficient heat transfer, which demonstrates the outstanding characteristics of its thermal conductivity and specific heat capacity. The results showed that the temperature at point A is stabilized at a high temperature, which can logically be explained by the fact that the bottom hole is affected continuously by the frictional heat, so the bottom hole always needs to be cooled to avoid the risk of reaching higher temperature. The good heat transfer of drilling fluids makes the temperature at the bottom hole to be always cooler and more stable. With nano drilling fluid, the temperature at the bottom hole is slightly lower in comparison with normal drilling fluid. However, the higher the distance between the observation point and the bottom hole is, the clearer the positive effect of nanofluid is observed. Using nanofluid, the average temperature at the upper position is found higher and the difference in average temperature at some positions can reach up to 2^{o}C in comparison with using normal drilling fluid. Another positive effect of the nano-drilling fluid is that the temperature does not increase too high and also does not decrease too low, so the temperature stays more stable during a drilling operation.

In Figure 6, we compare the heat transfer and the cooling effect of two types of drilling fluid in the annu-

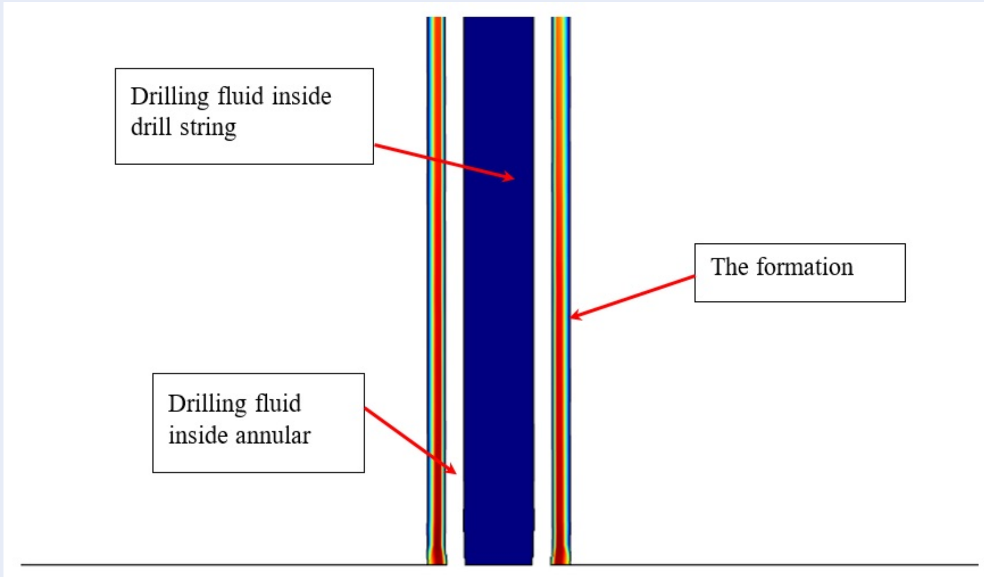

Figure 4: Illustration of the drill string, the annular and the circulation paths of the drilling fluid inside drill string and inside annular.

