Configuration Optimization of Ultrasonic Descaling Device for Condenser Based on Solidworks-Fluent

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Abstract: As a key component of the open circulation cooling system, the condenser of the power plant is very prone to fouling. After the condenser cooling pipe is scaled, the heat transfer resistance increases, which reduces the heat transfer coefficient and heat exchange efficiency of the heat exchange equipment, which is not conducive to improving the energy efficiency. Therefore, the research on condenser descaling technology has attracted widespread attention. Ultrasonic descaling is a new type of online descaling technology. Its application effect in descaling of condensers in power plants has been verified by actual engineering, but it lacks optimization of the arrangement and configuration of ultrasonic devices. In order to explore the influence of various ultrasonic parameters on the descaling effect, this paper builds a 3D geometric model of the condenser in Solidworks based on the relevant structural parameters of the N-20910 condenser, meshing the model reasonably and setting the boundary conditions. Then, in Fluent, the descaling effect is characterized by the pressure change curve of the specific position of the fluid in the condenser pipe. By setting three different ultrasonic inlet modes and different ultrasonic sound pressure functions, the effects of the quantity, power, frequency and distribution of ultrasonic descaler on the internal flow field and descaling effect of the condenser are compared and analyzed. The simulation results can provide effective help for the optimization and parameter setting of the ultrasonic descaling device of the power plant condenser.

1. Introduction
With the rapid development of industrialization and modernization, the problem of fossil energy shortage is becoming increasingly serious. Power industry plays a key role in energy industry, and condensing equipment is a very important heat exchange equipment for thermal power generating.

A study result shows that more than 90% of the heat exchange equipment has scaling problems\cite{1}. If condenser cooling pipes are scaled, the heat transfer resistance increases and the output power decreases. According to statistics, under constant inlet temperature, if exhaust temperature is reduced by 10\%, efficiency can be improved by about 3.5\%\cite{2}. Therefore, it is important to explore effective methods to achieve the best anti-scaling and descaling effect at a lower investment cost.

Traditional descaling methods are mainly divided into offline like high-pressure water jet cleaning and online like rubber ball cleaning or chemical cleaning. In recent years, a series of economical,
environmentally friendly and efficient new descaling technologies like high-pressure water jet robot online cleaning[3], electrostatic descaling and ultrasonic descaling[4] are developed.

High-pressure water jet cleaning costs much to start and shut down. Rubber ball cleaning is not thorough. Acidic reagents corrode the condenser copper pipe[5]. Robot cleaning has high requirements on servo drive system, sensing devices and rotary seal at the joint because of long-term underwater operation. Ultrasonic technology can not only descale but also prevent scale, and whether or not it is scaled on the pipe wall, the ultrasonic can enhance the heat transfer and improve the heat transfer efficiency. So this article focuses on the ultrasonic descaling technology.

2. Research methods and Influence Factors of Ultrasonic Descaling

Applications of ultrasound include three aspects: basic research[6], ultrasound inspection[7] and ultrasound treatment[8]. Ultrasonic descaling is an application of ultrasonic treatment.

There are currently four research methods for the effect of ultrasonic descaling:

1) Simulation experiment research is carried out by setting up an experimental device[9];
2) Numerical analysis research is conducted by setting up mathematical models[10][11];
3) Physical model simulation and analysis research is carried out by building the parametric model of the condenser on simulation software platform[12][13].
4) The effect of ultrasonic descaling in engineering applications is checked by comparing the fouling situation and economic benefits before and after applying ultrasonic descaling equipment.

Research on influence factors of ultrasonic descaling is concentrated on four aspects: ultrasonic parameters, heat transfer medium parameters, condenser parameters and environmental factors[14].

(1) Ultrasonic parameters include ultrasonic power, frequency, and standing waves.
(2) The parameters of the heat transfer medium include fluid temperature, flow rate, viscosity coefficient, surface tension coefficient, vapor pressure and so on.
(3) Condenser parameters include pipe shape and pipe diameter.
(4) Environmental factors include environmental pressure, descaler radius, quantity of scalers, and form of descaler distribution and so on.

