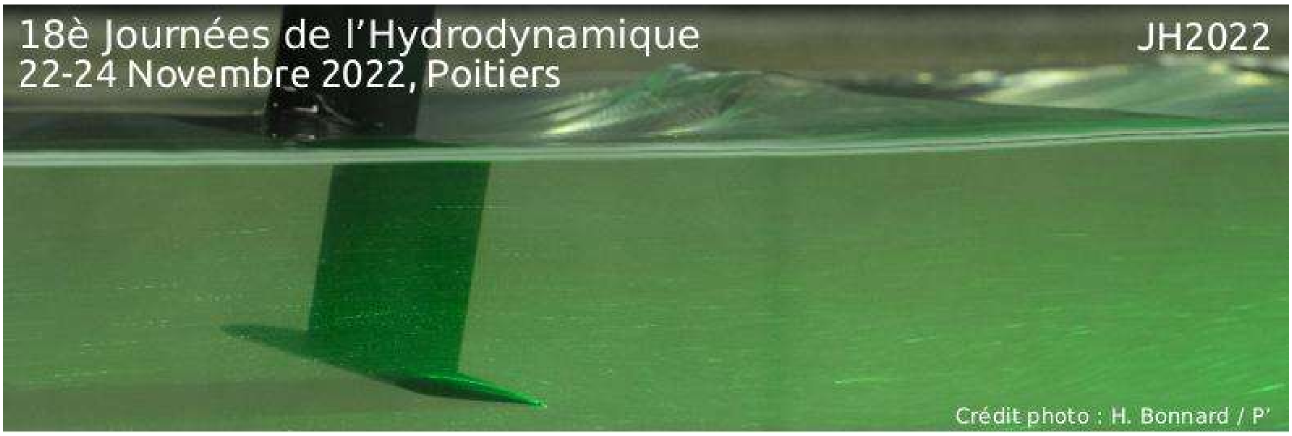

CFD MODELS TO INVESTIGATE CUTTINGS CONCENTRATION IN HIGH PRESSURE, HIGH TEMPERATURE CONDITION: APPLICATION TO HORIZONTAL DOUBLE-CURVE WELLS IN VIETNAM

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Résumé

L'étude du transport de déblais de forage dans l'industrie pétrolière permet d'estimer l'efficacité de l'évacuation des matières solides et d'assurer la performance des opérations de forage. Ce besoin est d'autant plus important pour les opérations de forage dirigé en environnements extrêmes tels que le puits de pétrole HTHP (haute température et haute pression) 10-P localisé dans le bassin de Cuu Long au Viet Nam. Le but de notre étude est de bâtir un modèle numérique pour étudier la concentration en déblais de forage dans ce puits dirigé. Le modèle 2D Euler-Euler est utilisé pour modéliser l'écoulement diphasique avec la phase solide considérée comme continue et la boue de forage modélisée comme un fluide non-newtonien. Le modèle numérique est validé par rapport au modèle théorique de Larsen. Les résultats permettent de confirmer le lien entre la concentration de déblais, la température et la pression, et de prédire l'accumulation de déblais à différentes sections du puits.

Abstract

The investigation of cuttings transport in petroleum drilling allows us to estimate the performance of solid material removal to ensure a prosperous drilling operation. This demand becomes more obligatory with drilling activities with directional drilling in extreme environment similar to our well of interest, the HTHP (petroleum well drilled in high pressure, high temperature condition) 10-P well located in Cuu Long basin, Vietnam. Our study aims to build numerical model to study concentration of cuttings in this directional well. The 2D Euler-Euler model is utilised to model the two-phase flow where the solid phase is treated as a continuous phase and the drilling mud is considered as a non-newtonian. The numerical models are then validated with theoretical Larsen models. Results of the calculation enable us to confirm the dependence of cuttings concentration and pressure and temperature and predict accumulations of cuttings at different sections of the wellbore.