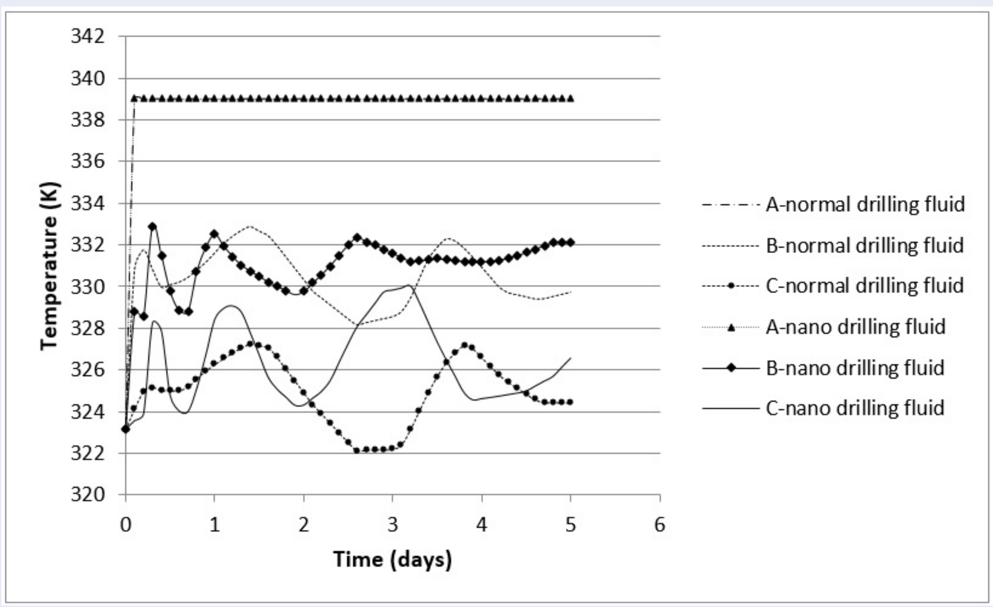

Figure 5: The temperature of the well at different points A, B and C when using nano-drilling fluid and normal drilling fluid.

