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SOUND PROPAGATION THROUGH A HEAT-EXCHANGER TUBES ARRAY IN POWER BOILES*

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Abstract

In this paper, a mathematical model of leakage sound propagation through a heat exchanger tubes array in boilers is established, which is based on the Twersky's sound scattering theory, transmission grating diffraction theory, Fabry-Perot's interference principle, and algebraic iteration method. The tubes array is made up of large number periodically arranged tubes immersed in air. Its acoustics transmission properties are examined experimentally and theoretically. The stopping frequency, passing frequency and its bandwidth of leakage sound through the tube arrays with different structure parameter are calculated. The definition of "deaf-band" and "audible-band" of inner tube leakage sound transmission of tube array are given. The experiments of sound propagation characteristic through tube array using electro-acoustic spectral and real air leakage spectral are studied respectively. It was tested that the "deaf band" position of electro-acoustic spectrum is consistent with the theoretical estimation. However, the width is wider than theoretical prediction. The transmission properties of leakage sound spectral is well consistent with theoretical one at low frequency, but different at high frequency. The reason is that the second sound radiation is produced by the interaction between leaking ejection fluid and tube array. The sound transmission characteristic with different rows is concluded at the same time. It offers the evidence for the orientation and location of leakage source well.

As same as the phononic crystals, the tube array structure has stop effect and pass effect on leaking sound propagation. The leaking sound radiation in tube array includes leaking jet noise and the second order noise caused by the interaction between the leaking jet and tube array.

1. INTRODUCTION

The accident of heat-exchanger crack in boiler has always been one of the major problems in power plant, which baffles the unit operation safely and economically. Some methods are used for tube crack detection in early period, such as Artificial Detection Method, conductivity

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Detection Method, mass balance Detection Method, and Acoustic Detection Method. At present, the detection using acoustic method is one of the most potential technologies in early leaking stage in boiler. However, there is lack of knowledge of the sound propagation through tube array of heat exchanger in boilers. The technology of acoustic detection was embarrassed without enough acoustic knowledge as diagnostic dependence. Therefore, it is important for academic research and engineering application to study the transmission property of leaking sound in boiler tubes.

In this paper, based on Twersky's sound scattering theory, transmission grating diffraction theory, Fabry-Perot's interference principle, and algebraic iteration method, a mathematical model of leakage sound propagation through the heat exchanger tube array is established. The cut-off frequency, pass frequency and bandwidth of leakage sound through different structure parameter heat exchanger tube array are calculated. The definition of "deaf-band" and "audible-band" of inner tube leakage sound of tube array are given. The experiments of sound propagation characteristic through tube array using electro-acoustic spectral and real air leakage spectral are studied respectively. It was tested that the "deaf band" position of electro-acoustic spectral is consistent with the theoretical estimation. The phenomenon is accord with which discovered by the international institute of "phononic crystal". The transmission properties of leakage sound spectral is well consistence with theoretical one in low frequency, and different in high frequency. The reason is that the second sound radiation is produced by the interaction between leaking ejection fluid and tube array. The sound transmission characteristic with different rows is concluded at the same time.

2. MATHEMATICAL FORMULATION

Suppose the tubes of heat exchanger are disposed uniformly along the *x* axial, the transverse distance of tubes is d_x, the out diameter is *d*, and the radius is *a*, as shown in Fig.1. Consider of the incidence of plane wave, and the propagation orientation is perpendicular with tube axial (*y* axial), that is, on the plane of the *x-z*, the expression of the sound pressure of the incidence wave:

$$p(r,\varphi) = p_0 e^{ik_0 r\cos(\varphi-\varphi_0)} \tag{1}$$

where p_0 is the amplitude of sound pressure, $k_0 = \omega/c_0 = 2\pi/\lambda_0$ is wave number in outside media, φ_0 is the angle between the incidence orientation and the z axial (normal of transverse rows).