I. Introduction

In rotary drilling, drilling mud play its significant role as a conduct to transport rock fragments, induced during the penetration of the drill-bit into the earth's crust, upwards to the surface. A feeble hole cleaning performance may lead to aggressive accumulation of cuttings at the disperse layer (low side) of the wellbore, which is considered a main cause of several problems to the drilling operation such as high torque and drag, excessive bit wear, stuck pipe [1],[2],[3] especially in deviated well. The efficiency of the cuttings transport depends enormously on operational parameters such as: mud pump flowrate which decides the annular velocity of the upward flows [14], [15]; rheology of the drilling fluid which plays a very important part in removing cuttings, especially in highly inclined and hozional wells [16], [14]; hole inclination which affects the process to evacuate cuttings out of the drilling well [13] and ROP (rate of penetration) and pipe rotation (rpm) which take their effects on the cleaning efficiency by reducing cuttings deposition and preventing the accumulation of the cuttings bed [13], [11], and properties of cuttings. Some numerical and experimental studies have been carried out to estimate effects of influential parameters on the performance of cuttings transport with applications to horizontal, vertical or inlined wells independently. However, very few considered a deviated well trajectory completely. Therefore, we aim in our research to create a two-phase 2D model to investigate the removal of cuttings in a 5-section deviated well. Both Euler-Euler (EE) and Euler-Langrange (EL) approaches could be used to solve two phase fluid-particle flow [5]. In which, the EL model treat cuttings as a discrete phase. Whereas, the Euler-Euler model considers both liquid and particulate phase, ie, it analyzes the distribution of solid phase and is adopted to solve this multiphase flow in the interest of saving time [9] while providing trustable results.

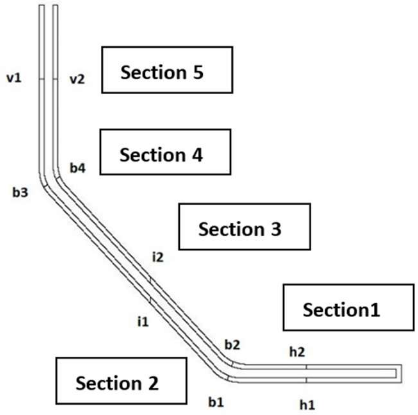

Figure 1.1. Reduced cuttings transport model with reference to the horizontal double-curve well, 10-P

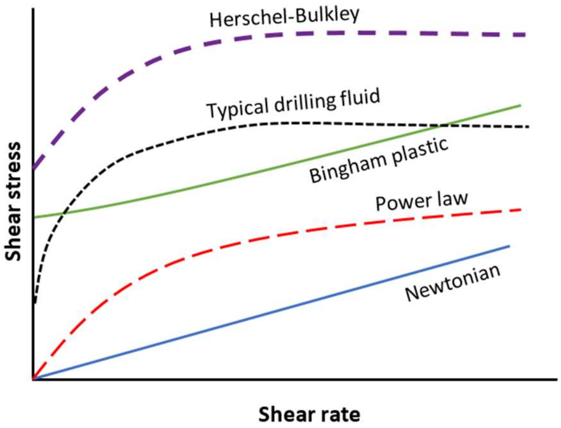

Figure 1.2. Rheology models of drilling fluid

The calculating domain is constructed as a reduced model refering to the well 10-P, the double-curve prospecting well, located at Cuu Long basin, offshore Vietnam, *figure 1.1*. It is composed of 4 typical geometries: vertical (section 5), curves (section 2,4), incline (section 3) and horizontal (section 1). Studying this complex well trajectory allows us to obtain a paranomic view of cuttings transport in deviated well [4].

The well 10-P is drilled in high pressure, high temperature (HPHT), ie., T ~ 150 ÷ 205°C and P ~ 10.000 ÷ 20.000 psi). Operating in this circumstance is considered one of the most challenging activities in the petroleum engineering due to the hardship of controlling relevant factors to achieve most favorable drilling performance [19], [20]. The high temperature and temperature at the bottom are believed to cause change to several drilling parameters down hole including rheological properties of the drilling fluid, which decides the efficiency of the cuttings removel and hole clearance [18]. Therefore, it is also compelling to investigate effects of those two above mentioned factors on the transport of cuttings. The drilling mud, due to its property of containing additives, should be taken for granted as non-Newtonian fluid characterized by features like: flowing as liquid and exhibiting elasticity, plasticity and strength similar to a solid to perform its function of keeping drilling cuttings in suspension. It is a big challenge to build a rheologocal law corresponding perfectly to the real non Newtonian luid such as Power law, Bingham plastic, Cross model or Hurschel-Bulkley model, figure *1.2,* [12,13]. For the sake of simplicity, the Power law model is used to characterize the dependence of rheology of the drilling mud on pressure and temperature. The upcoming 2-phase flow is expected to be turbulent. Among the 6 existing turbulent models compatible with Fluent, the realizable k-epsilon is taken to predict the flow patterns.

Calculations are carried out in concentric context. Cuttings shape is considered spherical with the sizes vary from very small to large with reference to the dimension of cuttings samples observed in situ. Various values of influence parameters (drilling fluid velocity, cuttings injection flowrate…) will be considered first with constant pressure and temperature to validate the realibility of the numerical model. Further calculations are then performed with the effect of pressure and temperature included respectively to crutinize the dependence of the cuttings transport on pressure and temperature.

