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To cite this article: E Orlik *et al* 2020 *J. Phys.: Conf. Ser.* **1677** 012194

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Numerical simulation of non-Newtonian hydrodynamics in an annular channel with tool joint

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Abstract. The paper presents the simulations of the local and integral characteristics of an annular flow with tool joints, depending on problem parameters. The structure of the flow in the vicinity of the coupling, in the areas of stagnant and reverse flow, is studied in detail. The characteristic length of separation and stabilization zones, i.e. the distance behind the joint where the flow reaches steady-state again is investigated. The sizes of pipes and tool joints in the study match those used while drilling. The numerical modelling is performed in 3D steady-state formulation for both laminar and turbulent regimes using original in-house software.

1. Introduction

To date, a substantial amount of experimental and theoretical works have been carried out to determine the pressure drop in annular channels with constant cross-section for Newtonian and non-Newtonian fluids [1, 2]. The increase in the eccentricity and rotation speed of the drill string is found to have a significant impact on the pressure drop in the channel. However, while drilling, mud circulates in an annular space of variable section between a drill string and a borehole wall. The changes in the cross-section are due to the fact that pipes are connected by tool joints of larger diameter. Separate studies have also been conducted on the influence of local resistances by couplings on drill string on pressure drop. Tool joints can significantly impact the flow hydrodynamics and pressure drop [3]. The drilling muds, as a rule, are non-Newtonian fluids of complex rheology whose viscosity depends on the shear rate. The models describing the turbulent flow of such fluids have been developed just recently [4], and the hydrodynamic characteristics of flows in an annular channel with tool joints is poorly understood. The information about the characteristics of stagnant zones in the vicinity of tool joints is important both for the sediment layer formation in the inclined wells [5] and for the heat transfer. It should be noted that a detailed study of hydrodynamics on tool joint has not been carried out. There are studies of vortex structures on diffusers in pipes, but only for concentric flows. In spite of the presence of experimental and numerical simulations of flows around tool joint [6], for the time being there are no dependences to calculate a pressure drop in an annular channel with tool joints that account for flow parameters, the geometric sizes of pipes and tool joints, eccentricity and fluid's rheological parameters. This paper presents the series of multi-parameter calculations to study the influence of well geometry, tool joint sizes, drill string eccentricity, and flow regimes on local and integral flow characteristics in the vicinity on the tool joint for Newtonian and power-law fluids.

2. Problem statement and research method

Scheme of tool joint in annulus is shown in figure 1. The stream flows from left to right. The constriction and expansion angles between drill string and joint are 15 and 35, respectively (characteristic technical data). Let us introduce the following designations: L is the length of the annular channel, and L_{tj} is the size of the tool joint. The pipe's inner and outer diameters are D_{ds} and D_{bh} and the TJ's diameter is D_{tj}. The sizes of pipes and tool joints in the study match those used while drilling. To characterize the impact of the tool joint geometry, a dimensionless geometric parameter η, which depends on the ratio of the cross-section areas on the tool joint and in the annulus, is introduced into the problem. The range $0.38 \leq \eta \leq 0.92$ is investigated in the work. The length of the channel is selected to be 4.5 m that matches the minimum size of a pipe used while drilling.
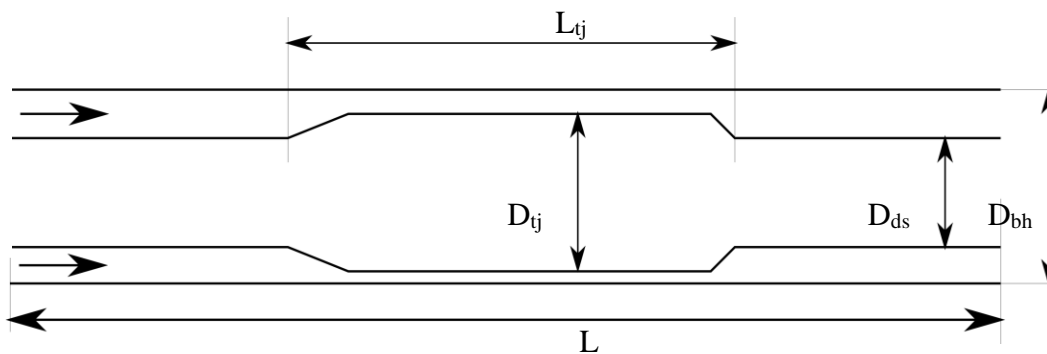

Figure 1. Scheme of TJ in annular channel.

