Numerical simulation and factor analysis of petrochemical pipe erosion-corrosion failure

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Abstract. Based on the behavior of carbon steel outlet tube in REAC pipes of Zhenhai Refining & Chemical Company, the mathematical model of fluid-solid interaction was established according to the mechanism of erosion-corrosion damage. The interaction between corrosion products protecting film and multiphase liquid was analyzed by numerical simulation method. The distribution of shearing stress on the inwall of elbow bend, and the distribution of principal displacement, stress and strain of corrosion products protecting film were disclosed, while the erosion-corrosion failure processes was studied. The simulation result coincides with that of the positioned thickness gauging which validated the reliability and feasibility of the finite element analysis software simulation method. The obtained results can be used in the erosion-corrosion failure analysis, structural optimization, in-service testing positioning, life prediction, risk assessment, safety and other security projects for multiphase flow pipeline.

1. Introduction

With the popular pipeline transport and rigorous operating condition, more and more accidents are induced by failure of pipeline, which is harm for manufacture, environment and public safety [1-3]. The failure forms of pipelines are diversified and its mechanism is complicated. Among them, erosion failure is most universal and non-predicted failure, erosion is local, sudden and risk. Erosion failure is interaction between corrosion and multiphase flow [4-7]. Erodent products protecting film is deformed by shearing stress. Based on the deformation of film, it affects fluid flow. Then the shearing stress is augmented. By this way again and again, it accelerates to wash away carbon steel. The substance of process is interaction between corrosion and multiphase flow.

This paper is based on theory of fluid-solid coupling. The elbow made of carbon steel in outlet ductwork of Hydrocracking Reaction Effluent Air Cooler (REAC) is the subject investigated. Fluid-structure numerical simulation is used to analysis erosion failure. Flow quality (velocity), pipe construction (diameter, curvature radius) and film property (Poisson ratio) are impact to erode. All the work will help for REAC tube bundle's on-site monitoring, on-line detection, optimization design and corrosion protection.

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2. Mathematical model

We can know that interaction between multiphase flow and erodent products protecting film is on the interface [8-9]. Based on above that, during the process of building up the equation and the mechanics model of the flow and the corrosion coupling function, we mainly consider the mechanics condition as following [10]: First, the distortion of coordinated-condition should satisfy the actual distorted condition of the erodent products protecting film. Second, the dynamics of coordinated- condition should satisfy the flow mechanics condition of the corrosive multiphase fluid medium. According to this, we are able to establish the unified coupling function equation as follows.

$$\phi_{fluid} = \phi_{pipe}$$
(1)

$$n \cdot \varphi_{fluid} = n \cdot \varphi_{pipe}$$
(2)

Among them, ϕ_{fluid} expresses the distorted field of fluid on the coupling interface; ϕ_{pipe} expresses the distorted field of the inner surface of pipeline protecting film on coupling interface; φ_{fluid} expresses the stress field of fluid on the coupling interface; φ_{pipe} expresses the stress field for the inner surface of pipeline protecting film on coupling interface.

Arbitrary Lagrange-Euler (ALE) [11-12] is used to solve the problem of fluid-solid coupling. In fluid region, Euler unit is adopted, and Lagrange unit in solid region, these two units are solved in ALE coordinates which lead that alteration of interface of fluid and solid is accord with the deformation of the film.

According to the fundamental principle of ALE, we can induce N-S equation of viscous multiphase flow:

Component of motion equation:

$$\frac{\partial \sum\limits_{k=1} \alpha_k \rho_k V_i}{\partial t} + \left(V_j - \hat{V}_j\right) \frac{\partial \sum\limits_{k=1} \alpha_k \rho_k V_i}{\partial x_j} = f_i + \frac{\partial[-p\delta_{ij} + \sum\limits_{k=1} \alpha_k \mu_k (\frac{\partial V_i}{\partial x_j} + \frac{\partial V_j}{\partial x_i})]}{\partial x_j}$$
(3)

Component of continuity equation:

$$\frac{\partial \sum\limits_{k=1} \alpha_k \rho_k V_i}{\partial x_i} = 0$$
(4)

k equation:

$$\sum\limits_{k=1} \alpha_k \rho_k \frac{\partial}{\partial x_i}(V_i k) = \frac{\partial}{\partial x_i}(\frac{\sum\limits_{k=1} \alpha_k \mu_k + C_\mu \rho k^2 / \varepsilon}{\sigma_k} \frac{\partial k}{\partial x_i}) + G_k - \sum\limits_{k=1} \alpha_k \rho_k \varepsilon$$
(5)