2. Methodology

In the current work, gas phase and bubble are neglected, thus, the flow coming upward consists of two phases only: drilling mud (fluid phase) and cuttings (solid phase). According to ANSYS Fluent, mathematical formulations for EE model are written in form of Continuity equation, Fluid-fluid momentum equation and fluid-solid momentum equation:

* Continuity:

$$\frac{1}{\rho_c}\left(\frac{\partial}{\partial t}(\alpha_c\rho_c) +\right) + \nabla.(\alpha_c\rho_c\vec{v}_c) = \sum_{m=1}^{N}(\dot{m}_{mc} - \dot{m}_{cm}) \quad (2.1)$$

* Fluid-fluid momentum equation:

$$\frac{\partial}{\partial t}(\alpha_m\rho_m\vec{v}_m) + \nabla.(\alpha_m\rho_m\vec{v}_m\vec{v}_m) = -\alpha_m\nabla p + \nabla.\bar{\bar{\tau}}_q + \alpha_m\rho_m\vec{g} + \sum_{c=1}^{N}\Big(K_{mc}(\vec{v}_m - \vec{v}_c) + \dot{m}_{mc}\vec{v}_{mc} - \dot{m}_{cm}\vec{v}_{mc}) + (\vec{F}_m + \vec{F}_{lift,m} + \vec{F}_{vm,m} + \vec{F}_{td,m})\Big) \quad (2.2)$$

* Fluid – solid momentum equation:

$$\frac{\partial}{\partial t}(\alpha_c\rho_c\vec{v}_c) + \nabla.(\alpha_c\rho_c\vec{v}_c\vec{v}_c) = -\alpha_c\nabla p - \nabla p_s + \nabla.\bar{\bar{\tau}}_q + \alpha_c\rho_c\vec{g} + \sum_{m=1}^{N}\Big(K_{mc}(\vec{v}_m - \vec{v}_c) + \dot{m}_{mc}\vec{v}_{mc} - \dot{m}_{cm}\vec{v}_{mc}) + (\vec{F}_c + \vec{F}_{lift,c} + \vec{F}_{vm,c} + \vec{F}_{td,c})\Big) \quad (2.3)$$

Where, $\vec{v}_m$ and $\vec{v}_c$ are velocity of the drilling mud (fluid phase) and cuttings (solid phase) respectively; ρ_m and ρ_c are densities of the two phases.

To verify effect of pressure and temperature, we consider also the case of non-newtonian fluid using Power law (PL) rheology model. The model can be simply expressed as:

$$\tau = K.\gamma^n \quad (2.4)$$

Where K is the consistency index which is directional proportional to the effective viscosity of the drilling fluid as non-newtonian, n is the power-law index. They receive the value of 0.00084 and 0.68 respectively as suggested in the study of Tomren [18].

Using EE approach, particle phase is regarded as continous phase and set as granular flow which obeys the granular viscosity model suggested by Syamlal et al, 1993. An estimation of the particles injection velocity has been made basing on the penetration rate (ROP). The experimental

Larsen model [5],[6],[7],[8],[10], which describes relation between cutting velocity Vc and the rate of penetration ROP as in the equation (Eq.(2.5)), is exploited to validate numerical results.

$$V_c = \frac{ROP}{36\left[1-\left(\frac{D_p}{D_h}\right)^2\right]C_c} \qquad (2.5)$$

Where, D_p represents diameter of cuttings, D_h is the diameter of the borehole, C_c is the concentration factor of cuttings.

Calculation data is recapitulated in the following table, *table 1.*

Table 1. Calculation data

Parameters	**Testing values**
Diameter of drillpipe, D_p, m	0.2
Diameter of wellbore, D_h, m	0.4
Distance between wellbore and drillpipe, r_i, m	[0:0.15]
Mud density, rho (γ), kg/m^3	1010; 1050; 1200;1300
Velocity of mud, V_f, m/s	0.04;0.08; 0.2; 0.4; 0.8; 1.0
Cuttings density, kg/m^3	2600
Cuttings dimension, D_c, m	0.001; 0.005;0.01
Cuttings velocity, V_c, m/s	0.008
Temperature, °C	60,100,120, 150, 200
Pressure, psi	12000
Turbulent intensity	8%

