A MULTI-PHASE CLOSED PIPELINES SIMULATION APPROACH FOR TRANSPORTATION OF HEAVY OIL WITH OPENFOAM IN HPC

Mr. Alomoy Banerjee[1] , Dr. Shambhunath Barman[2]

[1]*Paharpur Cooling Towers Ltd*

8/1/B Diamond Harbour Road Kolkata 700027, India

[2]*NIT Sikkim*

Barfung Block, Ravangla, Sikkim 737139, India

Corresponding Author Email: alomoybanerjee@gmail.com

Abstract

Transportation of heavy crude oil through closed pipelines is a challenging issue both in offshore and in land oil transportation. The scope of the present paper deals with the computational modelling of two phase extra heavy crude oil & water flow in OpenFOAM. In order to validate the flow model the pressure variation along the length of the channel are investigated, which shows the typical plot of two roughly constant pressure lines at different levels connected by a sharp change of pressure at the interface of two fluids. The validated flow model, aims at optimizing the kinematic viscosity of the multiphase flow, by regulating the flow velocity of the components, such that there is minimum viscous heat loss and hence minimum pump power consumption from the horizontal centrifugal pumping system.Using the OpenFOAM(Open Source Field Operation & Manipulation) software, which is free opensource software, developed in 2004, under GNU general public license, paraview has been used here as post processing tool. Multiphase flow simulation is done using the k-ε turbulence model in HPC of kanchenjungha cluster, NIT Sikkim, India.

Keywords: *Multiphase flow, Kinematic Viscosity, Pressure, OpenFOAM*

1. Introduction

The present world is in urgent requirement of energy. With the gradual decline in the reserves of middle and light weight oil, heavy crude oil and extra heavy crude oil are the only options left in order to solve the present energy crisis status. However, there are quite a few challenges that need to be encountered in order to handle heavy crude oil. One of the major issues that needs to be encountered in this regard, is the offshore and on land transfer of heavy crude oil through closed pipelines. This is primarily because of the high viscosity of these fluids, resulting in drag propagation at the molecular level of the fluid, resulting in interruption of the free flow of crude oil through pipelines. In order to counter the concerns related to heavy oil transport, three processes have been broadly proposed which include viscosity reduction, drag minimization and insitu oil upgradation. However for most practical purposes, where heavy crude oil transport has been dealt with (e.g. Canada & Venezuela), viscosity reduction of the oil is achieved by heating the pipeline system at regular intervals or by mixing heavy crude oil with light and middle oil/water/surfactants. The pumping system used to pump the extra heavy crude oil are horizontal multistage centrifugal pumps which are efficient both from mechanical and economic point of view. The back pull out design of the pump results in the replacement of important parts like mechanical seals and bearing assembly without dislodging the pump setup, motor or piping, through forklift. This minimizes the NPT (Non Productive Time) to 4-5 hours on part replacement, rather than the downtime of several weeks as evident from the above mentioned technologies.

2. Literature Survey

Anand B. Desmala et al [1] carried out research on flow characteristics of oil water two phase flow through a pipe using ANSYS FLUENT 6.2 by categorizing the flow into stratified, stratified wavy, slug and annular flow. The paper further went on to describe the various pressure distribution features for each of these flows.Nerea Herreras et al [2] compared two phase 2 Dimensional pipe flow in open and closed channels as well as inclined channel flows for both the cases. The thesis went on to compare the analytical solutions of the problem with the simulated results and validated the graphs and results obtained through Taitel Duckler map.Abdurahman Nour et al [3] worked on transport of viscous crude oil as oil water emulsions. The paper went on to model the physical and compositional aspects of heavy crude and the effect of crude oil concentration, mixing speed and temperature on kinematic viscosity of the oil water emulsion. Rasha Mohammed Abd et al [4] experimentally investigated the dynamic viscosity of crude oil-water emulsions as a function of water volume fraction as well as temperature. The paper further went on to conclude non Newtonian shear thinning of oil water emulsion and a reduction in oil viscosity by 14% on being emulsified with water. Liyana Nadirah et al [5] studied the rheological behaviour of two types of crude oil along with oil water emulsion experimentally in a Brookfield Rotational Digital Rheometer. The paper further proceeded to conclude about the non-Newtonian shear thinning behaviour of oil water emulsion at 30-60% volume of water and the power law model in order to demonstrate the non-linear relationship between shear stress and shear strain.

