

Numerical simulation of expansion of the cavity in tube-wall based on tube transportation of ultra-critical CO_2

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Abstract. The paper simulated the mechanical process of transportation of ultra-critical CO_2 using glass reinforced plastic pipe (GRP pipe). The gas expansion model of micro-cavity in GRP pipe was established based on the experimental results. By analyzing the physical process of gas expansion on the micro-pore, the computer simulation method was used to reveal the law of the stress and strain distribution in the tuber-wall. The results provided the basic research on the technology application of the transportation of supercritical pipe.

Introduction

In the petrochemical industry field, the CO_2 flood technology is a kind of more advanced technology. The technology started in American in 1973 at the Mississippi, following by Wenbury oil of Canada, North Sea oil of Britain and so on. The long distance and large diameter pipe transportation of ultra-critical CO_2 is the inevitable developing trend in the future. The technology solved also the worldwide problem on greenhouse emission. However, the technology of CO_2 phase or ultra-critical injection is still an issue to solve for applying on the long distant transport industry. Currently, the injecting CO_2 technology is usually used for difficultly mining crude oil, and the injection pressure is about 10~18MPa, that is, the super-critical level of well head pressure. Considering the CO_2 soluble in water and oil, the CO_2 injection can improve its solubility, and then increase the bulk and decreased the density of crude oil correspondingly. The technology can improve effectively the extract rate of oil by increasing the activity of oil layers and the flowability of crude oil.

Studies show that filament winding layer of GRP pipe usually exists the cavity and other flaws[1,3]. Therefore, the High-pressure CO_2 would penetrate laminated structure and accumulate in the cavity when the tube loads the continuous pressure. When the pressure of piping transport lasted for a proper time, the internal pressure on the cavity will tend to the balance[4,7]. Based on the above facts, the paper established the model, simulated the work process of the transport pipe and the developing law of expansion of the cavity in the laminated pipe. It can provide theoretical basis on high-pressure CO_2 injection pipeline system application.

Mechanical modeling

Fig.1 shows the cavity of GRP (curing be the aromatic amine) pipe under the SEM. When the transport pressure reached the ultra-critical CO_2 , the CO_2 would penetrate laminated structure, accumulate in the cavity and balanced at the constant value. For meeting the production requirements, the conveying substance and pressure were always changing in the transporting pipe. Therefore, these would lead to change of the tube-wall pressure, correspondingly. However, the CO_2 of penetrating and accumulating in the cavity couldn't release immediately and remain the balance pressure, but the pressure in the pipe decreased promptly. Therefore, the balance between the piping pressure and the tube-wall cavity pressure will be destroyed. So, the CO_2 of the micro-pore will expand and lead to the elastic-plastic deformation of laminated materials and increase the volume of the cavity (see fig.2).

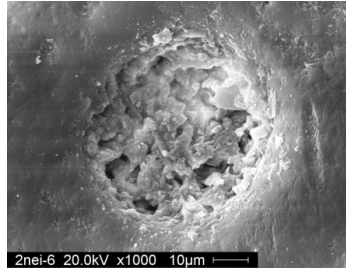


Fig.1 The cavity of layup

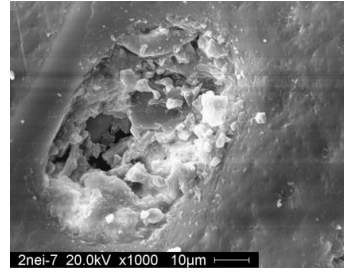


Fig.2 Cavity deformation by CO_2 expansion

When the cavity expansion exceeded the strength or deformation of matrix materials, the more plastic deformation will cause the matrix materials failure near the cavity. By the injection CO_2 high-pressure test, the results show that the laminated cavity will occurred the larger deformation caused by the expansion. Fig.3 is the laminated cavity after keeping the pressure for a while.

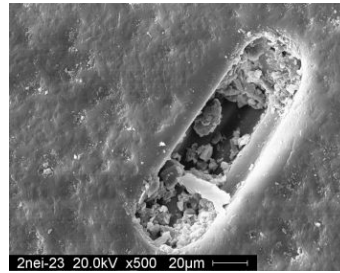


Fig.3 Laminated cavity

On the basis of manufacturing processes, material composition and the structure character of pipe, the pipe was made by winding fiber laminates in $\pm 30^\circ$ direction. Fig .5 is the mechanical model of the pipe.

