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Finite Element Simulation of the Shear Effect of Ultrasonic on Heat Exchanger Descaling

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Abstract. The shear effect on the interface of metal plate and its attached scale is an important mechanism of ultrasonic descaling, which is caused by the different propagation speed of ultrasonic wave in two different mediums. The propagating of ultrasonic wave on the shell is simulated based on the ANSYS/LS-DYNA explicit dynamic analysis. The distribution of shear stress in different paths under ultrasonic vibration is obtained through the finite element analysis and it reveals the main descaling mechanism of shear effect. The simulation result is helpful and enlightening to the reasonable design and the application of the ultrasonic scaling technology on heat exchanger.

1. Introduction
Heat Exchanger is a kind of thermal equipment widely used in industrial production. Usually the heat exchange equipment appears coking and fouling after a period of continuous operation. According to the research of Steinhagen et al, more than 90 percent of the heat exchangers have varying degrees of scale [1].

Ultrasonic anti-scaling is a new high efficiency scale removal technology. It can not only slow down the deposition rate of fouling particles on the surface of heat transfer equipment, but also effectively remove the scale which has been formed. Ultrasonic anti-scaling technology mainly uses the following four principles to achieve anti-scaling: cavitation effect, activation effect, shear effect and inhibitory effect [2]. Because of the distinction of physical properties and elastic impedance between scale and metal, the absorption and propagation speed of the ultrasonic waves is different. It results in the existence of velocity difference in the interface and the forming of shear force, which makes the scale layer loose and eventually fall off [3]. In this paper, the shear effect on the heat exchanger shell in the process of ultrasonic descaling is simulated, and the result is of reference value to the rational design and the application of the ultrasonic descaling scheme.
2. Finite element model

The heat exchanger shell has been subjected to internal fluid pressure (shell side pressure) and its own gravity before the installation of ultrasonic device. In order to determine the influence of static load on dynamic analysis, ANSYS/LS-DYNA implicit-explicit method is adopted to obtain the results of the implicit solver as the initial stress of the explicit analysis. Solid 185 element is used in the implicit analysis, and is converted to the corresponding solid 164 explicit element in the explicit analysis. The main material parameters are listed in Table 1.

| Name       | Material            | Yield strength /MPa | Density / (kg·m$^{-3}$) | Elasticity modulus /Pa | Poisson’s ratio |
|------------|---------------------|---------------------|-------------------------|------------------------|----------------|
| Shell      | 20R                 | 245                 | 7850                    | 2.01×10$^{11}$         | 0.3            |
| Scale      | Carbonate scale     | —                   | 2710                    | 1.07×10$^{9}$          | 0.3            |

The ultrasonic transducer is welded to the outer surface of the heat exchanger shell, so the vibration load is applied to the outer surface of the shell directly. In order to simplify the model, only the main structure such as tube plate, shell and support are established and a layer of scale, 5mm thick, is built on the inner surface of the heat exchanger to simulate the scale layer, where the influence of tube bundles inside the heat exchanger is ignored. Because of the symmetry, 1/4 model is created, as shown in Fig.1.

The load and boundary conditions imposed in the static analysis are as follows: symmetric constraint is applied on the symmetric surface of the 1/4 model, which means that the line displacement of the perpendicular plane is zero; full freedom constraint is applied on the base of support; the shell-side pressure (1.57 MPa) and gravity are applied on the shell; the membrane stress $\sigma_m$ caused by internal pressure because of the removal of the head of the heat exchanger is applied to the face of the shell:

$$\sigma_m = \frac{\pi R_1^2 P}{\pi (R_2^2 - R_1^2)} = 32.32\text{MPa}$$  \hspace{1cm} (1)$$

where $P=1.57\text{MPa}$ is the shell-side pressure of the heat exchanger, $R_1=500\text{mm}$ is the shell inner diameter, $R_2=512\text{mm}$ is the shell outer diameter.

The Mises equivalent stress contour under the static load of a heat exchanger with an ultrasonic transducer is shown in Fig.2. The maximum Mises equivalent stress of the shell under the static load is about 88.7 MPa, which appears at the connection between the support
and the shell. It is the phenomenon of stress concentration caused by the discontinuity of the structure.

