USE OF THE STEADY-STATE ORIFICE EQUATION IN THE COMPUTATION OF TRANSIENT FLOW THROUGH PIPE LEAKS

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الخلاصة

لقد استعراضنا في هذه الدراسة استخدام طريقة الخواص العددية لمحاكاة التدفق غير المنظم في الأنابيب بوجود تسرب ما على امتداد الأنابيب، وقمنا بالتفقید المعادلات العددية ذات العلاقة حيث تم تقييم دقة استخدام معادلة التدفق المنظم من فوهة لحساب معدل التدفق عبر المنظم من فتحات تسرب في أنوابيب. كما قمنا بالتجربة وفحص نموذج تسرب عشوائي بشكل فتحات (شفق) مختلفة تم استخدامها عدما في أنوابيب التجربة. وتتبع هذه الأنسب من فتحات تسرب ضيقة محضية، وفتحة ناتجة عن لحام ضعيف، وفتحات صغيرة متقاربة، وفتحة طويلة طويلة، وفتحة ناتجة من وصلة سياقية ضعيفة بين أنوابيب. وتمتجرد عدة قيم لتدفق منظم لكل واحدة من هذه الفتحات لإكمال استخراج متوسط معامل الفتحة الذي يماثل معامل التدفق من خلال قوة. ثم بعد ذلك تم تمرير تدفق شديد التغير (عدم الانظام) من خلال كل واحدة من فتحات التسرب واستخدام معامل الفتحة الذي تم إيجاده سابقا لحساب تاريخ قيمة التدفق من خلال الفتحة عبر هذا التدفق المتغير. وقد تم قياس تدفق التدفق المحسوسية هذه مع نظرياتها المقاسة، ووجد أنه يمكن وفقا لدقيعا استخدام معادلة التدفق المنظم من خلال قوة لحساب قيمة التدفق غير المنظم من فتحات التسرب في الأنابيب، وبخاصة فتحات التسرب عادية الحجم.

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ABSTRACT

The implementation of the unsteady leak rate simulation by the Method of Characteristics is discussed, and the respective numerical equations are derived. The use of the steady-state orifice equation for the computation of unsteady leak rates from pipe through-crack or rupture is discussed and evaluated. Five different shapes of artificially made pipe through-cracks were experimentally considered. These types of leak sources include a circumferential crack, a loose weldment crack, multiple small cracks, a longitudinal long crack and a loose union fitting. Different values of steady-state leak rates were run through each of these crack types and a leak opening dimensional coefficient analogous to that of the orifice was established. Severe transient flow through the same leak opening was then run, and the average steady-state value for this coefficient was used to establish a leak rate history throughout the transient course. A comparison between this leak rate history and the corresponding measured rate was considered, and it was found that the use of the steady-state orifice equation for the computation of leak rate from pipe through-crack (rupture) during transient flow conditions was accurate for normal-sized leaks.

KEY WORDS: Pipe Leaks, Orifice Flow, Transient Flow, Unsteady Leak Rate.
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INTRODUCTION

In some real-time leak detection methods, such as that proposed by Al-Khomairi [1], the real-time simulation of a leak is an important routine in the leak detection process. Since a leak is issued from a through-crack or a rupture along a pipeline, the leak flow rate is a function of the pipe pressure at the leak location. In this case, the leak may be thought of as an orifice, and the flow through it is expected to be governed by the orifice equation, which is equal to a coefficient times the square root of the pressure drop across the leak.

The subject of leak rate from pipe cracks and ruptures has been extensively studied in the literature on fracture mechanics. In fracture mechanics, the intent is usually to study the relationships between the leak rate and the parameters of crack length, diameter, material, bending stress, and internal pressure. Furthermore, the growth of the crack opening with loading conditions is given considerable attention. For instance, Grebner et al. [2] discuss experiments on a decommissioned overheated steam reactor in Karlstein, Germany, which were performed on small-bore austenitic straight piping and on pipe elbows/branches containing through-wall cracks. The main goal was to determine the crack opening and leak rate behavior of the cracked components under different operational pressure and temperature loading conditions. The main finding was that the crack opening and initiation of crack growth can be described with the finite element technique, if it is applied with sufficient accuracy.

Since leak occurrence is usually instantaneous and the real-time detection methods detect the leak in a relatively short time, the growth of the leak opening is not important for the subject of leak detection; this growth in leak opening is usually driven by cycles of loading conditions over time. Thus, the leak opening is dealt with as if it were mostly constant, rendering it more analogous to an orifice or a nozzle than to a growing crack area. Since no literature on transient leak flow rates was found, except in the context of fracture mechanics, literature on transient orifice flow was sought for review for this study.