ε equation:

$$\sum\limits_{k=1} \alpha_k \rho_k \frac{\partial}{\partial x_i}(V_i \varepsilon) = \frac{\partial}{\partial x_i}(\frac{\sum\limits_{k=1} \alpha_k \mu_k + C_\mu \rho k^2 / \varepsilon}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_i}) + C_{1\varepsilon} \frac{\varepsilon}{k} G_k - \sum\limits_{k=1} \alpha_k \rho_k C_{2\varepsilon} \frac{\varepsilon^2}{k}$$
(6)

Among them, α_k expresses the volume fraction of k, ρ_k expresses mass density of k, V_i, V_j expresses component of velocity of fluid, f_i denotes force , P the pressure, μ_k the dynamic viscosity for the fluid, K the turbulent kinetic energy, ε the turbulent dissipation rating, Gk derivative of turbulent kinetic energy causing by velocity gradient.

Main constant of model are:

$C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.3$。

Kinematics of film is described by the way of Lagrange.

Balance equation:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + f_i = \kappa_i \tag{7}$$

Geometric equation:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{8}$$

Physical equation:

$$\sigma_{ij} = \lambda \delta_{ij} \varepsilon_{kk} + 2\mu \varepsilon_{ij} \tag{9}$$

$$\lambda = \frac{\upsilon E}{(1+\upsilon)(1-2\upsilon)}, \mu = \frac{E}{2(1+\upsilon)} \tag{10}$$

Where κ_i is the component pressure of film, ε_{ij} denotes Cauchy strain tensor, λ, μ Lame constant of film, E elasticity modulus of film, υ poison ratios.

3. Numerical method

Erosion failure of petrochemical pipe system involve two fields. One is flow field, the other is structure field. Coupled method of ordinal physical environment is used to analysis erosion failure, which is including establishing geometrical model, meshing, building fluid physical environment and structure physical environment, and so on. The process of numerical calculation is shown in figure 1.
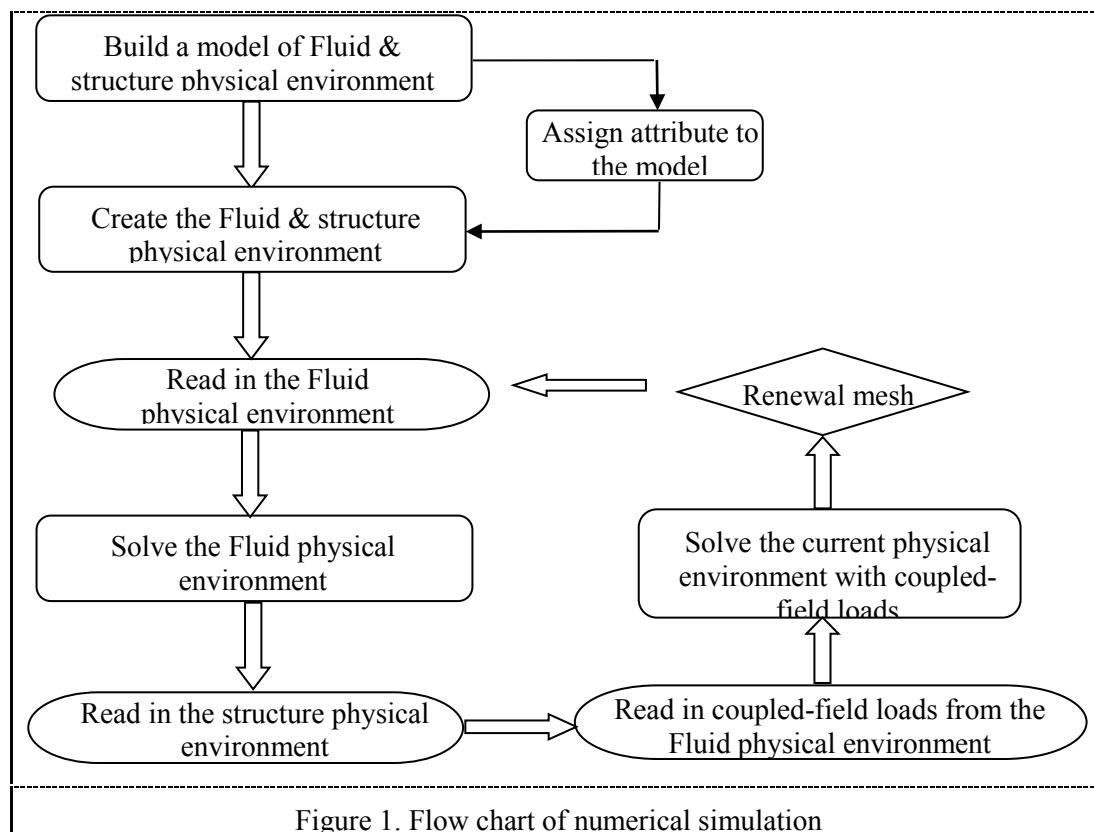
Figure 1. Flow chart of numerical simulation

