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Numerical Investigation of the Influence of Sand Particle Concentration on Long Radius Elbow Erosion for Liquid-Solid Flow

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ABSTRACT

Erosion caused by sand transportation in flow changing devices is a serious concern in the hydrocarbon and mineral processing industry, which entail to failure and malfunction of flow devices. In this study, computational fluid dynamics (CFD) with discrete phase models (DPM) were employed for analysis of carbon steel long radius 90-Degree elbow erosion due to the sand concentration of 2, 5 and 10% transported in the liquid phase. The simulation is completed with the Reynolds Stress Model (RSM) and Oka erosion model. The simulation result from the RSM model was validated by comparison with the erosion distribution results in the literature. The largest erosion zones have been identified at or near the outlet of the 90-Degree elbows outer wall surface with a maximum erosion rate appeared for 10% sand concentration. Furthermore, the relationships of turbulence intensity on erosion, particle trajectory, and particle mass concentration in the elbow pipe were discussed.

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1. INTRODUCTION

Sand particle erosion is preeminent mechanisms of material removal and frequently occurs in hydrocarbon and mineral processing industry. Erosion-induced damage arises when sand particles transported by the carrier fluid impact inner pipeline surface [1]. Erosion may cause significant damage to piping systems in the hydrocarbon production industry and bring about equipment malfunction and necessary replacement of the production equipment. In order to alleviate the erosion of pipelines, the massive cost is annually directed. If erosion induced damage is not detected, it might lead to malfunction of equipment, flow-changing devices and affects the operating safety of the whole process [2].

In the hydrocarbon production industry, the erosion of flow changing devices at high transportation velocities is a major concern [3]. Among various kinds of flow changing devices, the 90^o bends are an indispensable component used to alter the flow direction [3]. Studies reveal that the material disintegration due to erosion on bend configuration is fifty times higher as compared to straight configurations [4].

Most of the past studies in solid particle erosion have been related to the gas dominant flow for the standard elbow under normal flow conditions [5-8]. A thorough search of the relevant literature resulted in a limited study on numerical erosion mapping in elbows in liquid-dominant flow for different sand concentration. The CFD studies done in literature, mostly utilize discrete element model (DEM) or discrete phase model (DPM) to understand sand particle physics in a carrier fluid [9]. In DEM, the carrier fluid is a continuum phase while the solid particles are a dispersed phase in the flow field [10]. During DPM kinematic equation of solid particles was solved to extract dispersion and deposition of the solid phase to capture the effects that influence the flow solution [11]. In CFD-DPM, to account particle-particle interaction a Discrete Random Walk (DRW) model adopted to simulate flow physics. The DRW model assumes that erodent transit through progressive turbulence due to flow [5]. Interaction with turbulence eddies deviates the particle trajectories in the

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computational domain. There are few assumptions associated with the particle tracking: 1) The particle interaction is negligible in the presence of the sand particles; 2) Erodent are injected from the entry section of the computational domain with no-slip between the erodent and carrier liquid; 3) The erodent shape is considered spherical, and 4) the drag and buoyancy acts as the dominant forces on the erodent.

In the present work, the influential effect of sand concentration on 90º carbon steel elbow configuration was investigated using computational fluid dynamics simulation by introducing DPM. In the present study, Oka et al. [12] correlation are implemented to quantify erosion patterns in elbow geometry configuration with different sand concentration. The maximum locations of erosion-induced damage were closest to exit for all sand concentrations.

Furthermore, considering that in flow pipelines, large sand concentration, i.e. 10% in carrier fluid causes more erosive damage to pipe wall elbows as compare to 2 and 5% concentration, on which the limited studies, had been reported in the literature. This study highlights to quantify erosion in elbows under the impact of various sand concentrations transported in the liquid by adopting a CFD-DPM approach.

2. COMPUTATIONAL FLUID DYNAMIC SIMULATION

The ANSYS FLUENT software package used for the simulations of flow physics with erosion quantification. To entertain sand particles under steady flow condition an entrance length of 1m and an exist length 0.5m was added to the elbow configuration with an inner diameter of 0.51 m, schematic of geometric configurations and angle distribution are shown in Figure 1. The erosion rate, turbulence intensity, solid particle trajectories, and particle mass concentration distribution map was extracted from the simulation under liquid-sand flow. To assure the computational mesh quality 524000 elements with an element size of 0.003 mesh resolution used for all the simulations. To extract erosion rate and particle trajectories, DPM approach was introduced in simulation stages. The simulation parameters used to extract the erosion profile of the elbow configurations are listed in Table 1.

