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USE OF NON-DIMENSIONAL TRANSIENT PRESSURE TRACES TO CHARACTERIZE LEAKS IN WATER PIPELINES

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ABSTRACT

Fluid transients are important for water distribution systems both for its design and for operations. Controlled water transients have become an outstanding tool to locate and characterize faults or anomalies in pipelines. Results in this area of research have shown that transients can be successfully used for detecting and characterizing anomalies in pipelines. However, applications of these techniques usually depend on knowledge of the main characteristics of the analyzed system. The main objective of this paper is to present a non-dimensional transformation of transient pressure traces that is valid for characterizing the presence of leaks. Equations describing the non-dimensional transformation of pressure and time are presented, followed by the specific dimensionless numbers proposed to describe the characteristics of a leak. Numerical examples obtained using the Method of Characteristics (MOC) are included to show that the proposed transformation is general for pipelines with different dimensions (in terms of length, diameter and pipe wall material). In addition, a laboratory validation is presented, demonstrating that the proposed equations are valid to transform transient pressure traces and to compare the presence of leaks in pipelines. By presenting this transformation, transient based techniques with the capability of identifying different features simultaneously can be developed and existing techniques can be expanded to work without prior information on the dimensions of the pipeline.

Keywords: water pipelines, water hammer, pipe condition assessment, non-dimensional analysis, leaks

1 INTRODUCTION

Water pipelines are one of the key elements of water supply. Transmission pipelines can cover long distances and distribution pipelines are often underground making the monitoring and assessment of this infrastructure more difficult. Several different non-invasive techniques have been proposed and used to accomplish this task including acoustic, ground penetrating radar, electromagnetic techniques amongst others. However, most of these techniques are limited to a short working range and need to be applied locally (Colombo et al. 2009).

In response to this, transient wave methods have been developed for the past 25 years as a successful and cost-effective alternative to monitor and detect defects in pipelines. Transient waves are pressure waves that propagate along the pipeline in the fluid after a change in flow (i.e. the closure of a valve). These waves reflect from any defect in the pipeline and those reflections are measured at one or more points along the pipeline. The arrival time of the wave can be used to determine the location of the defect and the magnitude of the reflection indicates the severity of it (Gong et al. 2015).

This technique has been used in different variations to locate leaks (or bursts), blockages, corrosion, deterioration of the pipe wall, and air pockets in pipelines. However, the location of leaks and bursts has received special attention since it affects directly the water supply capacity of a system. Even though the use of transient wave technique is efficient, most of the applications require specific and detailed information of the analyzed system such as exact dimensions and materials and sometimes this is not possible to obtain given the age of the water systems. Therefore, there is a need for techniques that are accurate and based only on the data obtained from the pressure measurements and the basic information of the pipelines.

This paper presents a non-dimensional transformation of transient pressure (head) traces that is valid for the characterization of leaks in terms of its location and size. The equations for applying the non-dimensional transformation are presented, specifying how the characterization of the size of the leak is accomplished. By applying this transformation, two head traces from different pipelines but with a leak with the same characteristics will look the same, at least during the first $4L/a$ seconds after the closure of a valve. Numerical and experimental validation is included in this paper to prove that the non-dimensional transformation is accurate, and it does not depend on the dimensions or initial conditions of the analyzed pipeline.

2 BACKGROUND

Different methods using transient waves have been proposed for the detection and characterization of leaks. Liggett and Chen (1994) were the first to use transient signals with this objective. Using inverse transient methods, a methodology that compares a forward model data with the results of a numerical model, a WDS was calibrated to identify friction factors, leaks and unauthorized uses. Although successful, this approach is computationally expensive and requires a detailed numerical model. Later, Lee et al. (2007) conducted a series of analyses focused on understanding the limitations of using time reflectometry as a technique in laboratory and field applications. This method is popular due to its simplicity; however, achieving an automatic system that identifies leak reflected signals, and developing a general method that locates leaks independently from the measurement and generation points and that manages the influence of the wave speed can be highly challenging. This mainly again is due to the differences in the head traces from pipelines with different dimensions and the requirements of knowing these beforehand. To overcome this, some authors have proposed the use of non-dimensional equations as part of other existing techniques.

Wang et al. (2002) analyzed the transient signal in a pipeline by finding an equation that described the damping rate of the head according to the characteristics of a leak. As part of these equations, different dimensionless quantities were defined and incorporated into the unsteady flow equations including a non-dimensional head, flow, time and leak location. A similar approach is followed in this paper in terms of proposing non-dimensional quantities but its application is direct to a dimensional head trace obtained either numerically or in an experiment.

3 SYSTEM CONFIGURATION AND STEADY STATE MODELING

The system configuration selected to analyze and develop the non-dimensional characterization is presented in Figure 1. A single pipeline with a total length (L_T) connected to a reservoir at the upstream end and to a side discharge valve next to a dead end at the downstream end. The location of a potential leak is described by the distance from the reservoir to the anomaly (L_{leak}) and the position of the side discharge valve is fixed, always at the downstream end. The head measurements are also obtained at the downstream end of the pipeline (denoted G/M since it corresponds to both the transient generation and measurement point).

