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Overview of how the Calculation of Dynamic Temperature of Drilling Fluids is Closely Linked with Rheology

Knut S. Bjørkevoll[1]

[1]NORCE, Universitetsveien 19, 4630 Kristiansand, Norway

ABSTRACT

Based on many years of work with the calculation of dynamic temperature of drilling fluids during operations, a pedagogic overview of how the calculation of heat transfer and temperature is closely linked with fluid flow properties will be given. For example, the onset of vortices and turbulence due to imposed flow and rotation of the drill string / running string has a large impact on heat transfer. Changing from idealized laminar flow with only conduction radially to flow with vortices and turbulence with convective heat transfer also radially, causes a large boost of heat transfer, especially along the outer wall of the drill string. Clearly, the rheological behaviour of the fluid is essential. Different vibrational modes and other disturbances add to the complexity of the picture, such that some effects can be modelled from first principles, while others are too complicated for practical models and must be handled differently.

INTRODUCTION

Turbulence, vortices, and natural convection boost heat transfer, and are amongst the most important effect in calculating transient temperature effects while drilling. The onset of these effects depend on the rheology of fluids, and unfortunately for drilling most published studies of heat transfer have been done on relatively simple Newtonian fluids like air, water, and oil. Many of the studies consider flow inside or outside pipes and narrow annuli, because heat transfer in heat exchangers and motors are important applications.

While a good understanding of the thoroughly described heat transfer through air and water is an important and useful basis[1,2,3], there are also books and articles that derive and discuss formalism for non-Newtonian fluids. A good example is the book by A.H.P.Skelland[4], which gives generalization of heat transfer theory to different non-Newtonian rheological models.

The generalization to non-Newtonian fluids can be done by using formalism that has been developed and validated for Newtonian fluids, and generalize expressions based on dimensionless groups to non-Newtonian fluids similarly to what many have done for flow in pipes and annuli[5,6]. The mentioned transitions can be expressed in terms of Rayleigh, Taylor, and Reynolds numbers, and a natural approach is to replace the Newtonian viscosity by a generalized shear-rate-dependent effective viscosity defined such that the non-

Newtonian laminar frictional pressure loss has the same form for Newtonian and non-Newtonian fluids.

A relevant question is whether formulas that give heat transfer in narrow annuli are valid for wide annuli, like the annulus between a drill string and a wide casing or riser. A common approach here is to use dimensional groups and assume that results from narrow annuli can be generalized. This may be a dubious assumption since e.g. commonly used formulations of the Taylor numbers involve the third power of the outer annulus diameter such that it increases very much with outer diameter.

This articles uses an existing advanced mathematical model for drilling hydraulics and heat transfer to show how important the mentioned effects are for calculated temperature profiles, and it is argued that both experiments and modelling should to a larger extent address conditions typical for drilling. That is, non-Newtonian fluids in pipes and wide, eccentric annuli with rotation and vibration of the inner pipe.

A realistic but synthetic case is used to demonstrate and discuss the following major effects that depend on density, rheology profile, velocity profile, and flow geometry: Natural convection, forced convection with laminar and turbulence flow, and vortices triggered by rotation.

DETAILS

Natural convection

The degree of natural convection in a fluid column with no forced convection, depends temperature gradients, density, and rheology profile, and we use the Rayleigh number to determine when heat transfer is purely conductive and when it is by natural convection[1].

The Rayleigh number is defined by

$$\mathrm{Ra} = \mathrm{Gr}\,\mathrm{Pr}, \tag{1}$$

where Gr is Grashof number and Pr is Prandtl number. The Grashof number is defined by

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

where g is the gravitational constant, β is thermal expansion, ΔT is the difference between bulk and wall temperatures, D is diameter, ρ is fluid density, and μ is viscosity, and the Prandtl number is defined by

$$\mathrm{Pr} = \frac{c_p \mu}{k}, \tag{3}$$

where c_p is specific heat and k is thermal conductivity. Inserting into the definition of the Rayleigh number gives

$$\mathrm{Ra} = \frac{g\beta\Delta T D^3 \rho^2 c_p}{\mu k}, \tag{4}$$

which shows that natural convection can be dampened by increasing effective viscosity.