2. 1. Validation of CFD Model

The Oka erosion equation is considered for this research and the Reynolds Stress Model (RSM) is employed for turbulence modeling with enhanced wall treatment. Zhang [13] compares data extracted from Laser Doppler Velocimetry (LDV) technique and RSM to predict velocity and turbulence in elbows pipe configurations and found that the RSM accurately predicts flow field

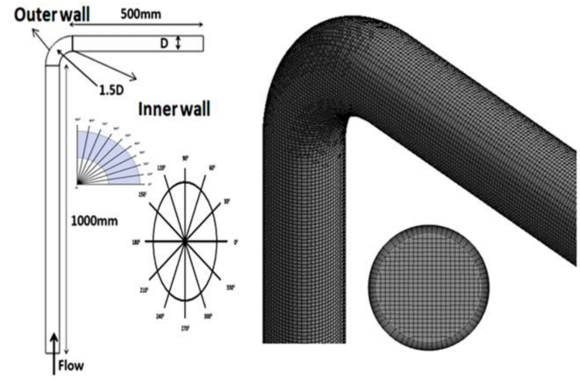


Figure 1. Computational Mesh and Geometry

TABLE 1. Simulation Setup

	Present Study	Reference [14]
Target surface	Carbon Steel	Stainless Steel
Erodent	SiO_2	SiO_2
Particle	250 micron	300 micron
Density	2650 [kg/m^3]	2650 [kg/m^3]
Shape	Uniform-sphere	irregular quartz
Sand	2% ,5% ,10%	-
Turbulence	Reynolds Stress Model	Reynolds Stress
Residuals	1e-5	1e-5
Turbulent	3.68 %	5%

and turbulence intensity. The erosion equation incorporated in ANSYS Fluent to quantify the erosion rate for the present study is outlined in Equation (1):

$$ER = 1\times10^{9} \times \rho_{w} kF(\theta)(H_{v})^{k_1} (\frac{V_p}{V'})^{k_2} (\frac{d_p}{d'})^{k3} \quad (1)$$

where ρw is the density of carbon steel, F(Ө) impact angle function, Hv is the carbon steel Vickers hardness, VP particle impact velocity, V' is the impact velocity of the reference particle, dp is the particle diameter and d' is the reference diameter. To verify the flow physics and erosion equation used for the present study, the validation model simulation parameters for air-sand flow are set identical as reported in literature [14]. The simulation parameters of the validation model are listed in Table 1. To capture flow pattern more accurately near the wall gradual refinement technique adopted near the vicinity of walls as shown in Figure 1. To assure the stability of results quality and computation use, a mesh independence study was presented in a separately published work [15].

The DPM erosion rate with an air velocity of 23 m/s is presented in Figure 2 for the comparison to validate the adopted model for the present study. The quantified results with "V" shaped scar at 47o on the elbow outer wall are identical to the simulation results as reported in literature [14]. Thus, the model adopted for the present study can be used to extract accurate erosion patterns.

3. RESULTS AND DISCUSSION

The results and discussion are outlined with erosion pattern, the turbulent intensity for three sand concentrations in the liquid-sand flow in the first section. Thereafter the particle trajectories under liquid dominant flow along the 90-degree elbow with particle mass concentration under various sand concentrations are presented.

3. 1. Erosion Pattern and Sand Particle Trajectories Figures 3a-3c present the extracted erosion profile and erosion rate in 2, 5 and 10% sand concentration by weight for carrier fluid velocity of 2 m/s with particle diameters of 250 microns. In liquid-sand flow, the erosion distribution relies on the path of the sand followed under flow conditions towards the wall surface. Figures 3a-3c reflect that particle impact with wall generates an erosion map with considerably larger erosion rate under 10 % sand concentration as compared with 2 and 5% sand concentration. Figure 4 shows that the large erosive zone generated due to the particles-wall interaction at high impact angle. Figure 3 displays that with consideration of sand concentration in a carrier fluid escalates the maximum erosion rate and erosion region. In addition, high sand concentration in carrier fluid results in maximum particle mass concentration region on the outlet side in 90o bends and will result in a higher erosive zone on the elbow outer wall surface. Thus, the high concentration maximizes the erosion in the liquid-solids flow leads to a more catastrophic impact to the wall surface and disintegrates more walls mass compared and turnout in an increase of the erosion rate. The selected particle trajectories and trajectory of sand particles inside a standard 90-degree elbow are shown in Figure 4. For liquid-solid flow, the particles follow the independent path and directly interact the outer wall of the elbow with path w–y–z and x-z as outlined in Figure 4. For the high sand concentration particles will impact location z with large impact angle and lead to the high erosion region at elbow outlet.