Fluid 142 three-dimensional fluid element model is chosen as the fluid dynamics analysis model in carbon steel elbow bend. And Solid 186 model is used to analyze the structure stress of protecting film. Meanwhile, mapping mesh is introduced to analysis of fluid dynamics and protecting film structure stress.

Fluid physical environment includes the evaluation of cell type, the infliction of boundary conditions and the setting of FLOTRAN. Speed inlet and pressure outlet are used as boundary conditions (in figure 2), while standard $k - \omega$ turbulence model is chose to the solution of FLOTRAN.

The boundary conditions of structure physical environment are shown in figure 3. And position constraints are the major ways to the solution. Fixed constraint is put on the inner surface of pipeline protecting film and both ends of the pipeline, to restrict the rigid translocation of protecting film. Flow shear stress to the wall is the load of the pipeline. By solving structure physical environment, the influence of multi-phase flow to protecting film can be found.
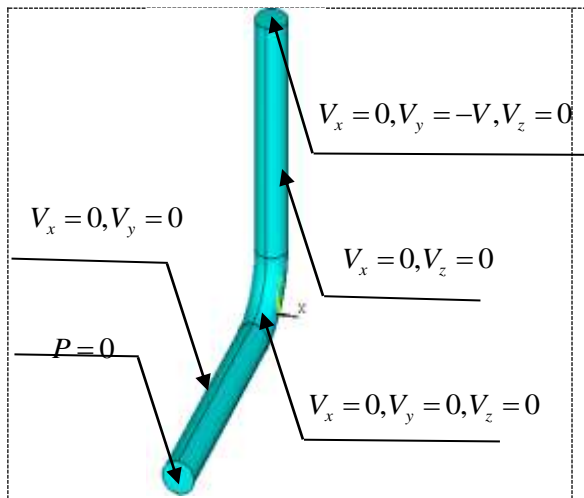
Figure 2. The boundary conditions of fluid physical environment.
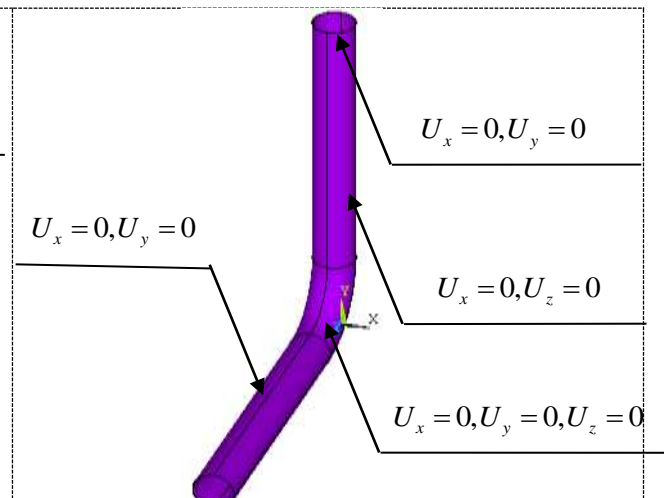

Figure 3. The boundary conditions of structure physical environment.

After reading fluid physical environment, the fluid dynamics analysis of carbon-steel pipeline can be done, and the distribution of fluid dynamics parameters would be obtained. With removing the existing physical information, structure physical environment is read and the analysis load of structure stress is exerted. As a result, the stress analysis of pipeline protecting film structure is done by solving structure physical environment. And then, the influence of multi-phase flow to protecting film is gotten. According to the deformation of protecting film, fluid grid coordinates is updated. Do the calculation of fluid physical field again, and the influence of protecting film deformation to multi-phase flow is found. The shear stress and pressure stress, which are gotten from the process, are used as the load of protecting film again. With that, the solution of structure physical environment field is obtained. Calculate circularly in turn, and the interaction between the two is realized.