Hayase et al. [3] discuss transient flow through a pipe orifice using numerical analysis. The study focuses on the transient flow structure and the characteristic time constants for the transient state. Washio et al. [4] developed a technique to measure fluctuating differential pressures with high fidelity. The technique was used in an experimental study on periodically changing hydraulic oil flows through an orifice. The findings support the validity of the traditional standpoint that the characteristics of an unsteady orifice flow can be approximately represented by those of a steady-state one.

Boronina et al. [5] investigated the effect of flow unsteadiness on the liquid flow rate measured by means of orifices. They found that the effect of flow unsteadiness on local drag coefficient of the orifice was significant. Recommendations were made on liquid flow rate computation when it was to be measured with orifices under transient conditions.

An orifice is a common component in pipeline systems and it is mainly used for flow rate measurement. When the flow is steady, the pressure loss across the orifice is proportional to the square of the flow rate passing through it. To know the characteristics of unsteady orifice flow, the steady-state equation for flow through an orifice is assumed to be valid for transient flow conditions. This assumption is verified by experiments.

A pipe through-crack or rupture results in a leak rate that is a function of the parameters of the leak opening. Unlike the fracture mechanics studies, the leak opening parameters were not given any attention in this study, as they were irrelevant to the leak problem. The focus in this study is to investigate the equation that relates the leak rate to the internal pipe pressure at the leak location during transient flow conditions. This is particularly important for some real-time leak detection methods, which rely on such equations in the leak simulation models [1]. The most common real-time leak detection methods are: the volume balance method and the pressure-flow deviation method. The former method states that “what ever goes into the pipe must go out” if the pipe is intact, otherwise a leak is suspected. It relies upon mass conservation, but it takes into account the changes in line pack due to pressure fluctuation. The latter method of leak detection is more sophisticated; yet, it is so accurate that it can detect leaks down to 0.5% of the normal flow rate. In this method, pressure and flow measurements are taken at both ends of a pipe leg. Some of these measurements are used as boundary conditions to drive a real-time model (RTM) and the rest of measurements will be used for comparison. The RTM provides computed quantities of pressure and/or flow. These quantities are compared to the corresponding measured ones. A close match can be observed between these measured and computed quantities if the pipe leg under consideration is free from leaks. If, however, a leak is present, discrepancies will be observed between

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the modeled and the measured quantities. If these discrepancies are with a pattern similar to that for a leak, the leak detection software will announce a leak and will run another routine to find its location. The leak size is usually taken as the difference between the upstream and the downstream discharge. The leak detection method suggested by Al-Khomairi [1] and called “The Least Squares Method” is based upon the pressure–flow deviation method. In this method of leak detection, the real-time simulation of “trial” leak rates is the heart of leak detection process and the leak location estimation. This, however, requires knowledge of the equation that relates pipe internal pressure to leak flow rate.

This study evaluates the use of the steady-state orifice equation for the computation of unsteady leak rates from pipe leaks. This is quite important for real-time, state-of-the-art, leak detection methods that are used nowadays. With accurate leak simulation, this method of leak detection can detect leaks as small as 0.25% of the normal flow rate [1]. To broaden the findings of this study, five different leak sources with different leak opening parameters are considered. These cases include: (1) circumferential crack, (2) loose weldment crack, (3) multiple small cracks, (4) longitudinal long crack, and (5) loose union fitting. Experimental runs were performed for each of the above conditions, in order to investigate the accuracy of using the steady state orifice equation for the computation of leak rates from pipe through-crack during transient flow conditions. Since real-time leak detection applications are considered recent areas of research, the subject of this study has been ignored in the literature on fluid transient and applied pipeline hydraulics.

It is important to first study the analogy between an orifice flow and leak flow. However, before discussing the analogy between the orifice and the leak, it would be useful to understand how the resulting equation for leak rate computation can be used to simulate a leak along a pipeline. The following sections show the derivation of the equations that govern leak simulation as part of the solution of unsteady pipe flow using the Method of Characteristics (MOC).