3. Results

3.1. Constant pressure and temperature

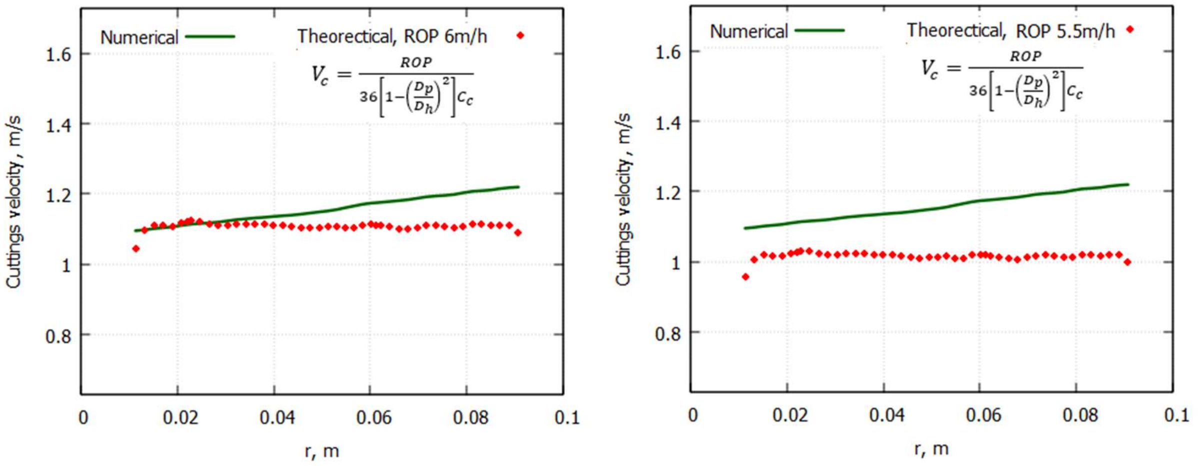

Figure 3.1. Theoretical vs numerical cuttings velocity, ROP = 5.5 and 6.0m/s (section 2)

Preliminary calculations were first carried out using reference data in the condition of constant temperature and pressure. The numerical cuttings velocity is presented in the above diagram, *figure 3.1* in comparison with cuttings velocity values, V_c, calculated from eq. (2.5). As observed, numerical model shows a tendency to increase the magnitude of cuttings velocity, especially in the case of lower ROP. However, the result is considered acceptable due to the difference in geometry between our calculating domain and the actual well. Thus, the model is used for further calculations. In the current research, two cases of simulation were carried out to investigate dependency of cuttings transport on cuttings size and velocity of the drilling fluid.

Results of calculations are extracted for the two branches of the domain from the bottom to the top as denoted in *figure 1.1*. We consider all 5 sections thoughout the calculating domain, two lines at each. *Section 1* with h1 and h2, is the horizontal part; *section 2* consists of bend 1 (b1) and bend 2 (b2); *section 3* is the inclined part with i1 and i2 at each branch; *section 4* composes of the two other bends b3 and b4; and *section 5* with v1 and v2 is vertical section. Length of each line equals r_i max = 0.1m corresponding to the distance between the borehole wall and the drillpipe as the well is concentric.

* *Study case 1: Dependence of cuttings velocity on cuttings size*

Figure 3.2, 3.3 demonstrates the relation between cuttings size on the transportation of cuttings with the red curve represents velocity of cuttings at the suspension layer and the other in black depicts velocity at the dispersed layer. As observed, cuttings velocity decreases sharply with the increase of cuttings mass and size at all the 5 sections. The higher the size of particle, the smaller the velocity of cuttings, especially at dispersed layer and as a consequence the faster the settelling of cuttings and the thicker the cuttings bed. V_c drops to very small values when D_c = 0.01m that enables us to predict a blockage if V_f remains unchanged. However, compare to results published by Shu, 2021, our model seems to overestimate magnitude of velocity in the annulus [16]. In figure 3.3, the concentration of cuttings of different size at 5 different sections is illustrated. As observed, the highest accumulation of cuttings corresponds to the case D_c = 0.005mm, not to the case of cuttings with largest diameter Dc = 0.01m. This seems to be a paradox at first, however, it's quite logic due to a confirmation that larger cuttings size benefits a higher removal than those of smaller size [17].