According to Twersky's theory and grating diffraction theory, diffraction waves of all levels propagate in different direction on two sides of one-dimensional tube row. If the attenuation modal is neglected and only the propagation modal considered, then transmission and reflection coefficients (similar to the wave diffraction efficiency of all levels) of the diffraction wave amplitude relative to incidence wave can be denoted as vector.

$$\begin{cases} T_{0v} = \delta_{0v} + 2\sum_{n=-\infty}^{\infty} C_v A_n e^{in\varphi_v} \\ R_{0v} = 2\sum_{n=-\infty}^{\infty} C_v A_n e^{in(\pi-\varphi_v)} \end{cases} \tag{2}$$

Where $C_v = 1/(k_0 d_x \cos\varphi_v)$. It is called diffraction coefficient. In equation (2), A_n is the multiples diffraction amplitude, and it can be get by the following equation:

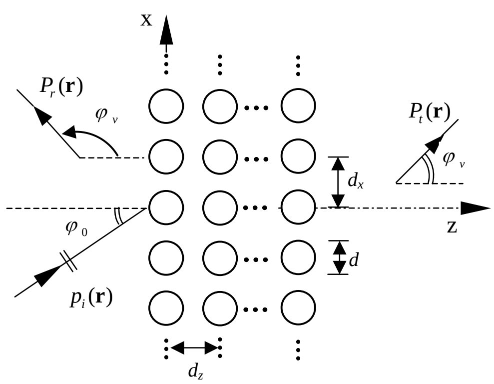


Fig.1 Geometry of tubes array

$$A_n = a_n(e^{-in\varphi_0} + \sum_{m=-\infty}^{\infty} A_m S_{n-m}) \tag{3}$$

where a_n is the scattering coefficient, S_{n-m} is Schlomilch series.

As incidence waves of the second tube-row array, these diffraction waves will reflect, transmit, and diffract on the second tube-row array. If d_z and d_x of the heat exchanger tube array of boiler is constant, the transmission and reflection coefficients of diffraction waves of all levels can be described as:

$$\begin{cases} T_{v\tau} = \delta_{v\tau} + 2\sum_{n=-\infty}^{\infty} C_\tau A_n^\tau e^{in\varphi_\tau} \\ R_{v\tau} = 2\sum_{n=-\infty}^{\infty} C_\tau A_n^\tau e^{in(\pi-\varphi_\tau)} \end{cases} \tag{4}$$

where $R_{v\tau}$ and $T_{v\tau}$ are elements of the $(v_+ + v_- + 1)\times(v_+ + v_- + 1)$ orders matrix R and T. The integers, v and τ, are represent as progression of transmission modal. The diffraction amplitude, A_n^v, depends on the incidence angle of the vth order transmission wave of the previous tube row on its own tube row. It can be acquired by the following linear equations:

$$A_n^v = a_n(e^{-in\varphi_v} + \sum_{m=-\infty}^{\infty} A_m^v S_{n-m}) \tag{5}$$

According to Fabry-Perot's interference principle, the total transmission field is the sum of multiple wave reflection and transmission between the first row and the second row. Suppose that $\mathbf{T}_2$ and $\mathbf{R}_2$ are matrixes of the total transmission coefficient and total reflection coefficient of the double-row tube array structure, then the total transmission field and reflection field are:

$$\begin{cases} \mathbf{T}_2 = T_1[\mathbf{I} + \mathbf{G}_2 R_1 + (\mathbf{G}_2 R_1)^2 + \cdots]\mathbf{F}_2 = T_1(\mathbf{I} - \mathbf{G}_2 R_1)^{-1}\mathbf{F}_2 = T_1\mathbf{K}\mathbf{F}_2 \\ \mathbf{R}_2 = R_1 + T_1[\mathbf{I} + \mathbf{G}_2 R_1 + (\mathbf{G}_2 R_1)^2 + \cdots]\mathbf{G}_2 T_1 = R_1 + T_1\mathbf{K}\,\mathbf{G}_2 T_1 \end{cases} \tag{6}$$

where $\mathbf{K} = (\mathbf{I} - \mathbf{G}_2 R_1)^{-1}$, $\mathbf{F}_2 = \mathbf{D}T_2\mathbf{D}^{-1}$, $\mathbf{G}_2 = \mathbf{D}R_2\mathbf{D}$, $[D]_{v\tau} = \delta_{v\tau}e^{ik_0 d_z \cos\varphi_v}$. T_1 (T_2) and R_1 (R_2) are matrixes of the transmission coefficient and reflection coefficient of the first (second) row tube array.

