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The Effect of Orifices and Blockages on Unsteady Pipe Flows

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Abstract
The unique unsteady behavior of flow system components causes a major obstacle to the development of a precise transient analysis model for a pipeline. This research investigates the dynamic characteristics of orifices and blockages. The dynamic flow behavior through a pipe restriction can be represented by three different energy loss factors, which include the irreversible energy loss by turbulent jet flow, the kinetic pressure difference represented by the instantaneous flow acceleration and deceleration, and pressure wave dispersion by eddy inertia of the jet flow. The study proposes instantaneous inertia and frequency-dependent models to describe the kinetic pressure difference. The traditional steady-state characteristics of an orifice are used to calculate the net pressure loss, and the wave dispersion by turbulent jet flow is considered by the wavespeed adjustment method. An experimental investigation has been carried out for the single pipeline system with various orifices and blockages.

1. Introduction

Transient model based systems for pipeline monitoring and fault detection are the most promising techniques in terms of abundant flow information and high sensitivity. However, a real pipeline has a lot of flow system components and complex geometry, containing valves, orifices, blockages, joints, junctions, and complex boundary conditions with viscous effects. These cause unique unsteady behavioral characteristics during periods of rapid pressure or flow changes, and create a major obstacle in the development of a precise transient analysis model due to the lack of knowledge of the dynamic behavior of various components in the piping system.

This research investigates the unsteady hydraulic behavior of various orifices and blockages (axial-extended orifices) that affect the magnitude and phase of unsteady pressure wave by energy dissipation and dispersion, higher dimensional reflections, and nonlinear behavior. An orifice is the most widely employed flow-metering elements owing to its simplicity and low cost. It measures the rate of fluid discharge based on empirically steady-state characteristics obtained from the great volume of research data. Orifices are important elements from the viewpoint of pipeline system design because they can adequately represent many flow system components, such as valves, blockages, and joints. Blockages are common problems in most aged pipeline systems. Pipe flow can be severely curtailed by partial blockages, whose immediate impact is loss of deliverability and higher pumping costs [Adewumi et al., 2003]. They may also create water quality problems because stagnant water is left for extended periods of time. Blockages can arise from condensation, solid deposition, partially closed valves resulting from operator error, discrete partial strictures, or extended pipe constrictions.

The unsteady characteristics of orifice and blockage flow are generally assumed to be identical with the steady-state characteristics. Although this approximation has been used extensively to describe the physical phenomena of flow system components during transients, the unsteady behavior can deviate considerably from that predicted by steady characteristics [Moseley, 1966; Prenner, 1998]. The purpose of this research is to develop unsteady minor loss models that describe the dynamic behavior of orifices and blockages during fast transients. In order to ascertain the unsteady behavior of orifices and blockage, extensive experiments have been performed in a single pipeline system with various configurations of orifices and blockages.

2. Unsteady Pipe Flow Model Based on a Conservative Solution Scheme

To improve the sensitivity and applicability of transient analysis, this research uses a conservative solution scheme to describe the propagation of pressure waves through a pipe [Kim et al., 2005]. The conservation form of the governing equations without neglecting any term has been used to formulate unsteady pipe flow.

Continuity Equation

$$\frac{\partial}{\partial t}(\rho A)+\frac{\partial}{\partial x}(\rho AV)=0 \quad \textbf{(1)}$$

Momentum Equation

$$\frac{\partial}{\partial t}(\rho AV)+\frac{\partial}{\partial x}(\rho AV^2+pA)+\rho gA\sin\theta+\rho A h_f=0 \quad \textbf{(2)}$$