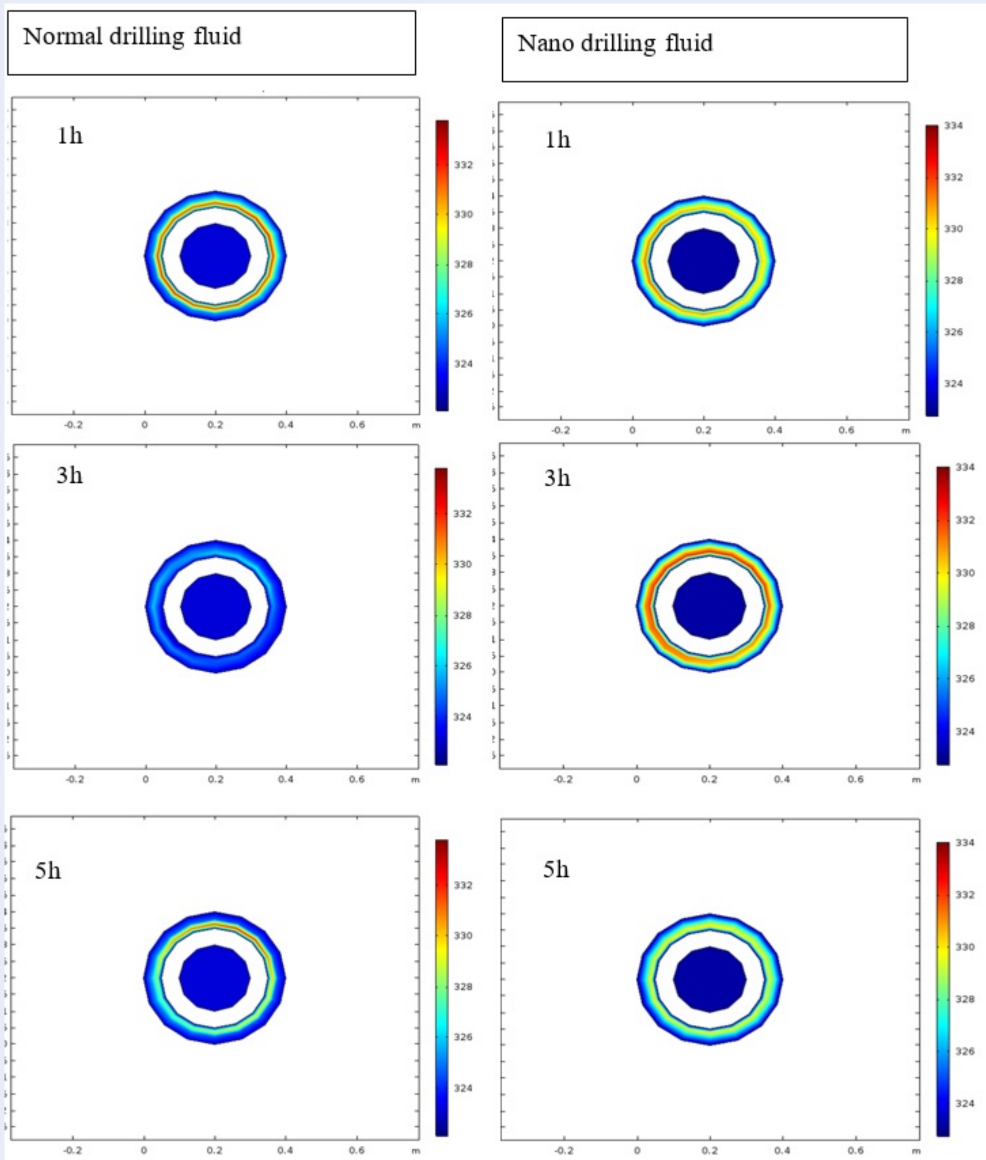

Figure 6: The temperature of the well after 1, 3 and 5 hours.

lar. Thanks to the very small size of nanoparticles and their high surface area per unit volume, the presence of CuO, ZnO nanoparticles in drilling fluid results in a better thermal conductivity and a lower specific heat capacity, which in turn accelerates the heat exchange process. In addition, nano-drilling fluid makes the heat transfer more quickly between locations and the temperature is transferred to the surface more rapidly.

The cooling effect in the formation

Another application of drilling fluids is the cooling effect in the formation. When a drilling operation is taking place, the drilling fluid may invade the formation and the heat exchange process occurs between the drilling fluid and the formation. A sandstone model is built with a porosity of 15% and a permeability of 20 mD. The formation surrounding the wellbore is 4 m in radius and the other parameters follow the wellbore model used in section 3.1. Simulation of the cooling effect of two types of drilling fluid was conducted and we consider three observation points from near the wells to further away with their coordinates are respectively D(2;1;5); E(3;1;5); F(4;1;5) for comparison between nano drilling fluid and normal drilling fluid (Figure 7).

Figure 8 presents the temperature inside the formation when the drilling fluid circulation is taking place. In formation, nano-drilling fluid still presents a better cooling effect than normal drilling fluid. The temperature at the point D (the nearest point from the wellbore) is the most reduced, and the nano fluid brought higher reduced temperature in comparison with the normal one. The farther away the position is, the less the temperature decreases.

As mentioned above, by adding nanoparticles into drilling fluid, nanoparticles not only enhance the thermal conductivity but also reduce the specific heat capacity of nano-drilling fluid. Lower specific heat capacity and higher thermal conductivity results in a higher rate of heat transfer, which leads to a quicker cooling effect. According to the Equation 1 and 2, CuO, ZnO nanoparticles added in the drilling fluid will reduce the specific heat capacity of drilling fluid, because the specific heat capacity of CuO, ZnO nanoparticles are much smaller than that of the drilling fluid. Therefore, the specific heat capacity of nano drilling fluid is smaller than normal drilling fluid. One the other hand, the thermal conductivity of CuO, ZnO nanoparticles are larger than that of the drilling fluid, consequently the thermal conductivity of drilling fluid is increased.

Figure 9 presents the result of the cooling effect with two types of drilling fluid. In the formation, the temperature of the reservoir around the wellbore is cooled when the drilling fluid invades the formation. But far away from wellbore, the amount of drilling fluid is less because of low porosity as well as the speed of invasion reduces due to the friction with matrix. In addition, the drilling fluid absorbs heat during the invasion process resulting in the cooling effect decreasing. Therefore, further away from the well, the temperature of the reservoir is not much reduced, the change is not significant and the temperature is more stable. The speed cooling at the bottom hole is lower than above layers due to the effect of heat generated by the friction between the drill bits and formation. Figure 9 also indicates that the cooling effect of nano-drilling is faster with a shorter time in comparison with normal drilling fluid. These results indicate clearly that the cooling effect of nano-drilling fluid is better than normal drilling fluid both formation and wellbore, because the nanofluid with a better thermal conductivity and a lower specific heat capacity will result in a faster heat transfer between locations. Especially in the wellbore, the temperature is spread to the surface more rapidly and the more stable heat transfer which contributes to the reducing of the temperature at the bottom hole. The surrounding area is also cooled quickly and the average temperature is much reduced. All things emphasize the superiority of nano-drilling fluid compared to normal drilling fluid.