The geometry size of pipe: the thickness both laminates and matrix is 1mm, the in-diameter and ex-diameter is 38mm, 48mm respectively.

The materials of the pipe: the elastic modulus is 22.8GPa, the axial elastic modulus is 12.6 GPa, Poisson's ratio is 0.38, the max transporting pressure is 17MPa.

Assuming the tube-wall existing a cavity and the cavity was simplified the sphere and its diameter is $D=1mm$. fig.6 is the model of pipe with cavity in the tube-wall.

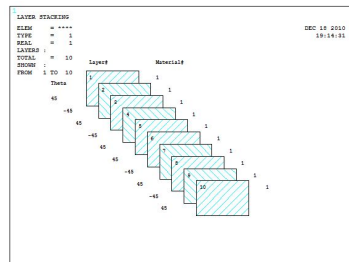


Fig.4 Laminated structure of tube wall

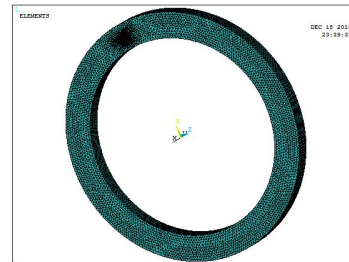


Fig.5 The model of pipe with cavity

The model detail and the meshing of the model is shown in Fig.7

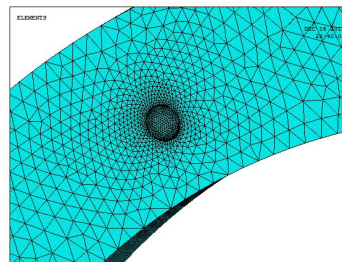


Fig.6 Cavity and the meshing

For the spherical cavity forming by aeration porosity in the tube wall, when the pressure of the tube decreased sharply, the balance of the in- and ex- tube wall would be destroyed and lead to

expand of the gas in the spherical cavity immediately. Based on the gas-solid coupling relation, Assume the process is expansion in the constant pressure without heat exchange and mass lost. By the ideal gas Eq. 1

$$\frac{PV}{T} = Rn. \quad (1)$$

Assume the gas is the ideal gas, that is, the process is a process with constant mass and temperature. The above equation can be simplified the following Eq. 2

$$P_1V_1 = P_2V_2. \quad (2)$$

T – gas temperature

V – volume of gas

P – pressure

Because the pressure of transportation pipe decreased sharply, the CO_2 will expand and lead the cavity increased rapidly (see fig.8). The materials near the sphere cavity of tube wall will induce complex stress and strain field. And meanwhile, the balance equation is $\Delta V_{gas} = \Delta V_{cavity}$. ΔV_{gas} is expansion increment of gas volume, and ΔV_{cavity} is the expansion increment of sphere cavity. Fig.9 is the normal displacement of each point on the cavity surface.

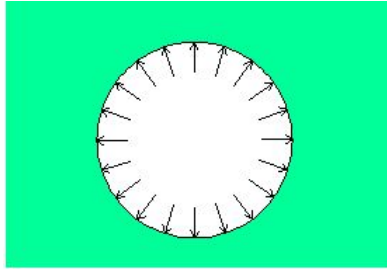


Fig.7 CO_2 expansion in cavity

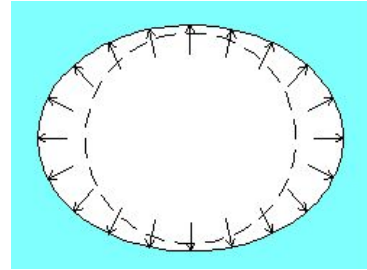


Fig.8 Normal displacement of cavity surface

With the expansion process of the cavity surface induced by the CO_2 expanding, then, the gas pressure decreased and the stress and strain of materials surrounding the cavity increased until the gas pressure of cavity(p_{gas}) is equal to the reverse compressive stress($p_{reverse}$) induced by deformation of the surrounding materials. Fig.10 is the balance state under the pressure of the p_{gas} and $p_{reverse}$

