THE INVESTIGATION OF SOUND ATTENUATION BY TUBULAR HEAT EXCHANGER ARRAYS AND THE CORRESPONDING SOUND-REDUCING SPECTRUM

Genshan Jiang*, Yuechao Liu, Yapan Wu, Duoduo Chen and Weilong Xu

School of Mathematics and Physics, North China Electric Power University, Baoding, China 071003
e-mail: gsjiang@ncepu.edu.cn

The acoustic propagation characteristics of boiler heat exchanger tube array are investigated based on the research methods about phononic crystals. Plane wave expansion method was used for numerical calculation to get the elastic band gap diagram of tube array (band structure), while the COMSOL software was used to simulate the sound propagation characteristics. Setting the transverse pitch, longitudinal pitch, pipe diameter size and other parameters of tube array that should be meet the economizer structure, making the band gap picture of elastic wave after the sound getting through tube array by MATLAB calculating and conducting a simulated experiment through the COMSOL software, finally the paper can get the influence of furnace tube to sound transmission. And work through experiments, in order to offer new idea and method on processing acoustical signal in the power station boiler.

Key words: boiler tube array; economizer pipe; phononic crystal.

1. Introduction

Because of the complicated acoustic transmission environment formed by the boiler heat-exchanger tube array, the sound signal has changed obviously through the tube-array environment, and it takes great influence on the accuracy of the acoustic detection technology.

The tube array in the boiler is composed of 2D phononic crystals structures of periodic arrangement. This paper has analyzed acoustic propagation characteristics in the boiler with the theory of Phononic Crystal. Based on the method of Phononic Crystal Theory to the investigation on acoustic propagation characteristics of heat-exchanger tube-array of economizer tubes and superheater tubes in the boiler, change of sound signal through the periodic tube array has been obtained. It has important practical significance and theoretical value for detection of leakages in the boiler tube array, sonic soot cleaning and acoustic measures of the flow field and temperature field.

In recent years, the research about Phononic Crystal has made a great progress. The concept about Phononic Crystal was put forward by Kushwaha M.S. et al. in 1993 based on the comparison between Traditional Crystal and photonic crystal. Since the special array structures have different effect on the travels of sound. Goffaux et al. and Wu et al. study separately about how the rotation of the square section scatterer of 2D solid and Fluid Phononic Crystal affect band gaps.
met Cicek, Olgun Adem Kaya et al. found that sound may split beam through regular triangle array. Sz-Chin Steven Lin, Tony Jun Huang, Jia-Hong Sun et al. found 2D Phononic Crystal can converge and diverge the sound energy. The research methods can be classed into FEM, transfer matrix method, multiple-scattering method, plane-wave method and so on. For 2D Phononic Crystal, plane-wave method is used widely which is successfully applied when it is used to calculate about Phononic Crystal with variety structures which are made by solid-solid, liquid-liquid, etc. This article is about the numerically study of furnace tubes by plane-wave method and Comsol finite element simulation with experiments.

2. Phononic Crystal model and the calculation equation

Phononic Crysta can be divided into one-dimension, two-dimension and three-dimension. In this paper, the tube array belong to 2D Phononic Crysta structure. Figure 1. is the tube array sketch, the location of the sound is plane wave incidence. The furnace tubes generally include sequence and stagger. This article adopts sequence structure to calculate and experiment. The structure diagram is show as Figure 1.

![Phononic crystal array geometry schematic diagram](image)

**Figure 1. Phononic crystal array geometry schematic diagram**

The outside diameter of the steel tube is 40mm in calculation, the a shows the rate of longitudinal pitch of tube array and outside diameter of the steel tube is about 1.5~2.0. The b shows the rate of transverse pitch and outside diameter of the steel tube is about 2.0~3.0.

The paper analyzed it by using plane-wave expansion (PWE) method and then the d’Alembert’s equation of 2D Phononic Crysta is

$$\rho(r) \frac{\partial^2 u(r,t)}{\partial t^2} = \nabla \cdot [C_{11}(r) \nabla u(r,t)]$$

(1)

The $u(r,t)$ was a displacement vector associated with position and time; $\rho$ and $C_{11}$ were density and elastic constants of various materials. and then defining a scalar potential $\psi(r,t)$ and a displacement field $u(r,t)$, the relationship between them is $\rho u = \nabla \psi$. So the equation can be rewritten in

$$\frac{1}{C_{11}(r)} \frac{\partial^2 \psi}{\partial t^2} = \nabla \cdot \left[ \frac{1}{\rho(r)} \nabla \psi \right]$$