In view of the fact that the research is based on the completion of condenser, some parameters have been determined, so only consider the influence of power, frequency, quantity and placement.

3. Condenser parameter model establishment

In this paper, the structure of the condenser is simplified and the parameter model of the condenser is constructed. By meshing the condenser parameter model and setting the entry conditions based on the assumed initial parameters, we get the model that can be calculated in Fluent.

3.1. Structural parameters of N-20910 condenser

N-20910 condenser is a single-shell, dual-flow, surface-type condenser, as shown in Figure 1. The main condensation zone cooling pipes are Φ25(mm) stainless steel pipes. The cooling water pipe bundle is arranged in triangle in the shell. The cooling water enters through front water room, rotates through back water room, and then flows out of condenser through front outlet room.
3.2. Simplified model of condenser 3D geometry
Structure is simplified to study the influence of ultrasonic wave on the flow field in the cooling pipe, only keeping front and back water room and condensing pipe. Simplified parametric model uses 7 cooling pipes to describe typical structure of the triangular arrangement, as shown in Figure 2.

![Figure 2](image2.png)

Figure 2. Triangular arrangement of condenser pipe bundles

As shown in Figure 3, ultrasonic inlets are installation positions of ultrasonic descalers. They are circular holes of Φ22 (mm), and evenly distributed at front and back water room shells. According to the needs of the simulation, we evenly distribute two, four or six circular holes.

![Figure 3](image3.png)

Figure 3. Simplified 3D geometry model of condenser

3.3. Mathematical model of ultrasonic wave propagation in ideal flowing liquid
When the ultrasonic wave acts on the liquid flow field, a large number of bubbles are generated in the liquid. The bubbles are repeatedly generated and collapsed, causing the fluid in the pipe to alternately change in sparse and dense, manifesting in form of changes in fluid internal pressure[10].
The sound pressure equation of ultrasonic action can be constructed. The sound pressure equation at the entrance of the ultrasonic descaler can be described as:

\[ P(t) = P_1 + P_2 \sin(2\pi f \cdot t) \] (1)

Where, \( P_1 \) — static pressure at the inlet, Pa; \( P_2 \) — average pressure; \( f \) — ultrasonic frequency.

3.4. Fluent pre-processing
Fluent is currently the most powerful computational fluid dynamics software tool available. It contains rich turbulence models and provides users with a secondary development interface (UDF). Therefore, this paper chooses Fluent as simulation software. Fluent pre-processing includes two parts: meshing and setting inlet conditions. Reasonable meshing can make the calculation quickly converge.

The 3D model is meshed in Pointwise, using non-structured grids, as shown in Figure 4.

![Figure 4. Meshing of the condenser physical model](image)

The inlet of the model is a semicircular surface of the forward water chamber, the inlet speed is \( v_{room} \), the inlet area is \( S_1 = 5713784.968 \text{mm}^2 \), the fluid velocity in the condensing pipe is \( v_{pipe} \), the cross-sectional area of the condensing pipe is \( S_2 = 1252.490874 \text{mm}^2 \).

Because all the condensation pipes are not drawn in the simplified model, there is a certain proportional between the flow rate in water room and in condensation pipe, that is, \( \frac{v_{room}}{v_{pipe}} = \frac{S_1}{S_2} \).

The object of this paper is flow field in the pipe, so the inlet speed needs to be converted. It is assumed that \( v_{pipe} = 0.7 \text{m/s} \), so \( v_{room} \), which is the speed of inlet in software, is 0.0004 m/s.

4. Simulation model building
This paper studies the ultrasonic descaling effect under three different ultrasonic inlet modes with different ultrasonic sound pressure functions.

4.1. Parametric model
A: Four circular holes with a diameter of Φ22 (mm) are evenly arranged around the wall surface of front water room close to the condenser pipe as an ultrasonic inlet, as shown in Figure 5.
Figure 5. Schematic diagram of model A ultrasonic descaler location

B: Six circular holes with a diameter of Φ22 (mm) are evenly arranged around the wall surface of front water room close to the condenser pipe as an ultrasonic inlet, as shown in Figure 6.

