Application simulation of the pulsed ultrasonic wave in soft scale removal of the heat exchange tube

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Abstract. It is a new descaling technology to use the ultrasonic wave to descale on the heat exchanger. The removal of the soft scale is an essential content of it. ANSYS/DYNA is used to simulate the impact of ultrasonic on descaling in this paper. This paper aims at the simulation of a heat exchange tube by loading different ultrasonic cycles and frequencies. The results of the simulation show that the effect of descaling is the best when the number of cycles in a pulse is 5, and the impact of descaling gets better with the increase of ultrasonic frequency in a specific range.

1. Introduction

Fouling can be defined as the formation of deposits on heat transfer surfaces that impede heat transfer and increase the resistance to the flow of fluids over the surface [1].

Ultrasonic descaling is an efficient and new energy-saving technology. It can slow down the formation of scale in heat exchangers. In addition, it can also remove the existing scale [2]. The ultrasonic descaling technology has four descaling principles: cavitation theory, activation theory, shear theory, and suppression theory. The shear theory is mainly due to the different propagation speed of ultrasonic waves on the scale and metal. The physical properties of the fouling and the metal are different. There is a difference between the speed of two interfaces, so a relative shear force is formed, which causes the scale layer to fall off.

Aiping Zhang [3] numerically simulated the propagation characteristics of ultrasonic waves in three tube types: the straight tube, the ribbed tube, and the corrugated tube. The sound pressure distribution diagram of ultrasonic waves in three tube types was obtained. Zhihua Wang [4] calculated the structural response of the heat exchanger under the force from ultrasonic based on ANSYS software. He analyzed the distribution of shear stress between the wall of the heat exchanger and the fouling under the ultrasonic. Shaolv Lu [5] explained the hard scale and used ANSYS software to simulate the shear stress between the inner shell wall and the hard scale.
The paper is to investigate the descaling of ultrasonic on the tube. Based on the work done by the predecessors, the author focuses on the impact of pulsed ultrasonic on the soft scale.

2. Model

In this paper, a model of a heat exchange tube with a length of 2000mm is established. The outer diameter of this tube is 25mm. The thickness of it is 2.5mm. A layer of 0.5mm solid is attached to the inner surface of the tube as a soft scale model, as shown in Figure 1. The material of the heat exchange tube is 10 steel. This paper uses a viscoelastic constitutive model to simulate the physical model of the soft scale. Maxwell model is one of the constitutive models of viscoelastic materials; the specific formula is:

\[ f(t) + p_1 \dot{f}(t) = q_1 \dot{\gamma}(t) \]  

(1)

In viscoelastic material, \( f(t) \) represents the shear stress; \( \dot{\gamma}(t) \) represents the shear strain. \( p_1 \) and \( q_1 \) are coefficients of the viscoelastic material. The values of them depend on the specific material. Table 1 is the material parameters of the soft scale.

Table 1. The viscoelastic material.

| Name    | Mass density /kg/m³ | Elastic modulus /Pa | Short-term elastic shear modulus /Pa | Long-term elastic shear modulus /Pa |
|---------|---------------------|---------------------|--------------------------------------|-------------------------------------|
| soft scale | 1840                | 4.31 × 10¹¹        | 1.899 × 10⁹                          | 3.17 × 10⁸                          |

LS-DYNA, as the most famous general nonlinear dynamic analysis finite element program in the world, can simulate all kinds of complex problems in the real world. The Solid185 element is used in the implicit analysis. During the explicit analysis, the Solid185 is converted to the Solid164. The Solid164 element has no real constants and the dynamic problem analysis use it only. This element supports all permitted non-linear characteristics. It is an 8-node unit and there are 9 degrees of freedom at each node: UX, UY, UZ, VX, VY, VZ, AX, AY, and AZ. However, in this element, only displacement is the real physical degree of freedom.

In the static analysis, the gravity and the internal pressure of the heat exchange tube are applied. According to the design condition, the internal pressure is selected to be 1.57MPa. The boundary condition is fully restricted at the position of Z = 0.

Figure 1. Model of a heat exchange tube.

Figure 2. Mises stress after the implicit analysis.
Figure 2 shows the Mises stress obtained by the tube after the implicit analysis. The maximum stress of implicit analysis is 39.521MPa, which appears at the restricted position on the left because the structure generates stress concentration at this position.

3. Effect of ultrasonic cycles on descaling

The result of different cycles in an ultrasonic pulse on the shearing force at the interface between the tube and soft scale is investigated. Take the amplitude $A$ of an ultrasonic wave as 0.005mm, the frequency $f$ as 20kHz. As shown in Table 2.