CONCLUSIONS

This research allowed us to deduce the following conclusions:

1. The thermal conductivity of nano-drilling fluid increases when nanoparticles are added in water-base mud and oil-base mud.
2. The specific heat capacity of nano-drilling fluid is smaller than that of normal drilling fluid.
3. With nano-drilling fluid, the heat transfer is better and more efficient.
4. Inside the annular, the heat transfer exerted by nano-drilling fluid is faster than by normal drilling fluid.
5. Inside the formation, the cooling effect of nano-drilling fluid is better than normal drilling fluid and the amount of reduced temperature can reach 7^{o}C.

Nano-drilling fluid, therefore, offers positive effects such as helping to reduce the temperature and to stabilize the temperature, especially in complex stratigraphy and in high-pressure high-temperature wells.

CONFLICT OF INTEREST

The authors certify that they have no conflict of interest with any organization or entity in the subject matter or materials discussed in this manuscript.

AUTHOR CONTRIBUTION

Pham Son Tung conceived the presented idea of the research. All authors developed the theory, performed the computations, discussed the results, and contributed to the final manuscript.

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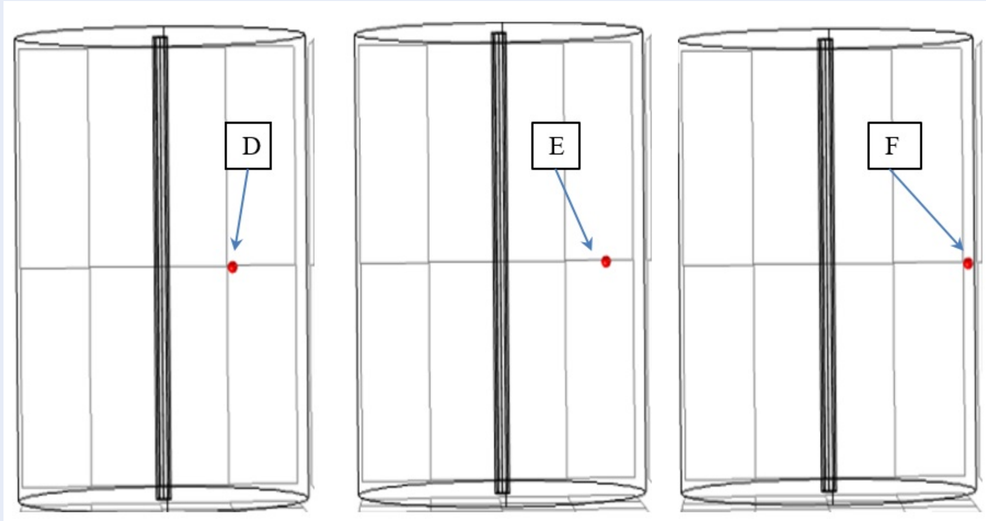

Figure 7: The three points D, E and F inside the formation where cooling effect caused by nanofluid and normal fluid will be compared