**LEAK SIMULATION**

The method of real-time leak simulation discussed herein is based on the solution of unsteady pipe flow by the Method of Characteristics (MOC). Details on the use of the MOC for pipe flow simulation can be found in Wylie & Streeter [6]. Leak is simulated by considering a flow diversion at the desired leak location as shown in Figure 1. However, the leak must be considered at a computational section (\( N_L \)). Thus, the continuity equation at the leak location takes the following form:

\[
Q_{p1} - Q_{p2} - q_L = 0
\]

where \( Q_{p1} \) is the discharge just upstream of the leak location; \( Q_{p2} \) is the discharge just downstream of the leak location and \( q_L \) is the leak flow rate.

**Figure 1. Leak simulation by the Method of Characteristics (MOC)**

The \( C^+ \) compatibility equation upstream of the leak location and the \( C^- \) compatibility equation downstream of the leak location are used to relate the head to the flow rate at the leak location [6] as follows:
\( C^+ : H_i = C_p - B Q_i \); and
\( C^- : H_i = C_M + B Q_i \).  
(2)

\( C^+ : H_i = C_p - B Q_i \); and
\( C^- : H_i = C_M + B Q_i \).  
(3)

where \( H_i \) is the head at section \( i \); \( Q_i \) is the discharge at section \( i \); and the coefficients \( C_p, C_M \) and \( B \) are known constants when the equations are applied and are given by the following equations, respectively:

\( C_p = H_{i-1} + B Q_{i-1} - R Q_i \left| Q_{i-1} \right| \);  
(4)

\( C_M = H_{i+1} - B Q_{i+1} + R Q_i \left| Q_{i+1} \right| \); and

\( B = \frac{a}{gA} \).  
(6)

where \( a \) is speed of pressure pulse; \( A \) is area of pipe and \( g \) is the gravitational acceleration constant.

These compatibility equations are used to find the head and discharge at any interior computational section along the pipe being simulated. Thus, with \( Q_i \) replaced by \( Q_{P1} \) in Equation (2) and by \( Q_{P2} \) in Equation (3), Equation (2) and (3) can be rewritten in the following forms:

\( Q_{P1} = \frac{C_p - H_L}{B} \), and
\( Q_{P2} = \frac{H_L - C_M}{B} \).  
(7)

in which \( H_L \) is the head at the leak location and represents \( H_i \) in Equation (2) and (3).

The net inflow at the leak location is equal to zero; thus Equation (1) takes the form:

\( \frac{1}{B} \left( C_p - 2H_L + C_M - B q_L \right) = 0 \).  
(9)

Rewriting Equation (9) in a more convenient form with respect to the head at the leak location gives:

\( H_L = \frac{C_p + C_M - B q_L}{2} \).  
(10)

Substituting for \( H_L \) in Equation (7) and (8), the flows just upstream and downstream of the leak location are given by:

\( Q_{P1} = \frac{1}{2B} \left( C_p - C_M + B q_L \right) \), and
\( Q_{P2} = Q_{P1} - q_L \).  
(11)

The leak rate \( (q_L) \) is not constant; but rather is a function of the head at the leak location. For simplicity, the leak is assumed to discharge fluid to the atmosphere. When the value of \( q_L \) is known, Equation (11) and (12) are required to proceed with the simulation of unsteady pipe flow with a leak present along the pipe. These equations evaluate the discharge values at the leak section \( (Q_{P1} \) and \( Q_{P2}) \) at every computational time step. The evaluation of the leak rate \( q_L \) during transient flow conditions is explained in the following sections.

Due to the apparent analogy between a leak from pipe through-crack and an orifice flow with respect to the head drop and flow rate relationship, this study evaluates the use of the orifice equation to compute the flow rate through leak. The orifice equation is given by:

\( q = C \sqrt{\Delta H} \),  
(13)

where:

\( q \) is the discharge across the orifice;
$C$ is the dimensional orifice coefficient and is a function of the orifice opening and pipe parameters; and $\Delta H$ is the head drop across the orifice (the upstream head minus the downstream head).

Using Equation (13) for a pipe leak computation and assuming the leak discharges fluid to the atmosphere, the head drop across the leak opening is equal to the internal pressure head ($H_L$) at the leak location. Thus, Equation (13) can be rewritten in the following form:

$$q_L = C_L \sqrt{H_L}$$  \hspace{1cm} (14)

where

- $q_L$ is the leak rate;
- $C_L$ is the dimensional leak opening coefficient; and
- $H_L$ is the head at the leak location and is the head drop across the leak opening.