To get an idea about the relevance of natural convection for drilling fluids, we consider fluid outside a 3.5 inch drill string in a 8.5 inch hole with static conditions. Typical order of magnitude values are $g = 9.8$ m/s^2, $\beta = 1e-4$, $\Delta T = 5$ K, $D = 0.064$ m (annulus gap), $\rho = 1500$kg/m^3, $c_p = 1200$ J/(kg K), and $k = 0.4$ W/(m K). This gives

$$Ra \approx \frac{9.8 \cdot 10^{-4} \cdot 5 \cdot 0.064^3 \cdot 1500^2 \cdot 1200}{0.4 \cdot \mu} \approx \frac{8500}{\mu} \tag{5}$$

With a critical Rayleigh number of 6000, we can see that viscosity needs to be as high as 1.4 Pa s = 1400 Cp to prevent natural convection. But as natural convection is most relevant with no flow, the effective viscosity of fluids with only a small positive yield point may exceed this, and when circulation and drilling starts, the relatively small effect of natural convection will be largely wiped out after one or a few full circulation rounds.

Note that much of the literature on natural convection considers Prandtl numbers 7 and 0.7, which are representative values for water and air respectively (depending on temperature and pressure though), while realistic drilling fluid may have $\mathrm{Pr} > 100$ at low shear rates, such that published results for the Newtonian water and air should be used with care. However, in the lack of accurate measurements for realistic drilling fluids, we take the commonly used approach for generalizing viscosity to non-Newtonian fluids, and assume that it will give reasonable results.

For drilling, natural convection has a very small effect on most operations because gravity driven movements in static columns will be hindered by yield points and gelling, and it is considered reasonable to ignore it completely. Figure 1 shows a simulation of one hour of circulation followed by one hour of no circulation, and it can be seen that the predicted effect of natural convection speeds up heat transfer in the static period, but still the impact on a drilling operation as a whole will be relatively small.

