Simulation of the shear effect in the ultrasonic descaling of the heat exchanger which produces viscoelastic soft scale

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Abstract. The research object of this paper is a heat exchanger that produces viscoelastic soft scale in a chemical company. The finite element software ANSYS is used to simulate and analyse the shear effect in the ultrasonic descaling process. In the research, the parameters of the Prony series model of viscoelastic materials were obtained by fitting the relaxation modulus data, then the shear stress on the interface between the scale and shell of the heat exchanger was calculated by transient dynamic method, and finally the influence of ultrasonic parameters on the shear effect strength was explored by setting multiple working conditions. The results show that the strength of shear effect increases with the increase of ultrasonic amplitude or the decrease of ultrasonic frequency, so it is advisable to use the high-amplitude and long-pulse ultrasonic wave for scale removal. The simulation method and conclusion in this paper can provide reference for ultrasonic parameter selection in descaling of heat exchange equipment.

1. Introduction
Heat exchange equipment is widely used in industrial production, and scaling of heat exchange equipment is hard to avoid. Scaling equipment will reduce heat transfer efficiency, increase production cost, affect product quality, and even bring hidden danger to safe production due to corrosion under scaling [1]. In practical application, ultrasonic descaling, a new technology, is widely used in power and petrochemical industries due to its advantages such as safety, environmental protection and on-line descaling [2]. Ultrasonic descaling mainly uses four mechanisms: cavitation effect, shearing effect, inhibition effect and activation effect. This article focuses on the shearing effect. The principle of shear effect is: when ultrasonic wave acts on the shell of heat exchanger, the metal shell and scale will vibrate at the same time, and the difference of physical characteristics and elastic impedance of the two will lead to relative shear stress between the metal wall and scale layer, which will cause scale to fall off the wall of the heat exchanger [3]. Therefore, the shear stress value on the interface between the heat exchanger wall and scale can represent the strength of shear effect, so as to judge the effect of descaling.

If linear elasticity and Newtonian fluid (ideal viscosity) are used as the two ends to construct the material system, the materials between them are all linear viscoelastic materials [4]. The scale type of heat exchanger studied in this paper is viscoelastic soft scale. In ANSYS, the viscoelastic material models include Prony series and Maxwell models. In this paper, relevant parameters of Prony series are obtained by fitting the relaxation modulus data, and then the material characteristics of viscoelastic material are introduced into the finite element calculation.
2. Finite element model

2.1. Geometric model
The research object of this paper is the heat exchanger of tar naphthalene initial steam tower in a chemical company, and descaling is carried out for the shell pass area. Considering the actual structure of the heat exchanger and the number of transducers, part of the shell side is taken as the research object and the symmetry of the structure is used to build a 1/2 shell side model to simplify the calculation. Figure 1 and 2 show the established geometric model of the shell and the scale layer attached to the wall.

2.2. Material parameters and element types
The shell wall and baffle are made of 20R, yield strength is 245MPa, elastic modulus is 200GPa, Poisson's ratio is 0.3 and density is 7850kg/m^3. Viscoelastic material of scale is introduced into finite element calculation by Prony series model. The basic form of Prony series is:

\[ G(t) = G_\infty + \sum_{i=1}^{n_i} G_i \exp \left(-\frac{t}{\tau_i^G}\right) \]  
\[ K(t) = K_\infty + \sum_{i=1}^{n_i} K_i \exp \left(-\frac{t}{\tau_i^K}\right) \]  

In the formula, \( K_\infty \) and \( K_i \) are the bulk modulus, \( G_\infty \) and \( G_i \) are the shear modulus, \( \tau_i^G \) and \( \tau_i^K \) are the relaxation times of Prony series.

According to relevant paper [5], if the Poisson's ratio of viscoelastic materials is approximately constant, \( G(t) \) and \( K(t) \) can be unified in the form of the relaxation modulus \( E(t) \). Similarly, the relaxation modulus \( E(t) \) can also be expressed in the form of Prony series.

\[ E(t) = E_\infty + \sum_{i=1}^{n_i} E_i \exp \left(-\frac{t}{\tau_i^E}\right) \]  

PRONY.MAC macro is provided in the "Viscoelastic standard program package" of ANSYS. The relevant parameters in formula 3 can be obtained by fitting the experimental data of relaxation modulus \( E(t) \), and then the values of the correlation coefficient and exponent in the Prony series model can be obtained. This article selects a set of data of relaxation modulus over time provided in the help file of ANSYS. This set of data can also be obtained through stress relaxation experiments.