(2)

With the Bloch’s theorem, the solution of the equation can be written in

$$\psi(r,t) = e^{i(K \cdot r - \omega t)} \sum_G \psi(G) e^{i(G \cdot r)}$$

(3)

In the formula (3), the $K (k_x, k_y)$ means 2D Bloch wave in the plane and the $\omega$ is the angular frequency of the Bloch wave. The reciprocal vector of the 2D lattice is $G$. By using the two-
dimensional periodic of the density and elastic constant in a plane with the position vector 
\( r = (x_1, x_2) \), the \( 1/\rho \) and \( 1/C_{11} \) expanded into Fourier series in reciprocal space

\[
T(r) = T(x_1, x_2) = \sum_G T(G) e^{iG \cdot r}
\]  

(4)

The \( T(r) \) shows the \( 1/\rho \) or \( 1/C_{11} \) in the formula (4). And the Fourier coefficient is

\[
\sum_G T(G) = A_r^{-1} \int_A d^2 r T(r) e^{-iG \cdot r}
\]  

(5)

Where \( A_r \) is the area of the primitive cell. Integrating in the primitive cell and getting:

\[
T(G) = \left\{ \begin{array}{l}
\overline{T} = T_A f + T_B (1 - f) \quad G = 0 \\
(T_A - T_B) F(G) = (\Delta T) F(G) \quad G \neq 0
\end{array} \right.
\]  

(6)

Where \( A \) and \( B \) are two different components of phononic crystals. \( A \) is the steel column and \( B \) is the air. \( 1/T_A \) and \( 1/T_B \) respectively represent the density and the Elastic constants of the steel column and the air. The ratio of \( A \) in the primitive cell is \( f = \pi R_2 / A_r \). \( R \) is the radius of the cylinder in the air. \( F(G) \) is the structural factor of phononic crystals.

The above equation can be simplified as a standard feature equation:

\[
\sum_G D_{GG} \psi(G') = \omega^2 \psi(G)
\]  

(7)

Where the matrices \( P \) and \( Q \) can be given by the calculation above equation and the relation between \( P \) and \( Q \) is \( D = P^{-1} Q \)

\[
P_{GG'} = F(G - G') \Delta C_{11}^{-1} (1 - \delta_{GG'}) + \delta_{GG'} C_{11}^{-1}
\]

\[
Q_{GG'} = [F(G - G') \Delta \rho^{-1} (1 - \delta_{GG'}) + \delta_{GG'} \rho^{-1}](K + G)(K + G')
\]  

(8)

Solving the matrix \( D \) and getting its characteristic value and then calculating the arithmetic square root, the band structure of Phononic Crystals can be given by scanning the entire Brillouin zone.

3. Calculation and verification of band gap of two-dimensional Phononic Crystals

Figure 1 shows the 2D phononic crystal array structure. The cylinder’s materials and environment round them can be set to different materials. This paper has a numerical calculation with the parameters as Tab.1. Figure 2 shows gap structure diagram of the Phonon Crystal with column diameter(40mm) and the lattice size: \( a = b = 80\text{mm} \) in 20\(^\circ\)C. Figure 2a shows that it doesn’t be in the complete band gaps of sonic wave in the audible range (20Hz~20 kHz). But there are incomplete band gaps in a specific direction as range 1645 ~2458Hz, 3842~4073Hz, 5207~5257Hz, 7139~7252Hz, 9236~9325Hz in Figure 2b. Figure 2c shows the simulation results by COMSOL software. By comparison, the calculation in the low frequency range is in good agreement with simulation

<table>
<thead>
<tr>
<th>Material</th>
<th>Density(103kg/m3)</th>
<th>C11 elastic constants(109kg/m \cdot \text{s}^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal(steel)</td>
<td>7.8</td>
<td>290.24</td>
</tr>
<tr>
<td>Air(20(^\circ)C)</td>
<td>0.00129</td>
<td>0.000146</td>
</tr>
<tr>
<td>Air(1370(^\circ)C)</td>
<td>0.00023</td>
<td>0.000146</td>
</tr>
</tbody>
</table>
Supposing the temperature of the working boiler is the constant temperature field 1370°C. At this time, the density of the speed of sound and the air are 796.6 m/s and 0.23 kg/m³. The comparison between plane wave spreading and comso simulation is shown in Figure 3. The degree of inhibitory effect for array to the sound is increasing. The range of elimination frequency is getting big. The sound-transmission effect of low frequency remains the same.

