Advanced Numerical and Experimental Transient Modelling of Water and Gas Pipeline Flows Incorporating Distributed and Local Effects

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APPENDIX A

TRANSFER FUNCTION OF UNSTEADY FRICTION FOR TRANSIENT LAMINAR FLOW

Unsteady wall shear stress for transient laminar pipe flow is expressed as a function of $\partial\hat{V}/\partial t(s)$ in the Laplace domain with a transfer function $\hat{\phi}(s)$ [Zielke, 1968].

$$\hat{\tau}_o(s)=\hat{\phi}(s)\frac{\partial\hat{V}}{\partial t}(s) \qquad where\ \hat{\phi}(s)=\frac{\rho R_p}{\zeta_1\left(i\sqrt{\frac{s}{\nu}}R_p\right)-2}=\frac{\rho R_p}{i\sqrt{\frac{s}{\nu}}R_p\,\dfrac{J_0(i\sqrt{\frac{s}{\nu}}R_p)}{J_1(i\sqrt{\frac{s}{\nu}}R_p)}-2} \tag{A.1}$$

where the circumflex accent represents the Laplace transform of time variable, τ_o is the shear stress at the pipe wall, s is the Laplace variable, V is the mean velocity of fluid, ρ is the density of fluid, R_p is the radius of pipe, i is the unit imaginary number, ν is the kinematic viscosity, J_0 is the Bessel function of first kind and zero order, J_1 is the Bessel function of the first kind and first order, ζ_1 is the modified quotient of Bessel function of the first order defined as $\zeta_1(z) = z\cdot J_0(z)/J_1(z)$, and z is a complex number.

The inverse Laplace transform of Eq. A.1 is described as the inverse Laplace form $\phi(u)$ of $\hat{\phi}(s)$ and its convolution with the rate of change of velocity and with the time u in the convolution integral.

$$\tau_o(t) = \int_0^t \phi(u) \frac{\partial V}{\partial t}(t-u) du \tag{A.2}$$

To find the Laplace inversion of the transfer function, the complex inversion formula can be used

$$\phi(t) = \lim_{\omega \to \infty} \frac{1}{2\pi i} \int_{\sigma - i\omega}^{\sigma + i\omega} \hat{\phi}(s) e^{st} ds \tag{A.3}$$

where ω is the angular frequency. This complex inversion formula can be evaluated by using the residue theorem that is a powerful tool to evaluate path integrals of an analytic function over a closed curve.

$$\phi(t) = \frac{1}{2\pi i} \oint_C \hat{\phi}(s) e^{st} ds = \sum_{j=1}^{k} \mathbf{Res}\,[\hat{\phi}(s) e^{st}, s_j] \tag{A.4}$$

The transfer function (analytic function) is holomorphic (differentiable everywhere within some open space) on all open subsets of the complex plane except a set of isolated points, which are poles for the function as shown in Fig. A.1.

