Design and numerical analysis of a test-rig for the study of pipe-leak generated acoustic emissions

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ABSTRACT
This paper focuses on the design of a pipe-pump system for use in conducting research on the topic of pipeline condition monitoring using acoustic emission sensors. Analysis of acoustic emission properties, pipe leak fluid dynamics and frequency caused by fluid dynamic events are discussed to support the design of the test-rig and inform the future analysis of the acoustic emission signals. Computational fluid dynamics is conducted on a simulated leak with varying parameters to ensure that the design was suitable for test and verification of this type of condition monitoring. Plans for future work with regards to conducting testing on this pipeline are also discussed to support verification of the use of acoustic emission sensors for detecting and locating pipeline leaks.

1. INTRODUCTION
The objective of this research project is to design a pipeline-pump simulator (test-rig) to conduct condition monitoring on pipes using acoustic emission sensors. This project will also investigate the relationship between acoustic emission properties (e.g. frequency, modulations) and operating conditions/leak severity. Previously, acoustic emission testing has predominantly been used to monitor static structures (Miller, 1987). The methodology used in such applications will be adapted, in conjunction with fluid dynamics theory, to identify and locate leaks within a piping system.

Acoustic emission testing has typically been conducted on materials while using an external excitation in order to produce a guided acoustic wave. Far less research has been undertaken on adapting this sensor technology (and the related signal analysis) to detect the presence of leaks, pump cavitation, or other aspects of fluid dynamics simply by measuring the acoustic waves produced in the fluid and transferred to the pipe.

Pipeline leaks are common occurrences that can affect many sectors with the majority of financial loss occurring when they appear within the energy sector. An inability to swiftly and conveniently detect a leak can result in increased downtime of operations with consequently high loss of earnings. An example of this occurred recently at AGL's Lidell Power Station with outages as a result of an external boiler tube leak on March 21, 2016. In response, AGL had to shut down two of their four boiler units resulting in for a calculated loss of $20 million over two months (Orton, 2016). Developments in condition monitoring through research, such as acoustic emission (and microphone) testing, could result in decreased downtime in such examples. The research undertaken for this project could provide foundations for a new method of identifying pipeline leaks and is an important step in improving the efficiency of maintenance and repairs and reducing potential downtime in operation.

2. ACOUSTIC EMISSION
Acoustic emission (AE) is sensitive to changes in a materials microstructure (Kim, Yang, & Lee, 2011) (Vallen, 2002). This makes acoustic emission testing a useful tool for monitoring the structural integrity of a system while being non-destructive. An advantage of this testing method over other non-destructive methods is the ability to detect signals in real time. This condition monitoring technique is performed by detecting transient elastic waves in a material. These waves are typically generated by the rapid release of energy from a localised source in the material (e.g. cracks propagating, impacts, fast changes in surface pressure). Acoustic emission signals can be broken into either bursts or continuous emission. Burst acoustic emissions are related to individual events with short and defined time durations (Miller, 1987). Continuous acoustic emissions are sustained signals produced by overlapping events (Miller, 1987). Examples of the two are shown in Figure 1 and were obtained on a rotating machine test-rig at Queensland University of Technology.

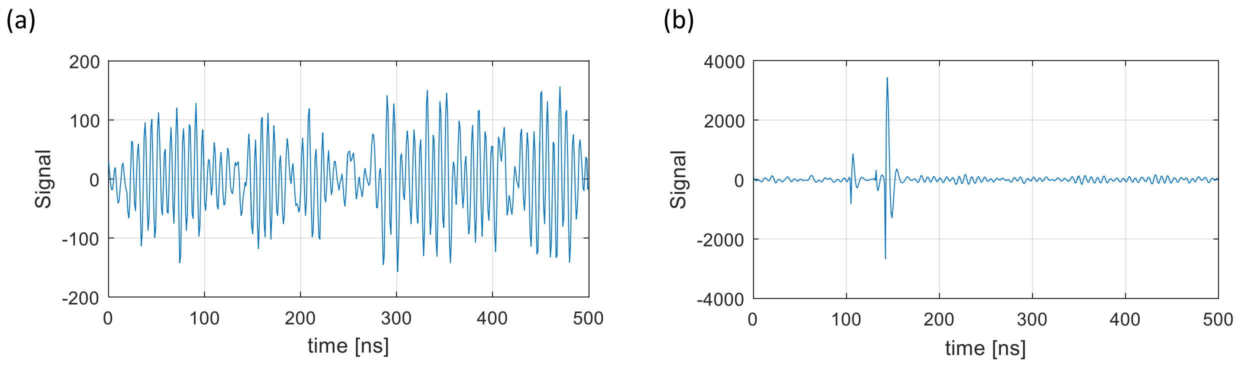

Figure 1: Acoustic emission signals (a) Continuous (b) Burst

A leak within a pipeline is expected to have a continuous nature, possibly containing modulation frequencies due to the turbulent flow through the orifice (see further discussion in the numerical simulation in Section 5).

