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Erosive corrosion in tube considering chlorine ions and bubbles via numerical simulation

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Abstract: Two-phase vapor-liquid flow containing bubbles and chloride ions can cause serious erosion corrosion to a tube. Numerical simulation of 90° bended model based on the Euler-Lagrange equation for water containing bubbles and chlorine ions is employed to find that the reason for corrosion is that chloride ion deposition reduces the thickness of wall，and that bubble breaking impacts the wall，damaging the protective oxide layer and aggravating corrosion.

1. Introduction

Vapor-liquid two-phase flow is widespread in the energy，chemical，petrochemical，nuclear industry and environmental engineering process，such as steam boiler，steam generator，steam regenerator and heat transfer equipment. Research on corrosion caused by the corrosive medium and bubbles have studied from the experiment flow field to the practical utilities with the development of the methodology. Based on various engineering practice，scholars have set up the physical and mathematical model of flow field corrosion, the theoretical and numerical simulation results were compared to verify the correctness of the model. Bubbles and aggressive ion existing in the fluid are very common in nature，which is also a very difficult problem concentrated in fluid mechanics.

Pressure increase caused by bubbles breaking and the failure mechanism of material can be explained by micro jet theory (Tomita et al., 1986).The crevice corrosion behavior of 13Cr stainless steel in NaCl solution was investigated mainly by electrochemical noise measurements, considering the influences of the crevice opening dimension and the area ratio of the electrode outside the crevice to the one inside the crevice. Results show that the increase of r value prolongs the incubation period of crevice corrosion, but crevice corrosion develops rapidly once the crevice corrosion occurs. The crevice corrosion develops preferentially at the crevice bottom and then spreads to the whole electrode surface.(Hu, Q.,et al.,2011).The key parameters of bubbles erosion corrosion are flow velocity， particle quantity and bubble volume fraction (Benedetto et al.,2003). With the steel corrosion in low acidic chloride-sulfide solutions the H^+ and S^{2-} concentrations in a crevice are found to decrease. The effect is responsible for the anodic process localization at points of crevices: micro-cavities, cracks in the iron sulfide layer or under hydrogen bubbles.(Podobaev, N.,et al.,1991).The influence of gas velocity, halogen salt type and salt concentration on bubble coalescence in a small bubble column were studied.(Nguyen et al.,2012). The bubble coalescence was determined by the relative change in the measured light intensities passing through the salt solutions and clean deionised water. It was shown that the transition salt concentration for bubble coalescence inhibition of all investigated salts decreases with increasing superficial gas velocity. Bubble coalescence behavior in aqueous electrolyte solutions exposed to an ultrasound field has been examined. At a sufficient interfacial loading of the adsorbed species, the hydrodynamic boundary condition at the bubble/solution interface switches from tangentially mobile to tangentially immobile, commensurate with that of a solid-liquid interface. This condition is the result of spatially non-uniform coverage of the surface by solute molecules and the ensuing generation of surface tension gradients.(Browne, C.,et al.,2011). When the experimental temperature is between 450 ~ 600 ℃, tube is serious damaged due to chloride deposit (Skrifvars et al.,2008). Under other circumstances, the bubbles flow can cause a type of surface erosion through mechanical action of the fluid itself. This process is called impingement. It involves removing loosely adhered, corroded surface layers from the metallic surface by high shear stress in the tube wall created by the flowing liquid (Kuźnicka,2009). Gas bubbling through a column of ionic liquid has been investigated using high-speed video and a conductivity method to measure a cross sectional averaged void fraction. For comparison, other liquids with similar physical properties, e.g., a glycerol/water mixture and glycerol/water with dissolved potassium chloride were also employed. The differences in flow patterns were revealed by analysis of the time series of conductance signals in the form of the probability density function, autocorrelation, and power spectrum density（Kaji, R.，2009）.Flow induced corrosion by solid particle impact, liquid impact or bubbles occurs in a wide variety of industrial and everyday life environments, such as pipes, heat exchanger, chemical reactors, liquid-solid heterogeneous catalytic reactors, and so on. Flowing fluid may cause the abrasion of the coatings, enhance the supply of oxygen and diffusion or transport of ions, as a result of influencing corrosion(Zhou, Q.X.,et al.,2010).Dispersed phase and chemical composition of water rich in chloride ions that result in loss of stability of protective oxide layer. High levels of chloride particles in the flue-gas can cause enhanced deposit formation, and in turn high content of chlorine in deposits may cause accelerated super-heater corrosion (Van,et al.,2009).Tube is subject to be erosion–corrosion in a given set of conditions, using numerical simulation techniques. The computation results prove to be erosion–corrosion effects owing to turbulence, bubbles dynamics affect and ensuing erosion rates. The effect of bubbles discretized in the fluid on the erosion–corrosion has seldom been considered and the experimental conditions are usually much different from practical industrial erosion–corrosion conditions (Chen,et al.2012). A three-dimensional model is performed in order to analyse chloride particles deposit in the flue-gas. The use of CFD codes for modeling of two-phase flow, it is important to know whether or not deposition will be present in some sensitive location. The predicted results show that the volume fraction of particles phase varies along with the flow field. Chloride particles may deposit where the area of high volume fraction (Chen,et al.2012).