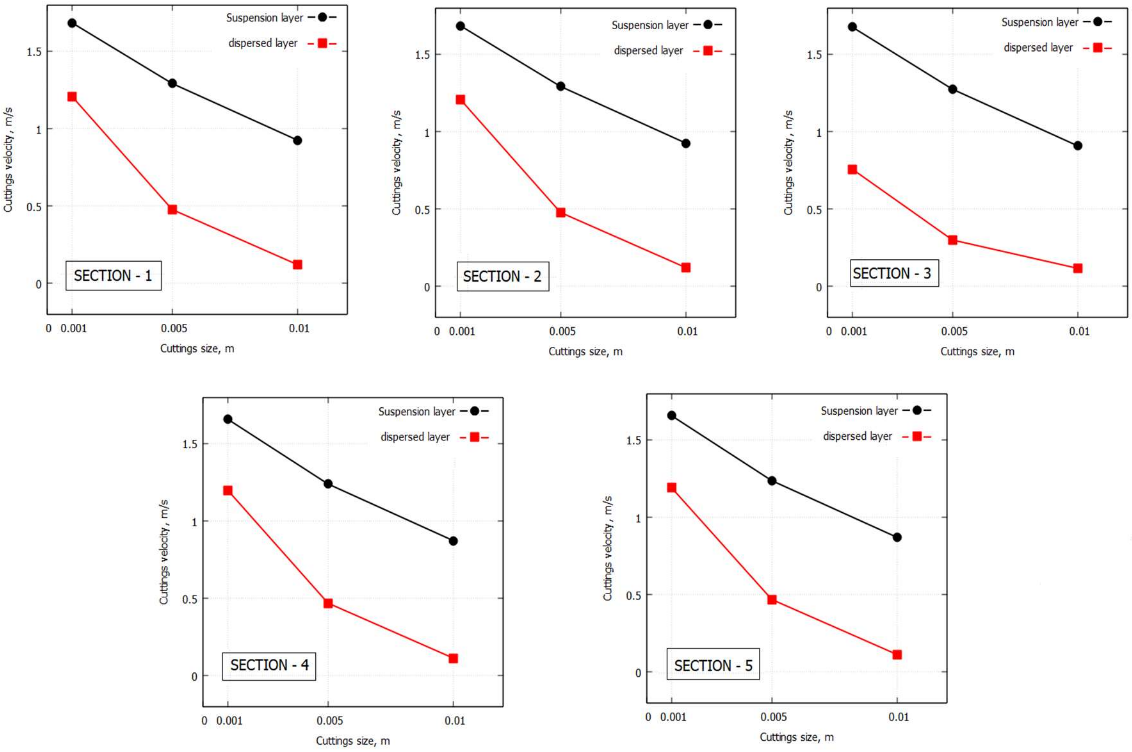

Figure 3.2. Effect of cuttings size D_c on cuttings velocity V_c at 5 sections (V_f at the inlet takes the reference value, V_f = 0.4)

