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# CFD investigation of the erosion severity in 3D flow elbow during crude Oil contaminated sand transportation

***Abstract***- *During upstream petroleum production operations, crude oil and sand eroded from formation zones are often transported as a mixture through pipes up to the well heads and between well heads and flow stations. The sand particles are carried by the flow momentum in streamlines that impinge the pipe walls, in particular at the elbows, resulting in seriously erosive damages. This can lead to a disastrous and costly failure in the system. Therefore, computing of erosion rate during the system operation is indispensable for predicting any potential failure in advance, and hence avoid it. Among all the fittings employed in piping systems, elbows are the most likely subjected to erosion resulting from sand particles carried with oil, where those particles deviate from the mainstream and impact the walls while passing through the bended section of elbows. To reduce the erosive damage produced by the solid particles, a numerical simulation based erosion prediction model has been employed to compute the relative erosion severity. In this study ,the potentials required to simulate the current problem comprehensively, various physical aspects have been combined together including flow turbulence, particle tracking, and erosion simulation. In addition to the comprehensive insights offered by the computational simulation of crude oil flow, high costs along with tedious efforts required for traditional experimentations can be avoided. The current analysis offers priceless physical insight towards serve this model as an alternative sand management tool, and can be used to quantify oil recovery. Furthermore, it can identify limiting steps and components; form a computer-aided tool for designing and optimizing the future pipe systems in order to enhance their lifetime through improving their erosion resistance, which is definitely will save considerable amount of time and cost.*

***Keywords***- *Crude oil, Sand; Contamination; CFD; Erosion; Solid particle; Elbow.*

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## 1. Introduction

One of the main ways, through which crude oil is damaging the environment nowadays, is its leakage from natural deposits [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 (Figure 1). The sand particles are carried by the flow momentum in streamlines that impinge the pipe walls, in particular at the elbows, resulting in seriously erosive damages. This can lead to a disastrous and costly failure in the system [2]. Pipe elbows erosion caused by sand particles has been of great interest recently due to its crucial role in the oil industry as well as practical applications concerning materials erosion. Both sciences of fluid dynamics and materials engineering are required together for addressing the problems involving erosion caused by solid particles carried with the fluid flow [3-5]. Therefore, predicting any potential failure in advance, and hence avoid it by computing the erosion rate during the system operation is indispensable.

The lack of efficient testing tools to evaluate the erosion rate resulting from flow through piping systems has been hampering the development of anti-erosion elbows. The phenomenon of sand erosion is too complicated as it incorporates a wide range of hydrodynamic and structural factors contributing either positively or negatively in its severity including oil characteristics and its flow rate, the sand rate and its particles properties, materials used for the fittings, and geometrical characteristics of elbows, i.e. size and shape. This is why it has become of great interest to reduce the damaging effects of the erosion resulting from solid particles through manipulating these design factors simultaneously.

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**Figure 1: Piping systems in oil industry showing erosion occurs in elbows.**

Therefore, various predicting methods were developed to limit the erosion consequences. Amongst them, the CFD based erosion simulation has been found quite efficient and applicable to the too complicated engineering applications [6, 7].

In this study, a three-dimensional CFD model has been developed that describes a turbulent transport of sand particles and 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.

## 2. CFD modeling

*I. 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 (Figure 2).

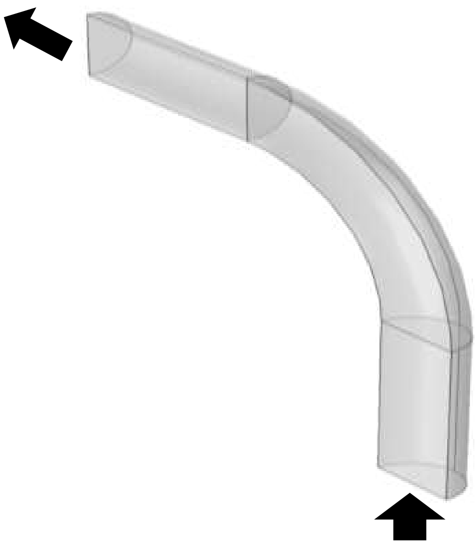

**Figure 2: Three dimensional computational domain**

*II. Modeling Equations*

*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];