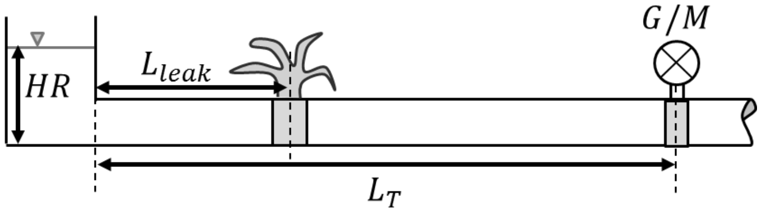


Figure 1. Pipeline configuration.

In order to obtain an accurate non-dimensional transformation of the head traces, no previous assumptions are made in the numerical modeling with regard to the initial conditions of the system. The steady state hydraulics of the pipeline are represented in Figure 2. In general, the flow through a leak and the flow through the side discharge valve, before the generation of the transient event depends on the HGL along the pipeline. In the same way, the resulting HGL depends on the outflows.

Leaks have been modeled as circular orifices with fixed diameters and a discharge coefficient of 0.6 that discharges to the atmosphere. Therefore, the flow through the leak can be expressed as a function of the head at the location of the leak. In addition, the side discharge valve was modeled as an element to discharge water into the atmosphere with an energy loss coefficient of 0.05 when fully opened. Given that this side discharge valve can be partially open at the steady state (to simulate the creation of a small transient event), reference values for the valve are found using the maximum flow through the pipeline and a valve totally opened.

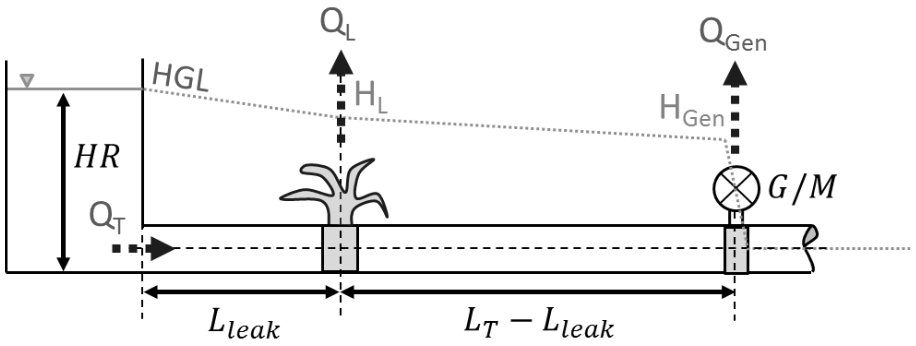


Figure 2. Pipeline steady state modeling.

Finally, the outflow at the reservoir is calculated by adding the flow through the leak and the side discharge valve. For the examples shown a remaining base flow was discarded but if the system changes to a continuous pipeline (instead of a dead end), the outflow at the reservoir would include this base flow. The steady state modeling proposed forms a system of three equations and three unknowns. The three unknowns are the flow at the reservoir, the head at the leak location and the head just upstream the side discharge valve. The three equations are the head loss in the segment of pipe upstream the leak, the head loss in the downstream segments of the pipe and the continuity equation. These three non-linear equations can be solved using any numerical method. However, MATLAB embedded functions were used in this case which includes trust-region and Levenberg-Marquardt algorithms (MathWorks 2019).

4 A NON-DIMENSIONAL TRANSFORMATION

The purpose of the non-dimensional transformation of a head trace is to obtain a method to transform any head trace that includes a leak response into a standardized form that allows its characterization. This transformation is proposed in two parts: the transformation of the head trace and the non-dimensional characterization of the location and the size of the leak. By applying this transformation, the head trace of two different pipelines would look the same if the leaks in both have the same non-dimensional characteristics.

4.1 Head transformation

Previous authors have normalized the head in a pipeline by establishing the ratio between the head at any moment of time and a reference head (Wang et al. 2002). However, the normalization proposed in this paper considers two different reference heads: the steady state head and the initial head rise after the closure of the side discharge valve.

$$H^*(t) = \frac{H(t) - H_0}{\Delta H_i} \qquad [1]$$

The proposed non-dimensionalization is shown in Equation 1. $H(t)$ is the original head trace and $H^*(t)$ represents the non-dimensional head. First, the steady state head in the pipeline (H_0) is subtracted to obtain only the variation of head in the pipeline after the transient event. In addition, this variation of pressure is divided by the initial head rise. By doing this, the final normalized head is always a proportion of this initial head rise.