Acoustic emissions tests are conducted using one or more sensors, preamplifiers and a data acquisition device. Acoustic emission sensors are typically piezoelectric sensors which transduce a travelling acoustic wave into an electric measurement (Mostafapour & Davoodi, 2013). The ability to detect an acoustic emission far from the source, combined with the use of multiple acoustic emission sensors, also allows for the utilisation of this condition monitoring technology for source location (Serridge & Licht, 1987).

Leak location can be performed using two AE sensors (Maninder, Dixon, & Flint, 2010) placed either side of the leak. The location algorithm computes the time difference between the acoustic emissions, measured at the two sensor locations, and compares it to the wave propagation speed to obtain an estimate of the position.

3. FREQUENCY ANALYSIS OF PIPE LEAK PHENOMENON

Leaks in a high pressure pipe generate stress waves within the pipe walls across a wide range of frequencies, typically within the range of 1 kHz-1 MHz (Kim et al., 2011). However, in this research it is expected that this continuous acoustic emission contains, either as a distinct harmonic or as a modulation of the continuous wide-band phenomenon, a characteristic frequency representative of the geometry of the leak and the key fluid conditions represented in the simple pipe diagram of Figure 2.

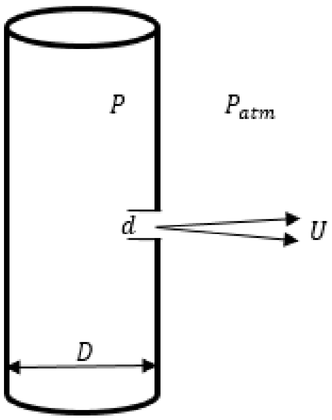

Figure 2: Pipeline leak key geometry and fluid conditions

In particular, the key parameters expected to influence the frequency content (or modulation) of AE are:

- U is the mean velocity through the crack
- d is the mean orifice diameter

- D is the pipe inside diameter
- P is the pressure inside the pipeline, with P_{atm} indicating the atmospheric pressure

The likelihood of significant production of acoustic emissions due to the leak depends on the level of turbulence of the flow in proximity to the leak. In particular, it is expected that an unstable turbulent flow would cause high and fast pressure fluctuations that are more likely to result in acoustic emissions. This condition necessitates large Reynolds numbers (Re>1000). Reynolds number is represented as (Rahman & Brebbia, 2012):

$$Re = Ud/\nu \tag{1}$$

where ν is the kinematic viscosity of the fluid ($1 \cdot 10^{-6}$ m^2/s for water). The mean velocity through a small orifice can be determined exactly using CFD, or approximately using the Bernoulli equation, the diameter of the orifice and the inner velocity and pressure of the pipe (neglecting turbulence losses). This results in a velocity, U, growing with the square root of the pipeline pressure P (relative to P_{atm}).

In order to obtain an analytical ad-hoc estimation of the frequency range of the fluid pressure fluctuations (in turn generating or modulating the acoustic emissions), the vortex shedding theory is applied, comparing the disturbance of the orifice to the one introduced in a fluid velocity field by an infinite cylinder of diameter d. The frequency of vortex shedding in such conditions is governed by the Strouhal number (Vit, Ren, Travnicek, Marsik, & Rindt, 2007)

$$St = f_s d/U \tag{2}$$

where f_s is the frequency of vortex shedding.

The Strouhal number depends on the surface condition of the pipe as well as the Reynolds number of the flow, however, for a wide range of Reynolds numbers ($1 \cdot 10^3$ to $1 \cdot 10^5$), it is relatively constant and remains approximately 0.2 for both smooth and rough surfaces. This value will be used in combination with CFD simulations to provide an indication of the frequency of interest for the analysis of the leak acoustic emission. In particular, an order of magnitude indication of the frequency of interest will be given by:

$$f_s = St\, U/d \tag{3}$$

with U dominated by the pipeline pressure P.