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

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

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 k-ε model because it is more accurate than the k-ε model for flows involving strong streamline curvature [8], where formulation of this turbulence model is as follows:

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

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

Where,

$$\mu_T=\rho\frac{k}{\omega}\ ,\alpha=\frac{13}{25},\beta=\beta_o f_\beta,\beta^{*}=\beta_o^{*}f_\beta \qquad ...(5)$$

$$\sigma=\frac{1}{2},\sigma^{*}=\frac{1}{2} \qquad .....(6)$$

$$\beta_o=\frac{13}{125},f_\beta=\frac{1+70X_\omega}{1+80X_\omega},X_\omega=\left|\frac{\Omega_{ij}\ \Omega_{jk}\ S_{ki}}{(\beta_o^{*}\omega)^{3}}\right| \qquad ..(7)$$

$$\beta_o^{*}=\frac{9}{100}f_\beta^{*}=\begin{cases}1 & X_k\le 0\\ \frac{1+680X_k^2}{1+400X_k^2} & X_k>0\end{cases}$$

$$X_k=\frac{1}{\omega^{3}}(\nabla k.\nabla\omega) \qquad ...(8)$$

Where $\omega_{ij}$ represents the mean tensor of rotation rate.

$$\Omega_{ij}=\frac{1}{2}\left(\frac{\partial\overline{u_i}}{\partial x_j}-\frac{\partial\overline{u_j}}{\partial x_i}\right) \qquad ...(9)$$

And $S_{ij}$ is the mean strain rate tensor.

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

$$P_k = \mu_T \begin{pmatrix} \nabla u: \left(\nabla u + (\nabla u)^T\right) \\ -2/3*(\nabla . u)^2 \end{pmatrix} - \frac{2}{3}\rho k \nabla . u \quad .... (11)$$

*2. Particle Motion in a Fluid Model*

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

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

Where mp refers to the particle mass in kg, v is the particle velocity in m/s, FD stands for the drag force in N, Fg is the vector of gravitational force in N, and Fext represents any other external source in N.

The drag force (FD) can be computed as;

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

Where $\tau_p$ 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 turbulent dispersion term is rewritten as;

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

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

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

Where k is the turbulent kinetic energy, while φ is 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 $\rho_p$ represents the particle density in kg/m$^3$, ρ stands for the surrounding fluid density in kg/m$^3$, while g is the gravitational direction.

*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 modeled [4-7].

*A. The Finite Model*

Finnie defined the volume removed from a surface as:

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

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

Where the parameters are defined as follows:

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.

*B. 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:

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

$$F(\alpha) = \begin{pmatrix} 5.40\alpha - 10.11\alpha^2 + 10.93\alpha^3 - \\ 6.33\alpha^4 + 1.42\alpha^5 \end{pmatrix} \quad ...(20)$$

Where C is a dimensionless model coefficient, Fs 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.

*C. 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:

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

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

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

*III. 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 (COMSOL v5.2). 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 of44772 domain elements in total, 8908 boundary elements, and 590 edge elements, which was found to provide sufficient spatial resolution (Figure 3). An iterative solution for the coupled equations was followed, where an error criterion of $1.0 \times 10^{-6}$ 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 major steps: flow modeling, particle tracking, and erosion prediction. The flow initial and boundary conditions have been listed in Table 1 [9].