Figure 6. Schematic diagram of model B ultrasonic descaler location

C: Six circular holes with a diameter of Φ22 (mm) are evenly arranged, four around front water room and two along the horizontal diameter of back water room, as shown in Figure 7.

Figure 7. Schematic diagram of model C ultrasonic descaler location

4.2. Ultrasound program

With ultrasonic pressure added, flow field in pipe generates pressure fluctuations, which causes ultrasonic cavitation and shearing. The greater the pressure fluctuations, the more obvious the cavitation and shear effect, the better the descaling effect. Considering the operating frequency of ultrasonic cleaning system is generally 20~40kHz, this paper sets four different ultrasonic pressure function, sound pressure function and corresponding ultrasonic parameters are shown in Table 1.

| Sound pressure function /Pa          | Amplitude/Pa | frequency/Hz |
|--------------------------------------|--------------|--------------|
| a P1=10000sin(2π • 20000 • t)       | 10000        | 20           |
| b P2=15000sin(2π • 20000 • t)       | 15000        | 20           |
| c P3=20000sin(2π • 20000 • t)       | 20000        | 20           |
| d P4=10000sin(2π • 40000 • t)       | 10000        | 40           |

Write UDF programs of the above four waveforms separately and import them into Fluent.

4.3. Simulation model

In order to study the effects of each ultrasonic parameters, the above parameter model and ultrasonic program are combined as Table 2.
Table 2. Simulation models corresponding parameter model and ultrasonic function combination

| Ultrasonic inlet (Parameter model) | Ultrasonic function /Pa |
|-----------------------------------|-------------------------|
| M1 4 around front water room (A)  | P1=10000sin(2π·20000·t)(a) |
| M2 4 around front water room (A)  | P2=15000sin(2π·20000·t)(b) |
| M3 4 around front water room (A)  | P3=20000sin(2π·20000·t)(c) |
| M4 6 around front water room (B)  | P1=10000sin(2π·20000·t)(a) |
| M5 4 around front water room and   | P1=10000sin(2π·20000·t)(a) |
| 2 around back water room (C)      | P4=10000sin(2π·40000·t)(d) |

Note: In M6, there are 4 inlets around front water room and 2 inlets around back water room. The relative two are in a group, one group loaded with P3, and the other group loaded with P4.

4.4. Save results
Flow field calculation is actually using solver in software to continuously iterate parameters of flow field and getting data infinitely close to real solution. Based on ultrasonic frequency of 20kHz,

\[ T = \frac{1}{f} = \frac{1}{20000} = 5 \times 10^{-5} \text{ (s)} \]  

50 steps are calculated in each cycle, the calculation step length is \( 10^{-6} \) (s), and the data is saved every 10 steps. After the calculation is converged, choosing 6 consecutive points can draw a complete waveform of one cycle of fluctuation.

5. Simulation results and analysis
The length of condenser pipe in simulation model is 6m. An observation point is taken every 1.5 meters from inlet of condenser pipe. Three points can be taken in the single-process pipe. The back water room is used as an observation point. There are 7 observation points in total, marked as d1～d7.

5.1. Pressure fluctuations at different points in the same model
Taking M1 as an example, importing the data saved by Fluent into Ensight for post-processing. Reading pressure cloud map of the fluid in the condenser, intercepting the cross section of each observation point and recording the pressure data at each observation point in Table 3.

Table 3. Pressure value of each observation point of M1 (Pa)

|       | d1   | d2   | d3   | d4   | d5   | d6   | d7   |
|-------|------|------|------|------|------|------|------|
| 0     | 21400| 17200| 12800| 7930 | 3030 | -1790| -6160|
| 1*10^-5s| 29800| 24900| 19900| 14600| 10100| 6110 | 2210 |
| 2*10^-5s| 27000| 22600| 17800| 12600| 7830 | 2580 | -2120|
| 3*10^-5s| 14800| 10700| 5960 | 555  | -4870| -10300| -14600|
| 4*10^-5s| 11000| 6360 | 1590 | -3300| -8230| -12800| -17400|
| 5*10^-5s| 21100| 16200| 11300| 6500 | 1880 | -2970| -7470 |

Input data into Matlab for Fourier curve fitting and obtain the fluctuation curve as Figure 8.
In the model, the flow field pressure gradually decreases from inlet to outlet, so reference pressures d1−d7 in Figure 8 decrease gradually. When ultrasound propagating in liquid, the absorption attenuation is very small, so the attenuation is negligible.