4. TEST-RIG DESIGN

The design of the test-rig, including the leak geometry and the system operating conditions, will significantly affect the parameters and frequency content of the acoustic emission signals generated in the leak.

In particular, the system pressure, P, has been shown to have a significant effect on not only the flow rate from the leak, but also the acoustic emission signals recorded. Two main effects of the pressure on AE are expected: (i) an increase in pressure would lead to an increase in velocity and therefore an increased Reynolds number, which would, in turn, increase the likelihood (and intensity) of acoustic emission generation; (ii) the same increase in velocity would also cause an increased frequency of the vortex shedding phenomena at the orifice, which is highly likely to modulate the AE signal. Experimental research conducted by two different groups, Lee et al. (Lee & Lee, 2006) and Smith et al. (Smith, Rao, & Gopal, 1979) indicated that as system pressure increases so does the flow rate and in turn the AE V_{rms}. Where V_{rms} is the root mean square of the AE Voltage signal and represents the true energy that this signal has.

Research conducted on leak detection illustrated that the shape of the leak source played a crucial role on the acoustic emission signals that were recorded (Smith et al., 1979). It was found that leaks through a crack had a considerably higher signal level than the corresponding values for leaks through a circular leak. This was attributed to the equivalent hydraulic diameter of the orifice being smaller in the crack than that of the circular orifice. Using this information in conjunction with Equation 3 leads to higher frequencies being expected as well as recorded by the AE sensors.

4.1 System components and layout

A new pipeline system was constructed in order to study the characteristics of AE generated by a pipeline leak in different operating conditions. The test schematics are reported in Figure 3.

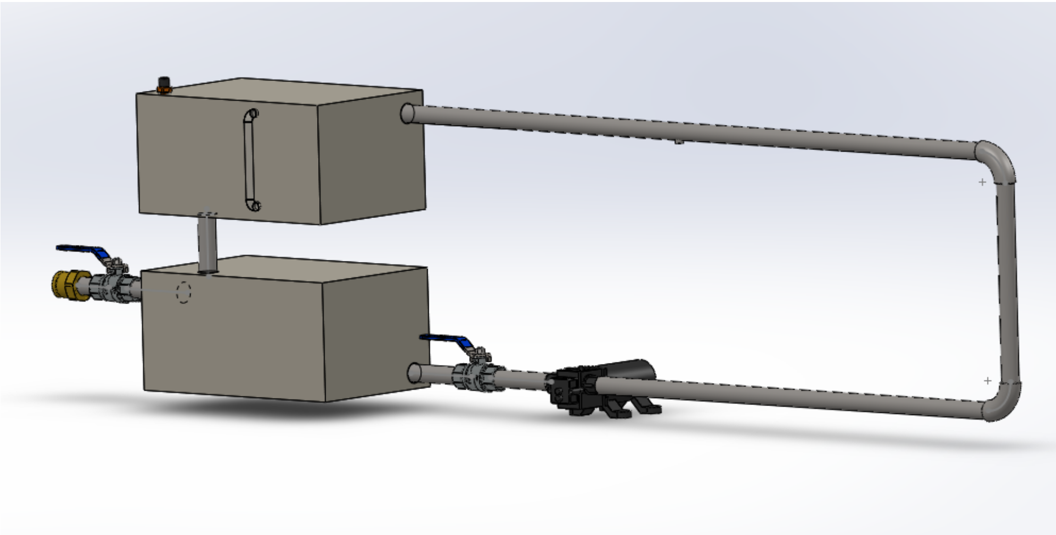

Figure 3: Pipeline design

The system consists of one test pipeline, where the leak is, and a return pipeline. In order to pressurise the system, an attachment was placed onto the side of the bottom tank with a view to connect mains water. Mains water in Queensland has a pressure that can vary in the range of 500 to 700 kPa, with Queensland University of Technology campus being at the upper end of this range. Small pressure valves were installed on the top of the upper tank to control the actual operating pressure.