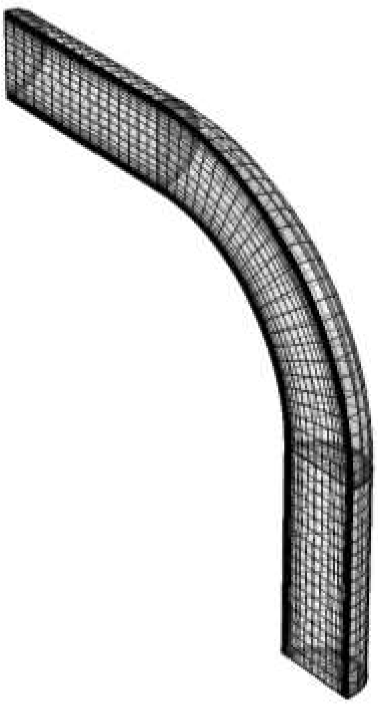

**Figure 3: Three dimensional computational mesh of the domain.**

**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 |
| Pipe material | iron |

## 3. Results

Figure 4 shows the velocity distribution of the crude oil passing in the pipe elbow. The figure shows there is a separation zone after the bend which is consistent with the results of Homicz [10]. Figure 5 shows a corresponding pressure distribution in the pipe elbow. The visualizations of the sand particle trajectories transport through the pipe elbow are shown in Figure 6. Particles that move through the pipe bend without touching the walls have been hided; therefore the only particles that have made contact with surfaces of the pipe bend are shown. The color expression is the acute angle of incidence in degrees, measured from the surface normal. It is clear that the particles only strike the surface at grazing angles.
Three different erosion models are used to simulate the rate of erosive wear on the surface of the pipe elbow of the contaminated crude oil with sand particles. Figures 7-9 show the Finnie, DNV, and E/CRC erosion respectively. An example of erosion happens in pipe elbow during flow a contaminated crude oil with sand particles shows in Figure 10 with good similarity to the CFD model.

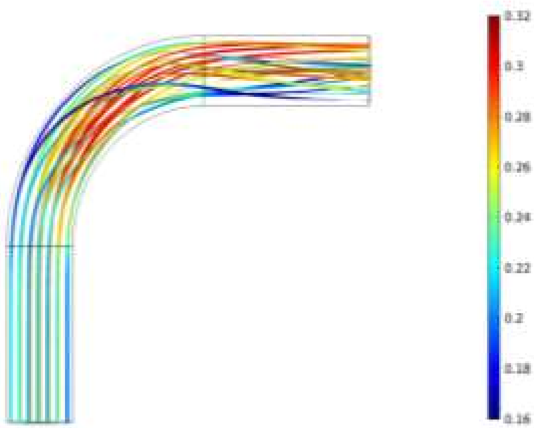


**Figure 4: Velocity streamlines [m/s] in the pipe elbow.**

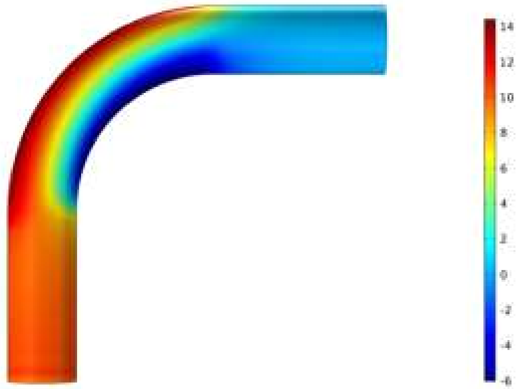


**Figure 5: Pressure [Pa] in the pipe elbow.**

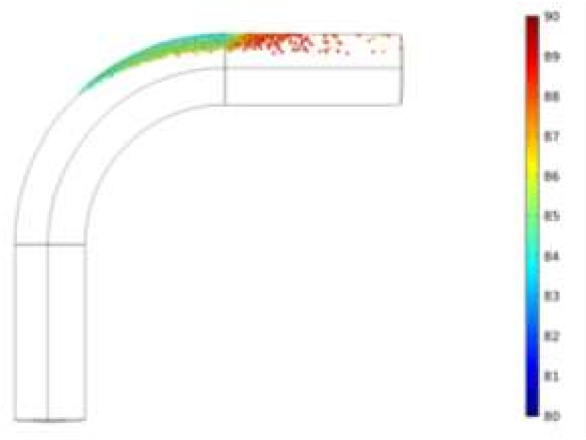


**Figure 6: Visualizations of the sand particle trajectories transport through the pipe elbow. The color expression is the acute angle of incidence [degree], measured from the surface normal.**