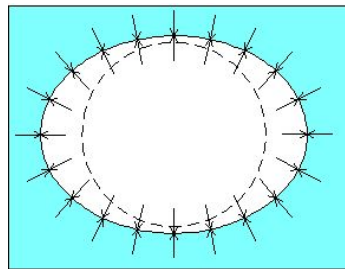


Fig.9 The balance state of p_{gas} and $p_{reverse}$

When the gas expansion increment is equal to the cavity expansion, and meantime the gas pressure is equal to the normal stress induced by the deformation of exterior materials, the expansion process is at the dynamic balance state. The balance equations were described as follow Eq. 3 and Eq.4

$$\Delta V_{gas} = \Delta V_{solid}. \quad (3)$$

$$p_{gas} = p_{reaction}. \quad (4)$$

The FEM calculation was carried based on the balance equations. Firstly, Assume dV_n is the tiny increments of gas expansion. The gas pressure inside the cavity (p_{n+1}) can be calculated by the following Eq.5 and Eq.6

$$P_n V_n = P_{n+1} (V_n + dV_n). \quad (5)$$

$$dp_{n+1} = p_n - p_{n+1}. \quad (6)$$

The cavity surface was applied the normal pressure increment dp_{n+1} , and the according stress and strain field was calculated on the iterative calculations method until the pressure of gas and the cavity exterior is close to the balance. Fig.11 and fig.12 represent the stress field and strain field surrounding the cavity of the in-tube wall.

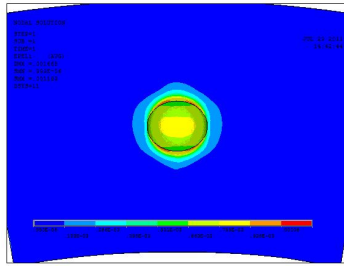


Fig.10 The stress field surrounding the cavity

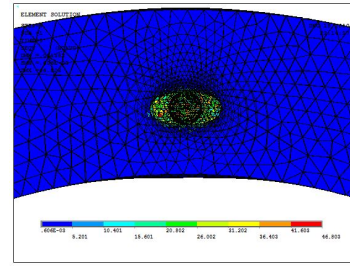


Fig.11 The strain field surrounding the cavity

The distribution laws of the stress and strain show that the micro-cavity deformation expands all around along the fiber laminates and the higher-lower expansion is lower compared to this laminates. Therefore, the cavity developed to be ellipsoid. The pipe was wound from multi-layer fiber, and therefore, the function of the top laminated materials is different with that of the bottom. The role of the bottom material of the cavity is equal to the arch, and inner layer of the tube wall is in the state of radial compressive and hoop tension. However, the top laminated material play a role of the hoop, and inner layer of the tube wall is in the state of radial and hoop compressive. Therefore, the gas expansion was restricted by the laminated materials, and the cavity evolved into ellipsoid (see fig.13).

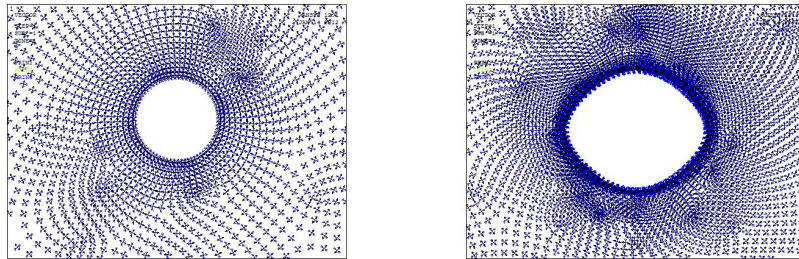


Fig.12 the vector distribution of principal stress near the cavity

Considering the cavity expansion evolved in the layer, the weakest parts were the interface of fiber and laminated resin, and especially, ends of the ellipsoid are prone to cause the stress concentration and failure of the laminated resin. And the simulated results were consistent with the experiment (shown in the fig.2 and 3).

Conclusion

Using pipeline transportation, the gas pressure is very high and the transportation pressure made the tube wall in the state of radial compressive and hoop tension.

To the cavity, in-ring material at its bottom played the arch role and loaded the compressive stress and ex-ring material acting as the hoop loaded the tension stress. Loading with the gas-transport pressure, the ex-ring material was taken as a good stiffness hoop and made the cavity in stability state.

When the operating pressure of the pipe was released sharply, the radial stress and hoop stress of all the laminates deceased or disappeared and led to the stiffness of the tube wall decreasing. Even the in-ring at the bottom of the cavity still loaded the compressive stress and the ex-ring at its top loaded with the tension stress, but the cavity will be instability, expand rapidly and then form “bomb effect” for the stiffness decreasing. The deformation of the cavity developed into ellipsoid because the weakest parts were the interface of fiber and laminated resin.

Acknowledgements

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