5.2. Effect of power on ultrasonic descaling result

Power is an important factor that affects ultrasonic descaling. The power control groups selected in this section are M1, M2, and M3. Four ultrasonic descalers with amplitudes of 10000Pa, 15000Pa, and 20,000Pa are respectively distributed around front water room. Taking the data at d6 as an example, plot the pressure fluctuation curve at d6 under three model conditions, as shown in Figure 9.

List the fitting curve of pressure fluctuation at point d6 in M1, M2 and M3 respectively, and calculate the maximum pressure, minimum pressure and pressure difference, as shown in Table 4.

| Pressure fluctuations at point d6 in M1, M2 and M3 |
|---|---|---|
| M1 | M2 | M3 |
| pressure function | f(x)=1246cos(x)+10150sin(x)-3318 | f(x)=-1004cos(x)+15320sin(x)-3211 | f(x)=-1317cos(x)+20200sin(x)-3187 |
| maximum pressure/Pa | 6832 | 12109 | 17013 |
| minimum pressure/Pa | -13468 | -18531 | -23387 |
| pressure difference/Pa | 20300 | 30640 | 40400 |

Ultrasonic power of M2 is increased by 50% compared with M1, pressure difference is increased by 51%. Ultrasonic power of M3 is increased by 33% compared with M2, pressure difference is increased by 31.8%. Pressure difference increases with power increase, but the growth trend slows down after exceeding a certain range.
5.3. Effect of the quantity of descalers on ultrasonic descaling result
The control group of the quantity of ultrasonic scalers selected in this section is M1 and M4. The parameters applied by each ultrasonic descaler are the same. M1 is equipped with 4 descalers and M4 is equipped with 6 descalers. The pressure fluctuation curve at d6 is shown in Figure 10.

![Figure 10. Pressure fluctuation at the same point under different ultrasonic descalers quantity](image)

List the fitting curve of pressure fluctuation at point d6 in M1 and M4 respectively, and calculate the maximum pressure, minimum pressure and pressure difference, as shown in Table 5.

|                  | M1                                      | M4                                      |
|------------------|-----------------------------------------|-----------------------------------------|
| pressure function| \( f(x) = 1246\cos(x) + 10150\sin(x) - 3318 \) | \( f(x) = -1374\cos(x) + 16880\sin(x) - 2311 \) |
| maximum pressure/Pa | 6832                                   | 14569                                   |
| minimum pressure/Pa | -13468                                 | -19191                                  |
| pressure difference/Pa | 20300                                  | 33760                                   |

The quantity of ultrasonic descalers in M4 is increased by 50% compared with M1, the total power is increased by 50%, the flow field pressure difference is increased by 66%, the flow field pressure difference increases with the increase of the quantity of descalers. Considering cost and energy consumption, the quantity of descalers cannot be increased indefinitely.

5.4. Effect of single frequency or mixed frequency of ultrasonic on descaling result
Literature [15] proposed that, compared with single frequency radiation, the combined radiation of two or more ultrasonic frequencies can significantly increase the cavitation yield. In this section, M1 and M6 are selected as the frequency control group. The four descalers in M1 are all input with 20kHz ultrasonic waves. In M6, the relative two descalers are in a group, one group input with 20kHz and the other input with 40kHz. The pressure fluctuation curve at d6 is shown in Figure 11.