4. Analysis of influence factors

4.1. Simulation analysis of actual failure cases

The failure of carbon-steel elbow bend in the outlet pipe system of hydrocracking reactor effluent in Zhenhai, is taken as an example. The dimension is $\phi114\times13.5$ mm, the radius of curvature is 1.5 DN, and the flow velocity is 5 m·s^{-1}. The physic-chemical natural parameters of working condition medium are shown in table 1. In equation (8), λ and μ are calculated equivalently according to elasticity ways. Meanwhile, nominal elastic modulus is 0.12 GPa, nominal Poisson's ratio is 0.49[13], and the value of thickness is 0.1 mm (gotten by erosion-corrosion simulation experiment).

Table 1. Natural parameter of the causticity multiphase stream in the elbow bend

Parameter	Phase		
	Gas phase	Liquid phase	Water phase
Mass density/ kg·m^{-3}	21.8	814.4	995.1
Volume phase fraction/ %	91.924	7.834	0.242
Viscosity/kg·m^{-1}·s^{-1}	1.01×10^{-5}	1.89×10^{-3}	6.18×10^{-4}

Based on the fluid-structure simulation analysis of erosion-corrosion failure, several findings are obtained, including the distribution of shear stress on the inwall of elbow bend, the distribution of main displacement, stress and strain of erodent products protecting film. The distribution of shear stress on inwall of elbow bend is shown in figure 4. In this diagram, zone A is on the side face of the exit of elbow bend. The shear stress of position A is larger, with the value of 6.044 Pa. Corresponding to the same area, the main displacement, stress and strain of protecting film also have larger value. And zone B has the maximum. The maximal tensile stress is 15.397 Pa and the maximal elastic stress is 3.8212×10^{-7}. They are shown in figure 5 and figure 6 respectively.
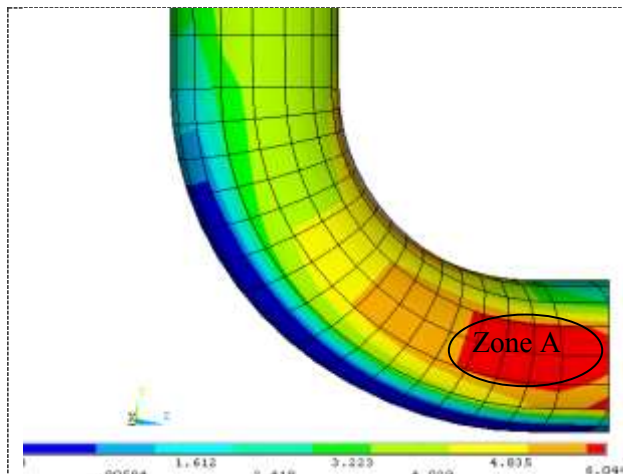

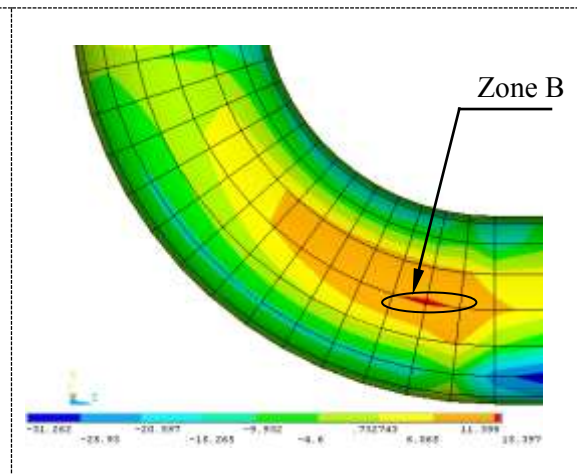**Figure 4.** Wall shear stress of elbow bend.

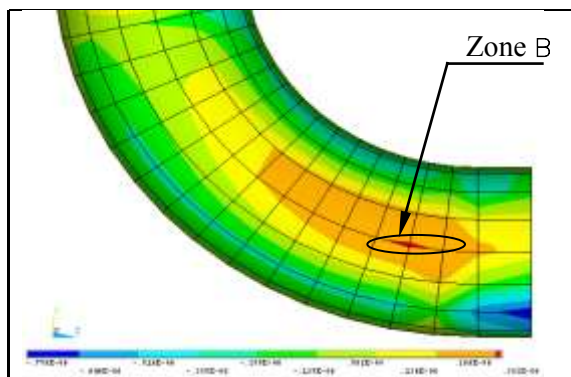**Figure 5.** Stress of erodent products protecting film.