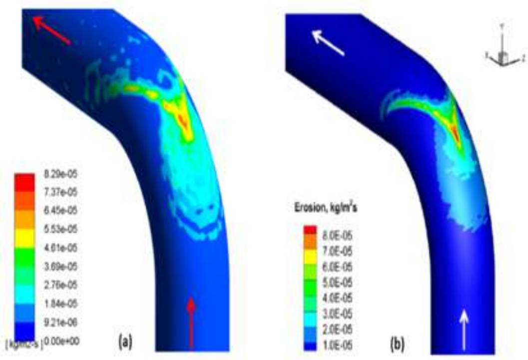


Figure 2. Comparison erosion pattern simulation for air velocity (a) V_g =23 m/s (b) V_g=23 m/s based on literature [14]

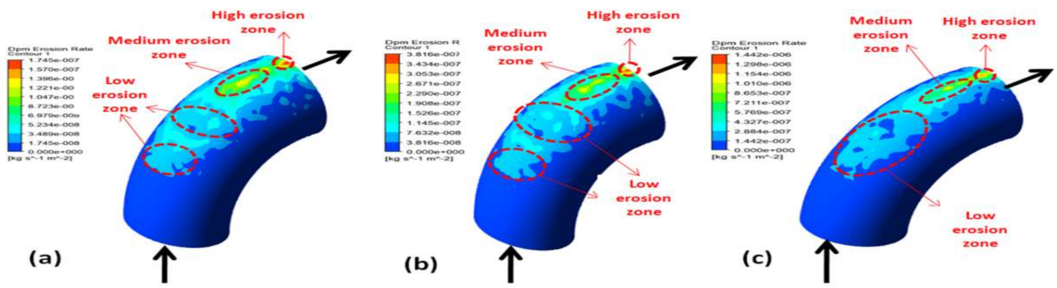


Figure 3. Erosion contour and particle trajectories 90° elbow at different sand concentration (a) 2 %, (b) 5 %, and (c) 10 %

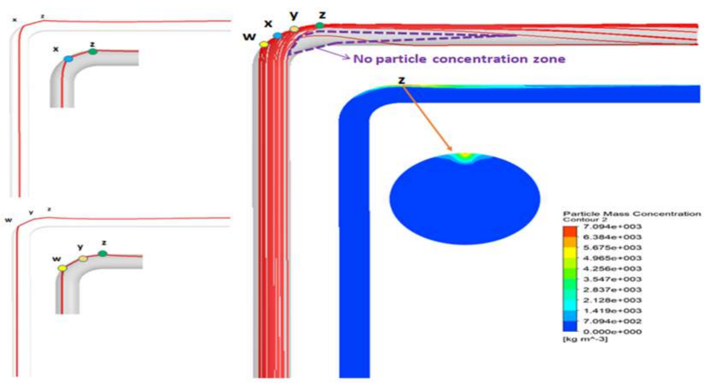


Figure 4. Sand trajectories for two chosen particles and standard case with 10% concentration

3. 2. Relationship of Sand Concentration and Erosion Rate Figure 3 depicts, the erosive zone is affiliated to the sand concentration in the carrier fluid and preeminent per flow conditions. Changing the sand concentration in carrier fluid will alter the flow conditions and results in the maximum erosion rate.

