Numerical Simulation of Underground Pipeline Leakage Noise

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Abstract

In this study, the leakage noise and the pressure field generated by the underground pipeline leakage were calculated by the Computational Fluid dynamics (CFD) software ANSYS Fluent based on the Ffowcs Williams-Hawkings (FW-H) equation and Large Eddy Simulation (LES). Different leakage hole shape were carried out in the simulation. We considered two conditions for the pipeline: the pipeline was surrounded by the air and the soil simulated by the porous materia. The second one was closer to the real situation. In the first condition, the results demonstrated that the aerodynamic noise frequency mainly ranged from 0 Hz to 500 Hz that was in good agreement with the literature. The thin and ellipse shape with larger pressure loss got the maximum overall sound pressure level (OASPL) due to stronger interaction between the wall and the fluid. The farther the receiver was from the leakage, the OASPL obtained by the receiver was lower. In the second condition, the frequency range was mainly distributed under 300 Hz and was different from the first condition. Besides, the OASPL was also lower than the first condition. These results were due to the soil characteristics of reducing velocity and pressure that contributed to lower wall stress and pressure variation.

1. Introduction

The climate change nowadays has significantly altered the precipitation pattern that contributed to the increment of flood and drought. These phenomena resulted in the increasing risk of water scarcity in the earth. The underground water leakage prevention is an essential way to maintain water resources. Besides, the underground water loss also led to the problems of soil liquefaction and foundation hollowing that may cause many casualties during the earthquake. Therefore, the underground water loss prevention technology has become an important issue. There are several current detected method of underground water leakage and they can be divided into non-invasive method and invasive method. The invasive methods are used in the detection of underground water leakage such as smart ball and CCTV. The disadvantage of invasive methods is that sensors are difficult to move and take out in the silting pipelines. The non-invasive methods include traditional leakage detector and intellectual pipeline. The previous method has the disadvantages of immense manpower, slow search speed, dependence on experiences and non-automatic identification. The principle of the intellectual pipeline is to measure the decreasing value of the pipeline pressure [1][2]. It means that the high enough pressure is necessary in the pressure measurement. Hydrophone is a potential method to substitute traditional leakage detector, but depends on acoustic database with enough data, powerful algorithm, and undisturbed measuring environment. Computational Fluid Dynamics(CFD) is an useful tool to calculate the flow field and acoustic field in different conditions and has the advantage of less cost.

In this study, we surveyed the literatures related to the leakage noise of the simulation or experiment before. Chalgham et al. measured the decibel value in the location of the leakage as the sound acoustic power level of the sound source in the simulation [3]. The point source and the acoustic diffusion equation of the COMSOL software were used to simulate the acoustic field in the two inch pipe. Ben-Mansour, et al used ANSYS Fluent to conduct the simulation of the acoustic field and flow field in the four inch pipe [4]. The steady result was set as initial solution into the DES model to calculate the decibel value in the different locations of the pipe. The results of the FFT spectrum and the power spectral density spectrum showed that the leakage noise was obvious in the frequency range of 220 Hz to 500 Hz. The simulation results will be verified by the subsequent experiments. Perrier et al. applied the soild mechanics module, acoustic module, and the pipeline module of the COMSOL software to calculate the distribution of the acoustic field [5]. The results were imported into the database of the leakage location detection app that used to find the leakage location according to different pipe length and pipe material. Zheng et al. used ANSYS Fluent software to conduct the simulation of the power spectral spectrum of the 0.5 inch pipe [6]. The results demonstrated that the frequency was higher than 200 Hz. Fu et al. used ANSYS Fluent software to simulate the flow field and the flow rate of the circle leak hole and the

rectangular leak hole of the 2 inch pipe in the same back pressure [7]. The simulated result was verified by the experiment. Jujuly used ANSYS Fluent software to simulate the steady pressure field, flow field, and transient field of the submarine oil pipeline leakage [8].

The literatures above focused on the flow field, pressure field, and acoustic field of the pipeline. The impact of different shapes of the leakage hole and their leakage noise were seldom mentioned. The leak shape may be different in the real situation. Besides, the numerical model of the current study related to leakage noise were conducted by the pipe with leakage and atmosphere environment. However, most leakage happened in the underground environment surrounded by the soil in the real situation and difficult to observe. The acoustic characteristic may be changed in different conditions. Therefore, the impact of the shape of the leakage hole and soil will be calculated by the ANSYS software in this study.