Energy Equation

$$\frac{\partial}{\partial t}\rho A\left(\delta+\frac{1}{2}V^2\right)+\frac{\partial}{\partial x}\rho AV\left(\delta+\frac{1}{2}V^2\right)+\frac{\partial}{\partial x}pAV+g\sin\theta\,\rho AV+\rho AV h_f+\frac{\partial qA}{\partial x}=0 \quad \textbf{(3)}$$

where, x = distance along the pipe, t = time, ρ = fluid density, A = cross-sectional area of the pipe, V = fluid mean velocity, p = fluid pressure, g = gravitational constant, θ = angle of pipe from horizontal, and h_f = energy loss due to hydraulic resistance. The rate of heat addition per unit mass is denoted by q, and δ is the internal energy. The final term of energy equation represents heat transfer from fluid to external environment. The compressibility of a slightly compressible fluid is introduced with the definition of bulk modulus of elasticity *K* (Eq. 4). Most transient analysis model uses the assumption of linear-elastic behavior of pipe wall, which is relatively accurate for describing hydraulic transients in metal or concrete pipes. The elasticity of the pipe wall and its rate of deformation are a function of pressure only (Eq. 5).

$$\frac{d\rho}{\rho} = \frac{dp}{K} \quad \textbf{(4)} \qquad\qquad \frac{dA}{A} = \frac{D}{eE}dp \quad \textbf{(5)}$$

where, *e* = pipe wall thickness, *D* = internal diameter of the pipe, and *E* is Young's modulus of elasticity for the pipe. The conservative scheme solves for four (*p*, *ρ*, *A*, *V*) or five dependent variables if temperature is included rather than two (*p* and *V*) in the standard approach. The conservative scheme directly calculates the fluid density and pipe wall deformability at every computational time step. Thus, the wavespeed is updated at every step without being actually calculated directly. This procedure has significant advantages for analyzing a pipe system with variable wavespeeds. The energy equation can consider heat transfer across the surface of the pipe due to temperature gradients and the conversion of frictional work into thermal energy. Also, the scheme can simulate gas transient flows by slightly modifying the basic structure of solution. The implicit solution algorithm of finite difference method (FDM) is used to solve the system of non-linear partial differential governing equations by a Newton-Raphson iterative procedure.

3. Unsteady Friction Loss Models for Pipe Wall Resistance

Understanding the unsteady hydraulic resistance behavior caused by pipe wall shear stress is of great importance for the dynamic calculation of transients in pipeline systems. Steady friction models cannot accurately describe the real physical phenomena of fast transient events. A popular unsteady friction model is the convolution-based weighting function type. Weighting functions exist for laminar flow [Zielke, 1968] and more recently for smooth and rough pipe turbulent flow [Vardy and Brown, 2003; 2004]. The implementation of this type of model results in numerous convolutions of conditions at all time steps in the past that considerably increases computational time. Efficient algorithms that provide an approximation of full convolution exist for the solution to improve computational time. The total energy loss is comprised of steady and unsteady energy loss parts as follows.

$$h_f(t) = \frac{fV(t)|V(t)|}{2D} + \frac{16\nu}{D^2}\int_0^t \frac{\partial V}{\partial t^*} W(t - t^*)dt^* \quad \textbf{(6)}$$

where, ν = kinematic viscosity, *f* = Darcy-Weisbach steady friction factor, *W* = weighting function, and t^* = time used in the convolution integral. The weighting functions are defined in terms of the dimensionless time $\tau = 4\nu t/D^2$.

4. Unsteady Minor Loss Models for Orifices and Blockages

After a fluid passes through the orifice bore restriction, the flow velocity increases very rapidly and the pressure drops abruptly. This is the conversion of potential energy to kinetic energy. As a fluid flows through an orifice, the bore restriction of an orifice generates a convergent jet flow that continues to contract for a short distance downstream of the orifice plate before it diverges to fill the pipe at the reattachment point. The minimum cross-section of the jet flow is known as the *vena contracta* with minimum pressure and maximum velocity. When the fluid leaves the *vena contracta*, its velocity decreases and its pressure increases as kinetic energy is converted back into potential energy. Although the flow velocity at the downstream of the orifice recovers to the velocity of the upstream, the pressure does not reach quite the value that it would have had in the absence of the device. There is a permanent pressure loss (net pressure loss; irreversible pressure change) across the restriction due to the energy dissipation by turbulent eddies of the convergent jet flow. A blockage, which may be considered as the orifice with a significant axial-extended dimension, can be applied to orifice hydraulic component with additional inertia and resistance in the vicinity of the component.