Figure 3 shows the erosive wear in the elbow due to all sand concentration resulted in the disintegration in the outer wall surface at or near the outlet. As illustrated by the erosion distribution, the particles are more inclined to impact at the outlet for 2 and 5% sand concentration and when the concentration change to 10% the erosion location is shifted to near the elbow outlet side. The erodent particles will cause more percussion the outer wall near the inlet side for 10% sand concentration and high particle mass concentration zone appears at near elbow outlet sides as compared to 2 and 5% as shown in Figures 5a-5c. The maximum particle mass concentration for 90o elbows in Figure 5 shows when the sand concentration is less in carrier fluid the maximum concentration zone appears on the elbow outer surface with significantly less erosion induced damage as compared to the high sand concentration. The maximum erosion rate of 90° elbow under 10 % sand concentration is 4 mm/year located in the annular angle ϴ = 90° at the outlet and under 5% sand concentration is 1.5 mm/year at annular angle ϴ = 90° as illustrated in Figure 6(a). The simulation results show that the maximum erosive zone of large sand concentration, i.e. 10% located adjacent to the exit wall and the reduction in erosion rate is observed for low sand concentration, i.e. 2% with a maximum erosion rate of 0.6 mm/year located at the outlet as shown in Figures 6a and 6b. The simulation study shows that for 90° elbow, sand concentration is primarily suspected for altering the erosion rate. This can be observed in Figures 6 (a) and 6(b). By comparing 90^{o} elbow erosion rate the maximum erosion rate under 2% sand concentration is 2.5 times less than 5% and 6.6 times less compared to 10% sand concentration. As a result, taking all the above under consideration, the low sand concentration operating condition in the carrier fluid is recommended for suitable cases.

3. 3. Relationship of the Sand Concentration and Turbulence Intensity Figure 7 presents that turbulent intensity significantly increases the particle-wall interaction and erosion rate at the elbow outlet on the outer wall. The high-intensity turbulent flow towards the outlet of 90° elbow escalates particles and results in

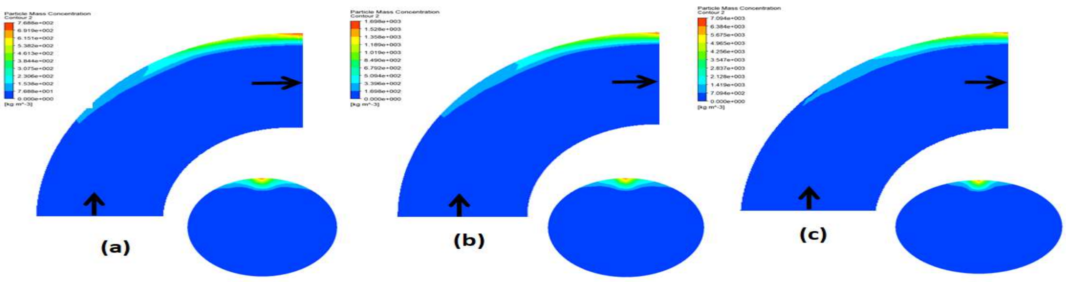
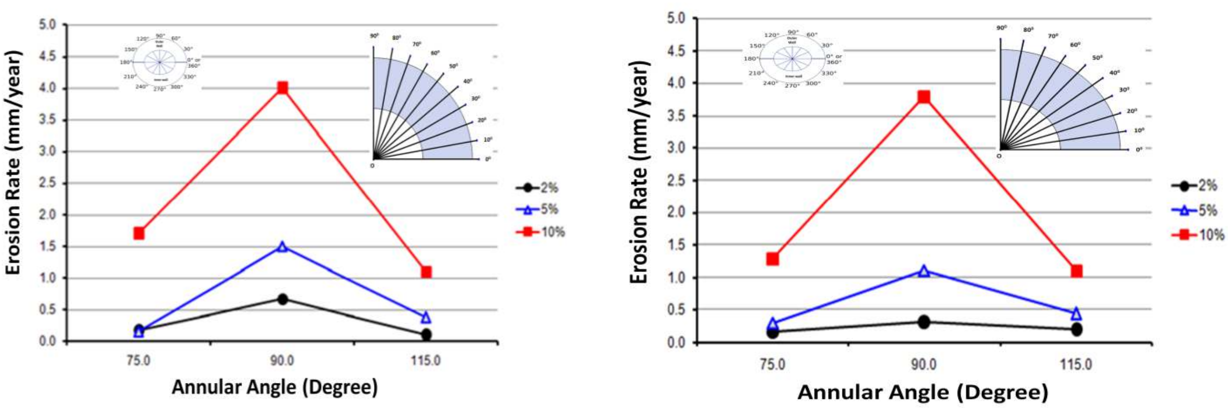


Figure 5. Contours of Particle Mass Concentration for 90-degree elbow (a) 2%; (b) 5% and; (c) 10% sand concentration



(a) (b)

Figure 6. Numerical erosion rate vs. annular angle for 90^{0} elbows between curvature angle (a) 0^{o} -15^{o} (b) 15^{o} -30^{o}