Fluid flow within the pipeline is controlled by a 12 Volt DC pump. The selection of the pump was crucial since an incorrect one could have had significant impacts on the system. The pumps available with this type of voltage can be classified as either a gear or diaphragm. Gear pumps would be inappropriate when performing acoustic emission testing as the nature of these would produce excess signal noise. The pump used was, therefore, needed to be a diaphragm pump. As mentioned previously, the leak flow rate is dependent on the pipeline pressure. It is, therefore, ideal to be running at the highest possible pressures. The pump flow rate can be controlled by reducing the voltage supplied by an external power supply.

The pipeline system, as shown in Figure 4, was designed with a particular consideration on design simplicity. Focusing on this decreased the amount of project time spent on construction with increased time available for testing, analysis of results, and improvements in sequential tests. Component parameters for the pipeline can be seen in Table 1.

Table 1: Pipeline component parameters

Component	Value
Pipe diameter, *D (mm)*	20
Pipeline length, L (m)	1.98
Size of each tank, V (L)	10
Pump's maximum operating pressure, P (kPa)	413
Pump flow rate, q (L/min)	11.3

The criteria of design simplicity resulted in the selected pipes, and ports on the two tanks being threaded to allow the system to be disassembled when not in use as well as provide future adaptations to occur. Adapters were necessary to convert the pump inlet and outlet to be of the same dimensions as the pipe but should have minimal effect on the fluid flow at the leak location. The constructed pipeline underwent pressure testing before creation of the leak to ensure all unintentional leaks were eliminated. Some sealant was required but was in such a way that the criteria of being easy to dismantle was still achievable. Addition of a small support was also necessary before the first 90-degree elbow to support the pipeline's weight away from the tanks.

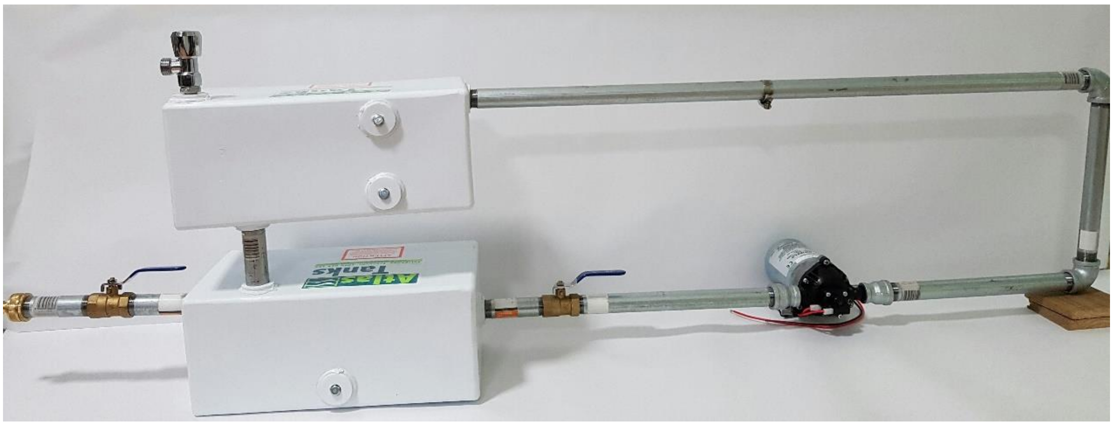

Figure 4: Constructed pipeline design

The leak was created and the pipeline underwent pressure testing again. Future experimental activity will test the system to a point where the pressure is reduced until flow occurs from the pump as well as testing the validity of AE for pipelines.

4.2 Leak Control

In order to study the effect of the leak severity on the measured acoustic emission signals, both in terms of signal power and frequency content, it is necessary to install a component which would allow for the control of the leak. It was decided that the leak would be controlled using the core of a schrader valve. This would be installed within a drilled hole in the pipe. This core provides the system with the ability to be securely sealed and can also handle the maximum pressure the system will endure (set by the pump). Additionally, it has an inbuilt seal on its body, which will aid in preventing any unintended leakage. The leak would be controlled by applying force to the spring controlled cap (Figure 5).

Figure 5: Schrader valve core

Figure 6 illustrates the ability for the core to be opened to provide a controlled leak. The possibility to control the leak allows for varying the leak properties and also provides the opportunity to easily collect a healthy (no leak) baseline for the comparison of acoustic emission signals. Implementation of this core gives control over leak orifice size which, at its largest, has an equivalent hydraulic diameter of 3 mm and, at minimum, 1 mm.