If only the zero-order diffraction wave of transmission and reflection are considered, then the matrix can be simplified by the plural form:

$$\begin{cases} \mathbf{T}_2 = T_1 T_2 \big/ (1 - R_1 R_2 D_{00}{}^2) \\ \mathbf{R}_2 = R_1 + T_1^2 R_2 D_{00}{}^2 \big/ (1 - R_1 R_2 D_{00}{}^2) \end{cases} \tag{7}$$

where $D_{00} = e^{ik_0 d_z \cos\varphi_0}$.

Since two-dimensional tube array of multiple rows is consisted of lots of one-dimensional equidistant tube rows. If the number of tube rows passed by leaking sound wave is N, then the angle of incidence wave is φ_0. Lots of diffraction angles, φ_v, are produced by the diffraction of the first-order tube row. The diffraction waves worked as incidence waves of next order tube row, and produce new diffraction waves.

According to equation (6), the total transmission matrix and reflection matrix, $\mathbf{T_N}$ and $\mathbf{R_N}$, can be acquired by the iterative method. When $\mathbf{T_N}$ and $\mathbf{R_N}$ of the n-1 order tube array are known, $\mathbf{T_N}$ and $\mathbf{R_N}$ of n order tube array can be calculated by equation (6) looking the n-1 order tube array as a single row structure.

$$\begin{cases} \mathbf{T_n} = \mathbf{T_{n-1}}(\mathbf{I} - \mathbf{G_n}\mathbf{R_{n-1}})^{-1}\mathbf{F_n} \\ \mathbf{R_n} = \mathbf{R_{n-1}} + \mathbf{T_{n-1}}(\mathbf{I} - \mathbf{G_n}\mathbf{R_{n-1}})^{-1}\mathbf{G_n}\mathbf{T_{n-1}} \end{cases} \tag{8}$$

where $\mathbf{F_n} = \mathbf{D_n} T_n \mathbf{D_n}^{-1}$, $\mathbf{G_n} = \mathbf{D_n} R_n \mathbf{D_n}$, $[D_n]_{v\tau} = \delta_{v\tau} e^{ik_0(n-1)d_z \cos\varphi_v}$, $[F_n]_{v\tau} = e^{ik_0(n-1)d_z(\cos\varphi_v - \cos\varphi_\tau)}[T_n]_{v\tau}$, $[G_n]_{v\tau} = e^{ik_0(n-1)d_z(\cos\varphi_v + \cos\varphi_\tau)}[R_n]_{v\tau}$, $\mathbf{T_N}$ and $\mathbf{R_N}$ are transmission coefficient matrix and reflection coefficient matrix of the nth row tube array respectively. In equation (8), the acoustic transmission property of the Nth row tube array can be calculated by iteration with n = 2, 3, …, N.

3. NUMERICAL AND EXPERIMENTAL RESULTS

3.1 Numerical Study on Acoustic Transmission and Reflection Coefficient of Tube Arrays

Applying the theory presented in above sections, we computed the transmission and reflection coefficients of some tube rows varying with the sound frequency, number of the tube-row and the structure of tube array. Fig.2 shows the influence of the sound frequency on the transmission and reflection coefficient of an array of 6 tube rows at *dx/d*=2.5, *dz/d*=3.0, d=42mm and t=1370℃. Fig.3 shows the influence of the tube spacing *dx/d*=2.5 on the transmission and reflection coefficient of an array of 10 tube rows at *kd*=2.0, *dz/d*=15.0 and d=57mm. Fig.4 shows the influence of the tube-row number N on the transmission coefficient of an array, at d_x/d=2.5, d_z/d=3.0, d=42mm. Fig.5 shows the transmission coefficient of an array varying with the tube row number and the sound frequency, at dx/d=1.25、dz/d=15.0、d=57mm. It is revealed that there are some stop-band and pass-band effects with the many tube rows when sound wave propagating through it. The stop and pass band distribution is related to the many tube rows structure parameter and temperature in boiler.

