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Research paper

Optimization CFD study of erosion in 3D elbow during transportation of crude oil contaminated with sand particles

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Abstract

The oil industry transport the crude oil, but with entrained solid particles. Throughout the production operations of the upstream petroleum, crude oil as well as sand particles corroded from the zones of the formation are regularly conveyed through pipes as a mixture up to the well heads and among well heads and flow stations. In this study, a three-dimensional CFD (Computational fluid dynamics) model has been developed that describes a turbulent transport of solid sand particles as well as crude oil through elbows to predict the erosions rates, where various physical aspects have been combined together including flow turbulence, particle tracking, and erosion simulation. The model has been used to investigate the different parameters that effect for crude oil and sand particles on the erosive wear rate on the pipe walls. Where, the parametric studied for crude oil are viscosity, density, velocity and temperature, also, the parametric studied for sand particles are parti-cles size, particles density and mass flow rate. Therefore, the investigation included evaluated the erosive wear rate on the pipe walls with different parametric studding by using numerical method with CFD technique. This model includes simulation of the three dimensional for turbulent flow, sand particle, and erosion rates modeling. Where, used three methods to evaluating the erosive wear rate on the pipe walls, The Finite Model, The Erosion Rate (E/CRC) Model and The Erosion rate (DNV) Model. Also, in this work can be prediction of the ero-sion position occur on the pipe wall with various parametric effect. Then, the results presented shown that the rate of erosion is increase with increasing the friction between the oil and pipe wall by variable the parametric of crude oil or sand particles. Also, the results are shown that the position of erosion variable dependent on the parametric of oil and sand. Finally, the work shown that the CFD technique is good tool can be used to evaluating the erosion rate and erosion position on pipe wall with various crude oil and sand particles parametric.

Keywords: *Crude Oi; Sand; Contamination; CFD; Erosion; Solid Particles; Elbow.*

1. Introduction

Leakage from natural deposits is one of the major ways that crude oil affects the environment, [1]. During upstream petroleum production practices, sands from reservoirs are often transported up to the well heads and from the well heads to flow stations. The entrained sand may deposit on the walls of the elbow pipe due to pressure drop causing problems of erosive wear in the pipe elbow and then crude oil Leakage. The erosion is occur on the wall of pipe elbows due to the momentum of the sand particles, that carries them across the streamlines of the fluid and all of these particles impinge the pipe wall elbows. Therefore, the pipe system is failure due to it erosion occurred of the pipe elbow, which can be really dangerous and also expensive [2]. Thus, considerable concern in the oil industry is the erosion of pipe elbows due to sand, then, the materials erosion science is the major practical in the research and development applications on this problem.
Therefore, the materials engineering and the fluid dynamics science it's being addressed for the problem of erosion elbow, [3-5]. Then, must be evaluated by many methods to calculate the erosion rates values for a certain operating conditions set to avoid any errors from occurring. Thus, the investigation of erosion rate it's occurred in the pipe wall included prediction for the erosion position in the pipe wall everyplace erosion is expected to occur, in addition to the erosion rate for pipe wall. Due to, a lack of passable testing will be procedure the movement in developing an erosion-resistant pipe elbows is hampered, that would allow for fast assessment of erosion in unique flow path designs. Sand erosion phenomenon is highly complicated; therefore, many factors are contributed to the erosion rate. These parameters divided to the parameters of fluid flow effect, sand characterization effect and other parameters. The fluid flow parameters included flow rate, all properties of the fluid, as well as the sand parameters include sand rate, sand particles properties, and the other parameters effect are the equipment of the walls materials and/or the fitting equipment, and also the features of the geometries such as the shape as well as the size. Therefore, many methods have been development to combating the erosion rate occurs due to the sand particles. One of these methods is the CFD, it based erosion modeling is very powerful and can be applied to predict erosion in much complex engineering geometry [6], [7].
In this study, three-dimensional CFD model has been developed and used that describes a turbulent transport of solid sand particles as well as crude oil through elbows to predict the erosions rates under various transport parameters. This work allows us to examine more pipe design choices and "what if" scenarios than ever before. Moreover, crude oil flow modeling provides insights into our fluid flow problems that would be very expensive or simply unreasonable by experimental techniques alone. The additional

insight and perception gained from the CFD simulation of the crude oil flow provides us confidence in our design, eschew the extra costs of over-specification, over-sizing, and decreasing risk.

2. CFD modeling

Three-dimensional CFD model of a turbulent transport of solid sand particles and crude oil through elbows to predict the erosions rates has been modeled, validated, detail presented, and discussed in detail by the current authors in their earlier work, [8]. In brief, the simulation model is built on the CFD technique and considers multi-component flow inside the crude oil flow elbows, [9-15]. The comprehensive simulation model includes: turbulent flow simulation, particle tracking, and erosion simulation.

2.1. Computational domain

As the numerical modelling of an entire elbow requires costly and powerful computing resources, not to mention the excessively long-time simulation needed; the investigated domain in the current simulation is focused on the three-dimensional section of the elbow only, Fig. 1.