**Figure 2. A partial flow chart for unsteady leak simulation**

In leak simulation, as a part of the unsteady pipe flow simulation, the steady-state leak rate must be known (usually assumed). Then, the initial steady-state head at the leak location is evaluated, and Equation (14) is used to evaluate the leak opening dimensional coefficient ($C_L$). Any subsequent computation of the leak rate ($q_L$) (i.e., in the next computational time step) requires the use of this coefficient and Equation (14). However, since the head at the leak location ($H_L$) itself is also a function of the leak rate $q_L$, an iterative procedure is carried out to repeatedly evaluate these
two quantities from Equation (10) and Equation (14), respectively, until no change is obtained in both quantities. When this final leak rate is known, $Q_{P1}$ and $Q_{P2}$ are evaluated using Equation (11) and (12), respectively. The same procedure is carried out in the next computational time step in order to compute the leak rate and the head at the leak location. This simulation process is partially shown as a flow chart in Figure 2. Thus, with the pressure head and the discharge values at the leak section taken care of, computations at other pipe sections are performed in the usual manner.

The relationship between the orifice coefficient [C in Equation (13)] and the flow rate (or Reynolds number, which is a constant times the flow rate) is an important parameter when dealing with an orifice as a flow measurement device. To investigate the analogy between an orifice flow and pipe leaks, experiments on leaks from pipe through-cracks are carried out and the relationship between the discharge through the leak and the head drop across it are established.

EXPERIMENTAL SETUP

Figure 3 shows a simple sketch of the experimental setup for this study. The pipe used in this experimental work was a 2.54-cm copper pipe, which was constructed in the Hydraulics Lab of Umm Al-Qura University. A multi-stage vertical centrifugal pump was used at the upstream end of the pipe. The pump is a Grundfos, Model CR-4-120, vertical, 12 stage, non self-priming, centrifugal pump fitted with a Grundfos standard motor. The pump takes water from a re-circulation storage tank and pumps it through the pipe and back into the re-circulation tank to form a closed loop.

Pressure sensors/transmitters were used just upstream of the leak to measure the pressure head at the leak. As the leak discharges fluid to the atmosphere, this pressure head is simply the head drop across the leak ($\Delta H$). The pressure transmitter used was a Rosemount AlphalineTM Pressure Transmitter (Model 1151) with an Upper Range Limit (URL) of 0-69 bar (0–1000 psi), and a calibrated span of 0–41 bar (0–600 psi) for this experimental work. Some of the key transmitter specifications are:

- **Output**: 4–20 mA dc, linear with process pressure.
- **Accuracy**: ± 0.25% of calibrated span.
- **Stability**: ± 0.1% of URL for six months.
- **Temperature effect**: Zero Error = ±0.2% URL per 56 °C (100 °F); Total Error: ± (0.2% URL + 0.18% of calibrated span) per 56 °C (100 °F).

The flow was measured upstream of the leak location using a Micro Motion ELITE sensor, Model: CMF100 (see Figure 3). The nominal flow range for this meter was 0–150 liters/min (330 lb/min), and the calibrated span for the experiment under consideration was 0–150 liters/min (330 lb/min). The flow transmitter displays volume flow rate, mass flow rate, fluid density, and fluid temperature at the same time. The first three quantities can be simultaneously transmitted via a data logger to a PC or a computer network. The accuracy of this sensor is ± 0.1% of the calibrated span.

Fluke 2645A was the data logger used in this experiment. This model has the capability of transferring data at a speed of 1000 readings per second. The instrument provides 20 analog channels and 10 computed channels. The pressure and the flow readings just upstream of the leak were acquired and transferred to a Pentium II PC by the data logger at a rate of one set of readings every 8 milliseconds.

Leaks can result from sudden ruptures along the pipe or from loose joints or joint weldment. The parameters of ruptures or cracks, such as crack length and width, may vary widely, depending on the pipe material and the loading conditions. Thus, in order to make this study more general, the following different artificially created leak sources were considered:

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Figure 3. Leak rate experiment setup
1. Circumferential crack.
2. Loose weldment crack between two pipes.
3. Multiple small cracks
4. Longitudinal long crack
5. Loose union.

### Table 1. Available Information on Dimensions of the Five Leak Sources

<table>
<thead>
<tr>
<th>Leak source</th>
<th>Leak length (mm)</th>
<th>Maximum width (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumferential crack (case 1)</td>
<td>26.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Loose weldment crack between two pipes (case 2)</td>
<td>21.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Multiple small cracks (case 3)</td>
<td>30.0(^a), 23.0, 25.0 (175.0)(^b)</td>
<td>0.2(^a), 0.3, 2.5</td>
</tr>
<tr>
<td>Longitudinal long crack (case 4)</td>
<td>154.0</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td>Loose union. (case 5)</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

\(^a\) The leak for this case (case 3) has three openings and the dimensions of these individual openings are shown and separated by commas.