2. Numerical model and setup

2.1 Ffowcs Williams and Hawkings equation

Ffowcs Williams and Hawkings put forward the Ffowcs Williams and Hawkings equation (FW-H equation) in 1969 [9]. The FW-H equation considered not only the turbulence but also the pressure perturbations generated by the moving solid boundaries in the field. The Ffowcs Williams & Hawkings equation (FW-H equation) as shown in equation (1).

$$\left(\frac{\partial^2}{c^2\partial t^2} - \nabla^2\right)p'(\mathbf{x},t) = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} - \frac{\partial}{\partial x_i}\left[p_{ij}n_j\delta(f)\right] + \frac{\partial}{\partial t}\left[\rho_0 u_n \delta(f)\right]$$
(1)

where $\mathbf{x}$ was the position of the receiver, t was the time that receiver obtained the sound, u_n was the velocity component normal to the solid surface, c was the sound velocity and p_{ij} was the compressive stress tensor. FW-H equation involved the time and spatial derivatives of integral terms. Farassat [10] rewrited the solution of FW-H equation and proposed the Formulation 1A applied in the ANSYS Fluent and useful to predict the aerodynamic noise caused by the fan, jet flow, and helicopter. He considered the subsonic flow condition which means the quadrupole volume integral term can be neglected and used the Leibniz integral rule to move the partial spatial derivative into the integration so that equation (1) could be solved as shown in equation(2).

$$p'(\mathbf{x},t) = \int \frac{\rho_0 \dot{v}_n + \dot{l}_r/c}{r(1-M_r)^2} + \frac{l_r - l_i M_i}{r^2(1-M_r)^2}$$
$$+ \frac{\rho_0 v_n + l_r/c}{r^2(1-M_r)^3}\left(r\dot{M}_r + cM_r - cM^2\right)dS$$
(2)

where the time of the equation (2) was in each retarded time, M_r was the Mach number of the moving solid source in the radiation direction, r was the radiation direction vector between the receiver and sound source surface, l_i was equal to $p_{ij}n_j$, and v_n was the surface velocity in the radiation direction. There were three source terms in equation (5). They represented quadrupole, dipole and monopole sources respectively. Quadrupole source was the source term in the solution of Lighthill's equation and it meant that the noise was generated by the turbulent flow of the fluid. Dipole source was produced due to the unsteady force distributed on the control surface which exerts on the fluid when the solid boundary was moving. Monopole source was generated by the volume displacement of the moving solid boundary.

The pressure perturbation obtained by FW-H equation could be used to calculate noise. Quantities of noise are evaluated in overall sound pressure level (OSPAL) with physical quantities unit dB. OSPAL was denoted by L_p and defined as the integration of ratio of acoustic pressure p_f and reference pressure p_{ref} whose value was 1×10^{-6} (Pa) in logarithmic form in each frequency of pressure spectrum as shown in equation (3).

$$L_p = 10\log_{10}\left(\int \frac{p_f^2}{p_{ref}^2}df\right)$$
(3)

2.2 Broadband Noise Source (BNS) model

Transient acoustic computations conducted by FW-H model were time-consuming, so ANSYS Fluent offered the other acoustic model, Broadband Noise Source model (BNS model), also called Boundary Noise Source model was a more time-saving and useful tool. It only required steady RANS turbulent model results and be able to locate sound sources in the flow field. Total surface sound power P_A emitted from the rigid body surfaces could be integrated on the rigid body surfaces.

$$P_A = \int_S I(\mathbf{y})dS$$
(4)

$$I(\mathbf{y}) = \frac{A_c(\mathbf{y})}{12\rho_0\pi c^3}\overline{\left[\partial p/\partial t\right]^2}$$
(5)

where $I(\mathbf{y})$ was the surface sound power contributed by per unit area of the rigid body surfaces, was correlation area and mean-square sound pressure term, $A_c(\mathbf{y})$ was correlation area and mean-square sound pressure term is estimated by turbulent kinetic energy, turbulent dissipation rate and shear stress in the near boundary layer of RANS turbulent model results to avoid mean-square pressure term becoming zero. The local surface acoustic sound power level could be computed in Equation (6) and its unit was dB.

$$L_w = 10\log_{10}\left(\frac{I(\mathbf{y})}{I_{wref}}\right)$$
(6)

where reference surface sound power per unit surface I_{werf} was 10^{-12} W/m².