Fig. 1: Three Dimensional Computational Domain.

2.2. Modelling equations

2.2.1. The turbulence flow model

A Newtonian and incompressible fluid having constant density is considered herein. The RANS forms of the momentum conservation as well as continuity equations are formulated as [8],

$$\rho\frac{\partial U}{\partial t} + \rho U.\nabla U + \nabla.\overline{(\rho u' \otimes u')} = -\nabla P + \nabla.\mu(\nabla U + (\nabla U)^T) + F \quad (1)$$

$$\rho\nabla.U = 0 \quad (2)$$

Where U represents the mean velocity, while $\otimes$ stands for the outer vector product. In this work, the k-ω model is carefully chosen over the model of k-ε, due to its further accurate than the model of k-ε for flows connecting strong streamlines curvatures [8], where formulation of this turbulence model is as follows,

$$\rho\frac{\partial k}{\partial t} + \rho u\,.\nabla k = \left(P_k - \rho\beta^* k\omega + \nabla.\left((\mu + \sigma^*\mu_T)\nabla k\right)\right) \quad (3)$$

$$\rho\frac{\partial \omega}{\partial t} + \rho u\,.\nabla\omega = \left(\alpha\frac{\omega}{k}P_k - \rho\beta\omega^2 + \nabla.\left((\mu + \sigma\mu_T)\nabla\omega\right)\right) \quad (4)$$

Where,

$$P_k = \mu_T(\nabla u : (\nabla u + (\nabla u)^T) - 2/3*(\nabla.u)^2) - \frac{2}{3}\rho k\nabla.u \quad (5)$$

$$\mu_T = \rho\frac{k}{\omega},\ \alpha = \frac{13}{25},\ \beta = \beta_o f_\beta,\ \beta^* = \beta_o^* f_\beta \quad (6)$$

$$\sigma = \frac{1}{2},\ \sigma^* = \frac{1}{2} \quad (7)$$

$$\beta_o = \frac{13}{125},\ f_\beta = \frac{1+70X_\omega}{1+80X_\omega},\ X_\omega = \left|\frac{\Omega_{ij}\,\Omega_{jk}\,S_{ki}}{(\beta_o^*\omega)^3}\right| \quad (8)$$

$$\beta_o^* = \frac{9}{100} f_\beta^* = \begin{cases} 1 & X_k \le 0 \\ \frac{1+680X_k^2}{1+400X_k^2} & X_k > 0 \end{cases},\ \text{for},\ X_k = \frac{1}{\omega^3}(\nabla k\,.\nabla\omega) \quad (9)$$

Where ω_{ij} represents the mean tensor of rotation rate.

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial\overline{u_i}}{\partial x_j} - \frac{\partial\overline{u_j}}{\partial x_i}\right) \quad (10)$$

And, S_{ij} is the mean strain rate tensor,

$$S_{ij} = \frac{1}{2}\left(\frac{\partial\overline{u_i}}{\partial x_j} - \frac{\partial\overline{u_j}}{\partial x_i}\right) \quad (11)$$

2.2.2. Particle motion in a fluid model

According to Newton's second law, the particle momentum can be formulated as [8],

$$\frac{d}{dt}(m_p V) = F_D + F_g + F_{ext} \quad (12)$$

Where, m_p refers to the mass of the solid particles in kg, v is the velocity of the solid particle in m/s, F_D stands for the drag force in N, F_g is the vector of gravitational force in N, and F_{ext} represents any other external source in N.
The drag force (F_D) can be computed as,

$$F_D = \left(\frac{1}{\tau_p}\right) m_p(u - v) \quad (13)$$

Where τ_p is the response time of particle velocity in sec, u stands for the flow velocity in m/s.
The instantaneous flow velocity presented in the drag force of the term of the turbulent dispersion is rewritten as,

$$u = U + u' \quad (14)$$

Where U is the time mean velocity while u' is a turbulent fluctuation velocity, which is written as,

$$u' = \varphi\sqrt{\frac{2k}{3}} \quad (15)$$

Where k is define as the turbulent kinetic energy, while φ is define as a normally distributed random number with zero mean and unit standard deviation. The gravitational force is formulated as,

$$F_g = m_p g\frac{(\rho_p - \rho)}{\rho_p} \quad (16)$$

Where ρ_p represents the particle density in kg/m3, ρ stands for the surrounding fluid density in kg/m3, while g is the gravitational direction.