\(^b\) The total length from the start of the first leak opening to the end of the last (third) opening.

It was not possible to control the dimensions and the shapes of these artificially made leaks, but they were considered so that they represent small to large leak sizes. Figure 4 shows sketches of the leak sources mentioned above, and Table 1 lists some details on the leak opening dimensions. For each of these five cases, an experiment was conducted to find the leak opening dimensional coefficient \(C_L\) in Equation (14) for different steady-state leak rates. A severe transient flow event was created for each leak case, and a measured leak rate history was established. The average value of the leak opening dimensional coefficient established for the steady-state flow conditions was then used during this transient flow condition to establish a computed leak rate history [using Equation (14) with \(H_L\) being measured]. A comparison was made between the computed leak rate history and the corresponding measured leak history. The accuracy of using the orifice flow equation in a leak flow problem was evaluated based on the extent of the deviation between these measured and the computed leak rate histories.

### RESULTS AND DISCUSSION

For each of the artificial through-cracks (leak openings), different steady-state leak rates were considered. Leak rates were imposed by controlling the pipe pressure. Due to the noise associated with the pressure and flow measurements, data were averaged over more than 3000 readings for each leak rate run. The results of these steady-state runs are plotted in Figures 5 and 6. Figure 5 shows the leak rate versus the leak opening dimensional coefficient for the five leak cases under consideration. The maximum value of the leak rate was dictated by the maximum pressure the pump could supply. The first three leak cases (cases 1, 2, and 3) showed almost constant dimensional coefficient \((C_L)\) over the full flow-rate range. Case 3 had small multiple leaks lying close to each other, and they formed a relatively large total opening size. However, since they were separated from each other, this allowed greater resistance to the changes in the leak opening, allowing an approximately constant leak dimensional coefficient, as Figure 5 illustrates. However, for case 4 (the longitudinal long leak), the variation of the leak dimensional coefficient was remarkable, ranging between 9 and 22 lpm/m\(^{1/2}\). This is obviously due to the large leak opening for this case which experiences elastic increase with pressure increase.

When performing the leak testing in case 5 (loose union), it was found that the variation of the leak dimensional coefficient with flow rate was unpredictable. In order to present these findings with clarity, the pipe was gradually pressurized to increase the leak rate, considering successively increasing steady-state leak rate values. Then the pressure was gradually decreased from the maximum value to the initial minimum value, considering successively decreasing steady-state leak rate values. The resulting curve for the leak rate versus the leak dimensional coefficient \((C_L)\) showed different curve patterns and values for the pressurization and the depressurization stages of this case (see Figure 5). The unusual curve for the union fitting leak was attributed to the fitting’s susceptibility to movement with pressure changes.
which caused changes in the area of the leak passages. Once the area changes, a corresponding change in the leak dimensional coefficient is expected. When comparing the large variation in the $C_l$ values between case 4 and case 5, one may note that for case 4 (longitudinal long crack) the leak dimensional coefficient changed considerably with the leak rate, but unlike that for case 5, this change was somewhat systematic and predictable. Furthermore, the change in the leak opening for case 4 (longitudinal long leak) appeared to be elastic and a function of the pressure.

![Image of five leak cases](image)

Figure 4. Shapes for the five leak cases (leak sources) investigated in this study
It is clear from the above finding that smaller leaks possessed better resistivity to area change with pressure. This was apparent from cases 1, 2, and 3 and was evidenced by the small variation of the $C_L$ values with the leak rate. For more flexible leak openings, i.e. as case 4, and joints susceptible to movement, i.e. as case 5 the value of $C_L$ changed considerably with the leak rate. When comparing Figure 5 to typical orifice meter curves, one may note an obvious analogy between the pattern of the curves for the first four leak cases considered herein and the orifice curves that relate the discharge through the orifice to the dimensional orifice constant. When plotting $C_L$ versus the square root of the head loss across the leak opening, it was found that the pattern of these curves was similar to those for the leak rate versus $C_L$ curves, as Figure 6 illustrates. The average value of the leak dimensional coefficient was evaluated for each of the five considered cases. Each of these average values was then used in severe transient flow conditions to establish a computed history for the leak rate through the same leak opening using the measured pressure head at the leak ($H_L$) and Equation (14). The severe transient flow in each case was created by continuous, high frequency cycles of upstream valve opening/closure. A measured corresponding history was obtained for the leak rate using the flow meter sensor.