4.1 Steady-State Flow Model

The pressure change through an orifice is generally taken into consideration by the well-known relationship, which is related to the velocity and beta ratio ($\beta = d/D$).

$$Q = \frac{C_d A_o}{\sqrt{1-(A_o/A_p)^2}} \cdot \sqrt{\frac{2\Delta p}{\rho}} \qquad \textbf{(7)}$$

where, Q = flow rate, A_o = orifice cross-section area, A_p = pipe cross-section area, Δp = differential pressure through an orifice, d = orifice bore diameter, and C_d = discharge coefficient. This research uses the empirical equation (commonly referred to as API or AGA equation) defined by ANSI/API 2530, AGA Report-3, and GPA 8185-85 to predict the discharge coefficient of an orifice [Spitzer, 1991]. Eq. 7 with the below equations is used for calculating the net pressure loss across the orifice.

$$C_d = \sqrt{(1-\beta^4)} \cdot K_p \cdot [1 + d(905 - 5000\beta + 9000\beta^2 - 4200\beta^3 + 875/D)/\mathrm{Re}_d] \qquad \textbf{(8)}$$

$$K_p = \frac{\begin{array}{c}0.5925 + 0.0182/D + (0.440 - 0.06/D)\beta^2 + (0.935 + 0.225/D)\beta^5 \\ + 1.35\beta^{14} + (1.43/\sqrt{D}) \cdot (0.250 - \beta)^{5/2}\end{array}}{1.01358 - 0.075\beta + 0.135\beta^2 - 0.063\beta^3 + 0.0131/D} \qquad \textbf{(9)}$$

where, K_p and Re_d are the flow coefficient and bore Reynolds number respectively.

4.2 Unsteady Flow Models (from the Standpoint of Kinetic Energy)

The details of the unsteady orifice flow are still not completely understood because of the essential difficulty of its complex unsteadiness. The total pressure loss across an orifice can be considered to comprise of two kinds of pressure differences in the unsteady flow. One is a kinetic pressure difference caused by accelerating or decelerating fluid through the orifice. The other is a pressure loss by energy dissipation in a turbulent jet flow at the downstream side of the orifice. The analytical solution of turbulent jet flow in unsteady pipe flow is extremely complex to calculate. The pressure loss due to the turbulent jet during transients is usually estimated by the steady orifice flow model. There are two different models to evaluate the unsteady kinetic difference pressure. One is the instantaneous inertia model depending on the effect of accelerating and decelerating the fluid in and out of the orifice. The other is a frequency-dependent orifice flow model based on the rate of change of velocity and the weighting function for velocity changes.

Instantaneous Inertia Model

Funk et al. [1972] introduced the dynamic orifice relationship to analytically describe the unsteady behavior of orifices and blockages based on the accelerating and decelerating flow through a restriction.

$$\Delta p = \left[\rho A_o / \sqrt{\frac{C_d A_o \pi}{2}} + \rho l_o \right] \frac{dV}{dt} + \left[\frac{\rho}{2C_d^{\,2}} + \frac{\rho f l_o}{4a_o} \right] V^2 \qquad \textbf{(10)}$$

where, a_o is the radius of the orifice and l_o is the axial length of the blockage. The first term of the first bracket represents the effect of instantaneous acceleration and deceleration flow across an orifice. The second terms in each bracket calculate the additional inertia and friction of an axial-extended orifice (blockage). The flow in the blockage region is assumed to act as transient plug flow that is fully developed flow. The first term of the second bracket is the steady-state energy consideration to describe the net pressure loss.