2.2.3. Erosion models

The Erosion feature calculates the rate of erosive wear or the total mass removed per unit area due to the impact of particles at a boundary. The following three models have been modelled, [4-7].

i) The finite model

Finnie defined the volume removed from a surface as,

$$V = \frac{cMU^2}{4p\left(1+\frac{mr^2}{I}\right)}[(\cos\alpha)^2],\ \tan\alpha > \frac{P}{2} \quad (17)$$

$$V = \frac{cMU^2}{4p\left(1+\frac{mr^2}{I}\right)}\frac{2}{P}\left[(\sin 2\alpha) - 2\frac{(\sin\alpha)^2}{P}\right],\ \tan\alpha \le \frac{P}{2} \quad (18)$$

Where the parameters are defined as following,
c (dimensionless) is the fraction of particles cutting in an idealized manner.
M [kg] is the total mass of eroding particles.
U [m/s] is the magnitude of the incident particle velocity.
p [Pa] is the material Vickers hardness.
m [kg] is the mass of an individual particle hitting the surface.
r [m] is the average particle radius.
I [kg-m2] is the moment of inertia of an individual particle about its center of mass. For an isotropic sphere, I=2mr2/5.
α [rad] is the angle of incidence, with α=0 tangent to the surface and α=π/2 normal to the surface.
P is a dimensionless parameter, defined as P=K/(1+mr2/I), where K (dimensionless) is the ratio of vertical and horizontal forces acting on the particle.
In the Finnie model, particles are assumed to remove mass from the surface via an idealized cutting mechanism. It does not predict any erosive wear by particles at normal incidence to a surface, and is recommended for modeling erosion of ductile materials by particles at small angles of incidence.

ii) The erosion rate (E/CRC) model

The E/CRC model defines the erosion rate in terms of the ratio of mass lost by the surface to mass of incident particles,

$$E = CF_s(BH)^{-0.59}\left(\frac{v}{1[m/s]}\right)^n F(\alpha) \tag{19}$$

$$F(\alpha) = (5.40\alpha - 10.11\alpha^2 + 10.93\alpha^3 - 6.33\alpha^4 + 1.42\alpha^5) \tag{20}$$

Where C is a dimensionless model coefficient, F_s is the particle shape coefficient (dimensionless), and BH is the Brinell hardness of the wall material (dimensionless). The angle of incidence α is measured in radians.

iii) The erosion rate (DNV) model

The DNV model defines the erosion rate in terms of the ratio of mass lost by the surface to mass of incident particles,

$$E = K\left(\frac{v}{1[m/s]}\right)^{-n} F(\alpha) \tag{21}$$

$$F(\alpha) = \begin{pmatrix} 9.370\alpha - 42.295\alpha^2 + 110.864\alpha^3 - 175.804\alpha^4 + \\ 170.137\alpha^5 - 98.398\alpha^6 + 31.211\alpha^7 - 4.170\alpha^8 \end{pmatrix} \tag{22}$$

Where, K and n are constants that depend on the surface material.

2.3. The grid used

The finite-volume method was used to discretize the governing equations, which are in turn solved using a commercial CFD code having the power to address multi-physics problems. Grid sensitivity has been performed to ensure that the solutions acquired using the selected mesh is independent of the grid size. The selected grid consists of 44772 domain elements in total, 8908 boundary elements, and 590 edge elements, which was found to provide sufficient spatial resolution, Fig. 2. An iterative solution for the coupled equations was followed, where an error criterion of 1.0×10^{-6} was considered sufficient enough to achieve the solution convergence. The solution was considered to be convergent when the relative error was less than in each field between two consecutive iterations. The initial and boundary conditions, the erosion prediction procedure in this work is a comprehensive procedure that based on a three-dimensional CFD technique, which has three most important steps: the turbulent fluid flow modeling, the solid particles tracking, and the erosion rates and the position prediction. The flow initial and boundary conditions have been listed in Table 1, [16-18].

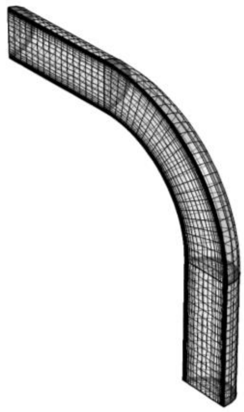

Fig. 2: Three Dimensional Computational Mesh of the Domain.

Table 1: Base Case Flow Conditions Used in the Model.

Parameter		Value
Temperature		298.15 K
Carrier fluid		Crude oil
Nominal velocity		0.3 m/s
Sand diameter		170 microns
Sand density		2200 kg/m^3
Mass flow rate of sand		0.6 kg/h
Oil viscosity		8 mPa.s
Oil density		850 k/m^3
Pipe diameter		0.2 m
	Modulus of Elasticity	200 GPa
Pipe material (Iron)	Poisson ratio	0.29
	Density	7870 kg/m^3

3. Results and discussion

The results presenting in this paper included evaluating the erosion of pipe wall by using numerical technique. Where, the numerical techniques is a good technique can be used to evaluating the results with a good agreement by comparison with other techniques, as present by many researches, [19-45].
The erosion prediction procedure in this work is a comprehensive procedure that based on a three-dimensional CFD technique, which has three main steps: turbulent fluid flow modeling, solid particles tracking, and erosion rates prediction. Therefore, the turbulent fluid flow modeling and the solid particles tracking are presented as in [8], and the erosion rates and the position prediction are presenting in this work, where, Figures. 3-9 show the erosion happens in pipe elbow during flow a contaminated crude oil with sand particles under various transport parameters. Where, the figures shown two parts of different parametric effect on the erosive wear on the pipe walls, the first effect of crude oil parametric, and second, the sand particles parametric, as,

i) Crude oil parametric effect, included the flowing,
1) Effect of crude oil viscosity on the erosive wear rate on the pipe walls, as shown in Fig. 3.
2) Effect of crude oil density on the erosive wear rate on the pipe walls, as shown in Fig. 4.
3) Effect of crude oil velocity on the erosive wear rate on the pipe walls, as shown in Fig. 5.
4) Effect of crude oil temperature on the erosive wear rate on the pipe walls, as shown in Fig. 6.