4.2 Time transformation

In order to normalize time, the period of a reservoir-pipeline-valve system was used. A complete cycle of reflections after the water hammer event will happen in the $4L/a$ seconds after the closure of the side discharge valve. Therefore, the normalization of time is carried out by dividing the time in the original head trace by this value.

$$t^* = \frac{t}{4L/a} \qquad [2]$$

Equation 2 presents the non-dimensionalization in time. Previous authors have normalized time by dividing time only by L/a; however, since some pipe condition assessment techniques work with the first cycle of reflections; it is useful to have the time normalized in cycles that correspond to the period of the pipeline.

These two equations above transform the head trace into a non-dimensional form and are valid for any head trace after the generation of a transient event, no matter the anomaly that might be present or even if is an intact pipeline trace. However, by only doing these transformations it is not possible to characterize the presence a leak or any other anomaly. To accomplish these, two more non-dimensional quantities are proposed.

4.3 Leak Location

The first and most important characteristic about a leak or any other anomaly is its location. The most popular way of normalizing the location of an anomaly, that has been used previously by other authors is dividing the real location of the leak by the total length of the pipeline. In this paper the same approach is used and is shown in Equation 3.

$$Location^* = \frac{L_{leak}}{L_T} \qquad [3]$$

Following this equation, the non-dimensional location will always be a number between 0 and 1 representing the percentage of the distance from the reservoir where the leak is located. This non-dimensional location is valid for any anomaly, however in this paper focus will be only on the presence of leaks.

4.4 Leak Characteristics

In addition to the location of the leak, the size of the leak is also important in the characterization of this anomaly. Since the leak is usually modelled as a circular orifice, the diameter of this orifice would represent the size directly. However, in a real pipeline the leak might not a circular orifice. Therefore, the characterization of the size of the leak is proposed using the flow through the leak.

$$Size^* = \frac{Q_L}{Q_{Gen}} \qquad [4]$$

Equation 4 presents the non-dimensional size expression for the leak. As it was shown in Figure 1, Q_L is the flow through the leak and Q_{Gen} is the flow through the side discharge valve before its closure to create the transient events. A non-dimensional characterization using flows was proposed by Wang et al. (2002) using a generic reference flow, however, in this paper the reference flow is taken to be the side discharge valve flow.

For the purpose of this paper, the leak is always modelled as a circular orifice. Therefore, from the flow through the leak is possible to find the diameter associated with this flow based on Equation 5.

$$Q_L = \frac{C_d \pi D_L^2}{4}\sqrt{2gH_L} \qquad [5]$$

4.5 Application

The main purpose of the proposed non-dimensional approach is to transform a head trace based only on basic information of the system and on the head measurements. For example, to normalize the head, only the steady state and the initial head rise are necessary and these two can be obtained easily from the head trace. It is important to highlight that the side discharge valve closure does not need to be instantaneous for this normalization to be valid. What matters is the value of the head rise after the closure of the valve. For real pipelines it is enough to take an average of different pressure values obtained after the closure of the valve.

For the normalization of the time, the total length of the pipeline and its wave speed are required. In some cases, these characteristics of the pipeline might be known. However, in some other cases, their certainty is unclear. The wave speed can be determined if different measurement points are installed by calculating the travel time between two measurement points. Alternatively, the period of the pipeline $(4L/a)$ can also be obtained directly from the head trace by calculating the time of the first prominent reflection from the reservoir, which happens at $2L/a$ seconds.

Another requirement to characterize a leak based on the previous equations is the flow through the side discharge valve. Measuring this value during a transient test might be challenging depending on the available equipment. However, if the closure of the valve is rapid (not necessarily instantaneous) this flow can be obtained using the head rise in the pipeline and the hydraulic impedance following Equation 6.

$$Q_{Gen} = \frac{\Delta H_i}{B} \qquad [6]$$

This equation is obtained by applying the Method of Characteristics (MOC) to a situation like the one described in this paper. A similar situation is described in Bohorquez et al. (2019) where the generation of the transient wave is at any point of the pipeline. For this case, the side discharge valve is always at the downstream end of the pipeline. Following this equation, only with the head rise in the head trace and the hydraulic impedance (defined as $B = a/gA$ by Wylie and Streeter (1993)) it is possible to obtain an estimate of the flow through the valve it is closed.

In the following sections, numerical and experimental examples are shown to demonstrate that the non-dimensional transformation proposed is valid and allows the characterization of head traces after the generation of a transient event and with the presence of a leak.

5 NUMERICAL VALIDATION

A first validation was developed using a numerical model of transient flow using the MOC. The main purpose of the validation was to compare head traces that are generated from different pipelines with different characteristics after the application of the non-dimensional transformation. All the examples shown in this section correspond to the system configuration described in Figure 1, however, the specific dimensions are different.

For demonstration purposes, the selected examples correspond to the same non-dimensional location and size of a leak (Equations 3 and 4) in order to show that the results from the non-dimensional transformation is equivalent. The characteristics of the pipelines for Examples 1 and 2 are presented in Table 1. As it can be seen in the table, the length, diameter and initial conditions of both pipelines are completely different. In addition, Example 1 has been modelled with an instantaneous closure of the side discharge valve while Example 2 includes a closure time of 0.05 s.