2.3 Numerical model

The CFD software ANSYS Fluent was used to simulate the pressure field and acoustic field. No soil surrounding environment and soil surrounding environment were set as shown in Figure 1 and Figure 2 and called condition 1 and condition 2. The length and diameter of the pipe wee 120 in and 2 in respectively. The boundary condition was set by inlet velocity 2 m/s, outlet pressure 2 bar, leakage

outlet bar 1 bar, and no-slip on the wall. The fluid was water. Four receivers were located in the position of 1 m, 1.2 m, 2.6 m, and 2.8 m from the inlet along the centra line of the pipe. The leakage was located from the end of pipe in 12 in. The conditions of no leakage, square(width: 0.22 in), circle(diameter: 0.25 in), ellipse(major axis: 6.35 mm, minor axis: 1.5875 mm), and slender(length: 31.5 mm, width: 1 mm) with same leakage area are conducted in the simulation.
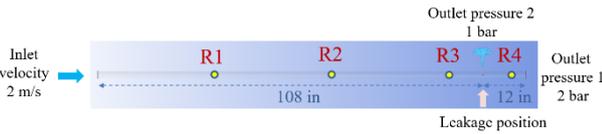

Figure 1: Computational zone in condition 1.
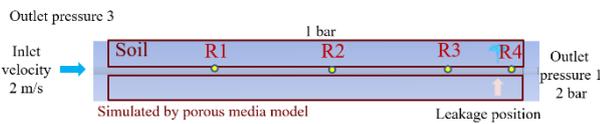
Figure 2: Computational zone in condition 2.

The standard k-ε model was applied in the steady state mode. In order to save computation cost for the computation, we started with the steady flow field calculation and used it as initial solution to conduct coupling calculation of flow field and acoustic field in the transient mode. The Large Eddy Simulation (LES) was used to capture the impact of eddies on the solid body and acoustic results in the transient mode. The time step was were set as 10^{-4} (s). Different size of unstructured tetrahedral mesh were conducted in the mesh of computational zone. The mesh size of straight pipe, zone near leak hole, and zone of leak hole were 5×10^{-3} (m), 5×10^{-4} (m) and 2×10^{-4} (m) respectively to meet the requirement of CFL condition and mesh independence analysis as shown in Figure 3. The mesh independence analysis was adopted before calculation in each condition to check for the mesh quality. The surrounding soil was simulated by the porous media model described by the non-linear Darcy-Forchheimer equation as shown in equation (7) to simplify calculation process.

$$\Delta p = \left(C_2 \frac{1}{2} \Delta n \rho |v| v_i + \frac{\mu \Delta n}{\alpha} v_i \right) \quad (7)$$

where C_2 was the inertial resistance coefficient (1/m), $1/\alpha$ was the viscous resistance coefficient (1/m²), Δn was the soil thickness, μ was the dynamic viscosity, v was the velocity, and ρ was the flow density. C_2 and $1/\alpha$ were set 1.2×10^{10} and 3.5×10^{5} according to ANSYS Fluent manual respectively.
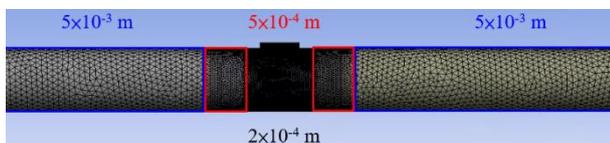

Figure 3: Mesh of computational zone

3. Results and discussion

The noise generated by the pipe flow and leakage involved three mechanisms of acoustic source. The first one was the water interacting with the wall of leakage hole wall and the pipe wall. The second one was the jet flow from the leakage hits the surrounding material such as soil, concrete or rock. Both of these mechanisms were dipole sound source and more obvious in the contribution of noise. The third one was the noise generated by vortexes in the pipe also called quadrupole sound source. Therefore, we discussed the simulation results including the static pressure distribution, steady acoustic results and transient acoustic results in the conditions of pipe surrounded by the air and soil in this section.