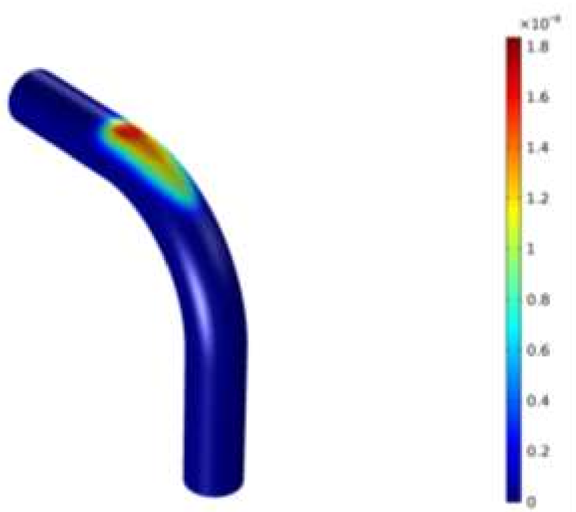


**Figure 7: Rate of erosive wear [kg/m$^2$.s] on the pipe walls, modeled using the Finnie model.**

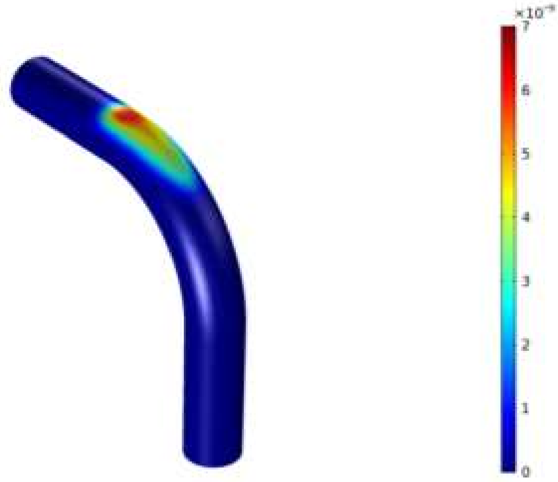


**Figure 8: Rate of erosive wear [kg/m$^2$.s] on the pipe walls, modeled using the DNV model.**

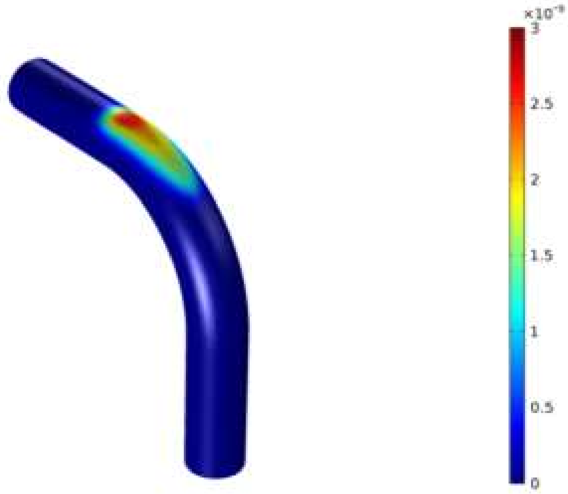


**Figure 9: Rate of erosive wear [kg/m2.s] on the pipe walls, modeled using the ECRC model.**

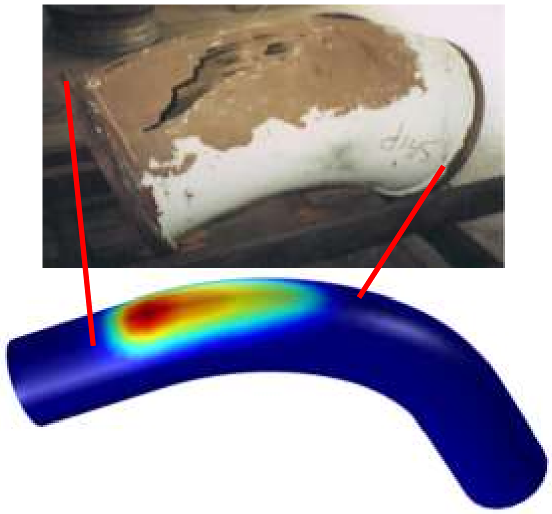

**Figure 10: Visual comparison between examples of the real erosions occurs in elbows and the result of the CFD model.**

## 4. Conclusion

1. Three-dimensional CFD model has been developed that describes a turbulent transport of sand particles and oil through elbows to simulate the erosions.
2. The comprehensive simulation model consists of turbulent modeling, particle tracking, and erosion simulation.
3. It was found that the model presented has the potentials to provide better understanding for the , complexly interacting and transporting phenomena, which are quite hard to be investigated experimentally.

**References**


[1] Rajab M. Abousnina, Allan Manalo, Weena Lokuge, Jim Shiau “Oil contaminated sand: An emerging and sustainable construction material,” International Conference on Sustainable Design, Engineering and Construction, Procedia Engineering, Vol. 118, pp. 1119-1126, 2015.

[2] Lekan Taofeek Popoola, Alhaji Shehu Grema, Ganiyu Kayode Latinwo, Babagana Gutti, Adebori Saheed Balogun “Corrosion problems during oil and gas production and its mitigation,” International Journal of Industrial Chemistry, Vol. 35, pp. 1-15, 2013.