The problem is considered as a steady-state flow of non-Newtonian fluid. Numerical simulations are carried out based on Reynolds-averaged Navier-Stokes equations supplemented by the k-omega shear stress transport (SST) turbulent model, using proprietary 3D software [7].

The stress tensor for a power-law fluid is determined by the relation $\tau = -pE + 2\mu S$, where S is the averaged strain rate tensor, and the effective viscosity coefficient is determined by the relation:

$$\mu = k_c \dot{\gamma}^{n-1} \tag{1}$$

Here p is the pressure, $\dot{\gamma}$ is the second invariant of the strain rate tensor, k_c is the consistency factor and n is the flow behavior index. Since drilling muds are, as a rule, pseudo-plastic power-law fluids whose power n<1, the flows with n varying from 0.5 to 1 are considered. The flow in the channel is described by the Reynolds number Re, determined by Metzner-Reed formula:

$$\text{Re} = \frac{(D_{bh} - D_{ds})^n U^{2-n} \rho}{8^{n-1} K'} \tag{2}$$

where $K' = k_c \left(\frac{3n+1}{4n} \right)^n$. The dimensionless parameter $\Omega^* = \omega D_{ds}/2U$ is the ratio of the rotational velocity of the drill string to the longitudinal flow velocity (U), and ω is the angular velocity. Ranges of parameters are defined as Re: $200 \div 20000$ and Ω^* up to 10.

We use a mesh generator of our own design, specially adapted for building grids in annular channels. The numerical algorithms of our code allow finding a stable solution even for cases of eccentricity of 0.99, when the drill string and well walls are practically in contact. These cases are difficult to simulate in commercial CFD packages. The mesh is dense in the contraction and expansion areas to resolve the vortex structures, as shown in Figure 2.
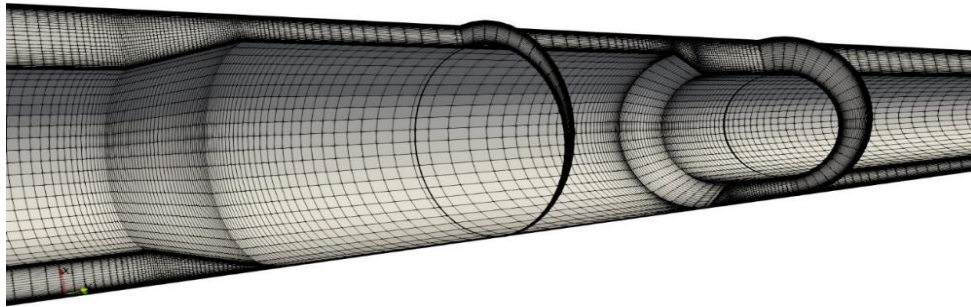
Figure 2. Meshed pipe with a TJ.