3.1 Static pressure distribution

Figure 4 and Figure 5 showed the static pressure distribution of the pipe flow in the condition of circle and ellipse shape which represented the symmetrical shape and the slender shape respectively during the leakage happened. It showed that the fluid in the hole formed an negative pressure zone that caused the fluid flowed in the hole along the streamline to the atmosphere environment. The flow with high velocity and turbulent kinetic energy hit the hole wall, caused the strong pressure variation on the wall and contributed to leakage noise. Figure 6 showed the results of the pressure variation rate along the centerline in the axial direction z. It demonstrated typical trends that the pressure variation rate first increased and then decrease to original static pressure value. Both conditions seemed no specific differences from the pressure variation results to explain the noise generating mechanism.
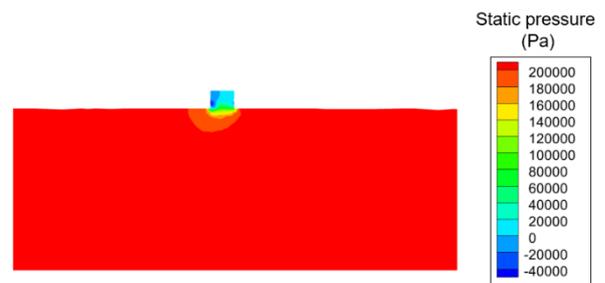

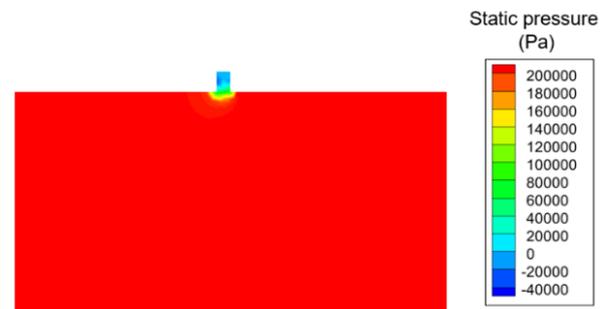**Figure 4**: Static pressure distribution of circle shape leakage

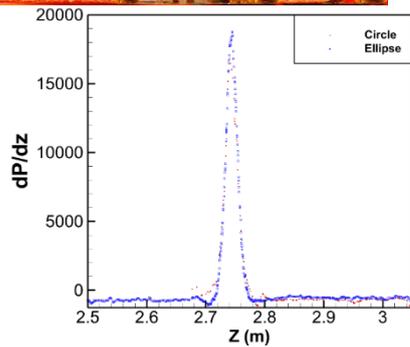**Figure 5**: Static pressure distribution of ellipse shape leakage

Figure 6: Pressure variation rate in axial direction

3.2 Acoustic results of pipe surrounded by the air

The FFT spectrum of four receivers were presented in Figure 7 to Figure 10. The vertical axis and horizontal axis represented sound pressure level and 1/3 octave band with clearer presentation of low frequency distribution respectively. The results showed that the leakage noise mainly distributed in the low frequency range about (0 to 500) Hz when leakage happened in comparison to the condition of no leakage. These results were in good agreement with literatures [4][6]. The sound pressure level value changed with different shape, but the distributed trends were similar. The OSPAL of four receivers were demonstrated in Table 1. The OSPAL of no leakage was about 152 dB. We found that the thin shape and ellipse shape presented a little larger OSPAL value. The circle shape and square shape took the second place. The OSPAL value decreased with farer transmission distance. When the underground water leakage occurred, the mechanism was that the high velocity fluid interacting with the leakage hole wall generated high shear stress and pressure variation which became sound source and generated sound wave. The ellipse shape and thin shape had larger pressure resistance than other shape, so the interaction between the fluid and hole wall got stronger in the same back pressure 1 bar. These phenomena also reflected on the BNS model. The transient results calculated by the FW-H equation clearly presented the FFT spectrum generated by the sound sources, but this method took long time to complete the simulation. The 8-core calculation was applied to conduct transient simulation and decrease calculation time in this study. The BNS model that had lower calculation time and useful to find sound sources in the system was used to calculate the surface acoustic power level of sound source. Figure 11 showed the distribution of the surface acoustic power level on the wall of the no leakage condition. The surface acoustic power level averagely distributed on the wall and the maximum value was 61 dB. Figure 12 demonstrated results of surface acoustic power level of other conditions. It was obvious that the hole wall formed an sound source. The maximum surface acoustic power level of conditions of square, circle, ellipse and thin were 119 dB, 133dB, 139 dB and 145 dB respectively. These magnitude trends were similar with the FFT spectrum in the low frequency range.
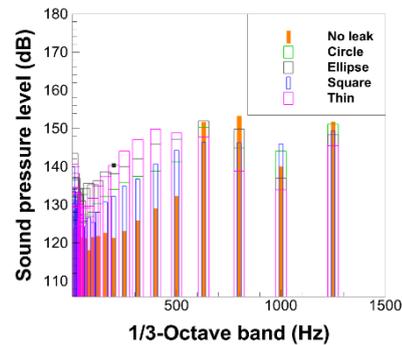