(a) (b)

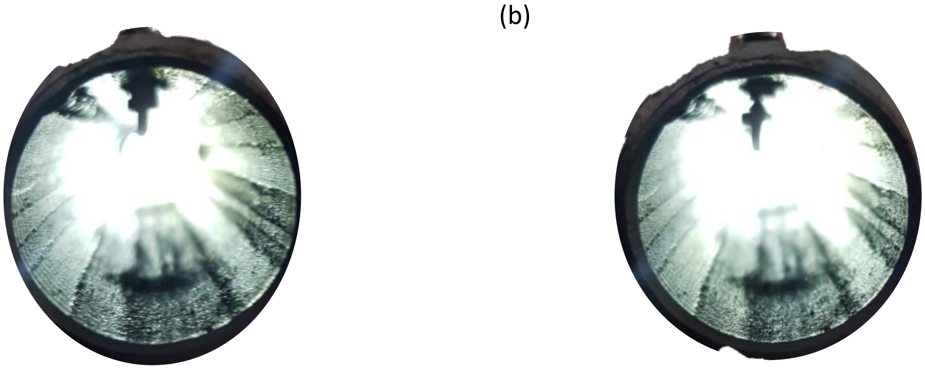

Figure 6: Valve core installed in pipe (a) Sealed (b) Unsealed with pressure added to the pin

4.3 Sensor mounting

The chosen material for the pipeline was galvanised steel since, with only a thin zinc layer on the surface, magnetic properties are maintained. Therefore, this does not affect the ability to use magnets for sensor mounting. The mounting must be set up in a way that the pipe has constant contact through the centre of the sensor. A bracket encases the sensor, which contains magnets that are linear to the direction of the pipe to provide stable mounting. The acoustic emission sensor used is the PAC-R15$^{\alpha}$, a uniaxial sensor with a working frequency range of 50-400 kHz. In order to also measure low frequency vibrations and sound emission in the audible range and accelerometer PCB 352C34 (with range 0.5-10000 Hz) and a microphone PCB 130E20 (with range 20-20000 Hz) will be installed on the test-rig.

(a) (b)

Figure 7: Sensor PAC R15α to be installed on the test rig: (a) sensor mounted in the magnetic holder, (b) sensor (the white surface is the sensor contact surface)

5. COMPUTATIONAL FLUID DYNAMICS ANALYSIS

Computational fluid dynamics (CFD) analysis was conducted on a leak of varying size to determine the leak velocity and the consequent Reynolds and Strouhal number at the orifice. This, in turn, allowed for identification of the frequency range characterising the expected phenomenon.

The software used to conduct the CFD on this pipeline design was SOLIDWORKS Flow Simulation. Due to the nature of the pipeline, the fluid flow remained relatively unimpeded up to the site of the leak and, as such, the model was simplified to only include the piping section containing the leak. Design parameters were applied to the model such that the pressure inside the pipe was at 413 kPa with the leak being exposed to atmospheric pressure. Fluid flow and the equivalent hydraulic diameter of the leak were altered over multiple tests to determine their effect on the exit velocity of the fluid. Figure 8 is a visual representation of the results obtained from one of the CFD simulations and is indicative of the general flow pattern observed in each simulation.

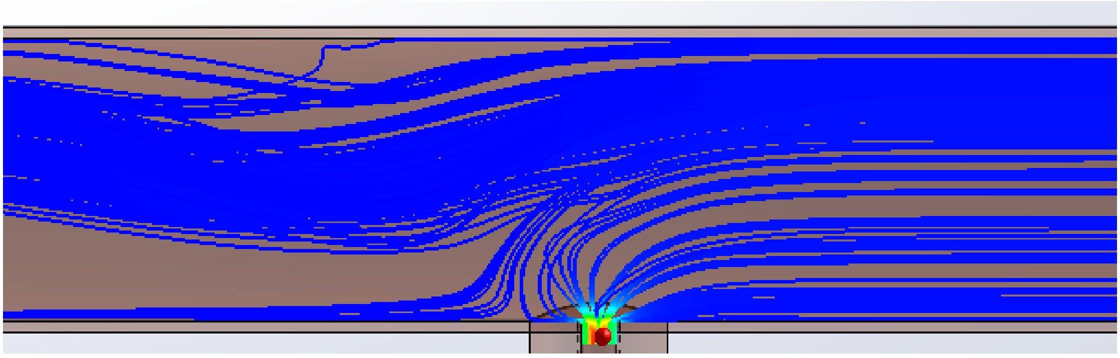

Figure 8: CFD of leak source at 413 kPa

The CFD results for the pipeline under a pressure of 413 kPa with differing pump flow rates and leak dimensions are displayed in Table 2.