Table 1. Properties of numerical examples.

Property	**Example 1**	**Example 2**
Head at reservoir – H_R (m)	66	38
Length – L (m)	356	1265
Diameter – D (mm)	427.40	211.60
Valve diameter – D (mm)	75	20
Leak diameter – D (mm)	34	12.82
Leak location – L_{leak} (m)	136.40	484.68
Wave speed – a (m/s)	1166	1178
Pipe wave period – $4L/a$ (s)	1.22	4.29
Valve closure time – Cl_T (s)	Instantaneous	0.05

Table 2 presents a summary of the hydraulic results of the transient simulation in both examples. As can be seen, the flow through the valve and the leak are completely different in both examples mainly due to the difference in the size of the side discharge valve (shown in Table 1). The initial head rise is also different in both examples. The only two characteristics that are the same, as mentioned previously, are the non-dimensional leak location and size.

Table 2. Hydraulic and non-dimensional properties of numerical examples.

Property	**Example 1**	**Example 2**
Flow through valve – Q_{Gen} (L/s)	35.53	3.83
Leak flow – Q_L (L/s)	19.60	0.21
Initial head rise – ΔH_i (m)	29.44	13.08
Non-dimensional location – L^* (-)	0.383	0.383
Non-dimensional size – $Size^*$ (-)	0.552	0.552

The original head traces obtained from Examples 1 and 2 are shown in Figure 3. Both head traces have been plotted on the same figure to show that the results are completely different. These differences are evident not only because the steady state head is different but are due to the differences in pipe lengths, and the development of the transient reflections after the side discharge valve closure which are completely different. The length of the pipeline in Example 1 is shorter, therefore the reflections from the reservoir arrive to the measurement point is faster and a complete cycle is achieved at an earlier time. This is also evident in Table 1 where the period of each pipeline is reported.

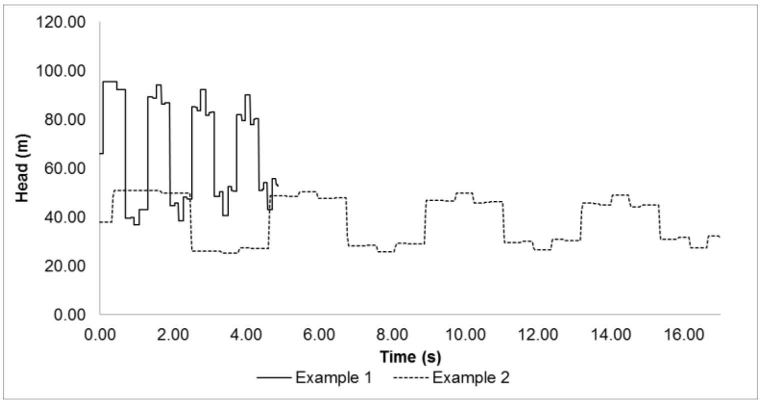


Figure 3. Head traces for Example 1 and 2.

With these results, the non-dimensional transformation proposed earlier in this paper was applied to Example 1 and 2. Figure 4 presents the non-dimensional head traces for both examples. As it can be seen in this figure, once the head and the time are normalized, the two traces become equivalent, especially during the first two periods after the closure of the side discharge valve. When the first $4L/a$ seconds are analyzed (corresponding to 1.1 approximately in Figure 4 given that the side discharge valve is not closed immediately after the beginning of the simulation), it is possible to note that the normalization of the head allows for an easy and quick comparison between the two traces and that the initial reflection of the leak looks almost the same in both examples. The differences come from the fact that in Example 1 the initial wave is completely sharp, while in Example 2 the side discharge valve has a finite closure time. In the same way, the differences in the rest of the trace come from the same fact and although these differences are visible, in general terms both traces are quite similar.

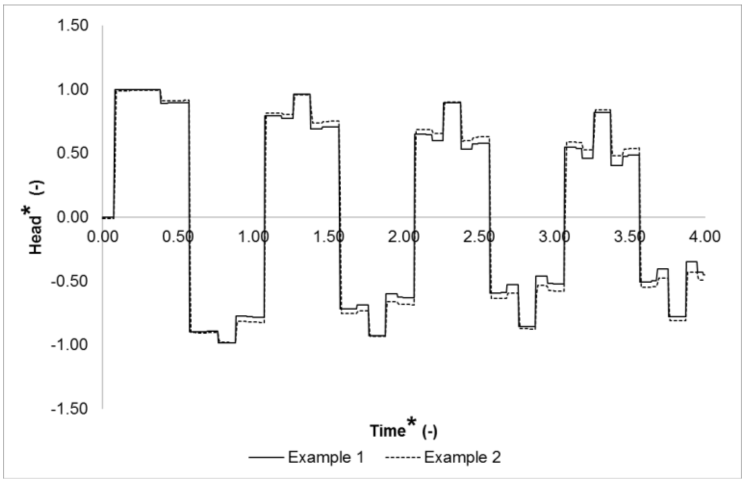


Figure 4. Non-dimensional head traces for Example 1 and 2.