** Study Case 2: Impact of mud velocity on the transportation of cuttings at different sections of the wellbore*

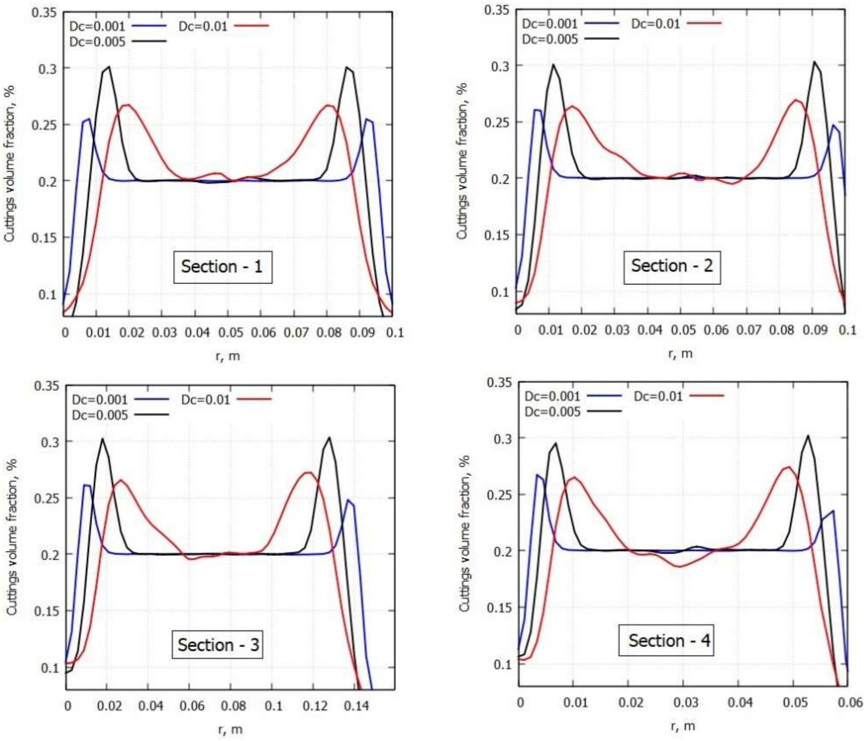

Fig 3.3. Volume fraction of cuttings for different sizes of cuttings, Dc

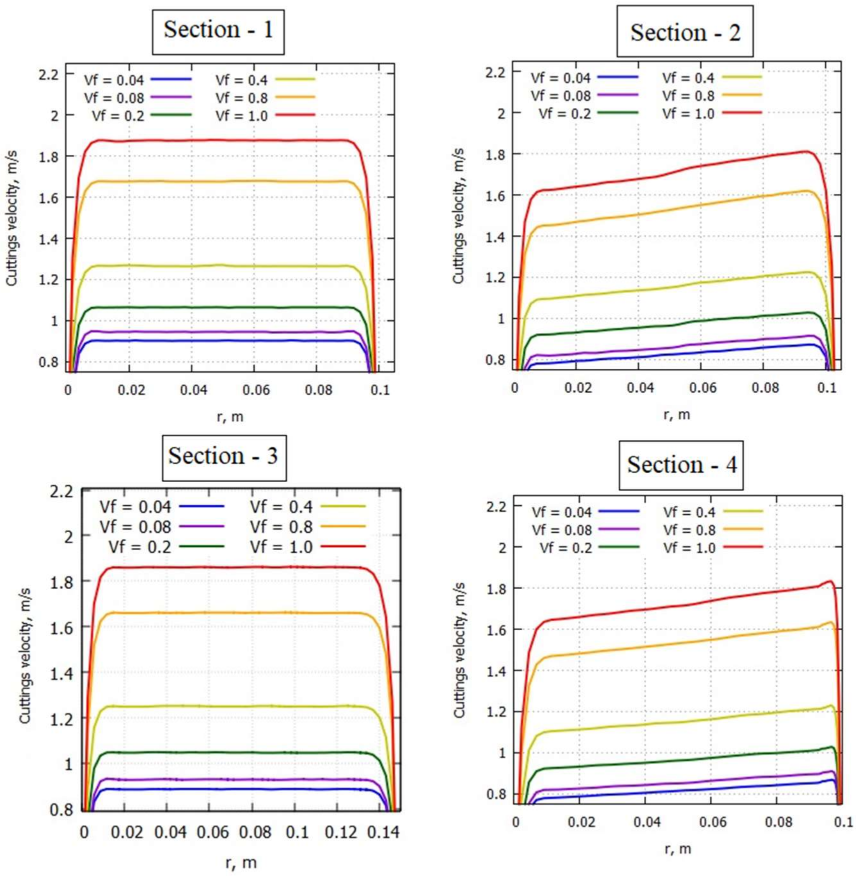

Figure 3.4. Cuttings velocity at different mud speeds

Figure 3.4 illustrates cuttings velocity at 5 different sections. Velocity curves seem to be flat and smooth around the centre of the pipe, whereas slight fluctuations are observed at the contact areas between the flow and the borehole wall and the pipe. At the two bends (section-2 and section-4), V_c tends to be smaller and linearly increases following the direction from the wellbore to its centre. This enables us to confirm a higher risk of cuttings accumulations at the lower sides of the two bends. Besides, it is a doddle to see that higher drilling mud velocity results in higher cuttings velocity. However, a too fast upcoming flow may not be a wise choice due to its capability to cause unstable conditions to the wellbore and the formation around. Therefore, further calculations should be implemented in order to determine the optimum flowrate to pump down the drilling must obtain maximum hole cleaning performance.