Frequency-dependent Model

The transfer function (Eq. 11) for the kinetic pressure difference across an orifice and blockage was developed by using the wave equation for two-dimensional viscous flow in the frequency domain [Washio et al., 1996]. The transfer function is solved with the aid of the Laplace transform, and the results of wave phenomena are given in the Laplace domain (s-plane).

$$\Delta p(s) = \rho j\omega A_o V(s) \left[2\psi G(a_o,\, a,\, j\omega) + \frac{l_o}{\pi a_o^2} \left\{ \frac{I_0(z)}{I_2(z)} \right\}^2 \right]$$

$$where,\ G(a_o,\, a,\, s) \cong \frac{(1/a_o - 1/a)}{2\pi(1-\cos\varphi)} \cdot \left\{ \begin{array}{l} 1 + \cot\frac{\varphi}{2} \frac{(1/a_o + 1/a)}{2} \sqrt{\frac{\nu}{s}} \\ + \frac{(2+\cos\varphi)\cdot(1/a_o^{\,2} + 1/a_o a + 1/a^2)}{6(1-\cos\varphi)} \frac{\nu}{s} \end{array} \right\} \qquad \textbf{(11)}$$

where, j = unit imaginary number, ω = angular frequency, ψ = correction factor for unsteady extending flow, a = pipe radius, $z = (a^2 s/\upsilon)^{0.5}$, I_0 and I_2 = modified Bessel functions of first kind of order 0 and 2, s = Laplace variable ($j\omega$), and φ = orifice conical angle with pipe axis.

This research transforms the frequency property (transfer function) of unsteady kinetic pressure difference into the time domain (t-plane) to find the impulse response using the numerical inverse of the Laplace transformation. The values of transfer function are plotted in the s-plane, and are fitted by a least-squares nonlinear regression to find a function that is suitable for the direct inversion of Laplace transform. The inversion of the fit function is the impulse response for the unsteady kinetic pressure difference of the orifice in the t-plane. According to the linear time-invariant (LTI) system theory, the output of system (unsteady kinetic pressure difference) is represented by the convolution of the input (the rate of change of velocity) to the system and the system's impulse response in the time domain. The weighting function type equation in Eq. 12 presents the unsteady kinetic pressure difference through an orifice. It is analogous with the unsteady pipe friction model. Fig. 1 and 2 show the calculated weighting functions for the experimental apparatus with various orifice bores and with various axial lengths (3 mm blockage bore).

$$\Delta p(t) = \rho A_o \int_0^t \frac{\partial V}{\partial t}(\eta) W_o(t-\eta) d\eta \cong \rho A_o \sum_{i=1,2,3...}^{n-1} (V^{n-i+1} - V^{n-i}) \cdot W_o(i\Delta t) \quad \textbf{(12)}$$

where, η = reflection time of each event used in the convolution integral, W_o = weighting function for a restriction, and n = current computational time step.

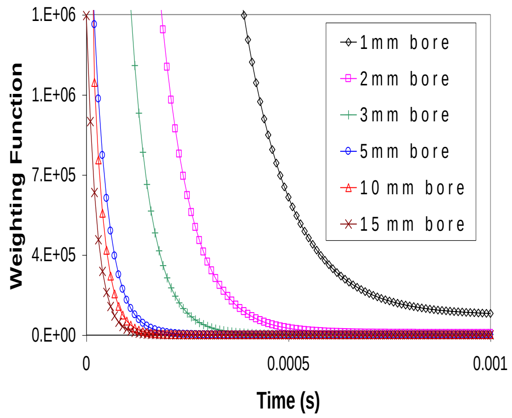


Figure 1. W_o for Orifices

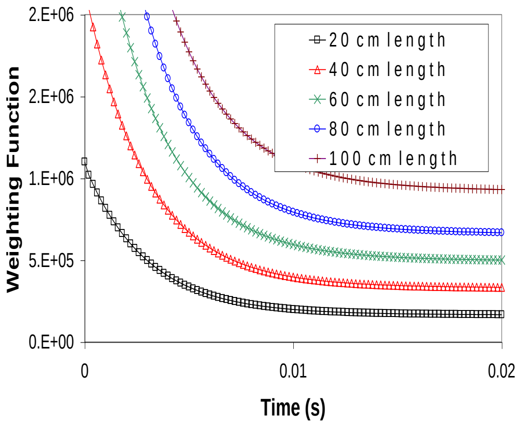


Figure 2. W_o for Blockages (3 mm bore)