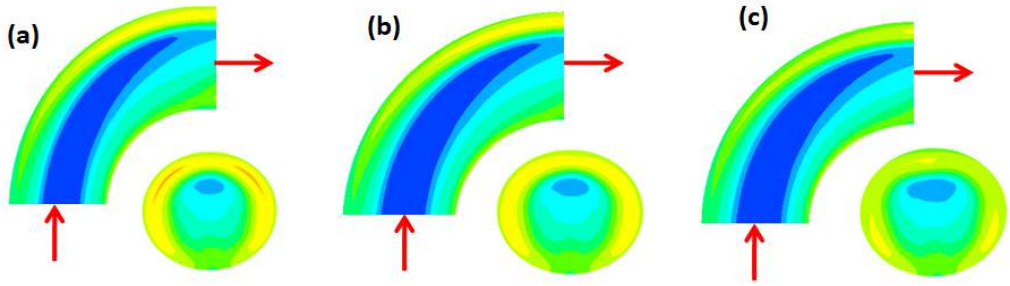


Figure 7. Turbulent intensity contours at outlet of 90^0 elbow with sand concentration (a) 2%; (b) 5%; (c) 10%

the more particles impact of the outer wall. This concludes that apart from the particle mass concentration and particle trajectory, turbulence intensity contributes to change the particle path in 90o elbows. Based on simulation results turbulence weigh more under 10% sand concentration at the outlet significantly contributes to enhancing erosion region and erosion rate. The turbulent intensity contours suggest that the contraction in the blue zone and the enlargement in the red and yellow zone signify the maximization of turbulent intensity. This means excessive turbulence is identified in elbow outlet under all sand concentration in the carrier fluid.

4. CONCLUSIONS

The CFD–DPM simulation technique was adopted to investigate the erosion-induced damage of carbon steel long radius 90-Degree elbow pipe under different sand concentration in the carrier fluid. Numerical results showed that the sand concentration in carrier fluid has an influence on the particle dynamics and the wear profile of the elbow. To verify the adopted erosion equation for simulations, the erosion distribution extracted from the present study was compared with previous literature. The following conclusions can be drawn based on obtained results: Firstly, in 90-Degree elbow, a sand particle concentration region induced a high erosive region on the elbow at the outlet side of the outer wall. When the sand concentration is changed to 10%, the particle trajectory changes and the particle concentration region slightly shifted from the outlet and caused a more destructive impact to the outer surface adjacent to the outlet side. Secondly, the high turbulence due to flow driven influences particle trajectories and induces more catastrophic particle-wall interaction at the outlet side and affect the erosion pattern. However, increasing sand concentration in carrier fluid not significantly changes the location of particle-wall interaction. Thirdly, the numerical simulation of erosion in the elbows geometrical configuration shows that reduction of the 10% sand concentration to 2% seems to reduce the maximum erosion rate up to 6.6 times. On the other hand, the 5% sand concentration in a carrier fluid reduces the maximum erosion rate up to 2.6 times compared to 10 %. Thus, the reduction of low sand concentration (e.g. 2% and 5%) in the carrier fluid is recommended for a suitable case.

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چکیده

فرسایش ناشی از حمل و نقل شن و ماسه در دستگاه های در حال تغییر جریان نگران کننده و جدی در صنعت هیدروکربن و فرآوری مواد معدنی است که منجر به خرابی و نقص دستگاه های جریان می شود. در این مطالعه ، دینامیک سیالات محاسباتی (CFD) با مدل فاز گسسته (DPM) برای تجزیه و تحلیل فرسایش آرنج ۹۰ درجه ای از فولاد کربن به دلیل فرسایش ماسه ۲٪ ، ۵٪ و ۱۰٪ در فاز مایع مورد استفاده قرار گرفته است. . شبیه سازی با مدل استرس رینولدز (RSM) و مدل فرسایش اوکا تکمیل شده و نتیجه شبیه سازی از مدل RSM با مقایسه با نتایج توزیع فرسایش در ادبیات تأیید شده است. بزرگترین مناطق فرسایش در یا در نزدیکی خروجی سطح دیواره بیرونی آرنج ۹۰ درجه با حداکثر سرعت فرسایش برای ۱۰٪ غلظت شن مشاهده شده است. علاوه بر این ، رابطه شدت تلاطم در فرسایش ، مسیر ذرات و غلظت جرم ذرات در لوله آرنج مورد بحث قرار گرفته است.

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