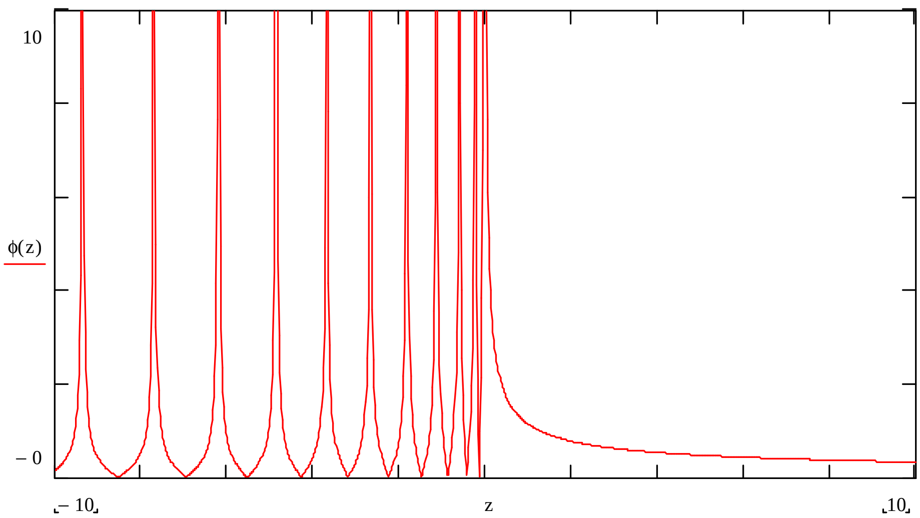


Figure A.1 Absolute Value of Transfer Function on the Complex Plane

The poles occur at the zeros of the denominator (DE) of the transfer function. The first root is s = 0 and an infinite number of root is $s_j = -\eta_j^2 \cdot \nu / R_p^2$. The constants η_j are obtained by the evaluating of $\zeta_1(\eta)-2=0$ as shown in Fig. A.2 and Table A.1. The interval between them is approaching π.

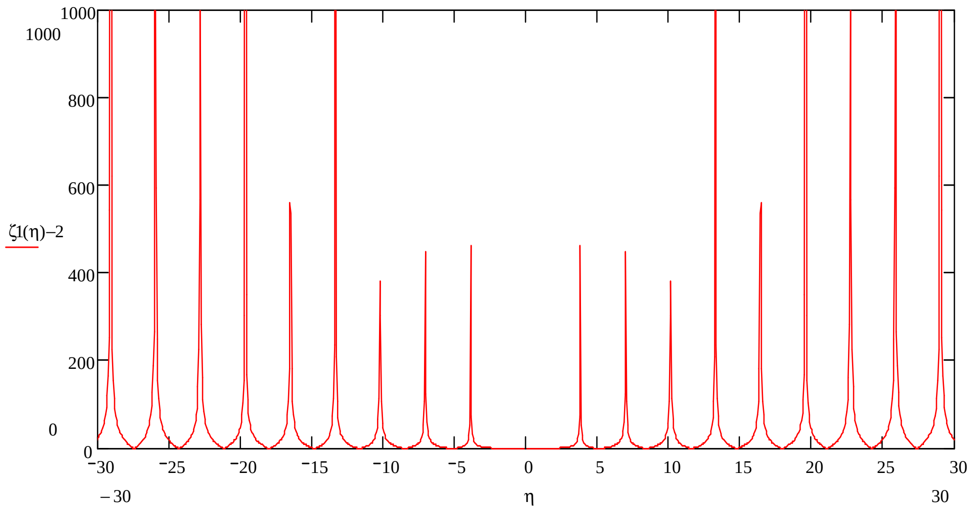


Figure A.2 Roots of the Equation, $\zeta_1(\eta)-2=0$

Table A.1 The First 20 Roots of the Equation, $\zeta_1(\eta)-2=0$

j	η_j	j	η_j
1	5.13562	11	36.86286
2	8.41724	12	40.00845
3	11.61984	13	43.15345
4	14.79595	14	46.29800
5	17.95982	15	49.44216
6	21.11700	16	52.58602
7	24.27011	17	55.72963
8	27.42057	18	58.87302
9	30.56920	19	62.01622
10	33.71652	20	65.15927

The function $\phi(t)$ is given by the sum of all residues of $\hat{\phi}(s)e^{st}$

$$\textbf{Res}\,[\hat{\phi}(s)e^{st},\ s_j]=\frac{\rho R_p}{\dfrac{\partial\zeta_1}{\partial s}(\eta_j)}e^{s_j t} \tag{A.5}$$

Differentiation of ζ_1 yields

$$\frac{\partial \zeta_1}{\partial s}(\eta_j) = \frac{R_p^2}{2\nu} \tag{A.6}$$

which is constant for all residues except the one at the origin. Therefore

$$\textbf{Res}\,[\hat{\phi}(s)e^{st},\ s_j] = \frac{2\nu\rho}{R_p} e^{-\frac{\eta_j^2}{R_p^2}\nu t} \tag{A.7}$$

By using Eq. A.4,

$$\phi(\tau) = \frac{4\nu\rho}{R_p} + \frac{2\nu\rho}{R_p}\sum_{j=1}^{\infty} e^{-\eta_j^2 \tau} \tag{A.8}$$

where the dimensionless time is, $\tau = \nu t / R_p^2$.