ii) Sand particles parametric effect, included the flowing,
1) Effect of sand particles size on the erosive wear rate on the pipe walls, as shown in Fig. 7.
2) Effect of the sand particles density on the erosive wear rate on the pipe walls, as shown in Fig. 8.
3) Effect of the mass flow rate of sand on the erosive wear rate on the pipe walls, as shown in Fig. 9.

Where, the parametric values investigation in the model are presented in Table 2.

Table 2: Range for Flow Conditions Used in the Model

Parameter	Value
	275.15 K
Temperature	298.15 K
	323.15 K
	0.2 m/s
Nominal velocity	0.3 m/s
	0.4 m/s
	120 microns
Sand diameter	170 microns
	220 microns
	1400 kg/m^3
Sand density	2200 kg/m^3
	3000 kg/m^3
	0.3 kg/h
Mass flow rate of sand	0.6 kg/h
	0.9 kg/h
	1 mPa.s
Oil viscosity	8 mPa.s
	20 mPa.s
	750 kg/m^3
Oil density	850 kg/m^3
	950 kg/m^3

Therefore, from the part one effects, shown in Figs. 3 to 6, can be shown the effect of crude oil on the erosive wear rate on the pipe walls as, Fig. 3 can be show the erosive wear rate on the pipe walls is decrease with increasing the crude oil viscosity, where, the rate of erosive wear decrease about 100% with increasing the viscosity from 1 mPa.s to 20 mPa.s. But, the Fig. 4 shown the erosive wear rate on the pipe walls is non-affected by change in crude oil density, where, the density of crude oil is changing from 750 to 950 kg/m3.

Also, in Fig. 5 can be shown that the erosive wear rate on the pipe walls is increase with increasing the velocity of crude oil, where, the rate of erosive wear is increasing with about 95%, when increasing the velocity of crude oil from 0.2 m/s to 0.4 m/s. finally, from Fig. 6 can be shown the erosive wear rate on the pipe walls is non-affected by change in crude oil temperature, where the temperature is changed from 275.15 K^o to 323.15 K^o. Also, in the effect of parametric was shown in part two, Figs. 7 to 9 can be shown the following effect of the sand particles on the erosive wear rate on the pipe walls, as, Fig. 7 shows that the erosive wear rate on the pipe walls is increase with increasing of sand particles size, where the rate of erosive wear is increase with 95% when increasing the sand particles size from 120 microns to 220 microns. Also, in Fig. 8 can be shown the erosive wear rate on the pipe walls is increase with increasing of sand particles density, where the rate of erosive wear increase about 85% when increase the sand particles density from 1400 kg/m3 to 3000 kg/m3. Finally, from Fig. 9 can be shown the effect of mass flow rate of sand on the erosive wear rate on the pipe walls, where, from the figure shown that the erosive wear rate is non-affected by change in the mass flow rate of sand, where, the flow rate of sand changes from 0.3 kg/h to 0.9 kg/h.

The causes of increased or decreased rate of erosive wear on the pipe walls is due to increased friction between the oil or sand and the pipe walls, therefore, the effect of parametric on the rate of erosive wear were shown in Figs. 3 to 9 due to increasing or decreasing the friction. Also, can be shows from the figures that the erosion positions on the walls pipe are not fixed at same location with change of the parametric studied. Where, the erosion position is variable dependent on the effect of trajectories transport through the pipe elbow, it depended on the parametric effect, where the trajectories transport through the pipe elbow is presented in [8].