[3] Samuel Eshorame Sanni, A. S. Olawale, S. S. Adefila “Modeling of Sand and Crude Oil Flow in Horizontal Pipes during Crude Oil Transportation,” Journal of Engineering, pp. 1-7, 2015.

[4] Y. Zhang, E.P. Reuterfors, B.S. McLaury, S.A. Shirazi, E.F. Rybicki “Comparison of computed and measured particle velocities and erosion in water and air flows,” Wear Journal, Vol. 263, pp. 330–338, 2007.

[5] Xianghui Chena, Brenton S. McLaury, Siamack A. Shirazi “Numerical and experimental investigation of the relative erosion severity between plugged tees and elbows in dilute gas/solid two-phase flow,” Wear Journal, Vol. 261, pp. 715–729, 2006.

[6] Xianghui Chen, Brenton S. McLaury, Siamack A. Shirazi “Application and experimental validation of a computational fluid dynamics (CFD)-based erosion prediction model in elbows and plugged tees,” Computers & Fluids, Vol. 33, pp. 1251–1272, 2004.

[7] M. Atkinson, E.V. Stepanov, D.P. Goulet, S.V. Sherikar, J. Hunter “High pressure testing sand erosion in 3D flow channels and correlation with CFD,” Wear Journal, Vol. 263, pp. 270–277, 2007.

[8] Maher A.R. Sasiq Al-Baghdadi “Applications of Computational Fluid Dynamics and Finite Element Methods in Engineering Education, Vol.1,” International Energy and Environment Foundation, ISBN-9781512122428, 2015.

[9] Hollebone, B. “The Oil Properties Data Appendix,” In Handbook of Oil Spill Science and Technology, Fingas, M., Ed. John Wiley and Sons Inc.: NY, pp 577-681, 2015.

[10] G.F. Homicz, “Computational Fluid Dynamic Simulations of Pipe Elbow Flow,” Sand Report, Sand2004-3467, Sandia National Laboratories, 2004.



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