Finally, the unsteady wall shear stress is expressed by

$$\tau_o(t) = \frac{2\rho\nu}{R_p}\int_0^t \frac{\partial V}{\partial t}(u)\, W(t-u)du \tag{A.9}$$

where $W(\tau) = e^{-\eta_1^2 \tau} + e^{-\eta_2^2 \tau} + e^{-\eta_3^2 \tau} + ...$ that is a function of the dimensionless time τ. The equation for energy loss by unsteady friction is

$$h_{uf}(t) = \frac{16\nu}{gD^2}\int_0^t \frac{\partial V}{\partial t}(u)\, W(t-u)du \tag{A.10}$$

Eq. A.10 can be easily calculated by the first-order approximation in MOC or FDM (including a conservative solution scheme).

APPENDIX B

TRANSFER FUNCTION OF UNSTEADY FRICTION FOR TRANSIENT TURBULENT FLOW

Unsteady wall shear stress for transient turbulent pipe flow is expressed as a function of $\partial\hat{V}/\partial t(s)$ in the Laplace domain with a transfer function $\hat{\Phi}(s)$ [Vardy and Brown, 2003].

$$\frac{\hat{\tau}_o(s)}{\rho \nu_w} = \frac{\hat{\Phi}(s)}{s}\frac{\partial \hat{V}}{\partial t}(s) \tag{B.1}$$

They idealized the flow distribution by two different viscous regions. One is annular region of width b ($b = 0.2\times$ *pipe radius* (R_p)) adjacent to the wall where the viscosity is assumed to vary linearly from ν_w at the wall to ν_c at the interface between the annulus and an inner core region. Another is the core region where the viscosity is assumed to be uniform and equal to ν_c. $\hat{\Phi}(s)$ is a transfer function between the transforms of the mean velocity and the unsteady component of the wall shear stress. It satisfies

$$\hat{\Phi}(s)=\sqrt{s/\nu_w}\cdot\begin{bmatrix} C_1(s)\cdot I_1\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -C_2(s)\cdot K_1\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right)\end{bmatrix}\cdot G(s)$$
$$-1/((\nu_c-\nu_w)/(b\cdot\nu_w)\cdot\nu_w)$$
$$\cdot\left(1-\nu_c/\nu_w-(\nu_c-\nu_w)/(b\cdot\nu_w)\cdot\left(R_p-b\right)/2\right)\cdot G_s \tag{B.2}$$

where

$$\frac{1}{G(s)}=\left(\left(R_p-b\right)+0.5b\right)\cdot\frac{(\nu_c-\nu_w)/(b\cdot\nu_w)\cdot\nu_w}{R_p^2\cdot s}$$
$$\cdot\begin{bmatrix}\begin{pmatrix} C_1(s)\cdot\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)} \\ \cdot I_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -C_2(s)\cdot\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)} \\ \cdot K_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)/2 \end{pmatrix} \\ -\begin{pmatrix} C_1(s)\cdot\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)} \\ \cdot I_1\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -C_2(s)\cdot\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)} \\ \cdot K_1\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)/2 \end{pmatrix}\end{bmatrix} \tag{B.3a}$$
$$+\frac{1}{R_p^2}\begin{bmatrix} 2\cdot\left(R_p-b\right)\cdot\sqrt{\nu_c/s}\cdot\left(1+H(s)\right) \\ \cdot\dfrac{I_1\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right)}{I_0\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right)}-\left(R_p-b\right)^2\end{bmatrix}$$

$$\frac{1}{G_s} = -\frac{2\left(\left(R_p - b\right) + b/2\right)}{R_p^2 \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2 \cdot \nu_w} \cdot \left[\begin{array}{l} \left(\dfrac{\left(R_p - b\right)}{2} + \dfrac{\nu_c/\nu_w}{\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)}\right) \\ \cdot \left(\nu_c/\nu_w \cdot \ln\left(\nu_c/\nu_w\right) - \nu_c/\nu_w + 1\right) \\ -\dfrac{\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right) \cdot b^2}{2} \end{array}\right]$$