A third example has been developed to show the capability of the non-dimensional head trace to represent different dimensional examples. Table 3 presents the characteristics and hydraulic results from a third example that has the same non-dimensional leak location and size than Example 1 and 2. Once again, it can be seen that the initial conditions and characteristics of the pipeline are different from the other examples. Given that this pipeline is the shortest of the three examples, its period is only 0.31 s. The purpose of this example is to show that any of the two non-dimensional head traces shown in Figure 4 can be transformed into a dimensional head trace that would be very similar to the head trace obtained from Example 3.

Table 3. Properties of Example 3.

PROPERTY	EXAMPLE 3
HEAD AT RESERVOIR – H_R (m)	55
LENGTH – L (m)	89
DIAMETER – D (mm)	573.40
VALVE DIAMETER – D (mm)	80
LEAK DIAMETER – D (mm)	45.90
LEAK LOCATION – L_{leak} (m)	34.10
WAVE SPEED – a (m/s)	1158
PIPE WAVE PERIOD – $4L/a$ (s)	0.31
VALVE CLOSURE TIME – Cl_T (s)	Instantaneous
FLOW THROUGH VALVE – Q_{Gen} (L/s)	59.07
LEAK FLOW – Q_L (L/s)	32.61
INITIAL HEAD RISE – ΔH_i (m)	27.00
NON-DIMENSIONAL LOCATION – L^* (-)	0.383
NON-DIMENSIONAL SIZE – $Size^*$ (-)	0.552

The non-dimensional head trace from Example 1 shown in Figure 4 has been transformed into a dimensional head trace by using Equations 3 and 4. The non-dimensional time of Example 1 was multiplied by the period of Example 3 and the non-dimensional head was multiplied by 27.00 m and the steady state head of Example 3 was added (these values are both shown in Table 3). Once the dimensional head trace was obtained, it was compared with the head trace obtained from the simulation of the transient flow model and the results are presented in Figure 5.

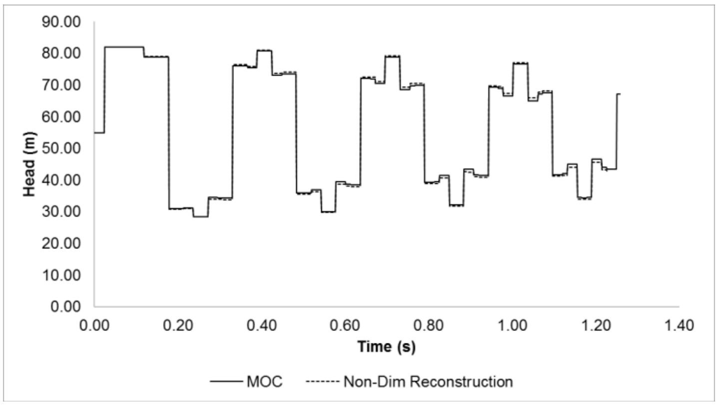


Figure 5. Head trace for Example 3 (Generated with MOC and generated from a different non-dimensional trace).

By inspecting Figure 5 is possible to see that the head trace obtained from the non-dimensional trace of a different system matches the head trace obtained from the numerical model, especially at the beginning of it. The first reflection of the leak is almost identical. There are some differences in the trace after two complete cycles of reflections mainly due to differences in the frictional energy dissipation because the equations proposed to transform the traces do not include friction. However, if only the first two cycles are used to identify the anomaly (in this case a leak), the transformation is successful.

The numerical validation presented demonstrate that the non-dimensional transformation is useful to obtain standardized head traces that are independent of the characteristics of the pipeline. By accomplishing this, techniques to locate anomalies that are general and do not require specific information about the analyzed system can be proposed and applied. The purpose of this paper, however, is to show that the non-dimensional transformation is valid and general.

6 LABORATORY VALIDATION

A set of laboratory tests have been used to validate the non-dimensional transformation proposed in a system that is different from the numerical examples shown above. A total of 4 experimental tests are shown where the configuration of the test corresponds to the one described in Figure 1. All tests were developed in the Robin hydraulics laboratory of The University of Adelaide. The first two tests were developed in 2005 as part of a previous research (Lee 2005) and the last two tests were conducted in the same pipeline for the purpose of this validation.

6.1 Laboratory Configuration

A schematic view of the pipeline is presented in Figure 6. The apparatus includes a straight 37.39 meters long copper pipeline with an internal diameter of 22.1 millimeters and 1.6 millimeters wall thickness. The difference in elevation between the two ends is 2 meters. The pipeline is connected to electronically regulated pressure tanks with in-line valves for flow control to give the apparatus the ability to simulate different boundary conditions. Depending on the test, one of these in-line valve was completely shut to simulate a reservoir-pipeline valve system.