3. Results and discussion

The performed calculations have brought us to several conclusions. Eccentricity (ecc) is a key parameter determining the size and shape of a separation zone. The separation zone is visualized using streamlines, while the stabilization one is determined from average pressure distribution in a section along the channel and from comparing velocity fields in the cross-sections. Figure 3 shows the current lines for the axisymmetric case and the numbers Re=5000 and 20000 of the power fluid and the Newtonian fluid for Re=5000. In this case, for a turbulent flow, the length of separation zone weakly depends on the flow rate and flow index n. The flow attachment point is located on a drill string that is visible in figure 3.
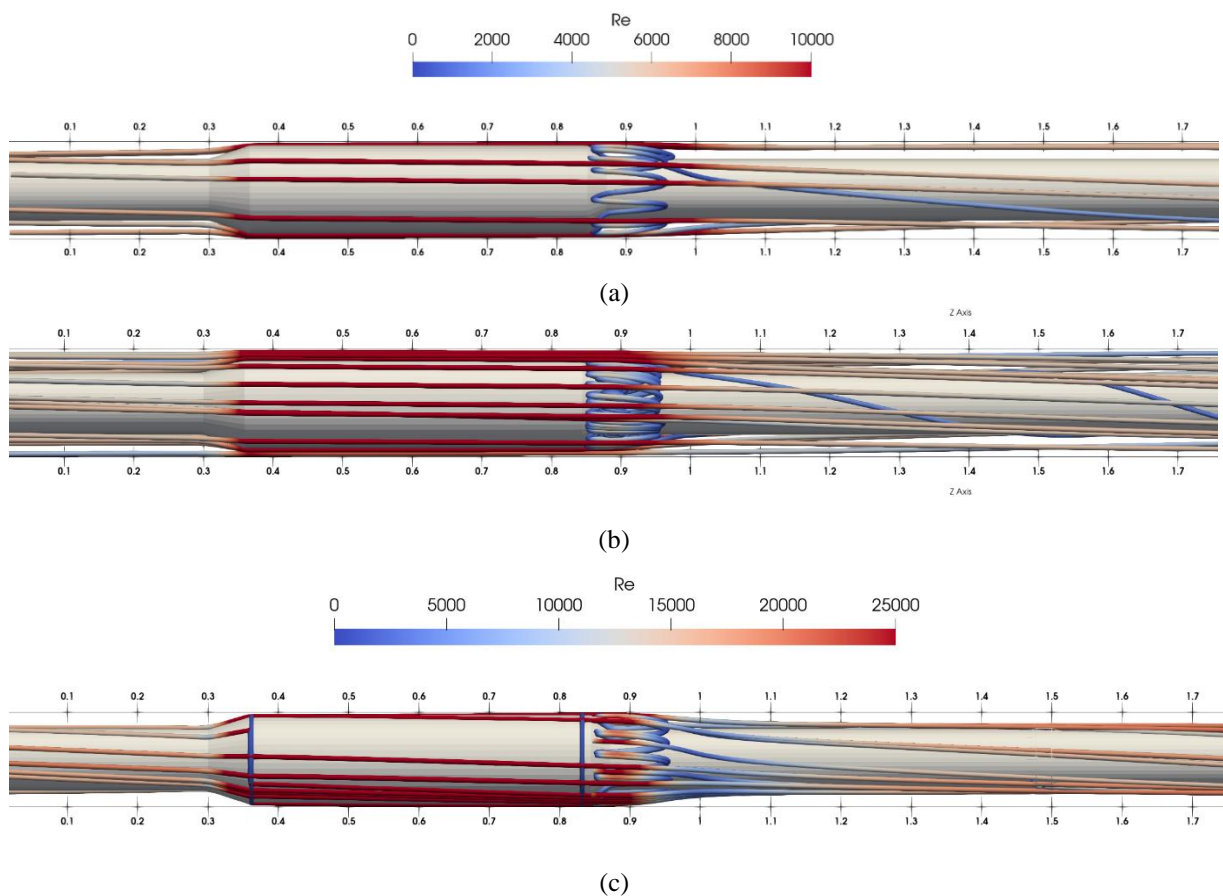

Figure 3. Stream lines. η=0.46, ecc=0.
(a) Re=5000, Ω*=0.1, n=0.6; (b) Re=5000, Ω*=0.1, n=1; (c) Re=20000, Ω*=0.1, n=0.6.