$$-\frac{\left(R_p - b\right)^2}{R_p^2 \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2 \cdot \nu_w} \cdot \left[\begin{array}{l} \dfrac{\left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2 \cdot \left(R_p - b\right)^2}{8 \cdot \nu_c/\nu_w} \\ + \ln\left(\nu_c/\nu_w\right) \cdot \left(\begin{array}{l} \dfrac{\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right) \cdot \left(R_p - b\right)}{2} \\ + \nu_c/\nu_w - \dfrac{\nu_c/\nu_w - 1}{\ln\left(\nu_c/\nu_w\right)} \end{array}\right) \end{array}\right] \tag{B.3b}$$

$$C_1(s) = -1/\left[\begin{array}{l} I_0\left(\sqrt{4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w \cdot 4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \\ - K_0\left(\sqrt{4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w \cdot 4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \end{array}\right] \cdot \left[\begin{array}{l} K_0\left(\sqrt{4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \cdot \left(1 + H(s)\right) \\ - K_0\left(\sqrt{\nu_c/\nu_w \cdot 4 \cdot s/\left(\nu_w \cdot \left(\left(\nu_c - \nu_w\right)/\left(b \cdot \nu_w\right)\right)^2\right)}\right) \end{array}\right] \tag{B.3c}$$

$$C_2(s) = -1/\left[\begin{array}{l} I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \end{array}\right] \cdot\left[\begin{array}{l} I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right)\cdot\left(1+H(s)\right) \end{array}\right] \tag{B.3d}$$

$$H(s) = -\frac{\begin{array}{l} I_1\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right)/I_0\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right) \\ +A_3(s)\cdot I_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -A_4(s)\cdot K_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \end{array}}{\begin{array}{l} I_1\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right)/I_0\left(\left(R_p-b\right)\cdot\sqrt{s/\nu_c}\right) \\ +A_5(s)\cdot I_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -A_6(s)\cdot K_1\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \end{array}} \tag{B.3e}$$

$$A_3(s) = -1/\left[\begin{array}{l} I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \end{array}\right] \cdot\left[\begin{array}{l} K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \\ -K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot\left(\left(\nu_c-\nu_w\right)/\left(b\cdot\nu_w\right)\right)^2\right)}\right) \end{array}\right] \tag{B.3f}$$

$$A_4(s) = -1/\left[\begin{array}{l} I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \end{array}\right] \cdot \left[\begin{array}{l} I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \end{array}\right] \tag{B.3g}$$

$$A_5(s) = -1/\left[\begin{array}{l} I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \end{array}\right] \cdot K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \tag{B.3h}$$

$$A_6(s) = 1/\left[\begin{array}{l} I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot K_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ -K_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \\ \cdot I_0\left(\sqrt{\nu_c/\nu_w\cdot 4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \end{array}\right] \cdot I_0\left(\sqrt{4\cdot s/\left(\nu_w\cdot((\nu_c-\nu_w)/(b\cdot\nu_w))^2\right)}\right) \tag{B.3i}$$

where s is the Laplace transform variable, I_n is the modified Bessel function of the first kind and *n*th order, K_n is the modified Bessel function of second kind and nth order, *G(s)* is the function relating the driving force and the mean velocity, and G_s is the steady flow equivalent of *G(s)*.

Similar to the transfer function of unsteady wall shear stress for transient laminar pipe flow, the transfer function of unsteady wall shear stress for transient turbulent pipe flow, Eq. B.2 with Eq. B.3a to B.3i, shows the set of isolated points that are poles for the function as shown in Fig. B.1.