5. Experimental Verification

The test pipeline is comprised of a straight 37.53 m long copper pipe with an inside diameter of 22.1 mm and a wall thickness of 1.6 mm. The pipeline is rigidly fixed to a foundation plate with a special steel construction at regular intervals along the pipe to prevent vibration during transient events and connects two electronically controlled pressurized tanks (WT and ET in Fig. 3). The pressure waves are recorded by high-resolution pressure transducer, and transferred by triggering via an amplifier and 16-bit A/D converter card to a personal computer with data acquisition interface based on LabVIEW software. The layout of system is shown in Fig. 3.

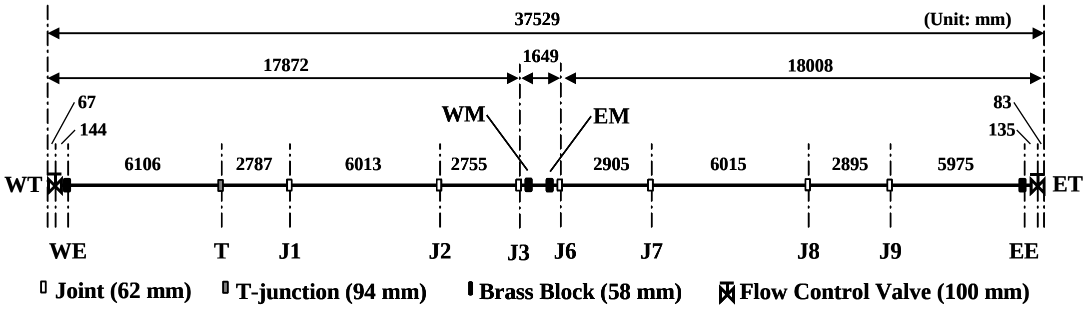


Figure 3. Pipeline System Layout

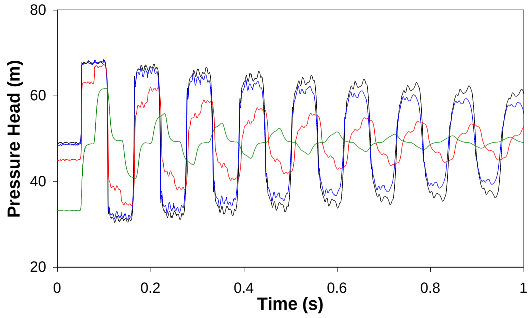
Measurement Data

Transients are generated at the WE by a side-discharge solenoid valve with a fast operating time (4 ms) after closing the west flow control valve, thus the pipeline system can be regarded as reservoir-pipe-valve system. Pressures are monitored at 4 points (WE, WM, EM, EE) at brass blocks along the pipeline and at the bottom of both tanks. The initial steady-state velocities are estimated by the volumetric method. All transient tests are conducted for 6 different initial steady flow conditions (from laminar to low Reynolds number turbulent flow) by adjusting tank pressures. The minor loss tests are executed by 2 mm thick brass orifice plates with 7 different square-edged concentric bores (0.5, 1, 2, 3, 5, 10, 15 mm) and with brass blockages with 153 mm axial length and 5 different bores (2, 3, 5, 10, 15 mm). The orifices and blockages are located in the middle of pipeline as shown in Fig. 4 and 5.