Figures 7 to 11 show comparison between measured and computed leak rate histories for each leak case considered in this study. Each time data are acquired by the data acquisition systems is called a “scan”. In this experimental work, data are scanned every 0.008 seconds (8 milliseconds). Figure 7 shows the very close match between the measured and computed leak rate histories for case 1 (the circumferential crack), even during very severe transient flow conditions. One may note the fluctuation of the computed leak rate plot at low leak rate values. This fluctuation was primarily caused by the noisy pressure data, which became more apparent at low pressure heads.
The same close match between the measured and computed leak rates could also be seen for case 2 (the loose weldment crack) and case 3 (multiple small cracks), as shown in Figures 8 and 9, respectively. However, for case 3, there was an evident lag between the experimental and the computed data. This was probably attributed to the distance between the small openings, which may have caused the leak to take a longer time to develop its full flow rate value than would be the case with a single leak. The change in the leak opening with pressure, in the case of the longitudinal long crack (case 4), was evidenced by the poor match between the measured and computed leak rates as shown in Figure 10. Figure 11 shows the computed and measured leak rate histories for case 5 (the leak from the loose union fitting). There
was almost no relationship between the measured and computed leak rate histories for this case. This result reflects the unpredictable and inelastic change in the leak opening with pressure for leaks from threaded pipe fittings.

![Figure 10](image1.png)

*Figure 10. Measured and computed leak rate histories for the case of the long longitudinal crack (case 4)*

![Figure 11](image2.png)

*Figure 11. Measured and computed leak rate histories for the loose threaded union fitting (case 5)*

The above results clearly indicate the suitability of the steady-state orifice equation for use in computing the unsteady leak rate history from minor to moderate leak sizes. This finding can be generalized for a wide range of leak shapes and sizes, except when the leak opening could potentially change with pressure (such as threaded joints), or very major leaks where the leak opening noticeably increases with pressure. Fortunately, major leaks can easily be detected without the use of sophisticated methods of leak detection. Thus, for small to moderate leak rates, simulation of the real-time unsteady leak rate can be achieved with sufficient accuracy using the steady state orifice equation.

**CONCLUSIONS**

The orifice equation was extended for use in the computation of leak rates from pipe through-cracks or ruptures. Five different artificially made leak opening shapes were considered in investigating the suitability of using the steady-state orifice equation as a relationship between the leak rate and the pipe internal pressure head during unsteady flow conditions. First, the steady-state dimensional coefficient for the leak, which is analogous to the orifice dimensional coefficient, versus the leak rate was established and was found to have a pattern more similar to a venturi meter than for an orifice or a nozzle. Then, for each of the leak types, the corresponding leak dimensional coefficient was used to compute the leak rate history during severe transient flow conditions. This computed leak rate history was compared to a corresponding measured leak rate history. It has been found that the orifice equation gives a very good estimation of the unsteady leak rate history for normal leak openings. However, long leak openings (i.e., extremely major leaks) resulted in significant error in leak rate computation. Furthermore, leaks from loose threaded pipe joints that are susceptible to...
movement during pressure changes showed that the leak rate computation using the orifice equation could be completely erroneous.

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NOTATIONS:

\( A \) = area of pipe;
\( a \) = speed of pressure pulse;
\( B \) = pipeline constant, \( a/gA \);
\( C \) = dimensional orifice coefficient;
\( C_L \) = dimensional leak opening coefficient;
\( C_p, C_M, \text{ and } B \) = known constants;
\( g \) = gravitational acceleration constant
\( H_i \) = head at section \( i \);
\( H_{i-1}, H_{i+1} \) = head at section \( i-1 \) and \( i+1 \), respectively;
\( H_L \) = internal pipe pressure head at the leak location and is the head loss across the leak opening;
\( q \) = discharge across the orifice;
\( Q_i \) = discharge at section \( i \);
\( Q_{i-1}, Q_{i+1} \) = discharge at section \( i-1 \) and \( i+1 \), respectively;
\( q_L \) = leak flow rate;
\( Q_{p1} \) = discharge just upstream of the leak location;
\( Q_{p2} \) = discharge just downstream of the leak location;
\( R \) = resistance coefficient and is a function of pipe friction factor, pipe diameter, and reach length, \( \Delta v \);
\( \Delta H \) = head drop across the orifice (the upstream head minus the downstream head).