Eli-Marie W.Sundt et al [6] explained the basic mathematical operations of Navier Stokes equation in terms of solution schemes familiar to OpenFOAM. The paper further ventures into finite element analysis of the pipeline and its corresponding representation in OpenFOAM.Matt Cray et al [7] illustrated the horizontal multistage centrifugal pumping system associated with transport of heavy crude oil and oil water two phase flow through pipelines. The report further investigated the relative advantages of horizontal multistage pumping with respect to reciprocating pumps and vertical turbine system.

3. Objective

The objective of this paper is to study the behaviour of oil water two phase flow in a closed pipeline system through Reynold's averaged simulation and in the process analysing the pressure distribution and viscosity variation along the length of the pipe for a stipulated time period through the k-ε turbulence model. The kinematic viscous behaviour is attempted to be optimized such that minimum pump power consumption takes place in order to transport the fluid mixture.

4. Mathematical Modelling

The two conservation equations that will be the fundamental basis of solution for the two phase flow are the continuity equation and the Navier Stokes equation:

$$\frac{D\rho}{Dt} + \rho \frac{\partial U_i}{\partial x_i} = 0 \tag{1}$$

$$\rho \frac{\partial U_j}{\partial t} + \rho U_i \frac{\partial U_j}{\partial x_i} = -\frac{\partial P}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \tag{2}$$

(I) (II) (III) (IV) (V)

Where τ_{ij} is the stress tensor expressed as a sum of static and deviatoric components and is expressed as:

$$\tau_{ij} = -\mu\left(\frac{\partial U_j}{\partial x_i} + \frac{\partial U_i}{\partial x_j}\right) \tag{3}$$

I- Local change with time, II- Momentum advection, III- Pressure Force,IV- Diffusion terms
V- Mass force/body force

The above mentioned equations (i, ii iii) are solved considering the multiphase flow of oil and water as a homogenous mixture whose homogenous multiphase flow velocity is given as u_H and multiphase flow density is given as ρ_H.

$$\rho_H = \frac{m}{U} = \frac{1}{\sum_{i=1}^{n}\left(\frac{x_i}{\rho_i}\right)} \tag{4}$$

$$u_H = U = \frac{m}{\rho_H} = \frac{M}{S\rho_H} \tag{5}$$

S- cross sectional area, M- mass flow rate, m- mass flow per unit area.

Continuity Equation for multiphase flow is modified as

$$\frac{\partial}{\partial z}(U\rho_H S) + S\frac{\partial \rho_H}{\partial t} = 0 \tag{6}$$

and the Navier Stokes equation is given as

$$\frac{\partial m}{\partial t}+\frac{1}{S}\frac{\partial(m^2 S/\rho_H)}{\partial z}=\frac{\partial \rho}{\partial z}-g\rho_H \sin\alpha-\frac{\tau_0 P}{S} \quad (7)$$

z- axial distance, t- time, p- pressure, α- angle of inclination of the channel
τ_o – wall shear stress tensor, P- channel periphery

5. OpenFOAM Modelling

OpenFOAM (Open Source Field Operation and Manipulation) is free open source software developed in 2004 under GNU general public license. It has a broad range of applications across all engineering fields as it deals with a huge variety of subjects ranging from complex fluid flows to heat transfer systems, to chemical reactions, acoustics and electromagnetics. The coding language used for this software is C++ and provides opportunity to code the solutions themselves.

The case modelled here is concerned with Canadian Athabasca heavy oil flow along with water. The oil mentioned above has an API gravity of 6 i.e. it is denser than water. The principal problem with the flow of the Athabasca oil is that if it is left to flow alone in pipelines the extreme high viscosity results in its conversion into a semi solid mass, thus choking the flow. Hence during industrial transportation of heavy Athabasca oil, water is mixed with the oil to enhance the flow ability of the mixture.