3.1. Pressure and temperature dependence

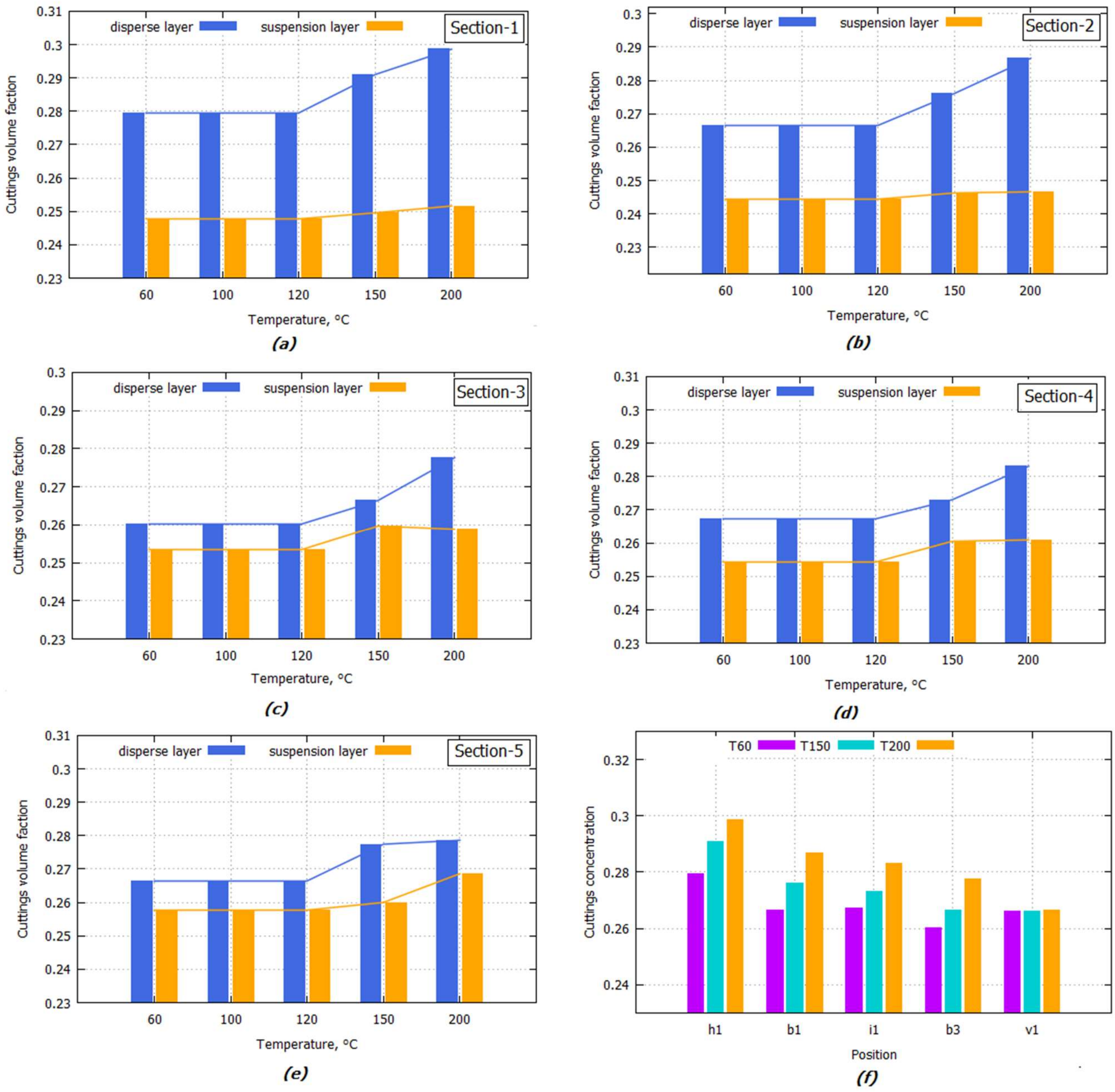

Figure 3.5. Dependency of cuttings concentration on temperature

Primary results with EE model appear to be in harmony with theorectical calculations in the previous calculations, this persuades us to continue the simulation with non-newtonian fluid. In those steps, calculations are carried out with constant velocities for both two phases while temperature and pressure vary. We expect to observe the defenceny of the transportation of cuttings on these two factors.

* Temperature dependence:

Temperature takes value of 60°C, 100°C, 120°C, 150°C, 200°C respectively for each computational case. Results are plotted in *figure 3.5* for all the 5 sections. It is observed at all 5 sections that the concentration of solid phase seems to be stable at normal drilling condition but it increases (approximately 9.4%) with the increase of temperature in the condition of temperature from 120°C to 200°C as pointed in *figure 3.5 (a),(b), (c), (d), (e).* This goes quite well with calculation of Wang [20]. which pointed out a fast change of viscosity of the water based drilling mud in the temperature range from 60°C to 120°C . At the first two sections, section-1 and section-2, effect of the suspension layer is small and so its ability to keep cuttings in suspension which lead to a higher settling at the disperse layer.