To simulate the leak, side-discharge orifices were connected at certain points along the pipeline. These possible locations are shown in Figure 6 as points 1, 2 and 3. The transient events were generated at points marked as G1 and G2 in Figure 6 given the installation of a side-discharge solenoid valve which can be closed in approximately 4 milliseconds.

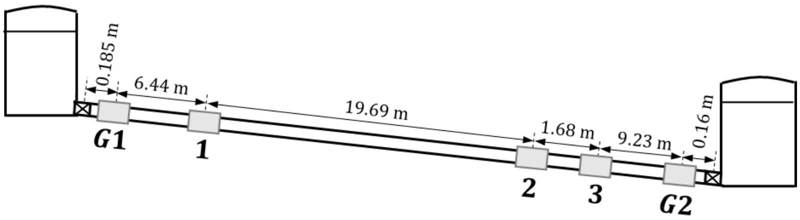
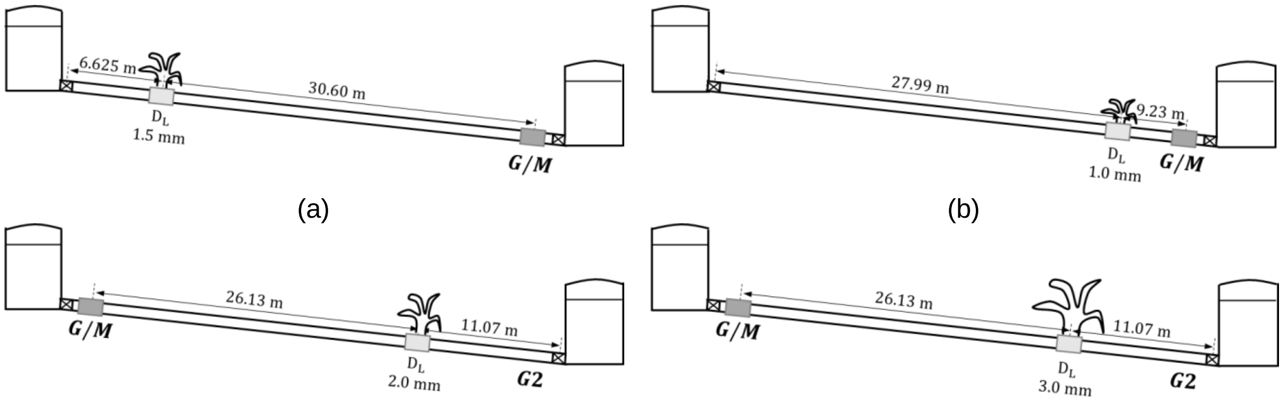


Figure 6. Laboratory setup.

6.2 Tests

Using the pipeline described above, four tests were used to validate the non-dimensional transformation of head traces. Figure 7 presents the location and the size of the leak for the four tests. As it can be seen, the leak size was varied between 1.0 and 3.0 mm. In addition, the location of the solenoid valve used to simulate a side discharge valve was changed between the two ends of the pipeline to create different examples. The head traces for test 1 and 2 were obtained from previous research conducted at the University of Adelaide (Lee 2005). Tests 3 and 4 were conducted in 2018 in the same pipeline with different flows through the main pipeline to illustrate the usefulness of the non-dimensional transformation.



(a) (b)

(c) (d)

Figure 7. Configurations of laboratory tests (a) Test 1, (b) Test 2, (c) Test 3 and (d) Test 4.

The value for the wave speed was obtained in two ways. In tests 1 and 2, the wave speed was obtained from the results reported by Lee (2005) as 1328 m/s. In test 3 and 4 it was calculated from the head measurements at two points of the pipeline from the time difference of the arrival of the first wave front. From these calculations the obtained wave speed was validated to be 1328 m/s. In addition, from the measurements the closure time of the solenoid valve was estimated to be 4 milliseconds. Table 4 summarizes the main characteristics of the tests including the non-dimensional location and size of the leaks in those tests.