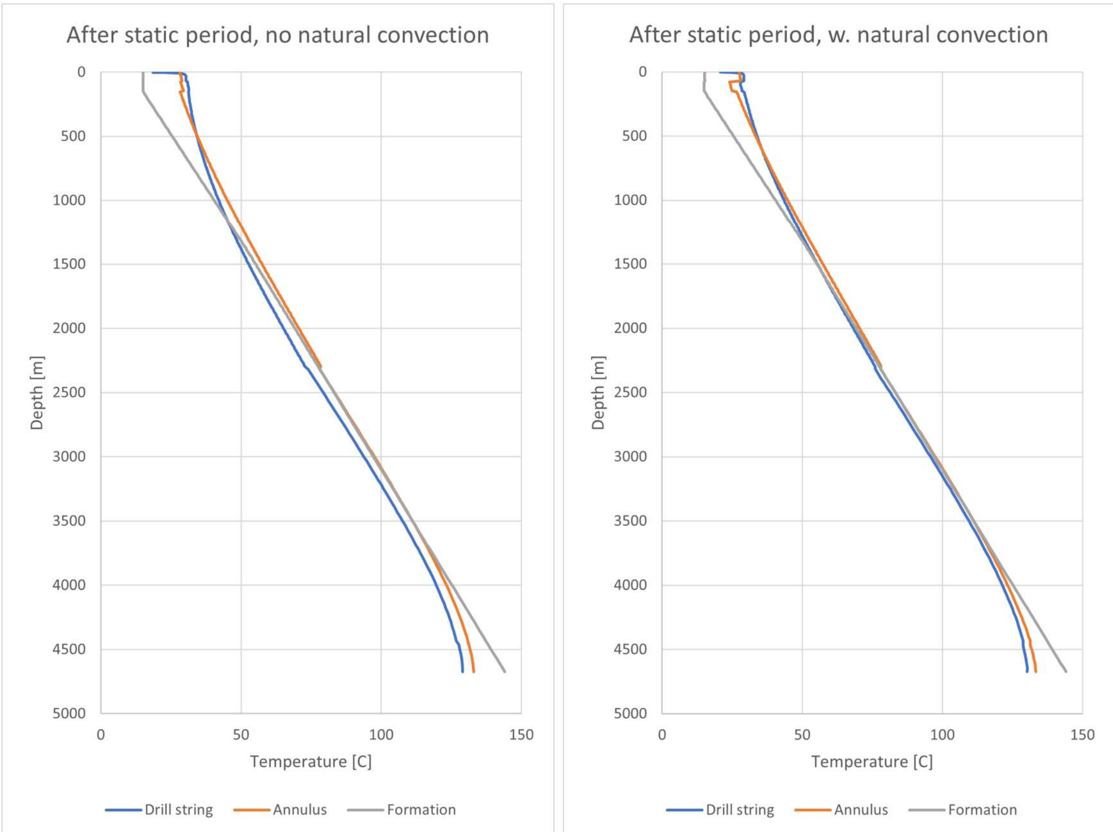

FIGURE 1: Temperature profile after one hour circulation and one hour static. Left figure without and right figure with natural convection. It can be seen that natural convection brings the temperature inside and outside the drill string much closer.

Laminar flow

Heat transfer with laminar flow depends on velocity profile, which depends on rheology profile, and on the distance from where laminar flow started. Depending on the fluid's properties, the development of the temperature profiles radially may take 10s of meters.

Heat transfer with laminar flow is relatively complex in itself because a long distance is needed to get to a fully developed radial temperature profile. This can be predicted by using work by Graetz[7,1] and others, and a generalization to non-Newtonian fluids is relevant because the radial temperature profile will be influenced by the radial velocity profile and the local viscosity vs. radial position. With the definition

$$\mathrm{Gz} = \frac{D_H}{L}\,\mathrm{Re}\,\mathrm{Pr}, \tag{6}$$

values from the example above, and Reynolds number 1500, we see that the Graetz number will be

$$\mathrm{Gz} \approx \frac{57000}{L}, \tag{7}$$

such that about 60 m from the beginning of laminar flow is needed before the radial temperature profile is considered fully developed[8,3]. Again, the details of how viscosity and Reynolds number are generalized for non-Newtonian fluids plays a central role for the calculation of heat transfer.

A relevant question is how realistic the idealized laminar flow over many tenths of meters is, especially with tool joints, a rotating drill string, and other disturbances that may cause radial flow components that enhance heat transfer and prevent coming to a fully developed radial temperature profile. Therefore, the maximum length of laminar flow has been introduced as a parameter that significantly enhances heat transfer if set to a relatively low value.

Turbulence and vortices

The degree of turbulence with no rotation depends on flow rate, geometry, density, and rheology profile. When rotation starts, vortices can be generated depending on rotation rate, geometry, density, and rheology profile. The review by Childs and Long[9] has a map flow regimes vs. Reynolds and Taylor number, which show how vortices are generated at very low Reynolds numbers due to rotation.

As in calculation of frictional pressure loss, the transitional phase is most challenging for getting accurate prediction. The following gradual transition is envisioned for axial forced flow with a rotating inner string:

1. Purely laminar flow, with Reynolds and Taylor numbers below critical values
2. Vortices along the inner string, with Taylor number exceeding its critical value slightly
3. Vortices extend outwards to the outer wall as Taylor numbers increase
4. Gradual transition to fully developed turbulence as Reynolds number increases

It is natural to address the extremes first and then find a transition that matches what is available of data and advanced simulations (like CFD).

The Taylor number, which is used to predict the onset of vortices due to rotation, can be formulated in different ways, either proportional to the rotation rate squared with critical Taylor number for the onset of vortices about 1700, or the square root of the same with onset of vortices at about 41. The first variant will be on the dimensionless form[1].

$$\mathrm{Ta} = \frac{4\Omega^2 R^4}{\nu^2}, \tag{8}$$

where R is a characteristic dimension perpendicular to the axis of rotation.