As the eccentricity increases, the flow pattern changes significantly. The size of the separation zone increases with the maximum separation observed for small Reynolds numbers. The flow attachment point displaces on a borehole wall where the annular space between the wall and the joint reaches its minimum (see figure (b)). From published data, we know that a wake length behind the obstacle increases with increasing oncoming flow velocity. However, in an annular channel, a fluid flow is limited by the channel's walls, and in case of non-zero eccentricity, the fluid enters the stagnation zone, reducing the separation zone with increasing the flow rate [8]. It has also been demonstrated that an increase of drill string rotational velocity (RPM) stabilizes the flow and eliminates the separation zone behind the tool joint. (see figure 4 (d)).
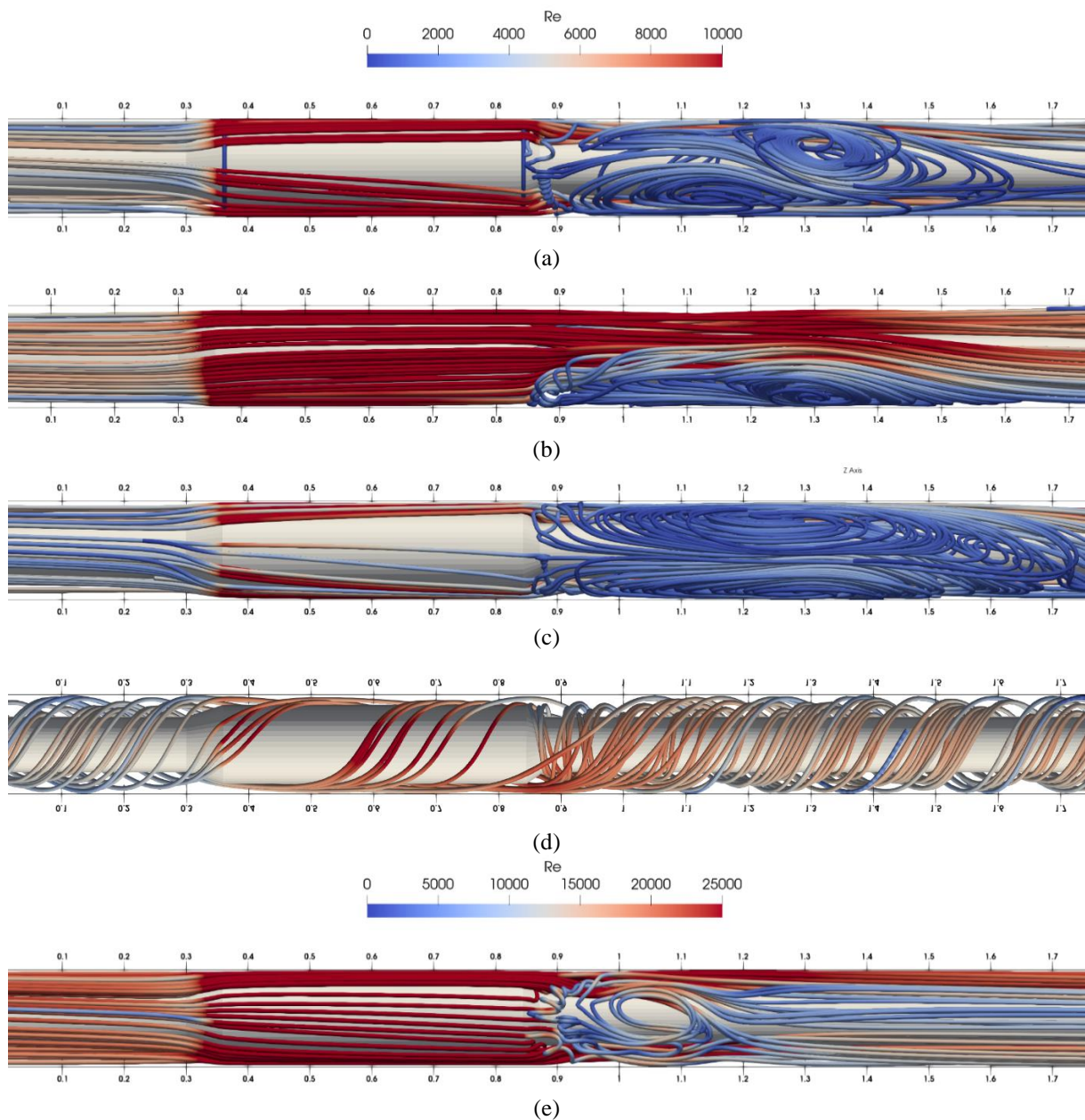