In the viscoelastic model, the Prony series model can directly use structural elements. In this paper, the transient dynamics calculation process uses solid186 structural element.

2.3. Boundary conditions and other settings
The applied loads and boundary conditions mainly include: (1) The internal pressure is 1.3MPa; (2) Apply symmetry constraints on the symmetry plane of the 1/2 model; (3) Set the constraint of full degree of freedom at the local position on one side of the model; (4) Apply the weight of the heat exchanger shell; (5) A membrane stress of 10.08MPa caused by internal pressure is applied to the end faces of both sides of the shell; (6) Apply sinusoidal displacement load caused by ultrasonic wave.
When solving, the analysis type is set as transient solution, and the solution method is Full method. In the solution control, the analysis option is set as small displacement transient, 100 cycles are iteratively calculated, and set to output the calculation results of each substep for analysis.

3. Results analysis

3.1. Simulation results of shear effect under working condition 1

According to previous relevant studies [3], the position where the shear stress exceeds 0.4MPa belongs to the effective descaling range. In order to explore the influence of ultrasonic parameters on shear effect, five working conditions as shown in Table 1 were set.

| Working condition | Ultrasonic amplitude /mm | Ultrasonic frequency /kHz |
|-------------------|--------------------------|---------------------------|
| 1                 | 0.5                      | 20                        |
| 2                 | 0.3                      | 20                        |
| 3                 | 0.1                      | 20                        |
| 4                 | 0.5                      | 30                        |
| 5                 | 0.5                      | 40                        |

In order to view and analyze the change of shear stress, 3 paths and 15 observation points are defined as shown in Figure 3. Path 1 and 3 are straight lines, while path 2 is a semicircular curve. The 15 observation points are uniformly distributed on the inner surface of the heat exchanger shell.

![Figure 3](image1.png)

Figure 3. The position of 3 paths and 15 observation points.

![Figure 4](image2.png)

Figure 4. The Mises stress of the shell under working condition 1.

Figure 4 and Figure 5 show the Mises stress of shell and scale after 10 ultrasonic cycles. In Figure 4, the maximum value of Mises stress is 68.4MPa, significantly lower than the yield strength of steel. In Figure 5, the Mises stress of the scale was very low overall, the maximum value of Mises stress is 0.76MPa.
Figure 5. The Mises stress of the scale under working condition 1.

Figure 6. Shear stress SYZ on the inner surface of the shell.

The contour plot of the shear stress under the total column coordinate system was read. In this coordinate system, SXY refers to circumference shear stress $\tau_{xy}$, SYZ refers to axial shear stress $\tau_{yz}$, and SXZ refers to axial shear stress $\tau_{xz}$. Figure 6 is the contour plot of shear stress SYZ. The maximum value of the absolute value of the shear stress SYZ is 15.9 MPa, the maximum value of the shear stress SXY is 23.9 MPa, and the maximum value of SXZ is 34.2 MPa.

Figure 7, 8 and 9 show the distribution of shear stress in three directions on the three paths.

Figure 7. Distribution of shear stress in three directions on path1.

Figure 8. Distribution of shear stress in three directions on path2.

Figure 9. Distribution of shear stress in three directions on path3.

On path 1, the maximum shear stress SXY, SYZ and SXZ are respectively 5.6MPa, 1.7MPa and 10MPa, and the descaling range is about 1/2. On path 2, the maximum shear stresses of SXY, SYZ and SXZ are 2.5MPa, 2MPa and 1.6MPa respectively, and the descaling range is about 3/4. On path 3, the maximum shear stress SXY, SYZ and SXZ are 0.7MPa, 1MPa and 3.6MPa respectively, and the descaling range is about 3/5.
After 10 cycles of ultrasonic waves, the shear stress values of 15 observation points were extracted as shown in Figure 10. Among the 15 observation points, the shear stress in at least one direction of each observation point exceeds 0.4MPa, which indicates that the shear effect of ultrasonic wave is relatively obvious under the working condition 1.