5.1 Reynold's Averaged Simulation

In order to account for the fluctuation of the parameters associated with the turbulence modelling of the concerned flow field, the velocity and pressure components of the multiphase flow are broken up into a mean part and a fluctuating part given as

$$u=\overline{u}+u', v=\overline{v}+v', w=\overline{w}+w', p=\overline{p}+p'$$

Where the 1^{st} term denotes the mean part and the 2^{nd} term denotes the fluctuating part. Hence the Reynold's averaged continuity equation is split into two parts and given as

$$\frac{\partial\overline{u}}{\partial x}+\frac{\partial\overline{v}}{\partial y}+\frac{\partial\overline{w}}{\partial z}=0 \quad (8)$$

$$\frac{\partial u'}{\partial x}+\frac{\partial v'}{\partial y}+\frac{\partial w'}{\partial z}=0 \quad (9)$$

and the Reynold's Averaged Navier Stokes Simulation (RANS) in Reynold's Stress tensor form

$$\rho \frac{Du_i}{Dt} = F_i - \frac{\partial p}{\partial x_i} + \mu \Delta \overline{u_i} - \rho \left(\frac{\partial u_i' u_j'}{\partial x_j} \right) \quad (10)$$

5.2 K- ε Turbulence Model

This model is applicable for flow of high Reynold's number where k denotes the kinetic turbulent energy and ε denotes the dissipation of the turbulent kinetic energy. The two operators k and ε are defined as

$$k = \frac{1}{2}\left(\overline{u_i' u_j'}\right) \quad (11)$$

$$\varepsilon = \nu \overline{\frac{\partial u_i'}{\partial x_j} \frac{u_i'}{\partial x_j}} \quad (12)$$

The transport equations for k and ε are defined from Boussinesq approximation as

$$\frac{\partial k}{\partial t} + \overline{u}_j \frac{\partial k}{\partial x_j} = \nu_t \left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i} \right) \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] - \varepsilon \quad (13)$$

$$\frac{D\varepsilon}{Dt} = C_{\varepsilon 1} \frac{\varepsilon}{k} \left(-\overline{u_i' u_j'} \right) \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] - C_{\varepsilon 2} \frac{\varepsilon^2}{k} \quad (14)$$

where v_t denotes the eddy viscosity from VonKarman-Prandtl equation given by

$$\nu_t = C_\mu \frac{k^2}{\varepsilon} \quad (C_\mu = 0.09) \quad (15)$$

The boundary conditions in order to solve the above transport equations are defined with an assumption of a turbulent intensity of 6% and an aspect ratio of 0.07. The boundary conditions are given by

$$k = \frac{2}{3}(U_{ref} T_i)^2 \quad (16)$$

$$\varepsilon = C_\mu^{0.75} \frac{k^{1.5}}{l} \quad (17)$$

Where U_{ref} is the reference internal velocity.

In the k- ε model the co-ordinates of different cells are defined in terms of the wall co-ordinate as y+, i.e. the distance from the wall. As stated earlier, the solution equations are applied on the cell centre first and then the results are interpolated by Gauss interpolation schemes to the rest of the cells. From the basic concept of boundary layer theory, the flow field is divided into the following sects in terms of the wall co-ordinate:

Table 1- k- ε model co-ordinates

Wall co-ordinate		Layer	Nature of Profile
y+<=5		Viscous Sub Layer	Linear
5<y+<30		Buffer Layer	Merge between linear and logarithmic
y+>30		Log Layer	Logarithmic

5.3 Solution

The solver used in order to solve the two phase flow of oil and water is Reynolds Averaged Simulation (ras) interFoam. This is used to solve flow of two incompressible imiscible fluids capturing the interface using the volume of flow (VOF) method. Turbulence is modelled using a runtime selectable incompressible RANS model. The most significant parameter which this solver considers in calculation is the surface tension. The continuity and transport equations are modelled in the following way:

$$\frac{\partial \alpha}{\partial t} + (U\nabla)\alpha = 0 \tag{18}$$

Where α denotes the volume fraction of a particular phase. This volume fraction is responsible for controlling the net viscosity of the multiphase flow, which is the principle modelling point of the project.

$$\mu_{mp} = \alpha\mu_{oil} + (1- \alpha)\, \mu_{water} \tag{19}$$

The solution algorithm followed here is the PIMPLE algorithm whose solution flowchart is given in fig 1.