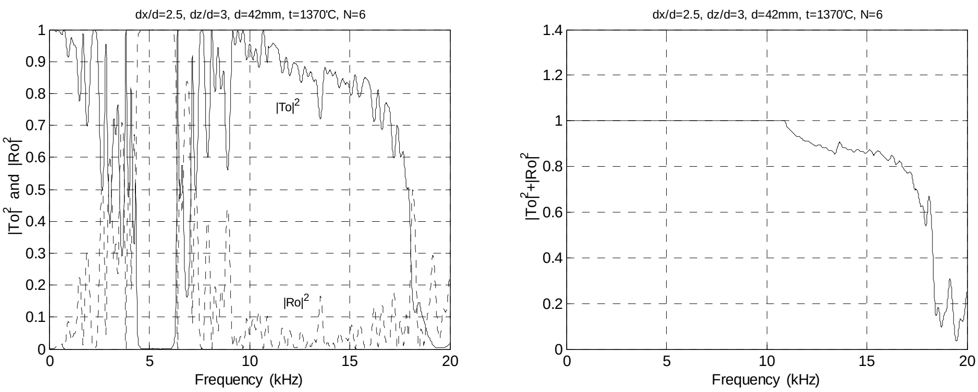


Fig.2 Influence of the sound frequency on the transmission and reflection coefficient of an array of 6 tube rows, at d_x/d=2.5, d_z/d=3.0, d=42mm and t=1370℃

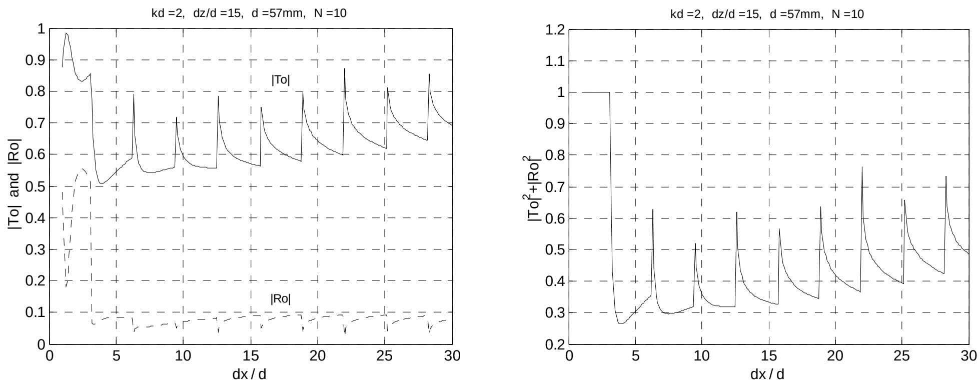


Fig.3 Influence of the tube spacing d_x/d=2.5 on the transmission and reflection coefficient of an array of 10 tube rows, at kd=2.0, d_z/d=15.0 and d=57mm

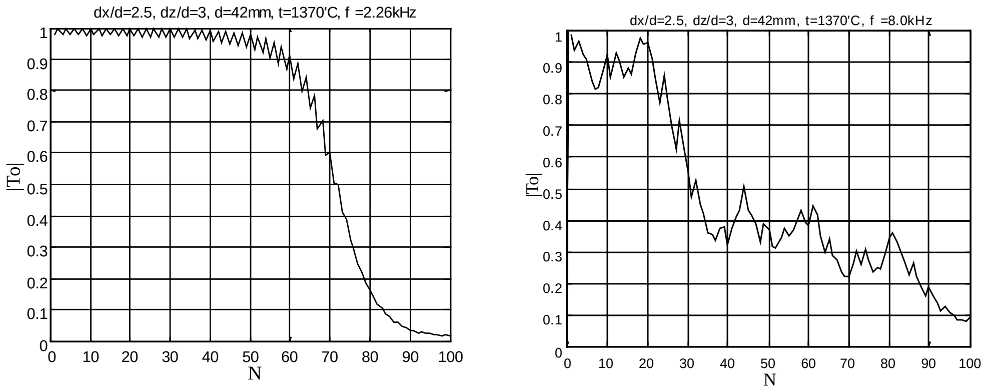


Fig.4 Influence of the tube-row number N on the transmission coefficient of an array, at d_x/d=2.5, d_z/d=3.0, d=42mm