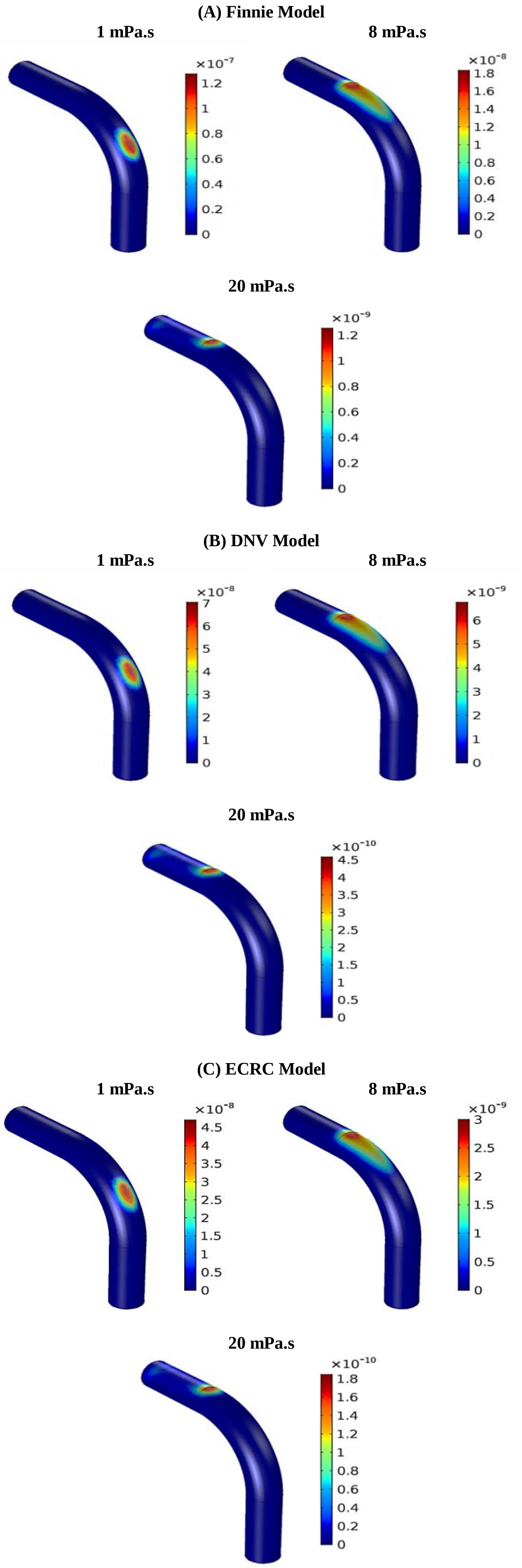

Fig. 3: Erosive Wear Rate [Kg/m^2.s] for Different Values Fluid Viscosity.

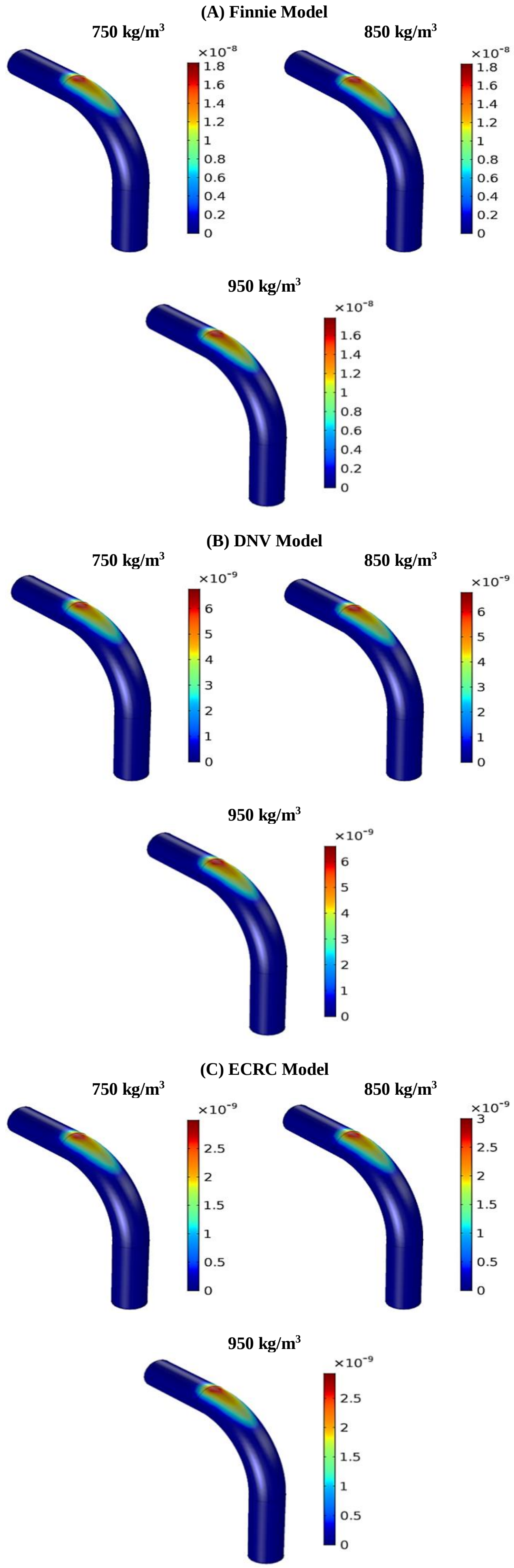

Fig. 4: Erosive Wear Rate [Kg/m^2.s] for Different Values Fluid Density.