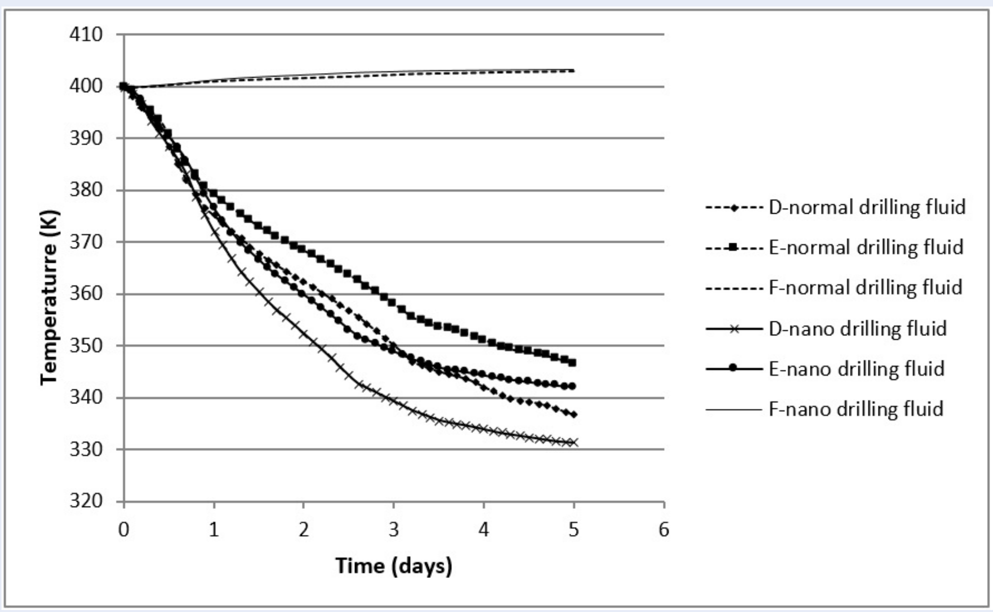

Figure 8: The temperature at different observation points D, E and F in the formation when using nano-drilling fluid and normal drilling fluid.

