Investigation of Sound Inducing Fluid Dynamics at Pipe Leak and Their Influences on Acoustic Emission Signals
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Abstract
This study aims to investigate the sound inducing fluid dynamic behaviour of a pipe section with a leak for two different leak configurations and the influence of fluid dynamic changes on acoustic emission (AE) signal features. It is found that turbulence and cavitation occur at the leak vicinity under high pressure. The intensity of these fluid dynamic changes is strongly related to the severity of the leakage. The AE responses to these occurrences are symptomatic to the leak severity. Interestingly, the cavitation is responsible for increasing AE RMS value, indicating severity of the damage.

Keywords
Acoustic emission (AE) technique; numerical study; cavitation; turbulence; AE RMS.

Introduction
A leak in a pipe generates sound waves when the fluid escapes through the leak. The sound generation is mainly associated with the turbulence in the leak vicinity. Additional events such as cavitation could occur and contribute to the sound generation at the leak vicinity [1]. In practice, it is not always possible to identify the leak sound generation phenomena. Computational fluid dynamics (CFD) simulation of a pipe can identify the events that occur at the leak vicinity for specific pipe dimensions and fluid properties. Understanding the sound generation phenomena at the leak is extremely important, as condition monitoring techniques of the pipeline are designed based on this knowledge. Usually, turbulence for internal flow occurs around $Re=10^4$-10$^5$ and causes sound generation [1]. Kaewwaenwoi et al. [2] defined the sound power for internal valve leakage from the turbulent flow as:
\begin{equation}
P_s = \frac{\rho u^3 \pi r^2}{\alpha^2}
\end{equation}
where, $P_s$ is the sound power (Watt), $\rho$ is the fluid density (kg/m$^3$), $V$ is the turbulent jet velocity (m/s), $D$ is the valve size for internal valve leakage (m), and $\alpha$ is the sound velocity in the fluid (m/s). This leakage sound generates surface vibrations in the structure. An acoustic sensor with a strong radial response is sensitive to this sound [3].

Acoustic emission leak detection technique is selected in this study because this technique has two significant aspects over other non-destructive techniques. These are i) AE energy is released from the test object, which is recorded by the equipment, unlike other methods where external energy is applied to detect the fault; ii) AE is capable of detecting a dynamic process (crack, plastic deformation etc.) occurring during degradation of structural integrity [3]. Acoustic emission (AE) is a transient phenomenon where elastic energy is released from a source within or on the surface of a stressed material [3, 4]. Previous studies [5, 6] found that fluid leakage generates continuous type (in the time domain) AE signals. RMS of AE signal is a more suitable parameter to interpret the continuous signals compared to other parameters (e.g. rise time, amplitude, peak, duration). AE RMS is directly related to the AE source mechanism. Thus, RMS has the potential to be related to the structure damage and damage severity assessment [15].

A couple of studies were conducted to observe the relationship between the AE RMS and the fluid leakage [7-9]. The generated AE signal can be measured in the form of acoustic velocity, $u$ (m/s), which is directly proportional to acoustic pressure, $p$. Sound power ($Ps$) generated from the turbulent flow is directly proportional to the pressure squared ($Ps \propto p^2$). Therefore, acoustic velocity, $u$, can be expressed as $Ps \propto u^2$. Here $u$ is the RMS value of the AE signals. Thereby, sound power is directly proportional to the squared RMS of AE signals as $Ps \propto AE_{RMS}^2$ [9]. Miller and McIntire [4] suggested that pseudo source of AE signals largely attribute to sound power generation at the leakage. A pseudo AE source refers to the process in metals such as leakage, cavitation, friction [3]. All these research works focused on internal leakage to develop a relationship between fluid parameters and AE signals. The external and internal leakage refer to the fluid lost in the atmosphere or displaced to another location of the system, respectively [10]. Thus, leaks in a pipe are considered as external leakage.

To best implement the AE technique within pipe condition monitoring, it is critical to understand the clearly how the sound induced fluid dynamics (such as turbulence, cavitation) change with different leak dimensions and how these changes influence the acoustic emission generation. Thus, this study aims to investigate sound generation fluid dynamic behaviour at the vicinity of a leak for two different leak configurations and the influence of fluid dynamic changes on AE signal features. Two small leaks with 1 mm and 0.3 mm diameter are selected for this study, considered as a large and small leak, respectively. The aspect ratio (pipe wall thickness to leak diameter) of both leak configurations are 2.5 and 8.33, respectively.