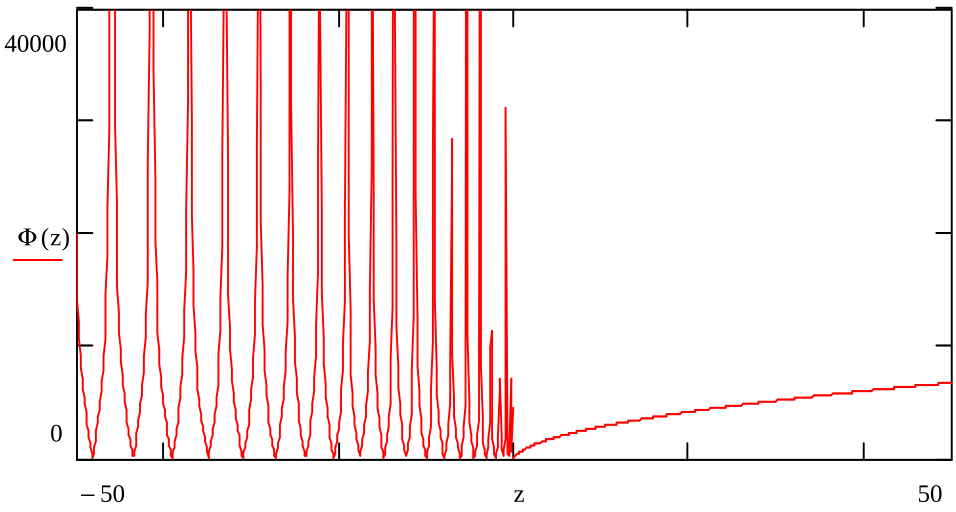


Figure B.1 Absolute Value of the Transfer Function on the Complex Plane

Although the inverse Laplace transformation of transfer function for laminar flow can be performed analytically to obtain an exact expression for the weighting function, there is no analytical solution to find inverse Laplace transform of Eq. B.2 because of the complexity of the equation. Vardy and Brown [2003] proposed a different approach by approximating the weighting function. The following part shows the procedure of the approximation.

The inverse Laplace transform of Eq. B.1 also can be expressed as a convolution based on the weighting function derived for unsteady laminar flow in the time domain.

$$\tau_o(t) = \frac{2\rho \nu_{lam}}{R_p} \int_0^T W \frac{\partial V}{\partial t} dt^* \qquad \text{(B.4)}$$

where T is the elapsed time since the beginning of the unsteadiness, $t^* = T - t$ is backward-measured time from the instant at which the integral is being evaluated, ν_{lam} is the laminar kinematic viscosity, the weighting function W is a function of t^* whereas the acceleration $\partial V/\partial t$ is a function of t. The Laplace transform of Eq. B.4 is

$$\hat{\tau}_o(t) = \frac{2\rho\nu_{lam}}{R_p}\hat{W}(s)\frac{\partial\hat{V}}{\partial t}(s) \tag{B.5}$$

By comparison with Eq. B.1, the transformed weighting function is

$$\hat{W}(s) = \frac{R_p}{2}\frac{\nu_w}{\nu_{lam}}\frac{\hat{\Phi}(s)}{s} \tag{B.6}$$

Fig. B.2 shows the absolute value of the transformed weighting function on the complex plane.