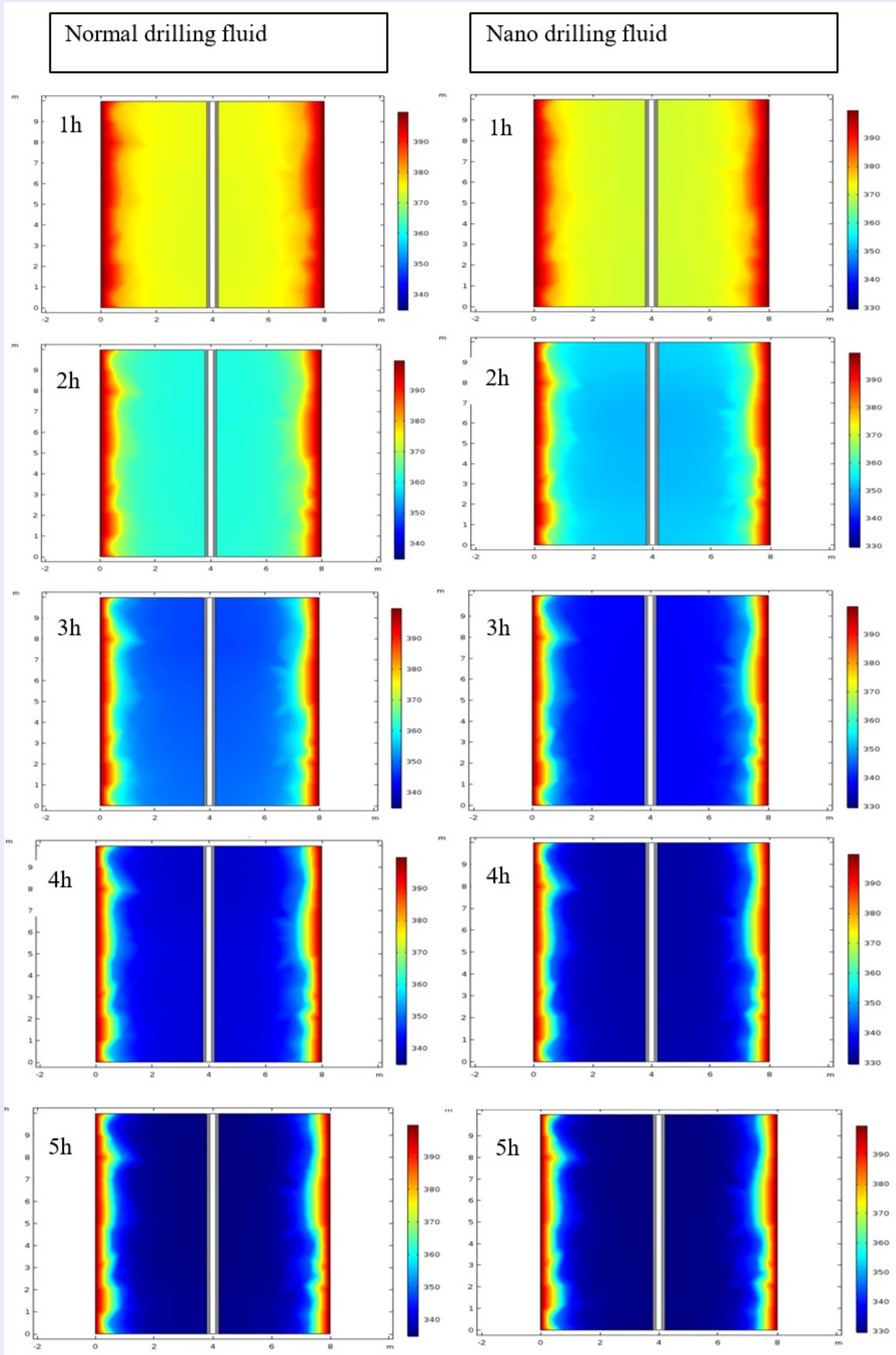

Figure 9: The variation of formation temperature at after 1,2,3,4 and 5 hours.

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Bài nghiên cứu

Mô hình hóa khả năng làm mát của dung dịch khoan sử dụng công nghệ nano

Phạm Sơn Tùng[*], Nguyễn Mai Tấn Đạt

TÓM TẮT

Dung dịch khoan đóng một vai trò quan trọng trong việc đảm bảo an toàn và thành công của quá trình khoan. Bên cạnh các loại dung dịch khoan thông thường như dung dịch khoan gốc nước hay dung dịch khoan gốc dầu, có một loại dung dịch khoan mới bắt đầu được nghiên cứu thời gian gần đây, đó là dung dịch khoan sử dụng công nghệ nano. Mục đích của bài báo này là nghiên cứu hiệu quả làm mát của dung dịch khoan nano được sử dụng trong ngành dầu khí. Nghiên cứu đã xây dựng một mô hình động bao gồm vỉa, giếng và cần khoan được mô phỏng trong trạng thái đang diễn ra quá trình khoan, với sự tuần hoàn dung dịch khoan trong cột cần khoan, đi vào khoảng không vành xuyến và trở ngược lên bề mặt. Phương trình Navier-Stoke được sử dụng cho dòng chảy của dung dịch khoan bên trong cột cần khoan và khoảng không vành xuyến, trong khi phương trình Darcy được sử dụng cho dòng chảy của dung dịch khoan và bên trong vỉa. Sự gia tăng nhiệt độ do ma sát gây ra giữa choòng khoan và đá vỉa ở đáy giếng cũng được tính đến trong mô hình này. Hai loại dung dịch khoan được sử dụng trong mô phỏng: dung dịch khoan thông thường và dung dịch khoan sử dụng công nghệ nano. Sự thay đổi nhiệt độ trong lòng giếng và thành hệ theo thời gian của hai loại dung dịch khoan này được quan sát ở một số vị trí khác nhau: ở đáy giếng nơi mũi khoan thường xuyên tiếp xúc với đá vỉa, và ở một vài điểm khác trong lòng giếng hoặc trong vỉa. Kết quả mô phỏng cho thấy, mặc dù nhiệt độ dao động trong cả hai trường hợp sử dụng hai dung dịch khoan khác nhau, nhưng tính trung bình thì dung dịch khoan nano cho hiệu quả làm mát tốt hơn so với dung dịch khoan thông thường. Bài báo này là nghiên cứu đầu tiên về ứng dụng hạt nano trong dung dịch khoan ở Việt Nam bằng phương pháp mô hình tích hợp. Cách tiếp cận được đề xuất trong bài báo này có thể được sử dụng hiệu quả cho các ứng dụng thực tế dùng dung dịch khoan nano cho khoan dầu khí tại Việt Nam. Tuy nhiên, cần lưu ý rằng nghiên cứu này mới chỉ xét đến khía cạnh kỹ thuật của việc ứng dụng công nghệ nano trong dung dịch khoan, trong khi đó việc nghiên cứu về khía cạnh tài chính để đưa công nghệ này vào thực tế sẽ là rất cần thiết.

Từ khoá: dung dịch khoan nano, mô hình đa vật lý, độ dẫn nhiệt, nhiệt dung riêng

Khoa Kỹ thuật Địa chất và Dầu khí, Trường Đại học Bách Khoa – ĐHQG-HCM

Liên hệ

Phạm Sơn Tùng, Khoa Kỹ thuật Địa chất và Dầu khí, Trường Đại học Bách Khoa – ĐHQG-HCM

Email: phamsontung@hcmut.edu.vn

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