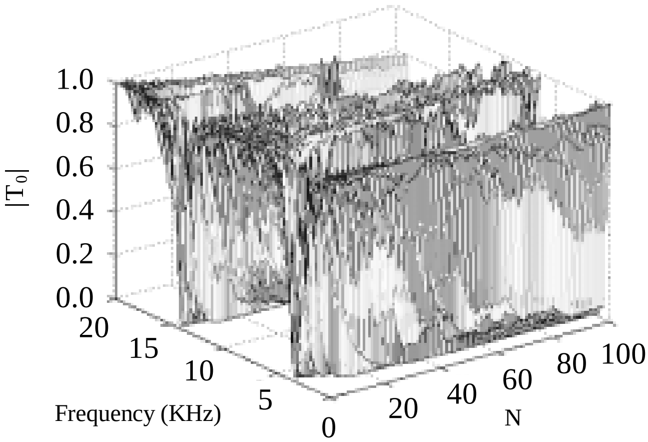


Fig.5 The transmission coefficient of an array varying with the tube row number and the sound frequency at d_x/d=1.25、d_z/d=15.0、d=57mm

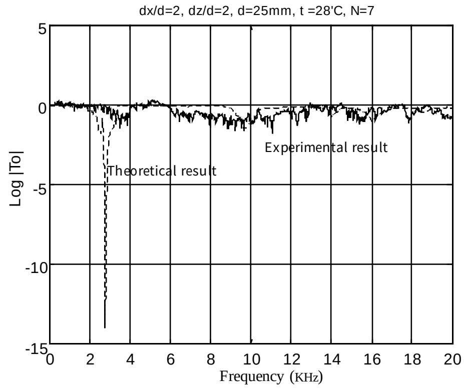
3.2 Experiment Study on Acoustic Transmission Coefficient of Tube Array by Electro-acoustic Spectral

The experiment on the acoustic transmission property of the periodic tube array structure is done by two sound sources (electro-acoustic source and leaking jet noise) respectively in semi-anechoic room of acoustic institute, Chinese Academy of Science.

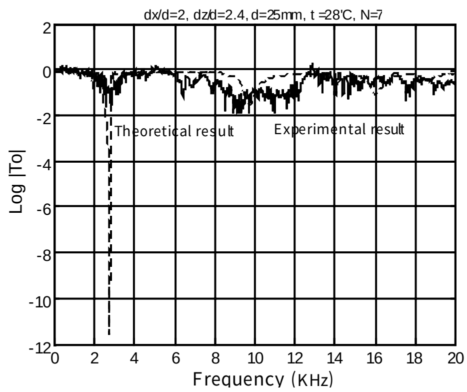
In experiment, the tube array is consisted by seven rows. The distances between two near rows are 5, 6, 8 and 10cm. every row is consisted of 15 steel tubes, whose outer diameter is 25mm and the distance between tubes (transverse direction) is 5cm. The electro-acoustic source is controlled by Spectra LAB and is set to be white noise (however, the spectral in high frequency is not uniform). In semi-anechoic room, the incidence spectral, transmission spectral and background spectral are tested from 0.3KHz to 20.0KHz. It is found that the pass band and stop band are really existed when sound wave passes through tubes array, and the result is accord with the theoretical calculation (in Fig.6).

3.3 Experiment Study on Acoustic Transmission Coefficient of Tube Array by Leaking Sound Spectral

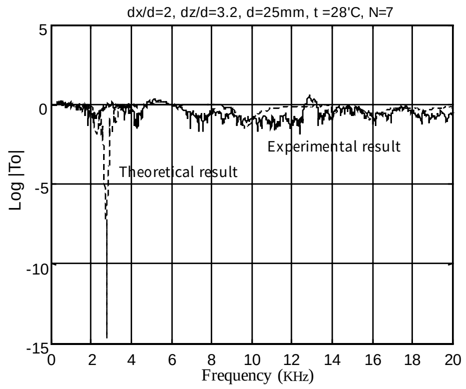
In experiment, the leaking jet sound of tube is used. The tube diameters are set to be 38mm and 60mm. The air pressures are set to be 0.5Mpa and 0.7Mpa. The leaking diameters are set to be 1mm and 2mm. In tube array, the tube distance of every row is 5.0cm, row distance is 18cm, and tube diameter is 25mm. In experiment, the distance between leaking point and nearest tube row is 27cm. The distance between microphone and nearest tube row is 15.5cm. Hence, the distance between microphone and leaking point increase by the number increasement of tube row. They are found by experimental and theoretical result that, firstly, the spectral property hardly varies when the leaking sound passed through tube array under 2000Hz, secondly, the spectral change can not be neglected when the frequency is higher than 2000Hz. Besides the pass effect and stop effect of tube array, the second sound radiation produced by the interaction between leaking jet and tube array influence the transmission spectral property even more seriously (in Fig.7).