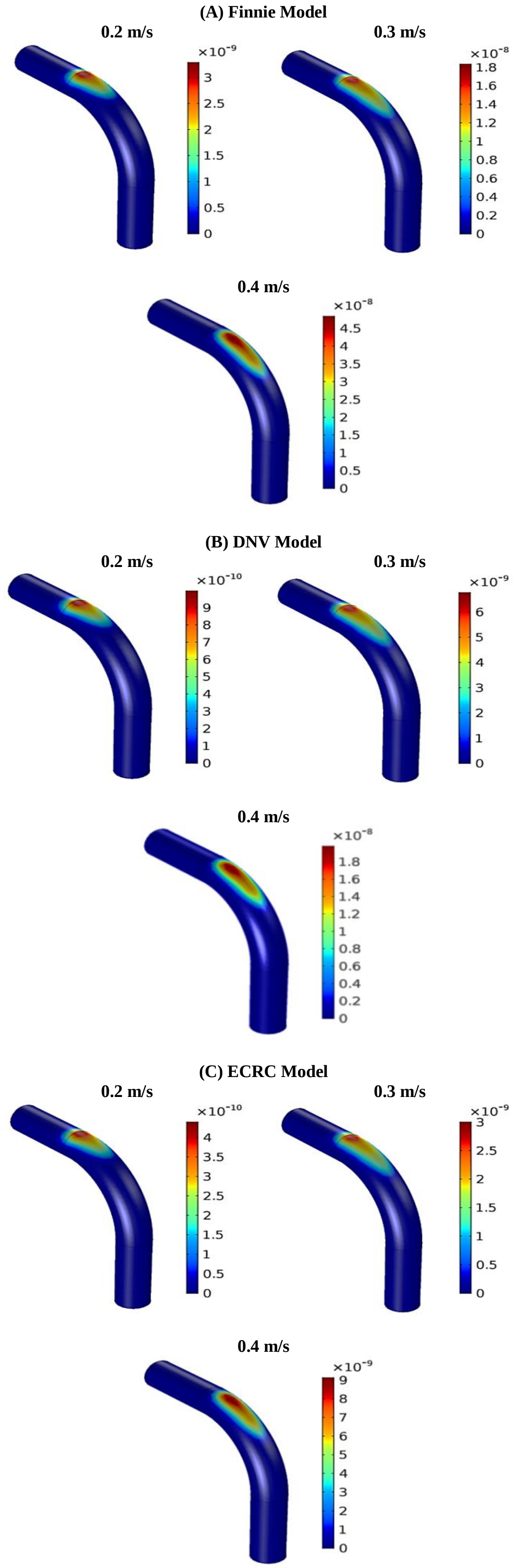

Fig. 5: Erosive Wear Rate [Kg/m^2.s] for Different Values Fluid Velocity.

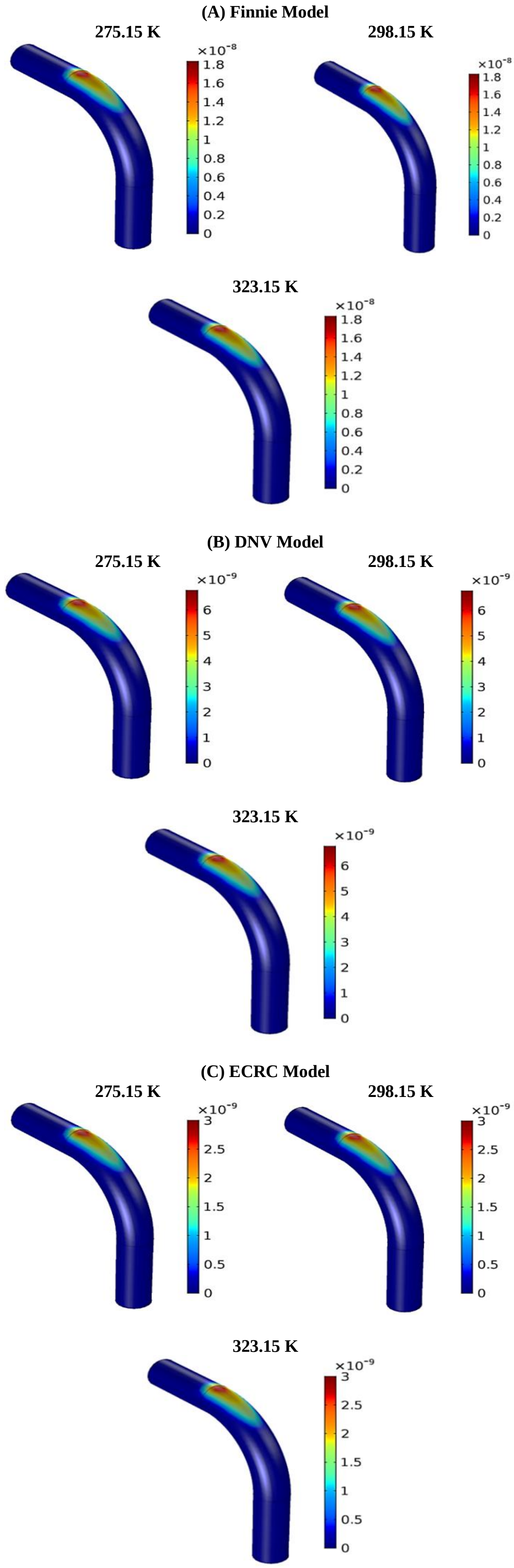

Fig. 6: Erosive Wear Rate [Kg/m^2.s] for Different Fluid Temperature.