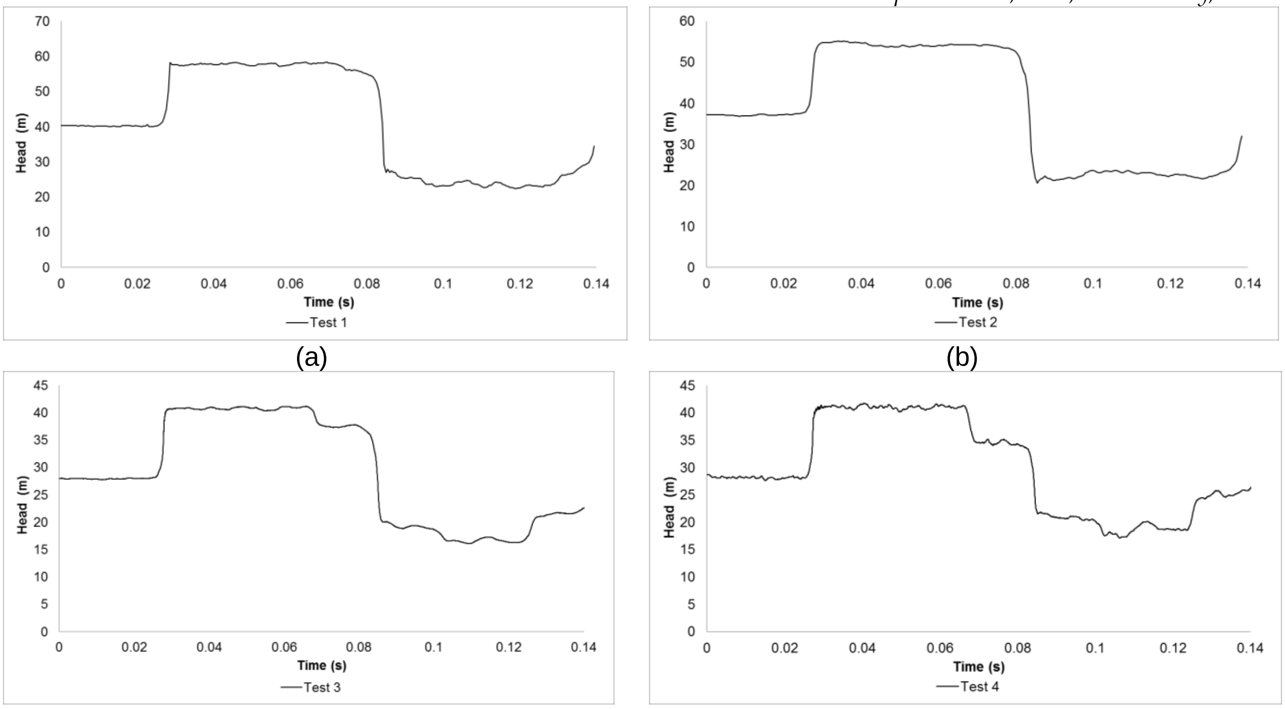
Table 4. Characteristics of Laboratory Tests.

CHARACTERISTICS	TEST 1	TEST 2	TEST 3	TEST 4
HEAD AT RESERVOIR – H_R *(m)*	40	37	27.84	28.20
LEAK DIAMETER – *D (mm)*	1.50	1.0	2.0	3.0
INITIAL HEAD RISE – ΔH_i *(m)*	17.70	17.92	12.92	12.96
FLOW THROUGH VALVE – Q_{Gen} *(L/s)*	0.0503	0.0510	0.0367	0.0369
LEAK FLOW – Q_L *(L/s)*	0.0297	0.0127	0.0441	0.0998
NON-DIMENSIONAL LOCATION – *L* (-)*	0.178	0.752	0.297	0.297
NON-DIMENSIONAL SIZE – *Size* (-)*	0.590	0.249	1.199	2.707

Table 1 shows that even though the tests were conducted in the same pipeline, the initial conditions and the non-dimensional characteristics of every test were different. Is important to note that the flow through the solenoid valve and the flow through the leak were calculated from the head traces using Equations 5 and 6.

6.3 Results

Results from the four tests are shown in Figure 8 and 9. Figure 8 presents the dimensional head traces for the first 0.14 seconds of the test which corresponds almost to a complete cycle of reflections ($4L/a$ seconds). In this figure, it can be seen that the response of the leak in Tests 1 and 2 is more subtle, mainly because of the size of the circular orifice that represents the leak. In both cases (Figure 8 (a) and (b)), the drop in pressure characteristic of the reflection of the leak is almost imperceptible. For tests 3 and 4 the leak is more prominent given that the size is larger. Even in test 4 some perturbance in the head is visible along the whole test mainly because a leak size diameter of 3.0 millimeters is disruptive in a pipeline of 22.1 millimeters of inner diameter.