Figure 4. Stream lines. $\eta=0.46$, ecc=0.66

(a) and (b) Re=5000, $\Omega^*=0.1$, n=0.6, bottom and side view, respectively; (c) Re=5000, $\Omega^*=0.1$, n=1, bottom view; (d) Re=5000, $\Omega^*=5$, n=0.6, bottom view; (e) Re=20000, $\Omega^*=0.1$, n=0.6, bottom view.

Thus, it takes about 20 hydraulic diameters $D_h = d_{bh} - d_{ds}$ to stabilize a flow behind the tool joint for the concentric flow and up to 40 if the drill string has eccentricity. It should be noted that a length of 4.5 m is sufficient for the flow to reach its stationary state in all cases considered. This is an important result for calculating the pressure drop in a well or channel with a large number of tool joints.
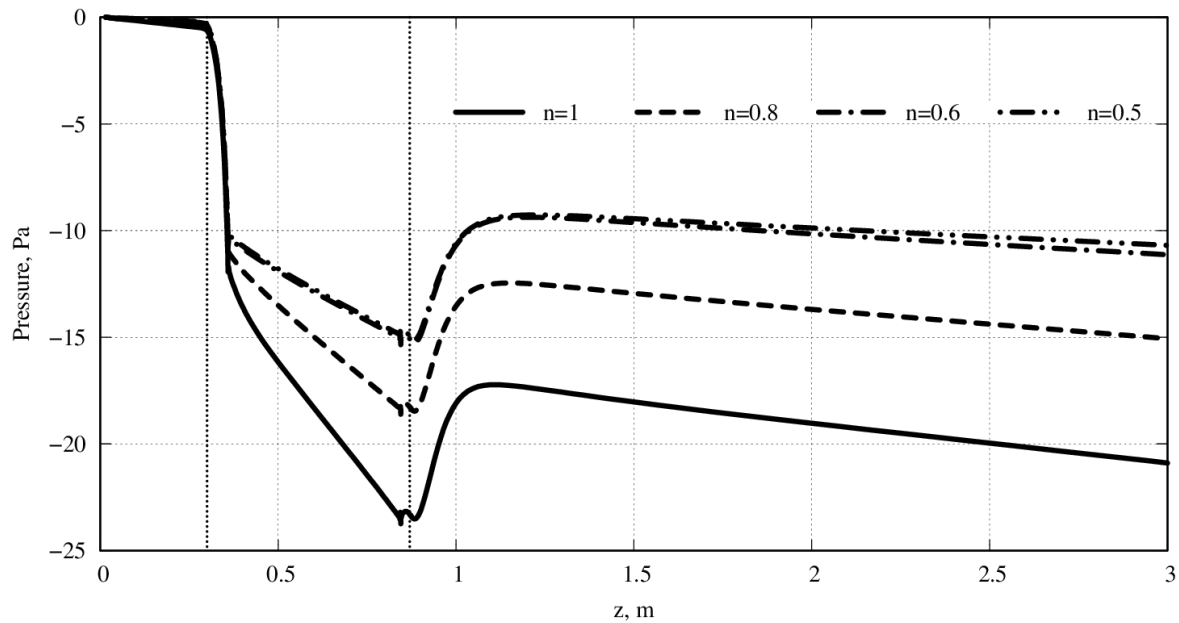