Table 2: CFD analysis, calculated Reynolds number and Strouhal number

Pressure (kPa)	Pump Flow Rate (L/min)	Orifice Diameter (mm)	Leak Velocity (m/s)	Reynolds Number	Strouhal Number
413	11	3	29.459	99010.76	0.2
		1	29.904	33502.13	0.2
	7	3	29.543	99293.08	0.2
		1	30.121	33745.24	0.2
	3	3	29.468	99041.00	0.2
		1	29.957	33561.51	0.2

The turbulent energy was included from the CFD results to provide a reference to compare to the signal power that will be recorded in the future acoustic emission signals, these values can be seen in Table 3. This will be particularly useful since it is difficult to record turbulent energy experimentally. Furthermore, it will be possible to validate the results of the CFD analysis in terms of total leak flow-rate as the experimental flow can easily be recorded by measuring the amount of water that is expelled from the pipeline at the leak for a given amount of time.

Table 3: Leak flow rate and turbulent energy as observed by CFD analysis

Pressure (kPa)	Pump Flow Rate (L/min)	Orifice Diameter (mm)	Leak Velocity (m/s)	Leak Flow Rate (L/min)	Turbulent Energy (J/L)
413	11	3	29.459	29.413	29.413
		1	29.904	33.972	33.972
	7	3	29.543	23.005	23.005
		1	30.121	29.486	29.486
	3	3	29.468	21.764	21.764
		1	29.957	29.995	29.995

Using the equation for the Strouhal number (Equation 3), an expected frequency can be calculated to determine a suitable sampling range. These are shown in Table 4.

Table 4: Expected frequency of the pipeline using CFD analysis

Pump Flow Rate (L/min)	Orifice Diameter (mm)	Leak Velocity (m/s)	Strouhal Number	Frequency (Hz)
11	3	29.459	0.2	1963.93
	1	29.904	0.2	5980.80
7	3	29.543	0.2	1969.53
	1	30.121	0.2	6024.20
3	3	29.468	0.2	1964.53
	1	29.957	0.2	5991.40

These expected frequencies are at the low end of the typical acoustic emission analysis range and are mostly expected to modulate the emission of continuous stress waves. However, in the event that actual harmonics are present at those frequencies, microphones can be added to the test-rig experimental setup in conjunction with being detected with the high-frequency band of the AE sensor.

This analysis has also highlighted some challenges that may arise from this experimental study. In some operating conditions, the leak would cause a macroscopic fluid vortex in the pipe (Figure 9), leading to potential variations in the acoustic emission signals detected by the sensor. The developed CFD model will, however, provide a good reference to identify these anomalous conditions.

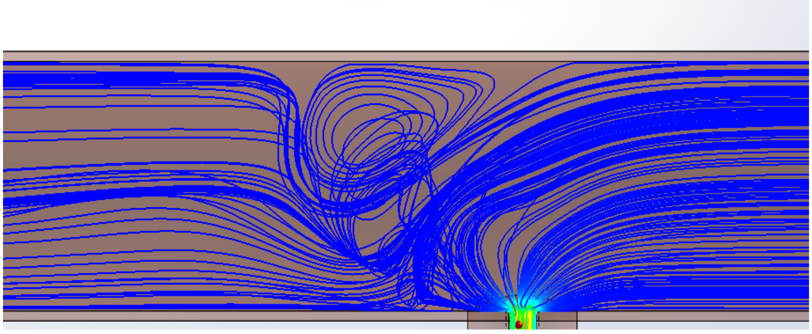

Figure 9: Fluid vortex occurring in CFD results

6. CONCLUSIONS

A design of a pipeline was undertaken for use in conducting research on the topic of pipeline condition monitoring using acoustic emission sensors. The design included a literature review on the expected characteristics of acoustic emissions in fluid dynamics and a computational fluid dynamic simulation of the design solution to ensure that the test-rig would be effective in the study of the effect of leak-generated acoustic emission. The test-rig is now ready and experimentation is underway for the collection of acoustic emission signals in presence of leaks under different operating conditions.

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