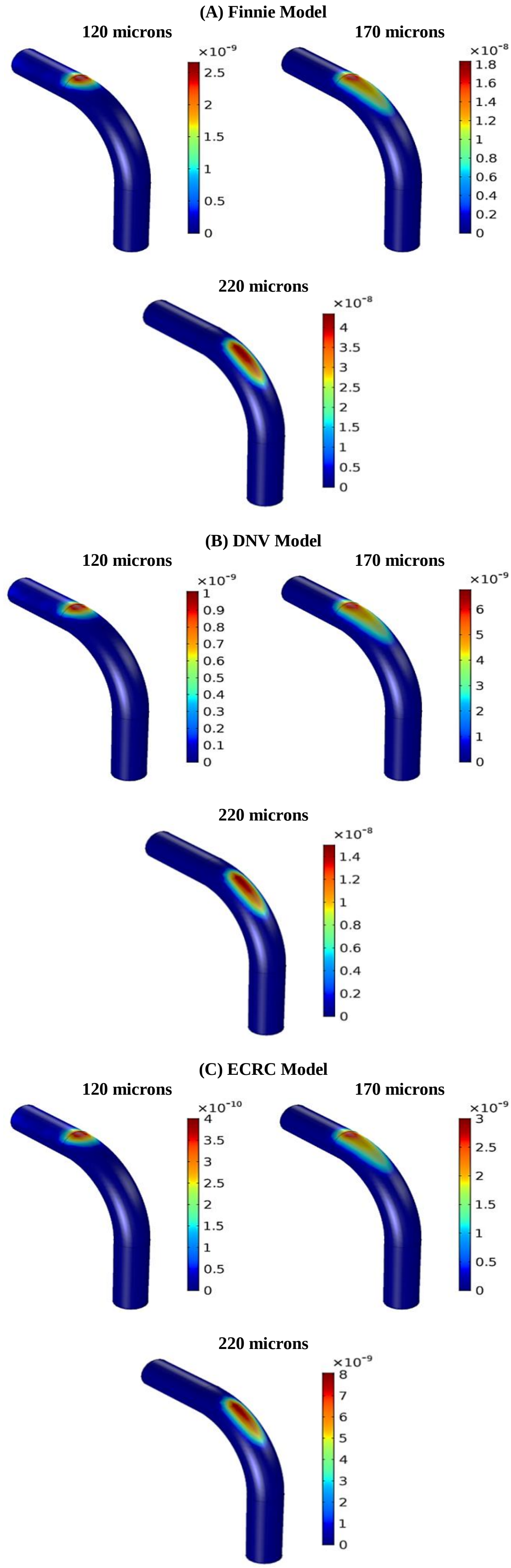

Fig. 7: Erosive Wear Rate [Kg/m^2.s] for Different Sand Particles Size.

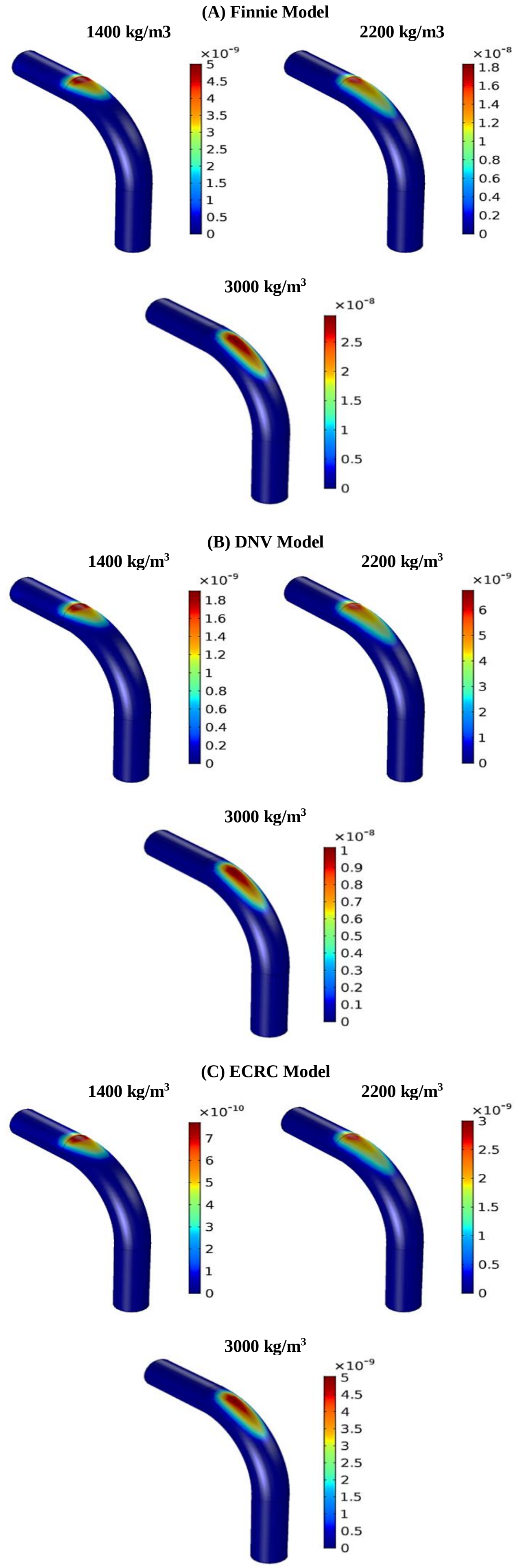

Fig. 8: Erosive Wear Rate [Kg/m^2.s] for Different Sand Particles Density.