Figure 5. Pressure distribution across tool joint depending on fluid rheology at constant flow rate. $\eta = 0.46$ Ecc=0.
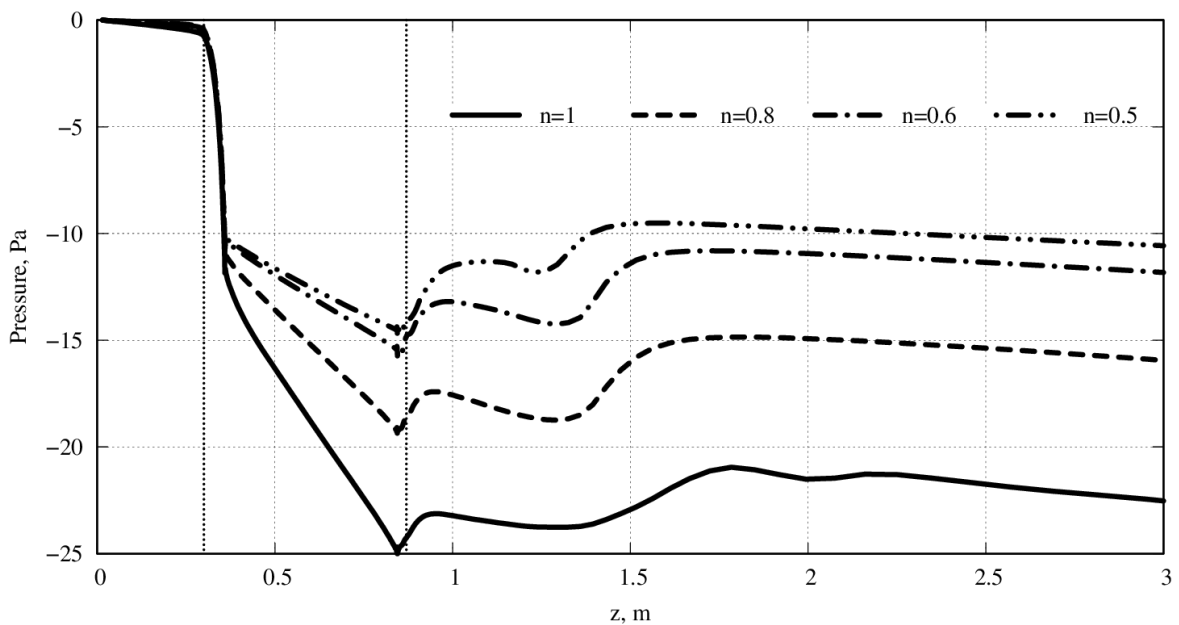

Figure 6. The same as figure 5. Ecc=0.66.

With the considered geometry (constriction and expansion angles), the separation region (stagnant zone) is observed only in the area of flow expansion behind the tool joint. In the area of constriction, fluid accelerates and, in the area of expansion, fluid decelerates and the stagnant area is formed,

leading to a change in the pressure distribution in the vicinity of the tool joint that is shown in Figures 5 and 6 for eccentricities ecc = 0 and 0.66, respectively. Here, the edges of the tool joint are indicated by vertical dotted lines. The flow rate is chosen constant in presented figures; and the Re numbers are different depending on the flow behavior index according to the formula above. The figures show that by changing the properties of the drilling fluid, it is possible to significantly reduce drag force in the pipe. The visualization of the result simulations shows that the separation region in the case of drill string eccentricity is more than halved with a decrease in the flow index n, which leads to a decreasing impact of tool joint on pressure loss.

Conclusions

Systematic multi-parameter hydrodynamic simulations of the flow in an annular channel around the tool joints have been carried out. The results of more than 2000 three-dimensional calculations have been analyzed. The character of the flow output behind the coupling to the steady state mode has been studied. The length behind the tool joint where the steady-state flow is realized has been defined. The influence of eccentricity on the separation zone location and its length has been analyzed. The results show that with an increase in the Reynolds number, the separation area decreases. In the case of the drill string rotation, the separation area is shown to decrease. With decreasing flow behavior index n (increasing viscosity), the separation area behind the tool joint is shown to decrease at the same value of the Reynolds number.

Acknowledgments

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