For annular flow, there is a freedom of choosing R, and a commonly used form is

$$\mathrm{Ta} = \frac{4\Omega^2 R_i (R_o - R_i)^3}{\nu^2}. \tag{9}$$

which has very different values for narrow and wide annuli. In the latter case, one can imagine vortices along the rotating inner string being less constrained when the outer boundary is far out, but then one would expect the expression to level out at some R_o rather then increasing asymptotically as R_o^3.

Heat transfer under fully developed turbulence can be modelled using the Stanton number

$$\mathrm{St} = \frac{\mathrm{Nu}}{\mathrm{Re}\ \mathrm{Pr}}, \tag{10}$$

with the heat transfer coefficient given by

$$h = c_p \rho v\, \mathrm{St}. \tag{11}$$

Different forms of the Nusselt number are given for turbulent flow, including the Dittus–Boelter equation, which reads

$$\mathrm{Nu} = 0.023\, \mathrm{Re}^{4/5} \mathrm{Pr}^{0.4} \tag{12}$$

for fluid being heated.

With this, heat transfer under laminar and turbulent flow can be predicted, and what remains is an adequate transition between the extremes. Further discussion is kept out of this article, except illustrated by the example simulations shown below.

MODEL

The model used for the example simulations is a combined dynamic 1D hydraulic model and a dynamic 2D temperature model with radial symmetry. The model is essentially the same as a widely used and validated commercial model, but it is also available internally for research purposes such that tweaking of details of the model is possible. The temperature model, which is the interesting part for this article, is based on the article by Corre et al[10] with many later adjustments and improvements, and it has all the above mentioned features built into it.

EXAMPLE SIMULATIONS

A set of simulations are run on a realistic test case, with the following characteristics:

- Near vertical down to 1000 m, then building gradually up to 20° from vertical down to the measured depth at the end of the simulated drilling,

[1] See for example https://en.wikipedia.org/wiki/Taylor_number

- Start with bit depth 4680 m and hole depth 4710 m,
- A typical riser and casing program: 21" riser to 150 m, 20" casing to 1000 m, 13 5/8" casing to 2500 m, 9 7/8" liner from 2300 to 4700 m,
- A yield power-law drilling fluid with high and low low-end readings as shown by Figure 2.

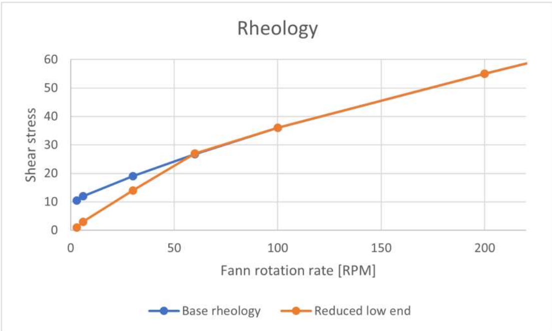

FIGURE 2: Rheology profiles used.

The figures below show temperature vs. measured depth at the end a dynamic simulation of the following sequence:

1. Circulate 1800 LPM with 100 RPM string rotation for one hour,
2. Stop both rotation and circulation for 10 minutes,
3. Circulate for 5 minutes
4. Drill to 4824 m over 2 hours.

The left part of Figure 3 shows a base simulation with all effects except natural convection included (the latter is not very relevant here since circulation and drilling are considered). Heat transfer from the annulus to the drill string is enhanced much by both Taylor vortices due to rotation and turbulence due to axial flow. Mud flowing down inside the drill string is heated and mud flowing upwards in the annulus is cooled down, thus bringing the two temperature profiles closer together. Heat generated by frictional pressure loss and by resistance to rotation is included, but is not discussed further here.