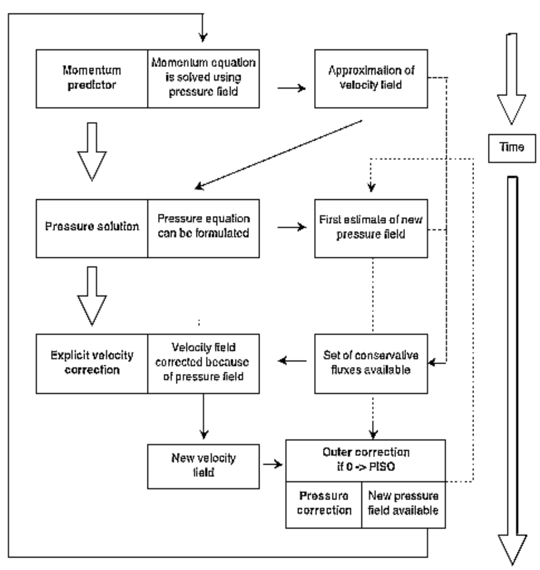

Fig 1- PIMPLE algorithm

6. Results

The case study initiated with a basic common model of plotting pressure along the length of the control volume as illustrated in the following figure. The purpose of modelling pressure is to validate the model against all multiphase flow standards.

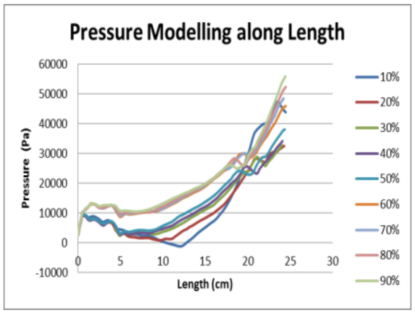

Fig 2- Pressure Modelling of Flow

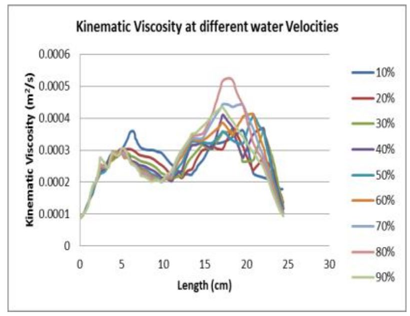

Fig 3- Kinematic Viscosity at different water velocities keeping oil velocity constant

Interpretation: In the plot of Fig 2, the water velocity is gradually increased from 10% to 90% of the oil flow velocity. In all the cases however, a roughly horizontal plot is obtained parallel to X axis, after which, there is a sharp rise in pressure that marks the interface of the two fluids. At the interface of the two fluids, owing to the difference in density, the pressure varies drastically. The interface zone affects the pressure typically at a zone of 10-15 cm along the length. In the initial part of the flow, water dominated the flow more because of its low viscosity and high flowability thus giving a roughly constant pressure plot. The plot is validated by Fig 4 from Masters Thesis "Two-Phase pipe flow simulations with OpenFOAM" NTNU Mechanical Engineering

Interpretation: The most interesting point in the plot in Fig 3 is the peaking of kinematic viscosity, when water flow rate is 80% of the oil flow rate. Theoretically, water is the less viscous fluid among the two and hence on increment of flow rate of water, the viscosity of the multiphase flow should monotonically decrease. So, this behaviour of oil water flow in the control volume section is something unprecedented. Keeping the oil flow velocity identical, the water velocity was fixed at 80% of it. Then the kinematic viscous behaviour of the flow was inspected on a time scale at an interval of 1 second. This is what resulted.