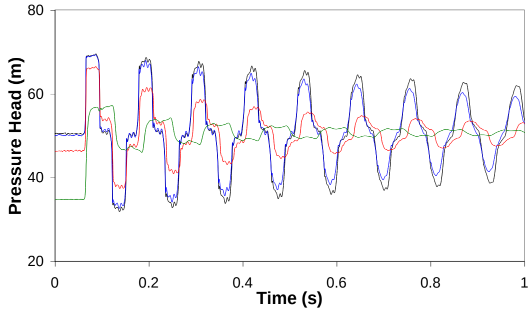
Figure. 4 Orifice Component

Figure 5. Blockage Component

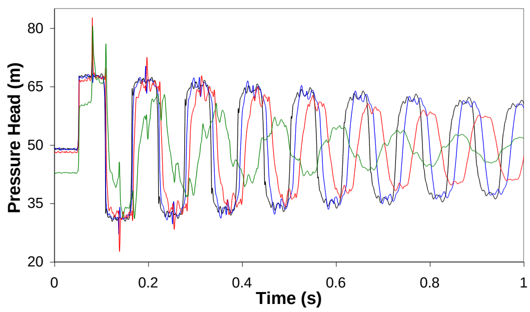
Fig. 6 shows the comparison between the measurement of intact pipe (without orifices and blockages) and the measured data with 2, 3, and 5 mm bore orifices and between the intact pipe and blockages with 3, 5, and 10 mm bore. The measured wavespeed of intact pipe is 1,340 m/s. The data sampling resolution is 4 kHz. The initial pressure drops indicates the net pressure losses by orifices and blockages. According to the decrease of bore, the magnitude of pressure decreases and complex multiple reflections are produced. The most important characteristics are the apparent changes in pipe wavespeed illustrated by the lagging or phase change of the pressure wave due to the reduction of bore. Specially, the data of 2 mm orifice and 3 mm blockage show significant changes of apparent wavespeed.



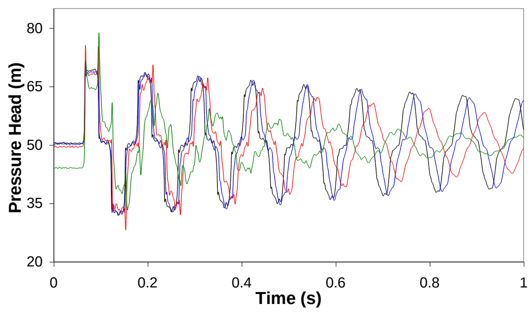
(a) Orifice Test Data (at the WE)



(b) Orifice Test Data (at the WM)



(c) Blockage Test Data (at the WE)



(d) Blockage Test Data (at the WM)

(The largest magnitude (black): intact pipe, the second (blue): 5 mm orifice or 10 mm blockage, the third (red): 3 mm orifice or 5 mm blockage, and the smallest (green): 2 mm orifice or 3 mm blockage)

Figure 6. Measurement Data

Simulation Results

Fig. 7 and 8 show the comparisons between measurement data (shown in Fig. 6(a) and 6(c), 2 mm orifice and 3 mm blockage) and simulation results using the steady model and proposed unsteady models for kinetic pressure difference. The initial flow velocity and Reynolds number are 0.1129 m/s and 2,780 for the orifice, and 0.1265 m/s and 3,094 for the blockage.

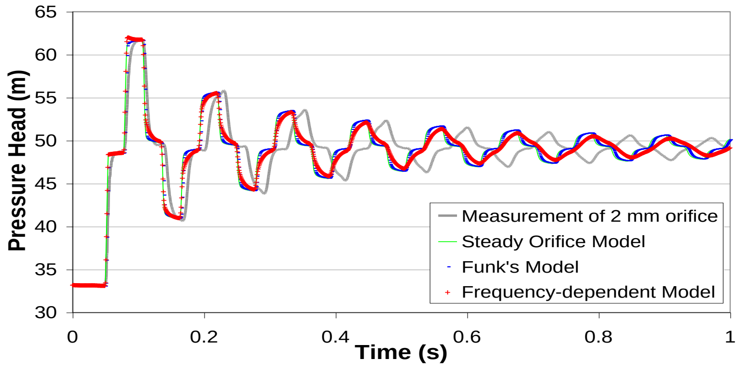


Figure 7. Simulation Results for 2 mm Orifice (WE)

The result of Funk's model is almost identical with the result of steady model, and frequency-dependent model has slight pressure attenuation in the orifice flow. In the case of transients by instantaneous valve closure, the kinetic pressure difference by instantaneous inertia flow is not a significant issue because the velocity variation is very small after closing a valve. However, the kinetic pressure difference models may be usefully applied for flow metering and transients with base flow. Although the magnitude of pressure wave can be appropriately represented by steady characteristics in these test cases, the results clearly demonstrate that the major unsteady phenomena across restrictions are serious wave lagging effect by the eddy inertia of turbulent jet flow.