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The purpose of this paper is to analysis and forecast the local electrochemical corrosion lead by chloride ion and erosion corrosion caused by discrete phase in pipe，and predict corrosion location and degree through the numerical simulation．

2. Conditions for bubbles

When pressure is 2300 Pa，the water will change into vapor under temperature of 25℃,forming a bubble(Brennen,1995)．In the actual operational process，the pressure inside the vessel is more high than a standard atmospheric pressure．The liquid will generate bubbles when the liquid pressure is reduced to saturated condition，or the velocity of the fluid or temperature increase．According to the definition of the pressure coefficient，surface pressure coefficient can be written as (Kinnas,et al.,1990):

$$C_{\mathrm{p}} = \frac{p_{\mathrm{b}} - p_{\infty}}{\frac{1}{2}\rho_{\mathrm{l}}\upsilon_{\infty}^{2}} \tag{1}$$

Where Cp is pressure coefficient， p_b is surface pressure（N/m^2）， p_∞ is infinity fluid pressure （N/m^2）， ρ_1 is the density of the fluid (kg/m^3)， v_∞ is infinity fluid velocity (m/s)．

3. Equation for bubbles

Physical quantities related to material corrosion are bubble size，shape，breaking characteristics，gas phase concentration and volume fraction．Bubble expansion theory can explain the interaction between bubble particles，the bubbles and the continuous phase，as well as the bubbles and the wall．Considering bubble by buoyancy and fluid by the gravity effect，we can get the gas phase under cylindrical coordinate equation of motion using the Newton's second law．

Equations describing instantaneous velocity component of bubble particle in the direction of axial, radial and tangential are as follows, respectively.

$$\frac{\mathrm{d}u_{\mathrm{b}}}{\mathrm{d}t} = \frac{1}{\tau}\left(u_{\mathrm{l}} - u_{\mathrm{b}}\right) + g \tag{2}$$

$$\frac{\mathrm{d}v_{\mathrm{b}}}{\mathrm{d}t} = \frac{1}{\tau}\left(v_{\mathrm{l}} - v_{\mathrm{b}}\right) + \frac{w_{\mathrm{b}}^{2}}{r_{\mathrm{b}}} \tag{3}$$

$$\frac{\mathrm{d}w_{\mathrm{b}}}{\mathrm{d}t} = \frac{1}{\tau}\left(w_{\mathrm{l}} - w_{\mathrm{b}}\right) - \frac{v_{\mathrm{b}} w_{\mathrm{b}}}{r_{\mathrm{b}}} \tag{4}$$

And the relaxation time τ is written as

$$\tau = \frac{96\rho_{\mathrm{b}} r_{\mathrm{b}}^{2}}{18\mu_{\mathrm{b}} C_{\mathrm{D}}\,\mathrm{Re}} \tag{5}$$

Where C_D is gas drag coefficient，μ_b is dynamic viscosity of gas phase，ρ_b is the gas density，

r_b is bubble radius, R_e is the local Reynolds number.

4. Geometric modeling

4.1. Computational Condition

Using Fluent software, a chemical enterprise actual process pipeline is chosen to evaluate the 90° bending tube model. The Euler-Lagrange method is used to deal with vapor-liquid two-phase flow containing discrete phase, in which liquid control equation is described by complete Navier-Stokes equation, the turbulence model is standard k - ε, and gas phase is described by the discrete particle motion equation. Discrete phase turbulent diffusion can be described through the discrete random orbit model. Physical parameters and boundary conditions of numerical model is shown by table 1. Grid partition of the model is shown in figure 1.

4.2. Discrete phase bubble distribution

Bubbles flow into the tube with water in the form of dispersed phase, using the surface jet source form. The speed

Table 1 Physical parameters and boundary conditions of numerical model.