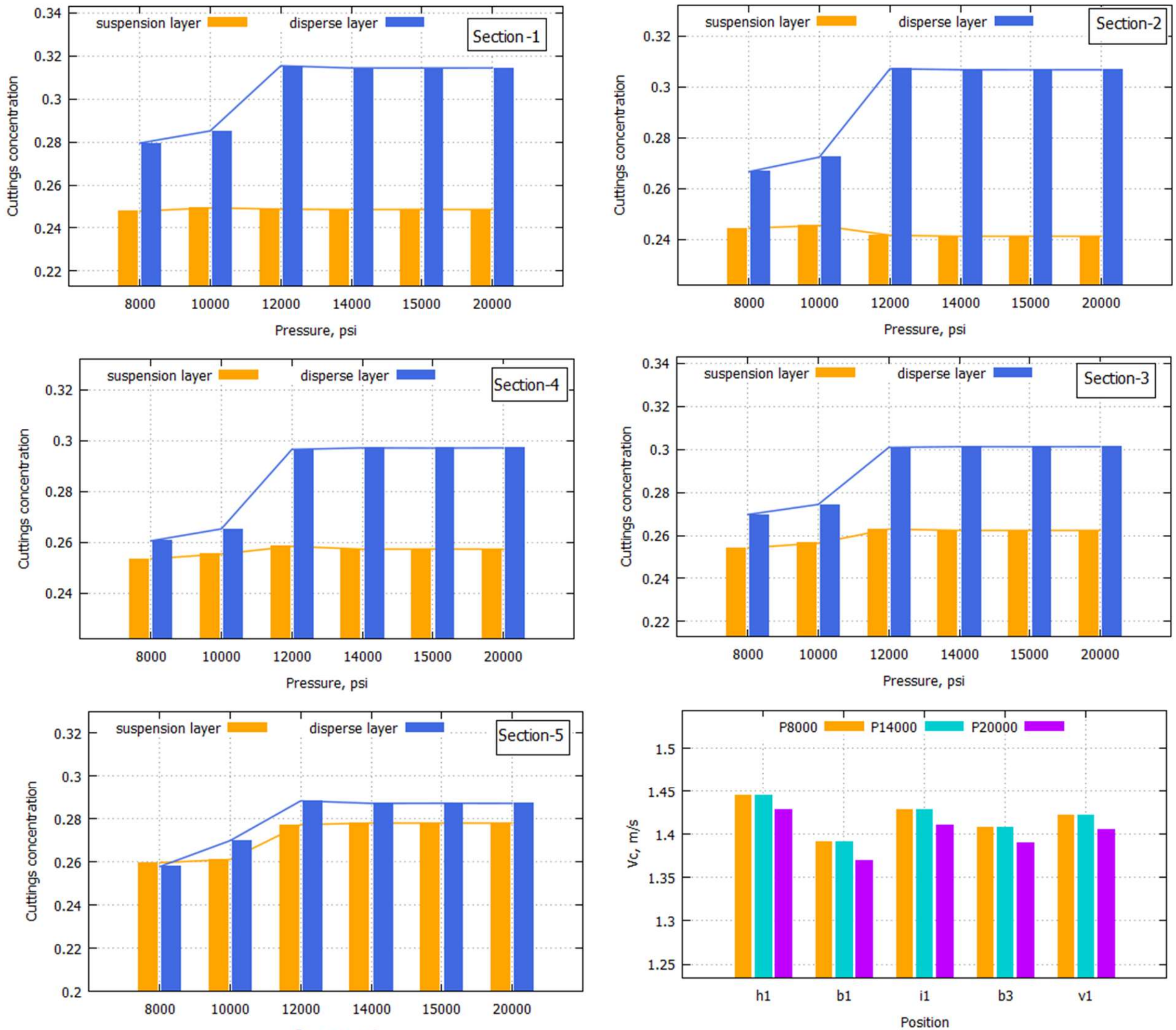

Figure 3.6. Dependency of cuttings concentration on pressure

Figure 3.5 (f) compares the concentration of cuttings in high temperature condition. Going from the bottom to the surface, solid material tends to concentrate at nearer position to the bit. At the nearest section to the surface, v1 (section-5), we observe a very small dependence of accumulation on temperature. This is not a coincidence due to the decrease of the effect of temperature at the position near the bottom.

* *Pressure dependence*

The values of presusre from 8000psi to 20000 psi are used for these calculations to examine the effect of pressure on the transport of cuttings. Results are plotted in f*igure 3.6*. The histograms demonstrate the highest change of cuttings concentration when it changes from normal to HTHP drilling condition (from below 8000psi to 15000psi). The pressure, like in the case of temperature takes it least effect at the position the farest to the bottom. Compared to drilling in normal environment pressure < 12000 psi, the concentration of cuttings is about 6% ÷ 9% smaller. We observe at section 2 (b1) the largest difference between the concentration of cuttings at the disperse and suspension layer. Besides, it is also pointed out in the last figure that cuttings velocity is smallest at this postion. These allows us to predict the higher accumulate of cuttings at the first bend section of the well, especially in the case of higher pressure.

4. Discussion and Conclusion

2-dimentional approach using E-E model was carried out in the current study to investigate a two-phase liquid-solid (drilling fluid as non-newtonian fluid and cuttings) flow in the directional well 10-P. Results show an increase of cuttings concentration at bends in comparison to the other positions of the well. Besides, it confirms a more effective removal with larger cuttings size. A thicker cuttings bed is witnessed at the horizontal at the bend sections and a higher concentration, (6-10% approximately) of cuttings is also observed in calculations with higher pressure and temperature which confirm a riskier of in extreme drilling operation.

Despite of these worthy insights, we are aware of disadvantages which may reduce the value of the study. Firstly, the 2D model may overevaluate velocities of flows at each branch of the domain and thus enhance the capability of the flow to carry particles upwards. It therefore allows us to examine the risk of blocking. Moreover, due to asymetric geometry of the domain, the rotary movement (RPM) of the drillpipe was not taken into account that induced a high settling of cuttings. Therefore, in order to ameliorate further study, 3D models are suggested for later calculations to capture 3 dimentional effects and to consider drilling parameters eliminated in the current research.

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