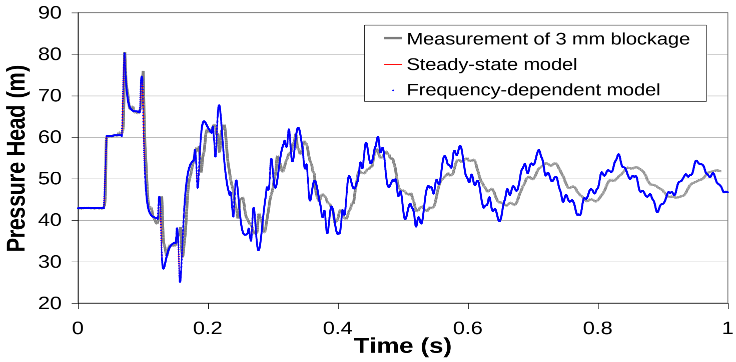


Figure 8. Simulation Results for 3 mm Blockage (WE)

Wavespeed Adjustment for Pressure Wavespeed Delay Phenomena

Pressure wave delay due to the slowing of the wave front through a restriction can be solved by two different wavespeed adjustment methods. The first is to consider the reattachment length of turbulent jet to define the zone of eddy inertia by jet flow. In the eddy inertia zone, the wavespeed decreases abruptly. Therefore, the local wavespeed of the zone is used for unsteady orifice flow analysis. The alternative method is to use the overall wavespeed of transient events. The overall wavespeed can be easily obtained by measured data. Fig. 9 shows the comparison between measurement data of 2 mm orifice flow and simulation result by wavespeed adjustment using the overall wavespeed. There is a good agreement. The overall wavespeed is 1,225 m/s for 2 mm orifice flow that is directly obtained by test data.

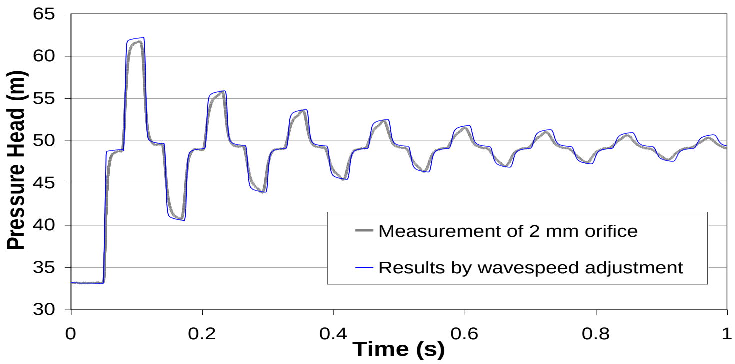


Figure 9. Simulation Results by Wavespeed Adjustment (WE)

6. Conclusion

This research presents numerical and experimental studies of how orifices and blockages affect pressure waves in a reservoir-pipeline-valve system, and investigates unique unsteady behavior during rapid transients. Two different unsteady minor loss models are used to describe the dynamic characteristics of orifices and blockages. The results of unsteady models based on the kinetic pressure difference are almost identical with that of steady model, and only show slight attenuation of pressure in the test conditions. Although the traditional steady-state model can appropriately represent the magnitude of pressure wave, the most important unsteady characteristics across a restriction are the phase delay effect by turbulent jet flow. The delay effect is modeled by wavespeed adjustment methods. The proposed research provides not only insight on complex hydraulic minor loss dynamics but also useful information for transient flow measurement.

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