Physical parameters of numerical model								Boundary conditions	
flow (m^3 h^{-1})		density(kg m^{-3})		viscosity ×10^{-5}(Pa s)		the initial phase volume fraction		flow(m s^{-1})	
bubble	water	bubble	water	bubble	water	bubble	water	bubble	water
0.32	3．68	0.946	958.4	2.19	28.24	0.08	0.92	2.1	3

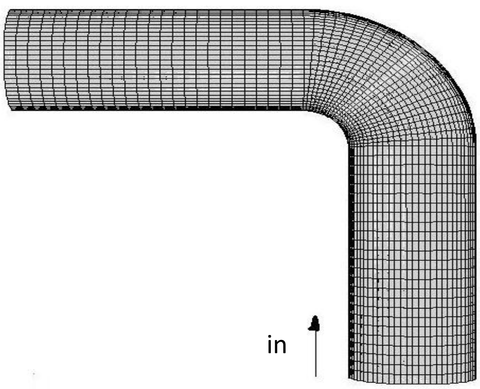

Figure 1. Grid partition of the model.

of bubbles is determined by the entrance of the fluid velocity gradient considering the phenomenon that wall will produce bubbles and increase the initial position of bubbles at the same time. Bubbles diameter change in 0．01 ~1 mm，and the distribution mode is described by Rosin-Rammler index formula，assuming that bubbles are along their orbital motion without any interfere．Entry take for constant velocity boundary condition，the dispersed phase take for elastic reflection conditions in the wall，and export take for escape boundary conditions．

5. Results and analyses

5.1. The volume fraction distribution of bubbles

From figure 2, it is obviously to show the maximum pressure in the elbow lateral. With the gradient descending of pressure is not distributed heterogeneously，it will cause local hydrodynamic increases to the tube wall，which is easy to produce wall corrosion．Considering phase problems, the lateral pressure is caused by the increase of fluid phase velocity．The pressure distribution away from the bending parts of is very uniform and fluid fluctuation is stable．But bubble particle volume fraction will reduce，bubbles will be concentrated in the place where pressure is lower，shown as figure 3．The 90 °bending parts is divide into five section，shown as figure 2．Bubbles flow with fluid together from the entrance，and began to focus on streamline center area．Bubbles gradually diffuse to the tube wall with the passage of time and flow rate reduction，at the same time, we can know the bubbles that collide section of tube wall will increase，the position where bubble concentration increase will have a bigger corrosion area．The results show that from section a to e，the bubble volume fraction increase gradually．From the section volume distribution situation，we can know that bubble is obvious circular distribution，and the numerical value is bigger as closer to the wall．Because of the influence of fluid，flow speed inside the tube is low and have a bigger volume fraction．At the same time, discrete phase injection does not change the motion of flow field．

5.2. The diffusion coefficient distribution of chloride ion

According to the effective diffusion layer theorem，chloride ion diffusion coefficient is used to reflect the resistance of wall to medium erosion，affecting corrosion process accelerated by flow．It is easier for chloride ion deposition in the wall and intrusion material surface promoting corrosion when chloride ion diffusion coefficient is larger．Usually，it is described by effective diffusion coefficient in actual situation，which is related to the velocity of ion in the fluid．The effective diffusion coefficient of chloride ion is shown as figure 4．

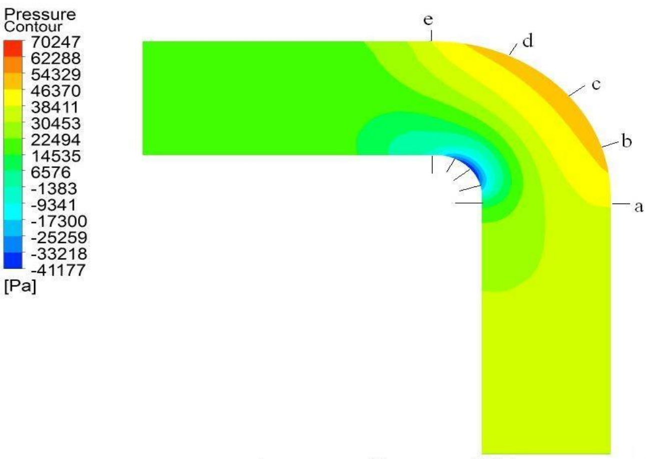

Figure 2. Surface pressure distribution cloud picture in model.

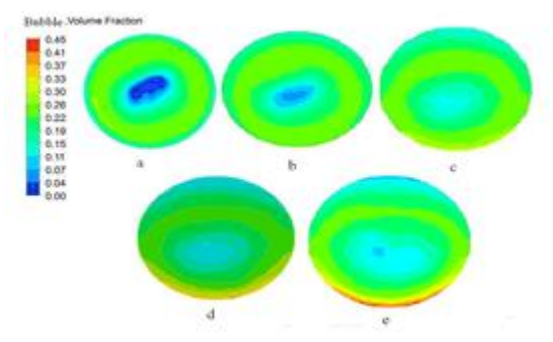

Figure 3. The bubble volume fraction distribution of each section in bend.