The burn noise in Power station keeps in the range 250~600Hz. The noise frequency in soot blower is about 850~3000Hz. The overall situation focus on the range of low frequency steadily and such array structure may eliminate some noise and reduce environmental noise. However, in this situation, there will be high requirement for the positions of acoustic leakage device. When the leakage sound frequency is just in the stopband, it is easy to miss some leakage sound and affect the operation of boiler. Seriously, it will result unplanned overhaul by shutting down the boiler and it can cause large economic loss. By comparing the projection among different tube arrays, what can be found is that tube array has weak effect on low frequency sound. So when doing the furnace cleanliness and maintenance, the acoustic wave can be chosen from low frequency to do the acoustic wave ash clean-out, in order to keep the maintenance job smoothly.

When doing the boiler survey by using acoustic method, it is need to consider the effect of the change of temperature on the acoustic parameter of the air and array. Because the temperature field
of boiler tube array is changing and the effect of boiler tube array on acoustic transmission closely relates to temperature, detecting system operates with some difficulties. However, the acoustic band gap figure by calculating higher and lower temperature situation, what can be found is photonic crystal which has the sequential boiler array structure does not have the situation where total acoustic wave stopband exists. But in some specific directions, there are direction stopband. So by setting detecting points in different directions, boiler acoustic signal can be detected and can get relatively accurate acoustic signal.

4. Experimental verification

Because of the material limitation, the diameter of steel tube in the test is 20mm and the tube spacing is 40mm, testing in the environment with 20°C temperature. The testing system figure is shown in Figure 4.

![Figure 4. The experimental structure diagram](image)

By calculating, frequency of acoustic band gaps under 6000Hz is 3219~4811Hz in T-X direction.

The structural parameters in Figure 2 are two times that of them in Figure 5. Figure 2 shows the first band gap is 1645 ~2458Hz. The band-gap width in Figure 5 is 2 times in Figure 2, and the same of start location of frequency. By comparison with Figure 2, as the component and the filling ratio stabilizing, the band gap will corresponding reduce (or increase) when the structure parameters of phononic crystals proportionally increase (or reduce).

![Figure 5. PWE calculation figure](image)
Figure 6 (tube array parameter: 40×40mm) shows spectrum change of the insert loss caused by difference of tube array. And the experiment has inserted the one row tube and eight rows for comparative. In the experiment, the insert loss spectrum doesn’t show obvious band gaps when row number of sound transmission is N≤3. When N≥4, the band gap has appeared and bandgap becomes large with the rows increasing.

![Insert Loss vs Frequency](image)

**Figure 6.** tube array parameter: 40×40mm

From the picture, when N=1, the insertion loss fluctuates in a small range, so the sound pressure level can be regarded the same as no tube inserting and there is an external interference signal around the wave band between 4274-4608 Hz. When N=8, there exists a clear noise elimination frequency and the forbidden band below 6000Hz is between 3660-4295Hz and 4532-4952Hz. There is a peak between the two bands which may be result from reverberant in the room, so 4295-4532Hz should be the interfering signal. Here if it is an anechoic room, such peak should not exist and noise elimination band should be 3660-4952Hz. Comparing with the calculative forbidden wave, low frequency offsets 441Hz and high frequency offsets 141Hz, so experiment is consistent with the calculative result.

### 5. Conclusion

By theoretical calculating and simulating tube array with the parameters of boiler economizer, some conclusions can be got as follows:

1) There is no significant band gap in the insertion loss spectrum rows N ≤ 3 until N ≥ 4, the band gap bandwidth becomes larger bandwidth while increasing the number of rows.

2) The noise elimination is not obvious during the Indoor jamming signal frequency range which is about 4274-4608Hz.

3) Acoustic phonon band gap is relevant to parameters about the materials of tube array, the effect of temperature change on the acoustic band gap should be considered in practical applications due to the acoustic parameters of the material will change partly while the ambient temperature changes.

4) When keep component element and filling ratio invariant, the larger or smaller the photonic crystal changes proportionally, the larger or smaller the band gap changes correspondingly.

The research about the acoustic transmission properties of power station boiler tube array can offer reliable theory foundation to the detection of the acoustic leakage of tube array, and also offer help to the technology of acoustic wave ash clean-out choosing suitable acoustic frequency. This research makes a great significance to the development of boiler acoustic theory and the technology application and also it has very important meaning to ensure boiler operating safely.
ACKNOWLEDGMENT

The work presented in this paper is carried out through the projects 11274111, 10974053 and 10774043 supported by National Natural Science Foundation of China (NSFC), and the project A2011502103 supported by Natural Science Foundation of Hebei Province.

REFERENCES