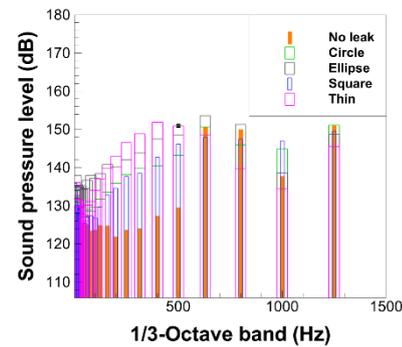Figure 7: FFT spectrum of R1 in condition 1

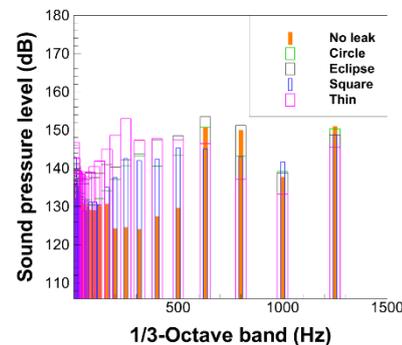Figure 8: FFT spectrum of R2 in condition 1
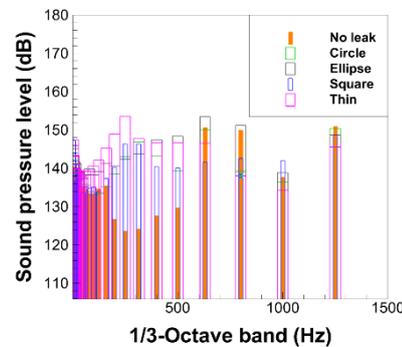

Figure 9: FFT spectrum of R3 in condition 1

Figure 10: FFT spectrum of R4 in condition 1

Table 1: OASPL (unit: dB) in condition 1

	Square	**Circle**	**Ellipse**	**Thin**
R1	156	158	159	157

R2	157	158	159	158
R3	157	159	160	161
R4	159	159	161	161
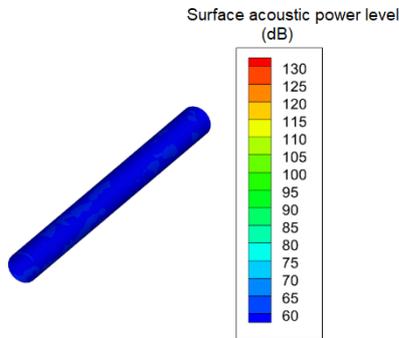
Figure 11: Distribution of surface acoustic power level of no leakage condition
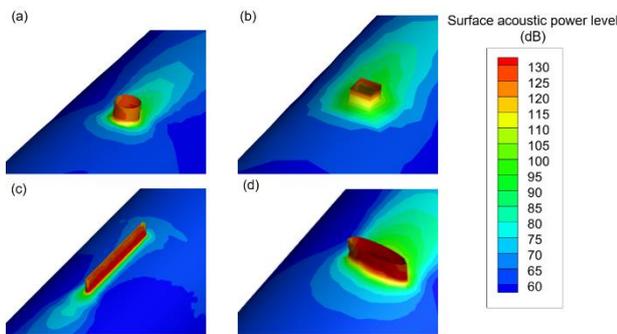
Figure 12: Distribution of surface acoustic power level of leakage in condition 1 (a)circle(b)square(c)thin(d)ellipse

3.3 Acoustic results of pipe surrounded by the soil

We compared the results of pipe surrounded by the air and soil. The ellipse shape and thin shape represented the slender shape. Since the shape of ellipse was similar with the shape of thin which was close to the real leakage and more representative, the simulation of shape of ellipse was excluded. The results showed that the leakage noise mainly distributed in low frequency range that under 300 Hz as shown in Figure 13 to Figure 16. There were no obvious differences in the high frequency range and even the sound pressure was little higher than other conditions. This meant that the soil led to different acoustic characteristics of leakage noise in comparison to the condition of pipe surrounded by the air. The trend of OASPL value was close to the results of pipe surrounded by the air as shown in Table 2. The surface acoustic power level distribution was also calculated as shown in Figure 17. It demonstrated that the surface acoustic power level was lower than the results of pipe surrounded by the air. The maximum surface acoustic power level of were 83 dB, 84 dB and 98 dB respectively. The reason was that the porous media had the characteristics of decreasing pressure and velocity. These characteristics contributed to reduction of pressure, wall stress, turbulent
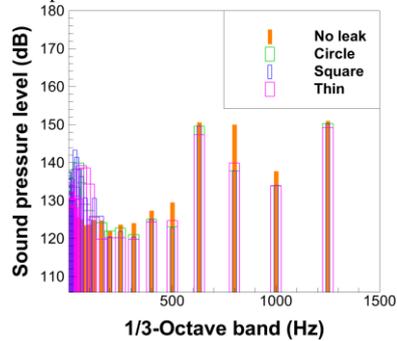
kinetic energy and turbulent dissipation rate of the fluid in the leakage. Thus, the noise became lower.