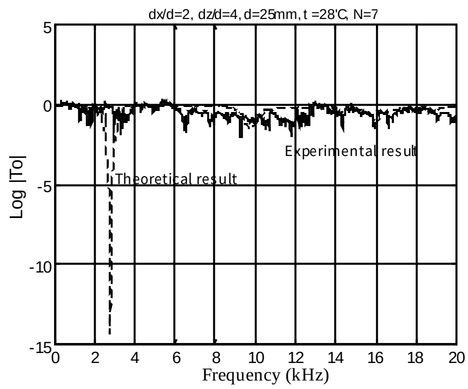
(a) 5×5(cm^2)



(b) 5×6(cm^2)

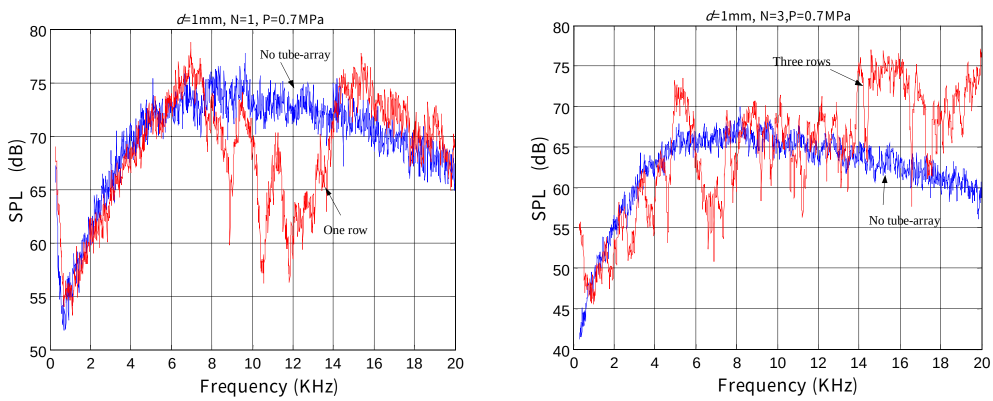


(c) 5×8(cm^2)



(d) 5×10(cm^2)

Fig.6 Compare the experimental results with theoretical one



(a) A set of one tube row (d_x=5cm) (b) A set of 3 tube rows (d_x=5cm, d_z=18cm)

Fig.7 Compare the sound transmission property foe one tube-row and three tube-row experimental results with no tube-row one

4. CONCLUSIONS

The transmission and reflection of sound waves in a set of tube rows has been examined in detail. One-dimensional arrays of tube as well as a series of several parallel tube rows were considered. It was found that the one-dimensional array of tubes acts like an acoustic diffraction grating. Below a critical frequency, where the tube spacing and the wavelength in the surrounding medium coincide, the grating acts like an elastic panel which transmits a plane incident wave in its original direction, but it is a choosing transmission. Above this critical frequency, a plane wave is scattered into more than one discrete direction. The transmission coefficient in the direction of the incident wave then decreases rapidly.

The transmission and reflection coefficients of a set of parallel equally spaced tube rows has been calculated, taking into account the multiple transmissions and reflections at each row. As same as the phononic crystals, the tube array structure has stop effect and pass effect on sound wave propagation, such as leaking sound. The cut-off frequency, pass frequency and bandwidth of leakage sound through different structure parameter heat exchanger tube array are calculated. The definition of “deaf-band” and “audible-band” of inner tube leakage sound of tube array are given. The experiments of sound propagation characteristic through tube array using electro-acoustic spectral and real air leakage spectral are studied respectively. It was tested that the “deaf band” position of electro-acoustic spectral is consistent with the theoretical estimation. The phenomenon is accord with which discovered by the international institute of "phononic crystal". The transmission properties of leakage sound spectral is well consistence with theoretical one in low frequency, and different in high frequency. The reason is that the second sound radiation is produced by the interaction between leaking ejection fluid and tube array. The leaking sound radiation in tube array includes leaking jet noise and the second order noise caused by the interaction between the leaking jet and tube array.

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