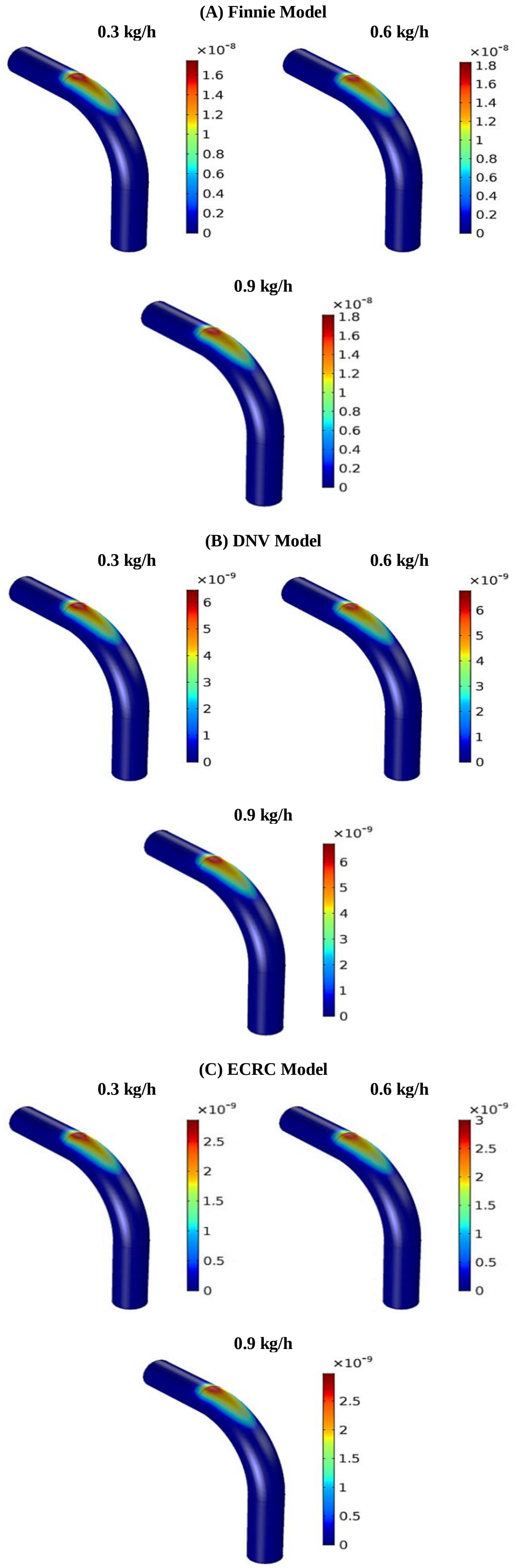

Fig. 9: Erosive Wear Rate [Kg/m^2.s] for Different Mass Flow Rate of Sand.

4. Conclusion

The research included evaluated the rate erosion and position erosion on pipe wall with different parametric of oil and sand particles effect with using of CFD technique of three erosion models, therefore, can be conclusion the flowing point from presented investigation, as,

1) The CFD technique is a powerful tool to evaluate the rate erosion and position erosion on pipe wall with different parameters include crude oil flow rate. Thus three-dimensional CFD model has been developed that describes the turbulent transport of the sand particles and the crude oil through elbows to simulate the erosions rates under various transport parameters.
2) The model is shown to be able to understand the many interacting, complex and transport phenomena that cannot be studied experimentally. There, the analysis offers valuable physical insight towards serve this model as an alternative sand management tool, and can be used to quantify oil recovery.
3) The erosion is increase with increasing the friction between the oil and pipe wall with variable the parameter affected on viscosity of oil flow through the pipe.
4) The position of the erosive wear on the pipe walls is variable with various the oil viscosity, oil velocity, sand particles size and sand particles density. But, the position of the erosive wear on the pipe walls is not variable with various the oil density, oil temperature and mass flow rate of sand. Where, the variable of wear occur as, the erosive wear rate on the pipe walls is increase with decreasing the oil viscosity, velocity crude oil, sand particles size, and sand particles density. But, the rate of the erosive wear is non-affected by change in oil density, oil temperature and the mass flow rate of sand.
5) The three models used were given the erosive wear for pipe with various fluid and sand particle parametric effect, thus, its models given different results of the wear. Then, for evaluating of the true value must be using the Two convergent values, its calculated by models.

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