Figure 6. Elastic stress of erodent products protecting film.

4.2. Spot thickness verification

In order to test the result of fluid-solid numerical simulation of erosion-corrosion damage and verify the reliability and feasibility of numerical simulation method, the spot thickness analysis of Zhenhai domestic REAC outlet pipeline system is carried out.

Combining the result of simulation, TT320 ultrasonic thickness gauge is used to measure the spot thickness of erosion-corrosion serious failure area in elbow bend. The position division of thickness points is shown in figure 7, and the specific result is expressed in table 2. From the statistical analysis result of spot thickness data, it can be found that the thinning volume of zone B which is in zone A on the side face of elbow bend exit is the largest, up to 5.9 mm.
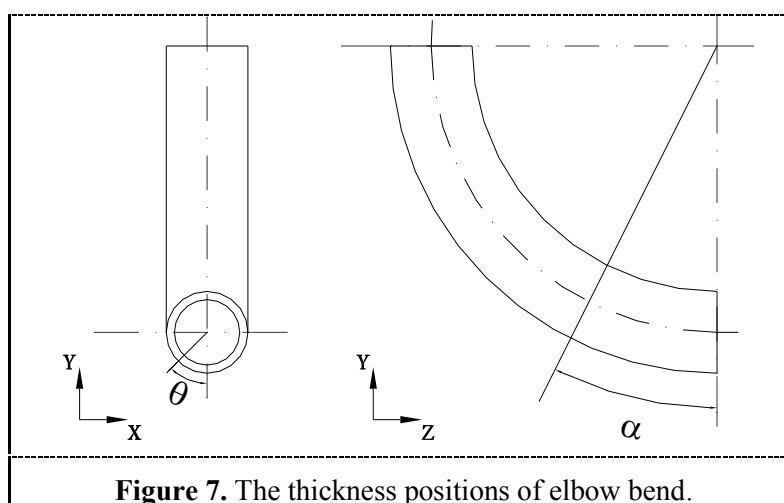
Figure 7. The thickness positions of elbow bend.

Table 2. The thickness thinning volume of elbow bend   /mm

θ α	180°	157.5°	135°	112.5°	90°	67.5°	45°	22.5°
0°	2.6	1.8	1.8	4.3	4.4	4.0	1.8	2.5
5.625°	2.3	2.0	2.8	5.0	4.8	3.5	2.5	2.1
11.25°	2.3	2.0	2.8	4.5	**5.9**	3.7	2.0	2.3
16.875°	2.3	2.0	3.0	4.7	4.8	3.7	2.1	2.5
22.5°	2.3	2.0	3.0	4.7	5.2	3.8	1.8	2.5
28.125°	2.1	2.3	2.8	4.5	5.2	3.0	1.8	2.3
33.75°	2.0	1.8	2.6	4.5	5.0	2.8	1.8	2.3
39.375°	2.1	1.6	2.5	3.1	4.8	2.6	1.8	2.2

   With the contrast of spot thickness data and the simulation result in chapter 3.1, the results show that: the larger that erodent protecting film, the more serious the erosion-corrosion failure, and the closer that the failure position and the numerical simulation. Zone A is the danger zone of erosion-corrosion in elbow bend, and the erosion-corrosion of position B in this zone is the most serious.

5. Conclusions
(1) The numerical model of fluid-solid interaction on multi-phase flow erosion-corrosion failure is set up, which provides theoretical foundation to the deep research of erosion-corrosion failure of multi-phase flow pipe system. According to the result of numerical simulation, the zone of erosion-corrosion failure in elbow bend is determined. And it can be used as the foundation of the location monitor and priority protection of pipe.
   (2) In the norms of API932-B[15], the way of limiting flow velocity is adopted to control erosion-corrosion failure of REAC. And it is inappropriate. The influence of some characteristic factors such as the diameter of typical tube, the radius of curvature and the Poisson's ratio of protecting film is also should be considered.

(3) In allowable conditions, the results of fluid-structure interaction numerical simulation of erosion-corrosion failure are used as bases to optimization design. By changing the structure characteristic of such tube with serious erosion-corrosion failure, the erosion-corrosion failure of tube can be reduced effectively. And it is conducive to the security and long-period operation of pipe system.

Acknowledgements

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