Figure 10. Calculation results of shear stress at 15 observation point.

3.2. Influence of ultrasonic parameters on shear effect

This paper mainly studies the influence of the amplitude and frequency of ultrasonic wave on shear effect. The shear effect of the five conditions listed in Table 1 was simulated, and the solution model and solution setting were kept unchanged during the calculation. Under working conditions 1, 2 and 3, the ultrasonic frequencies are the same and the amplitudes decrease in turn. Therefore, the influence of the ultrasonic amplitudes on the shear effect can be judged by the shear stress results under these three working conditions. Similarly, the influence of ultrasonic frequency on shear effect is judged according to the shear stress results under working conditions 1, 4 and 5.

| working condition | 1 | 2 | 3 | 4 | 5 |
|-------------------|---|---|---|---|---|
| Maximum of Mises stress | 68.4 | 49 | 23.6 | 56.5 | 34 |
| The maximum of shear stress SXY | 23.9 | 18 | 14 | 20.6 | 7.2 |
| The maximum of shear stress SYZ | 15.9 | 11.7 | 6.7 | 13.8 | 7.2 |
| The maximum of shear stress SXZ | 34.2 | 24.5 | 13.1 | 27.1 | 16.9 |

Table 2. Contour plot results under different working conditions.

Table 2 shows the contour plot results of the interface between the heat exchanger wall and scale under 5 working conditions, including the results of Mises stress and shear stress in three directions, with the units of MPa in the table. From Table 2, as the ultrasonic amplitude decreases or the frequency increases, the maximum value of Mises stress and shear stress also decrease, the shear effect of ultrasonic wave gradually decreases.

Table 3. The shear stress on the paths under different working conditions.

| working condition | 1 | 2 | 3 | 4 | 5 |
|-------------------|---|---|---|---|---|
| Path 1 | | | | | |
| The maximum of shear stress SXY | 5.6 | 0.1 | 0.7 | 1.4 | 0.39 |
| The maximum of shear stress SYZ | 1.7 | 0.1 | 0.3 | 0.6 | 0.2 |
| The maximum of shear stress SXZ | 10 | 2.2 | 0.8 | 1.7 | 0.62 |
| Effective descaling range | 1/2 | 2/5 | 3/10 | 2/5 | 1/10 |
| Path 2 | | | | | |
| The maximum of shear stress SXY | 2.5 | 1.7 | 1.9 | 0.47 | 1.04 |
| The maximum of shear stress SYZ | 2 | 1.5 | 1.6 | 0.65 | 0.63 |
| The maximum of shear stress SXZ | 1.6 | 2.2 | 1.4 | 1.1 | 0.3 |
| Effective descaling range | 3/4 | 3/5 | 1/2 | 2/5 | 3/10 |
Table 3 shows the shear stress results on three paths under five working conditions. In the three paths, with the decrease of the ultrasonic amplitude or the increase of the frequency, the maximum value of the shear stress on the path does not necessarily decrease, but the descaling range gradually decreases. Therefore, it can be considered that in the three paths defined, the shear effect gradually weakens with the decrease of the ultrasonic amplitude or the increase of the frequency.

Table 4 shows the shear stress data at the observation points. With the decrease of the ultrasonic amplitude or the increase of the frequency, the average shear stress of the observation points decreases gradually, and the number of observation points with at least one shear stress exceeding 0.4MPa also decreases gradually.

According to the model and working conditions in this paper, it is found that with the decrease of ultrasonic amplitude or the increase of ultrasonic frequency, the strength of shear effect also decreases gradually. Under the working condition selected in this paper, the shear effect under working condition 1 is the best.

4. Conclusion
(1) Under the boundary conditions set in this paper, the maximum Mises stress of the heat exchanger shell was 68.4MPa, which was lower than the yield strength of the material.
(2) Among the 5 working conditions set in this paper, the shear effect in working condition 1 is the strongest and has the widest range of shear effect.
(3) The strength of shear effect increases with the increase of ultrasonic amplitude or the decrease of frequency, so it is advisable to use the high-amplitude and long-cycle (long-pulse) ultrasonic wave for scale removal.

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