During the operation of the ultrasonic anti-scaling device, the transducers convert electrical signals into mechanical energy to achieve continuous high-frequency vibration. The dynamic load defined in ANSYS/LS-DYNA is applied in one load step. It means that the load varying with time is directly applied to the load-bearing part of the structure, which is different from the common ANSYS implicit structure analysis [4]. Therefore, the sinusoidal varying displacement time load is applied to the connection position of the shell and the transducer, and the propagation of the ultrasonic wave is simulated at last as the node displacement changes with time [5]. Sine-varying displacement time loads are defined in the form of an array, and the ultrasonic excitation in N cycles is achieved by means of an APDL cycle statement. Fig.3 shows the curve of vibration displacement changes over time in a period (the amplitude of transducer is 0.05mm and frequency is 20 kHz).

![Figure 3. The vibration displacement of the transducer changes with time (one cycle)](image)

3. Simulation results and discussion

The Mises equivalent stress of the heat exchanger shell in different time is shown in Fig.4. At t=\(T\) (a vibration period, \(5 \times 10^{-5}\)s), the maximum Mises equivalent stress, about 168.5MPa, appears at the top of the shell where the transducer locates. After a period of time, the maximum Mises equivalent stress in the junction is reduced to about 150 MPa. In the shell, a series of concentric "corrugations" centered on the transducer are presented, which is the effect of the ultrasonic vibration propagation simulated by ANSYS.

As shown in Fig.5, the following two paths are defined to study the variation of shear stress on the boundary of fouling and shell: at the interface between the shell and the scale, a path, defined as path1, is taken as path1 from the highest point of the shell to the lowest one in the cross section; in the connection of the shell and the transducer, another path, defines as path2, is taken in the same way.
(a) Mises equivalent stress contour at t=T

(b) Mises equivalent stress contour at t=20T

(c) Mises equivalent stress contour at t=50T

(d) Mises equivalent stress contour at t=100T

Figure 4. Mises equivalent stress contour on the shell of 4 different time

Figure 5. The position of path1 & path2 on the shell

The shear stress distribution curve (in cylindrical coordinate system) of path1 and path2 along the circumference of the shell at t=100T (0.005s) is shown in Fig.6. The node shear stress SX1 on path1 is between -0.429 and 0.42 MPa, but the shear stress SXZ and SYZ are almost zero. The node shear stress SX1 on path2 is between -2.92 and 4.3 MPa, and likewise the SXZ and SYZ are almost zero.
The shear stress curves on path 1 and path 2 are obtained in cylindrical coordinates. SXY, SXZ and SYZ in the ANSYS post-processing correspond to \( \tau_{\theta\phi} \), \( \tau_{r\phi} \) and \( \tau_{\phi\theta} \) can be understood as the circumferential shear stress between adjacent scale bodies, \( \tau_{r\phi} \) and \( \tau_{\phi\theta} \) as the axial shear stress, \( \tau_{\phi r} \) and \( \tau_{r\phi} \) as the radial shear stress. According to the theorem of conjugate shearing stress, in the two planes perpendicular to each other, the shear stresses must exist in pairs and have the same value, that means \( \tau_{\phi r} = \tau_{r\phi} \), \( \tau_{r\phi} = \tau_{\phi r} \), \( \tau_{\phi\theta} = \tau_{\theta\phi} \). After summarizing the path stress distribution of path1 and path2 under four different operating conditions, it is found that SXY is the largest shear stress and SXZ and SYZ are both small, that is, \( \tau_{\phi r} \) and \( \tau_{r\phi} \) are the largest shear stress, while \( \tau_{\phi\theta} \), \( \tau_{\theta\phi} \), \( \tau_{r\phi} \) and \( \tau_{r\phi} \) are small. It illustrates that the circumferential shear stress \( \tau_{r\phi} \) and the radial shear stress \( \tau_{\phi r} \) between adjacent scale bodies play major roles in the descaling process.

4. Summary
The propagating of ultrasonic wave on the shell and the shearing effect in descaling are simulated based on the ANSYS/LS-DYNA explicit dynamic analysis. The shell Mises equivalent stress contour and the distribution of shear stress in different paths under different ultrasonic vibrations are obtained through the finite element analysis. The results show that the circumferential shear stress and radial shear stress on the shell play major roles in the ultrasonic descaling process. It is helpful to promote the use of the ultrasonic anti-scaling technology and the installation of the transducer.

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