Numerical Method and Computational Domain
The fluid flow of an incompressible fluid is governed by the continuity equation and momentum conservation equation which are expressed as:
\begin{equation}
\frac{\partial u_i}{\partial x_i} = 0
\end{equation}
\begin{equation}
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial p}{\partial x_i} + \nabla \cdot \left( \tau_{ij} \right)
\end{equation}
where, $p$ is static pressure, and $u_i$ is the velocity component in $i$ direction. The numerical simulation uses finite volume method (FVM) to solve the governing equations (2-3) in ANSYS Fluent. The dimensions of the computational domain in figure 1 are adopted from the experimental set-up. The 3D geometries are created in SOLIDWORKS and then connected to Fluent for mesh generation, problem solution, and post-processing purposes. The boundary conditions of the pipe section with a leak can be found in table 1. To simulate the lab condition, pressure boundary conditions are selected. Liquid water with density 1000 kg/m$^3$ at 15°C and viscosity 0.001003 kg/m-s is selected as a flow medium. The SIMPLE algorithm is applied for the simulations in this study. Second order upwind scheme is selected for momentum, turbulent kinetic energy, and specific dissipation rate to obtain accurate calculation. Least squares cell-based scheme and second order scheme are selected for gradient, and pressure discretisation, respectively. The convergent criteria for all the studies are set such that
residual in the control volume for each equation falls below 1e-6.

![Figure 1. Schematic of computational domain](image)

| Boundary conditions                  |
|--------------------------------------|
| Pipe inlet                           | Pressure inlet |
| Pipe outlet                           | Pressure outlet |
| Leak outlet                           | Pressure outlet |
| Pipe wall & leak wall (pipe wall thickness) | No-slip stationary wall |

![Table 1. Summary of Boundary Conditions](image)

The mesh distribution of the 3D domain of both leak configurations can be found in Figure 2. Pitch conforming algorithm is applied to the 3D computational domain where a tetrahedron mesh shows good convergence. A refined grid is introduced close to the leakage area, and near the pipe wall for this study, as shown in Figure 2. For a grid sensitivity study, the global grid size is refined while other parameters are kept the same. Different grid sizes are generated to achieve a converged mesh size based on pressure drop. Mesh independence is achieved at 264,483 and 286,332 nodes for small and large leak configurations, respectively.

**Experimental set-up**

The experimental set-up has two parts: test set-up and AE data acquisition equipment. The test set-up in figure 3 consists of a 21.5 mm inner diameter with 2.5 mm wall thickness steel pipe section (900 mm long). Two pressure gauges are installed at the upstream and downstream of the pipe to control pipeline pressure and record the pipe outlet pressure, respectively. A Physical acoustic corporation (PAC) resonance sensor (AE R15 α) is mounted on the surface of the pipe section to capture AE signals. The AE sensor is connected to a high-pass (100 kHz) amplifier via a pre-amplifier. LabVIEW software is used for signal recording through communication with NI 9223 module.

![Figure 3. Pipe section with AE sensor position](image)

**Results and Discussion**

The linear proportional relationship between sound power due to turbulent flow and generated AE signal’s RMS has been adopted in this study for the external leakage. This relationship is valuable to discriminate a healthy pipe from a damaged/leaked pipe. To investigate this relationship and understand the influence of fluid dynamics on the AE signals for two different leak configurations, the results from the numerical study are compared with the experimental results.

**Numerical results and Discussion**

Figure 4 shows the velocity contour at the centre plane of the leak (x = 0) in the y-z plane for both leak configurations at 300 kPa inlet pressure. For both leak configurations, a rapid transition of velocity can be observed where the highest velocity presents at the centre of the leak. A conical region of the highest velocity is observed in the leak centre. The area of the highest velocity exists in the wider region adjacent to the leak inlet and tapers as it proceeds towards the leak outlet. Thus, the impacts on the pipe wall due to the velocity changes would be profound adjacent to the pipe wall. Even though the leak dimension is small, the change in velocity gradient clearly indicates the presence of a leak. To determine whether the turbulence present in the leak vicinity has enough energy to generate detectable sound, Reynolds number, Re, is calculated. The calculated Re for both leak aspect ratios are 23,818 and 6424, respectively. As suggested by Pollock and Hsu [1] and Kim et al. [11], that Re needs to be in the range (10^3-10^5) to generate detectable sound signals. Thus, the turbulence at the leak vicinity has enough energy to generate sound that can be detected by the acoustic sensor. The sound energy generated from the small leak has less sound energy compared to the large leak.

![Figure 4. Turbulence at leak vicinity for two leak conditions](image)

| Configuration | Theoretical | Numerical |
|---------------|-------------|-----------|
|               | Leak exit velocity, m/s | Sound power, W | Leak exit velocity, m/s | Sound power, W |
| 1 mm          | 24.5         | 2.03e-08   | 21                   | 1.49e-08      |
| 0.3 mm        | 1.83e-09     | 5.73e-10   | 19                   |                |
| No leak       |              | 5.73e-10   | 3.5 (pipe outlet velocity) | 2.53e-11      |

![Table 2. Theoretical and Numerical Sound Power due to Turbulent Flow](image)
To determine the amount of sound generated at the leak vicinity, the sound power equation found from literature (refer equation (1)) is applied in this study. In table 2, theoretical and numerical calculated sound power are presented for healthy and damaged pipe configurations. Theoretical leak exit velocity is calculated from an expression found from literature considering Bernoulli’s equation. The expression is not dependent on leak dimension. Thus, theoretical leak exit velocity is the same for both configurations. For the numerical sound power calculation, the leak exit velocity is adopted from the velocity contour of the simulation study. To obtain a baseline sound power and compare with the damaged pipe configurations, healthy pipe sound power is included where pipe outlet velocity is considered to calculate sound power. As the sound power expression is for turbulent flow, the sound is expected to be generated from the healthy pipe if there is enough turbulence present inside the pipe. It is clear from table 2 that the sound power generated from a large leak is more profound compared to the small one. There is also a quite clear difference in sound power for healthy and damaged pipe conditions. It is found that the sound power generated at a leak is relevant to the leak dimensions (diameter of leak hole, leak length/pipe wall thickness). When the pipe wall thickness is fixed, the sound power varies directly proportional to the leak diameter [12], which is visible in this study. Thus, having knowledge of leak induced sound power is valuable to estimate the leak severity.