![Figure 11. Pressure fluctuation at the same point under single frequency or mixed frequency](image)

List the fitting curve of pressure fluctuation at point d6 in M1 and M6 respectively, and calculate the maximum pressure, minimum pressure and pressure difference, as shown in Table 6.
Table 6. Pressure fluctuations at point d6 in M1 and M6

|       | M1                                      | M6                                      |
|-------|-----------------------------------------|-----------------------------------------|
| pressure function | f(x)=1246cos(x)+10150sin(x)-3318        | f(x)=-459cos(x)+15550sin(x)-3354        |
| Maximum pressure/Pa | 6832                                    | 12196                                   |
| minimum pressure/Pa | -13468                                  | -18904                                  |
| pressure difference/Pa | 20300                                  | 31100                                   |

Pressure difference of the M6 has increased by 53% compared with M1, indicating that under the same arrangement and power parameters of the ultrasonic descaler, two frequencies of 20kHz and 40kHz used for joint radiation is better than 20kHz radiation used alone.

5.5. Effect of ultrasonic power dispersion on descaling result

M2 and M4 are selected as the control group. M2 is equipped with 4 descalers of 15000Pa and M4 is equipped with 6 descalers of 10000Pa. Ultrasonic amplitude is proportional to power of descaler, M2 and M4 can be regarded as having the same total power and different degree of dispersion. The pressure fluctuation curve at d6 is shown in Figure 12.

Figure 12. Pressure fluctuation at same point under different degree of ultrasonic power dispersion

List the fitting curve of pressure fluctuation at point d6 in M2 and M4 respectively, and calculate the maximum pressure, minimum pressure and pressure difference, as shown in Table 7.

Table 7. Pressure fluctuations at point d6 in M2 and M4

|       | M2                                      | M4                                      |
|-------|-----------------------------------------|-----------------------------------------|
| pressure function | f(x)=-1004cos(x)+15320sin(x)-3211       | f(x)=-1374cos(x)+16880sin(x)-2311       |
| maximum pressure/Pa | 12109                                   | 14569                                   |
| minimum pressure/Pa | -18531                                  | -19191                                  |
| pressure difference/Pa | 30640                                  | 33760                                   |

Compared with M2, the pressure difference of flow field in M4 is increased by 10%, indicating that when the total power is the same, dispersing the ultrasonic descaling device is beneficial to improve the ultrasonic descaling effect, saving about 9% energy to achieve the same descaling effect.

5.6. Effect of the position of descalers on descaling result

M1, M4 and M5 are selected for the analysis of effect of the position of the descalers. M1 and M4 respectively arrange 4 and 6 ultrasonic descalers evenly around front water room, M5 arranges 4 ultrasonic descalers around front water room and two ultrasonic descalers around back water room. Each descaler parameters is same. The pressure fluctuation curve at d6 is shown in Figure 13.
List the fitting curve of pressure fluctuation at point d6 in M1, M4 and M5 respectively, and calculate the maximum pressure, minimum pressure and pressure difference, as shown in Table 8.

**Table 8. Pressure fluctuations at point d6 in M1, M4 and M5**

|       | M1                              | M4                              | M5                              |
|-------|---------------------------------|---------------------------------|---------------------------------|
|       | pressure function: f(x)=1246cos(x)+10150sin(x) | f(x)=-1374cos(x)+16880sin(x) | f(x)=-124cos(x)+9354sin(x) |
|       | maximum pressure/Pa: 6832        | 14569                           | 5185                           |
|       | minimum pressure/Pa: -13468      | -19191                          | -13523                          |
|       | pressure difference/Pa: 20300    | 33760                           | 18708                           |

Compared with M4, pressure difference in M5 is reduced by 44%, and is even reduced by 8% compared with M1. It is guessed that sound pressure field generated by ultrasonic descaler around back water room and that generated by descaler around front water room cancel each other out.

6. Conclusion
When quantity of ultrasonic scalers is the same, increasing ultrasonic power increases the pressure fluctuation, but the trend slows down after exceeding a certain value. In case the ultrasonic scalers have same parameters, the pressure fluctuation will increase accordingly with the increase of the quantity of ultrasonic scalers. When total input power is the same, the more dispersed the power, the more obvious the pressure fluctuation. In the case of same ultrasonic arrangement and power, alternately outputting ultrasonic waves of different frequencies causes greater pressure fluctuations than the same frequency. In the descaling of the N-20910 condenser, 6 ultrasonic scalers should be selected, evenly distributed around front water room, alternately using 20kHz and 40kHz frequency. The best choice of power is to generate ultrasonic sound pressure of 15000Pa.

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