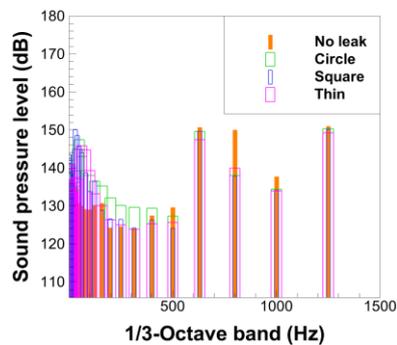**Table 2:** OASPL(unit: dB) in condition 2

	Square	Circle	Thin
R1	154	154	159
R2	156	155	159
R3	160	158	160
R4	161	160	162
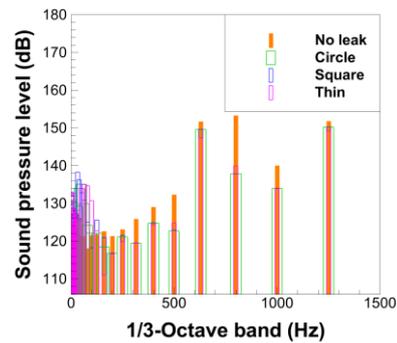
Figure 13: FFT spectrum of R1 in condition 2

Figure 14: FFT spectrum of R2 in condition 2
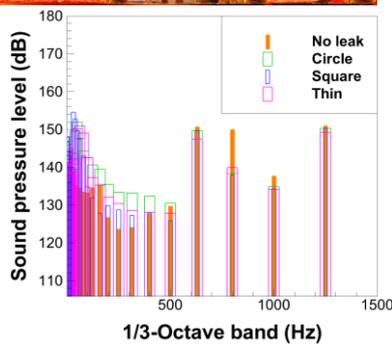

Figure 15: FFT spectrum of R3 in condition 2

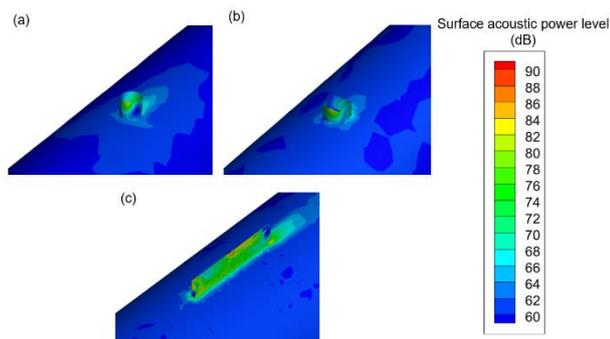**Figure 16**: FFT spectrum of R4 in condition 2

Figure 17: Distribution of surface acoustic power level of leakage condition in condition 2 (a)circle(b)square(c)thin

7. Conclusion

(1)In this study, the transient FW-H equation and steady BNS model were applied to conduct simulation. The results of both model were in good agreement.

(2)Both conditions presented different acoustic characteristics. The leakage noise generated by the pipe surrounded by the air ranged from 0 Hz to 500 Hz. And the pipe surrounded by the soil ranged from 0 Hz to 300 Hz lower than the other condition.

(3)The OASPL of the pipe surrounded by the air were higher than the other condition with different shapes of hole. The reason was that the porous media had the characteristics of decreasing pressure and velocity. These characteristics contributed to reduction of pressure, wall stress, turbulent kinetic energy and turbulent dissipation rate of the fluid in the leakage. Thus, the noise became lower.

(4)Different shapes of hole demonstrated the same trends of sound pressure level in the FFT spectrum and OASPL in both conditions. The slender shape showed the higher OASPL value than the symmetrical shape. The reason was that the slender shape had larger pressure resistance than other shape, so the interaction between the and the got stronger in the same back pressure 1 bar.

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