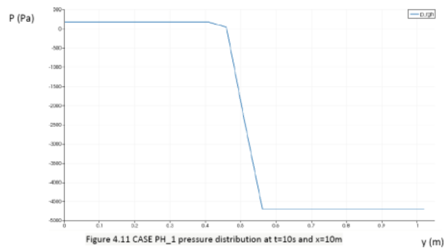

Fig 4- Theoretical Pressure vs length plot for gas water flow

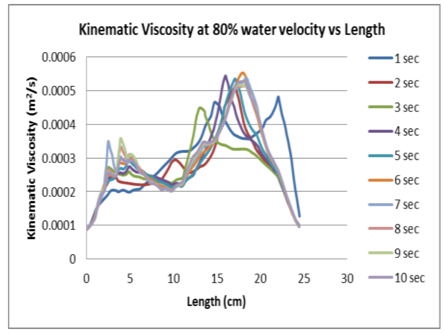

Fig 5- Kinematic Viscosity at water velocity 80% of oil velocity for 10 seconds

Interpretation: The plot illustrated above shows that the kinematic viscous behaviour of the multiphase flow stabilized roughly after 4 seconds from the start of flow. Hence it can be concluded that the attainment of the peak kinematic viscosity, when water flow is 80% of the oil flow velocity is a stable peak which stabilizes only after 4 seconds from the beginning of the flow.

In order to test, the consistency of the result obtained at a particular flow velocity of oil that the kinematic viscosity of multiphase flow is peaking as the water velocity attains 80% of oil velocity, a number of simulations were executed with different oil velocity as reference parameters. The results are shown in the following:

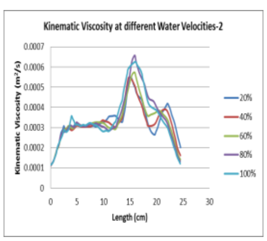

Fig 6- Oil (5 5 5)

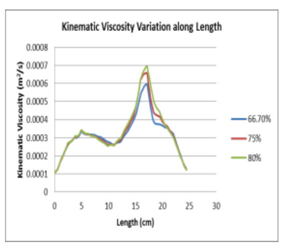

Fig 7- Oil (6 6 6)

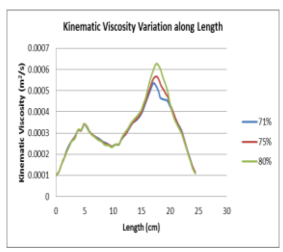

Fig 8- Oil (7 7 7)

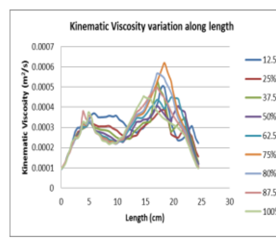

Fig 9- Oil (8 8 8)

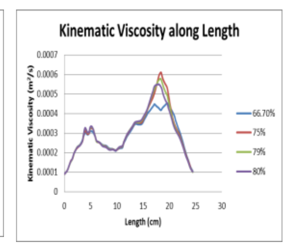

Fig 10- Oil (9 9 9)

Repeated observations show that the kinematic viscosity of the oil water multiphase flow peaked consistently at a zone between where the water velocity was 75-80% of the fixed oil velocity. Hence, this high kinematic viscosity causes viscous heat losses from the flow, thus resulting in extensive power loss. The particular observation indicates that when water is mixed to enhance the flow ability of oil, the water input can be manipulated, such that the horizontal multistage centrifugal pump has to deal with minimum kinematic viscosity of the mixture.

7. Conclusion

The steady peaking of the kinematic viscosity shows that when water velocity is reaching 75-80% of oil velocity, the van der Waal's force of attraction between two consecutive fluid layers peaks, resulting in reduced relative movement between two consecutive layers, which ultimately causes an increase in momentum diffusivity of the fluid layers. High kinematic viscosity results in enhancement of friction drag on pump impellers of horizontal multistage centrifugal pumping system significantly, resulting in significant power loss in order to overcome this drag.

The amplified kinematic viscosity meant that adjacent fluid layers need to do more work on each other in order to effect relative movement, due to the action of enhanced shear force. This extra work done is dissipated as heat resulting in power loss from the input supplied power. The maximum viscosity that can be handled by a pump impeller is limited by the size of its discharge nozzle. The correlation is empirically given as

$\eta_{max} = 300(D_{outletnozzle} - 1)$, where η is in SSU and D is given in inches.

8. Future Scope

The present study is entirely done through simulation modelling. Though paraview is extremely accurate with the generated results, this kinematic viscous behaviour of oil water multiphase flow needs to be tested experimentally. Experimental validation of the above phenomenon is extremely important as optimization of kinematic viscosity and hence optimization of pump power for crude oil pumping will be a remarkable discovery in the crude oil handling industry.

9. References

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