A pipe wall thickness sensitivity test is performed for a 1 mm leak to understand the influence of the pipe wall thickness on the cavitation formation at the leak vicinity. The test is performed with five different pipe wall thicknesses (Figure 7), starting from an infinitely thin pipe wall to 2.5 mm pipe wall thickness. As the pipe wall thickness starts to increase from the infinitely thin wall, the pressure distribution at the leak vicinity appears differently. The cavitation formation related to negative pressure at the leak vicinity for different pipe wall thicknesses is shown in figure 8. For the infinitely thin pipe wall, there is no negative pressure observed, and the pressure drops to 6 kPa. Thus, it can be said that there is no potential cavitation formation occurring in this case. The negative pressure starts to appear as the pipe has a minimum wall thickness (0.25 mm). With the increase in pipe wall thickness, the static pressure drops to negative pressure significantly. Thus, it can be said that cavitation formation occurs at this negative pressure. This pipe wall thickness study shows that cavitation is highly symptomatic with the pipe wall thickness. Therefore, reducing pipe wall thickness could help to avoid the adverse impact of cavitation on the leak vicinity.

**Experimental results and Discussions**

From the CFD simulation in this study, it is found that at the leak vicinity, there are two AE signal generating events present, including turbulence, and cavitation. It is known that while turbulent flow generates continuous AE signals, cavitation generates burst type AE signals. For such a continuous signal, RMS is a suitable candidate for extracting leakage relevant information [14, 15]. Table 3 represents the RMS value of AE signals at three different conditions at 300 kPa pipeline pressure. The AE RMS values of the small leak and the large leak are 10 times and over 200 times larger than healthy condition. Thus, any increase in AE RMS value for a healthy pipe suggests damage. At a fixed pressure and pipe wall thickness, the higher AE RMS indicates that more elastic energy is released from a large leak compared to a small leak.

Table 3 verifies the linear relationship obtained from the literature for external pipe leakage. The relationship states that sound power is directly proportional to the square of AE RMS. The sound power is calculated based on the numerical results, while squared AE RMS is calculated from the lab tests. The
sound power generated by the leak is directly influenced by the turbulent jet velocity. The turbulent jet velocity also influences AE RMS (i.e. elastic energy). Interestingly, numerical sound power magnitude is less than experimental AE RMS magnitude. For the numerical sound power calculation, only the turbulence effect at the leak vicinity is regarded. Cavitation is not considered in this calculation. AE instrumentation is designed to detect structural or liquid borne sound that is generated by a source [16]. Thus, AE signals are the collective effect of turbulent flow and cavitation at the leak vicinity. Thereby, the sound power obtained from the numerical study should always be less than the experimental AE signals. Additionally, there is a big magnitude difference in sound power and AE RMS value between two leak configurations. The answer is found in the numerical study. For the large leak, cavitation formation is significant, which results in increased sound power as well as AE RMS value. The relationship between sound power and AE RMS enables assessment of the damage severity based on sound power and RMS of AE signals with leak size.

| Conditions | Sound power from CFD, P (Watt) | AE RMS from experiment (Volts) | AE^2 RMS from experiment (Volts^2) |
|------------|-------------------------------|-------------------------------|-----------------------------------|
| 1 mm leak  | 1.49e-8                       | 4.80e-3                       | 2.30e-5                           |
| 0.3 mm leak| 5.73e-10                      | 2.14e-4                       | 4.54e-8                           |
| No leak    | 2.53e-11                      | 2.30e-5                       | 5.29e-10                          |

Table 3. Sound Power and AE RMS of Pipe Leakage Data

**Conclusion**

Numerical models were developed to investigate the fluid dynamic behaviour at two different leak configurations. It was found that turbulence and cavitation occurred at the leak vicinity under high pressure and the intensity of these fluid dynamic behaviours was symptomatic with leak severity. An experimental study was conducted to observe the influence of fluid dynamic changes at the leak vicinity on AE signals. The findings from this study showed that a specific AE signal feature (AE RMS value) was strongly symptomatic of leak characteristics (e.g. presence and severity) based on fluid dynamic changes. The sound power that obtained from the numerical study is in lower magnitude compared to the AE RMS because AE signals recorded all the physical phenomena. Particularly, cavitation formation was responsible for increased AE RMS value, indicating damage severity. Cavitation was found to be more significant for thicker pipe walls compared to the thin pipe wall sections.

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