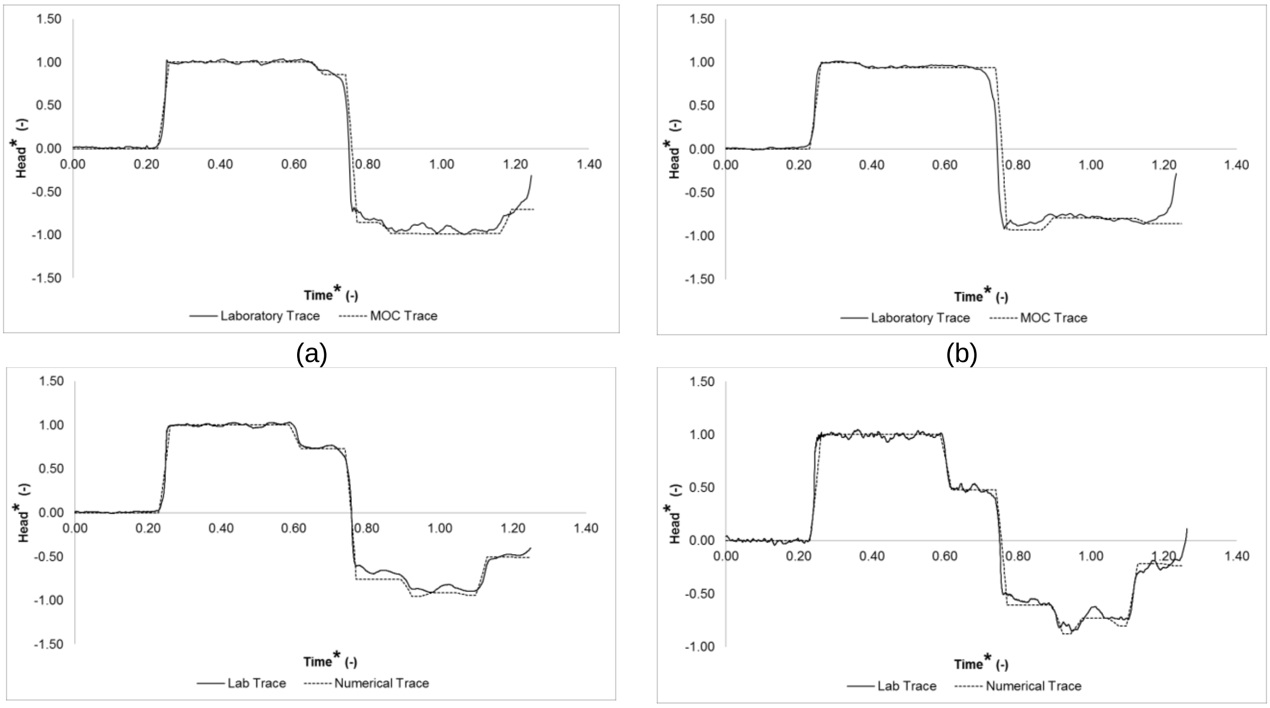
(a) (b)

(c) (d)

Figure 8. Head traces laboratory tests (a) Test 1, (b) Test 2, (c) Test 3 and (d) Test 4.

In order to validate the non-dimensional transformation, non-dimensional numerical head traces were generated and compared with the non-dimensional version of the traces from the laboratory tests. In a similar way as in the case of the numerical validation, the non-dimensional location and sizes of the leak were preserved for demonstration purposes. This comparison is presented in Figure 9 for all the tests.

In general, the head traces obtained from the laboratory matched successfully the numerically generated traces once the non-dimensional transformation is applied. For all tests, the moment in time at which the pressure drop due to the presence of the leak happens is the same time (as evidence of the location of the leak) and the non-dimensional magnitude of the drop is also similar for both cases (as evidence of the size of the leak). Even in test 4, where the head obtained from the laboratory displays some perturbance, the non-dimensional transformation allows the characterization of the occurrence of this leak.



(a) (b)

(c) (d)

Figure 9. Non-dimensional traces. Laboratory and numerical results. (a) Test 1, (b) Test 2, (c) Test 3 and (d) Test 4.

Although the match between the numerical and the laboratory non-dimensional traces is good, some differences are also evident. In tests 1 and 2 the reflection from the reservoir in the laboratory head trace arrives slightly before the numerical reflection. This could have happened because the wave speed reported by Lee (2005) was marginally underestimated. However, this discrepancy does not affect the accuracy to represent the location of the leak. In addition, in all tests there are differences after the first $2L/a$ seconds (corresponding to non-dimensional head values after 0.7 in non-dimensional time). This discrepancy might be present due to the effect of dissipation of the initial transient wave considering that the pipeline in the laboratory has more elements as joints.

7 CONCLUSIONS

This paper has presented a successful non-dimensional transformation for head traces in pipelines in the presence of a leak. The numerical and experimental validations have shown that regardless the dimensions, the initial conditions of the pipeline or the closure time of the side discharge valve (as long as this closure is still rapid). If the leak non-dimensional size and location is the same, the resulting non-dimensional head trace is the same, at least during the first few $4L/a$ seconds cycles after the closure of a side discharge valve. After this time, the energy dissipation in pipelines with different dimensions is different and both traces are no longer directly comparable.

This non-dimensional transformation can be useful for the development of leak location techniques to avoid the requirement of knowledge of the specific characteristics of the system. In addition, this non-dimensional approach is also useful for transforming a standard non-dimensional head trace in any dimensional head trace with information that is easily retrievable for an experimental test as it was shown in Example 3. Lastly, the same principle can be applied to other defects or anomalies that are typical of water pipelines such as blockages, pipe wall deteriorations or to detect changes in the configuration of the system such as the presence of unknown junctions or abrupt and significant changes in pipe material (changes from metallic pipelines to plastic segments).

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