Figure 3 is the map of an exhibition of an ultrasonic wave; it has a length of $2.5 \times 10^{-4}$s and contains five pulses. Also, the interval ratio of this wave is 1/1; that is, the interval width between every two pulses is equal to the pulse width.

A path is defined as shown in Figure 4 for viewing the results of stress. The nodal shear stress distribution along path1 is obtained in a rectangular coordinate system.

The following are the calculation results and analysis under various working conditions:

| Working condition | Ultrasonic amplitude (mm) | Frequency (kHz) | Number of cycles N |
|-------------------|---------------------------|-----------------|-------------------|
| 1                 | 0.005                     | 20              | 1                 |
| 2                 | 0.005                     | 20              | 2                 |
| 3                 | 0.005                     | 20              | 5                 |
| 4                 | 0.005                     | 20              | 10                |
| 5                 | 0.005                     | 20              | 15                |
| 6                 | 0.005                     | 20              | 20                |

3.1. Working condition 1

In this working condition, the frequency is 20kHz, the amplitude is 0.005mm, the number of cycles N is 1.

Figure 5 is the Mises stress contour when the first pulse is completed. The maximum equivalent stress is 43.297MPa. A small range of ripples appears in the place where the ultrasonic load is applied in the middle of the pipe, which reflects the role of the pulse well.
Figure 6 shows the shear stress distribution along path1 at the end of the first pulse. The dominant shear stress is SYZ, while SXY and SXZ are unchanged. It can be seen from the figure that SYZ has the highest point and the lowest point.

3.2. Working condition 2

In this working condition, the number of cycles N is 2. When the first pulse is completed, the maximum equivalent stress is 40.933 MPa. There is a small range of ripples in the middle of the tube where the ultrasonic load is applied, but the scale of ripples is more extensive than that of working condition 1. At the same time, the shear stress distribution is similar to the distribution of the working condition 1. As the number of cycles increases, the width of the curve also widens.

3.3. Other working conditions

The above are the effects of ultrasonic cycles on Mises equivalent stress and shear stress under the first two conditions. Also, when the number of ultrasonic cycles N is 5, 10, 15, and 20, the maximum stress at the beginning of each pulse and the end of each pulse is summarized. The maximum stress distribution is in Figure 7. In the same way, the shear stress distribution along Path1 is obtained, as shown in Figure 8.
The number of cycles affects the reverberation sound field. When the cycles are at a specific position, a stable reverberation field can be formed. In Figure 7, the maximum Mises stress reaches its peak when the number of cycles N is 5. At the same time, the maximum shear stress can also reach its peak, according to Figure 8. Therefore, it can be concluded that when the number of cycles N is 5, it is the best state of descaling.

4. Effect of ultrasonic pulse frequency on descaling

This section analyzes the effect of ultrasonic frequency on descaling. The amplitude of the ultrasonic wave is 0.005mm, and the number of cycles N is 5. Then, different ultrasonic frequencies are used for calculation and analysis. Working condition 1: frequency f=20kHz; condition 2: f=25kHz; condition 3: f=30kHz; condition 4: f=35kHz; condition 5: f=40kHz.

Take condition 2 as an example. When the first pulse is completed, the maximum equivalent stress is 43.176MPa. The ripples appear in the middle of the pipe where the ultrasonic load is applied. In working condition 2, a pulse is applied, as the frequency of the ultrasonic wave increases to 25kHz, the number of peak points of the shear stress distribution increases also.

Also, when the ultrasonic frequency f is 30, 35, and 40kHz, the ultrasonic wave is applied to the heat exchange tube according to these parameters. The maximum mises stress at the beginning of each pulse and the end of each pulse is summarized. Figure 9 shows the variety of the maximum Mises stress. It increases with the enlarge of the ultrasonic frequency. Similarly, Figure 10 shows the variety of the maximum shear stress. It also increases with extend of the ultrasonic frequency.

![Figure 9. variety of maximum mises stress.](image1)
![Figure 10. variety of maximum shear stress.](image2)

5. Conclusion

In the simulation of the heat exchange tube, a stable reverberation field can be formed when the number of cycles N is 5. At that time, the value of the maximum Mises stress reaches a peak value. Similarly, the maximum shear stress can also reach a peak. So, it can be considered that it is a good descaling state.

Also, the value of the maximum Mises stress increases with the enlarge of the ultrasonic frequency. Similarly, the maximum shear stress does it too. With the same pulse width and amplitude, the higher the frequency, the better the descaling effect.
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