5.3. Distribution of chloride ion deposition rate

Figure 5 shows the distribution area of chloride ion deposition in bend model．Chloride ion flow into the inlet of the model with fluid, then parts of them began to deposit in the model surface, and deposition rate is low．Analysis bend location where deposition is serious: more larger where radius of curvature is, more higher the deposition rate is in that area，and corrosion phenomenon exist along the entire wall；in the elbow extrados where affected by turbulence and have a high velocity，and chloride ion is easy washed．There is no deposition of chloride ion until the export straight pipe section where turbulence quantitative is small

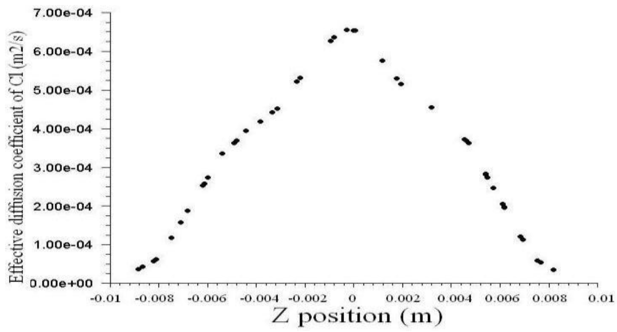

Figure 4. Effective diffusion coefficient of chloride ion in water in the z axis.

and have a small deposition rate．So the chloride ion mainly deposit in the elbow inside．We get the law of corrosion caused by chloride ion through analyses the deposition rate of it．Position where medium deposit in tube is influenced by turbulence quantity and flow boundary condition，while the deposition rate are not affected by the structure of the tube ．

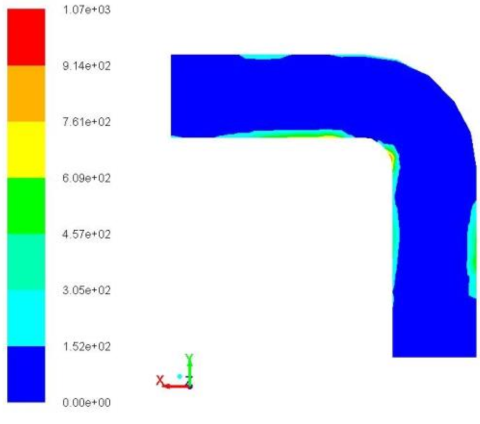

Figure 5. Deposition rate of chloride ion.

5.4. Distribution of bubble and chloride ion

The characteristic line can be divided into three stages shown as figure 6. In the initial stage, ions concentrate on the pipe wall because of chloride ions and water have same velocity and flow together. While the speed of bubble particles is less than the velocity of water, companying a small effect of turbulence, and do not impact pipe wall directly. When time is between 0.009 ~ 0.013 s, chloride ion and bubble are gather together mainly in bend area of the elbow for a long time, from which we can forecast that in this time particle impact curved pipe wall severely.

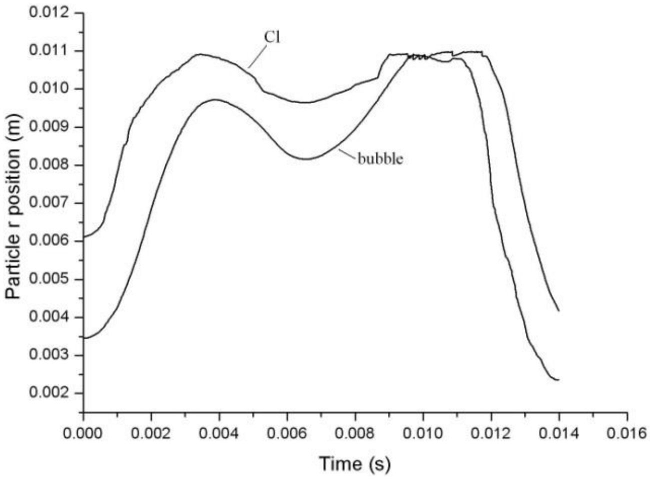

Figure 6. Distribution of bubble particles and chloride ion with time in the radial position (inlet velocity is 3 m/s)

6. Conclusion

According to the numerical simulation results of bend model, it is concluded that pipe flushing corrosion including two reasons:

(1) Fluid flow and corrosion medium chloride ion deposition, shown as the ion diffusion coefficient and change of chloride ion deposition rate, results in reducing thickness of wall, and deposition quantity is the biggest in bend.

(2)Bubble breaking impact on wall, make the protective film running off and aggravate corrosion. It is vulnerable to erosion corrosion in the elbow inside where bubble volume fraction is the largest.

Result of numerical simulation can predict the position where aggravate corrosion in tube and find out the deposition rule of chloride ion in the wall.

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