The right hand side is without the effect of ration on heat transfer to illustrate its importance. Vortices triggered by rotation add to radial convective heat transfer inside the annulus, and may increase heat transfer by more than an order of magnitude. The vortices generated by rotation also promote heat transfer from and to the surrounding formation, sea water, and air, but the experience is that this effect is small compared to the effect on heat transfer inwards.

The left part of Figure 4 shows a simulation without the effects of rotation and turbulence on heat transfer, i.e. it uses the laminar flow formalism. Then the radial flow of heat is purely laminar, This clearly shows how important it is to get the transitions to non-laminar flow correct, also for non-Newtonian fluids.

The right hand part of the figure illustrates how it may be important to get the development of radial temperature profile from nearly flat at the inlet to fully developed

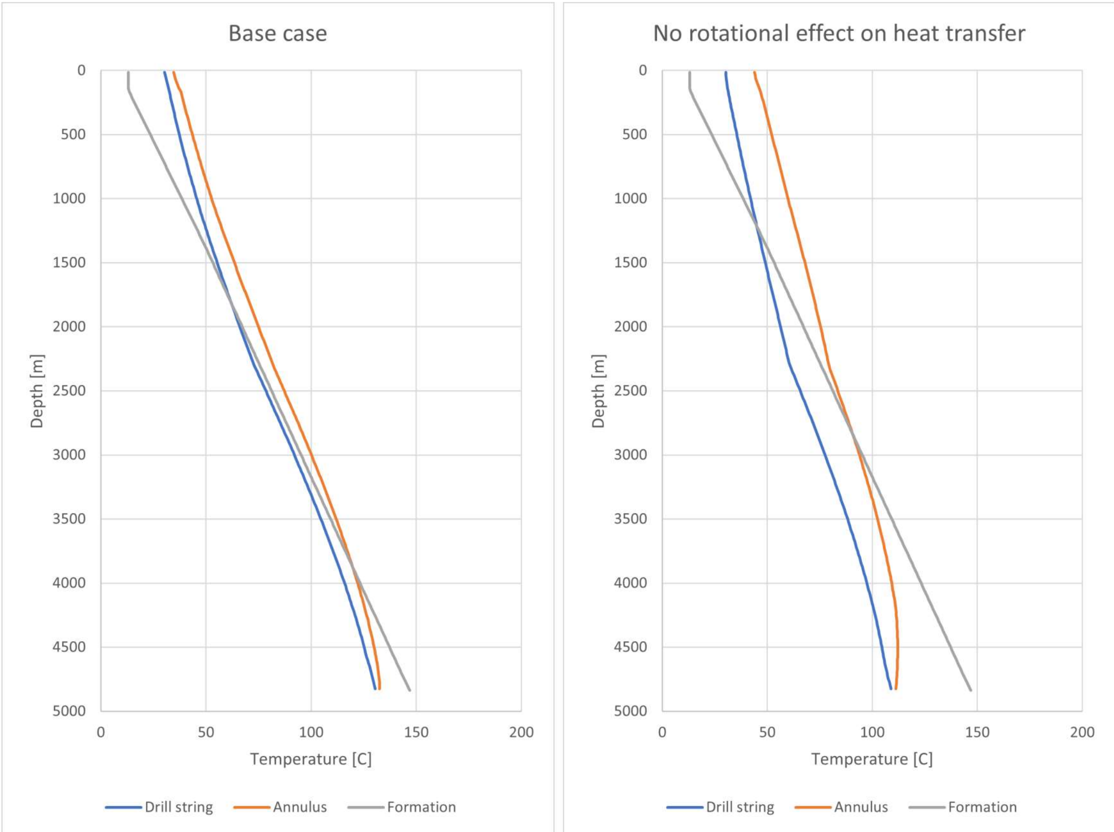

FIGURE 3: Base case with and without rotational effect on heat transfer

correct. With the longer maximum length of laminar flow, the right part shows heat transfer with near ideal laminar flow, i.e. no radial flow components in a flush pipe, while the shorter maximum length of the left hand simulation is meant to account for an anticipation that flow is not perfectly laminar. This is also a phenomena that would be relevant to study closer for realistic non-Newtonian fluids.

CONCLUSIONS

The article shows through simulations of an artificial, but realistic drilling case, that flow behaviour, and thereby rheology, is very important for heat transfer. It is shown how natural convection, vortices due to rotation, and turbulence due to axial flow boosts heat transfer and change dramatically the predicted temperature profile. Thereby accurate prediction of temperature depends on the ability to predict accurately transitions from laminar flow to flow with vortices and turbulence.

As drilling moves forward with many challenging wells to be drilled within petroleum, geothermal energy and CO_2 storage, to mention some applications that will be large in many years to come, it is worth getting more accurate observations and models for such conditions.

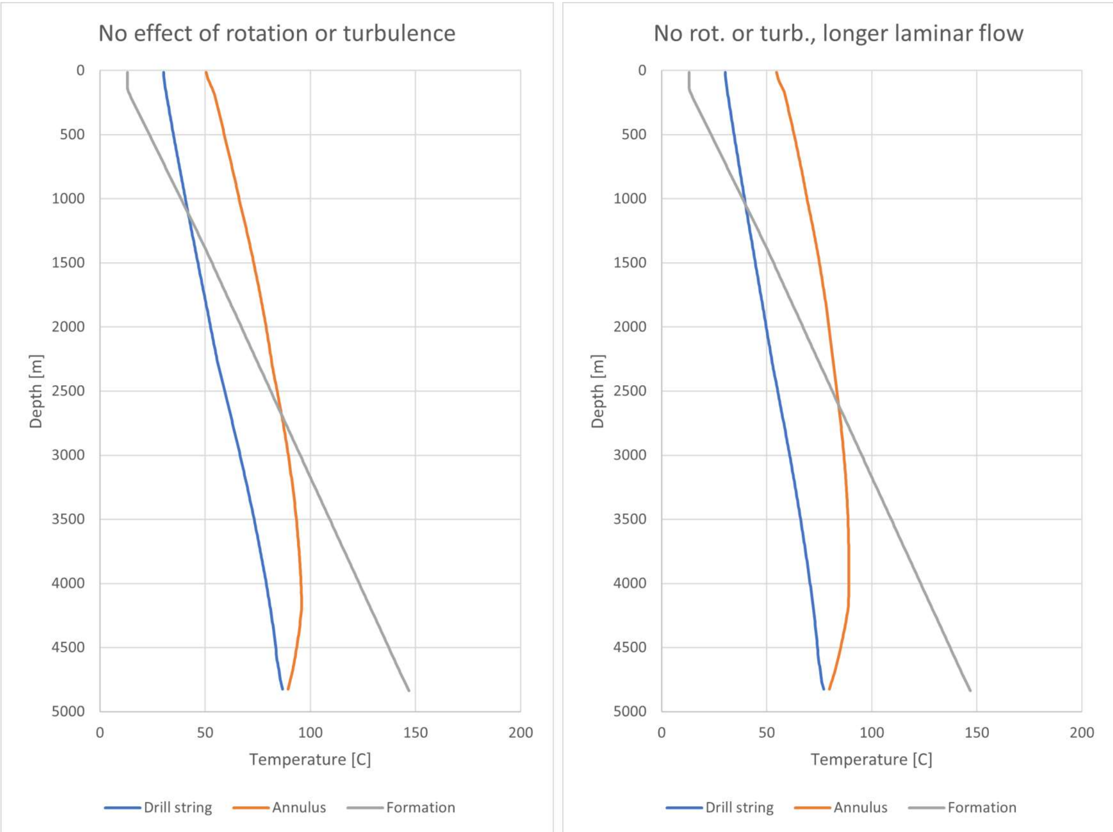

FIGURE 4: Base case without effects of rotation and turbulence on heat transfer; the right hand plot with maximum length of laminar flow inside the drill string increased from 10 to 60 m

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