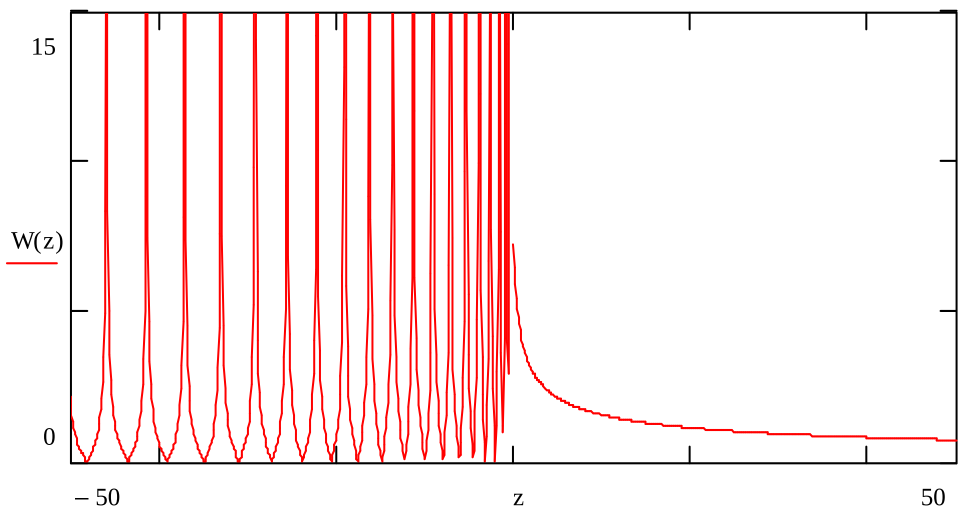


Figure B.2 Absolute Value of Weighting Function on the Complex Plane

The transformed weighting function is approximated by a simple function that is possible for application of an inverse Laplace transformation.

$$\hat{W}_{app}(s) = \frac{A}{\sqrt{s+B}} \tag{B.7}$$

where A and B is the coefficients for the approximated weighting function and the subscript *app* represent the approximation of weighting function.

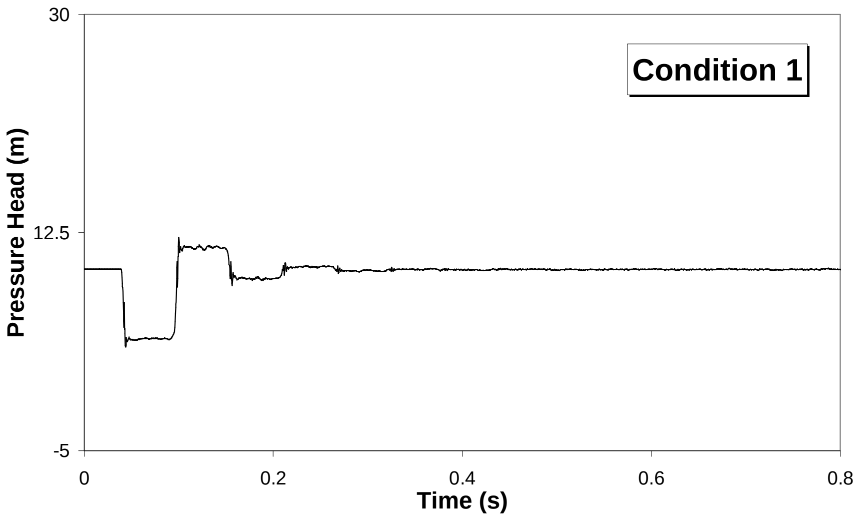
The inverse Laplace transform of the approximated weighting function, Eq. B.7, is

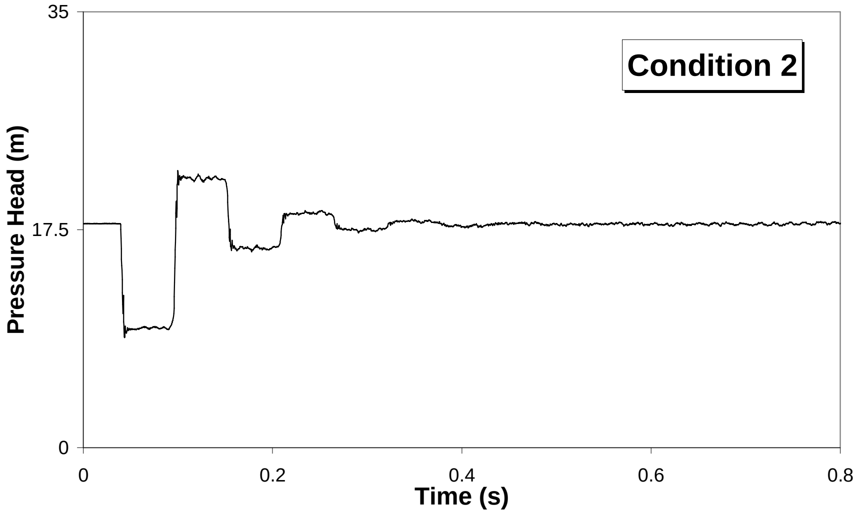
$$W_{app}(\tau) = \frac{A^* e^{-B^* t}}{\sqrt{\tau}} \tag{B.8}$$

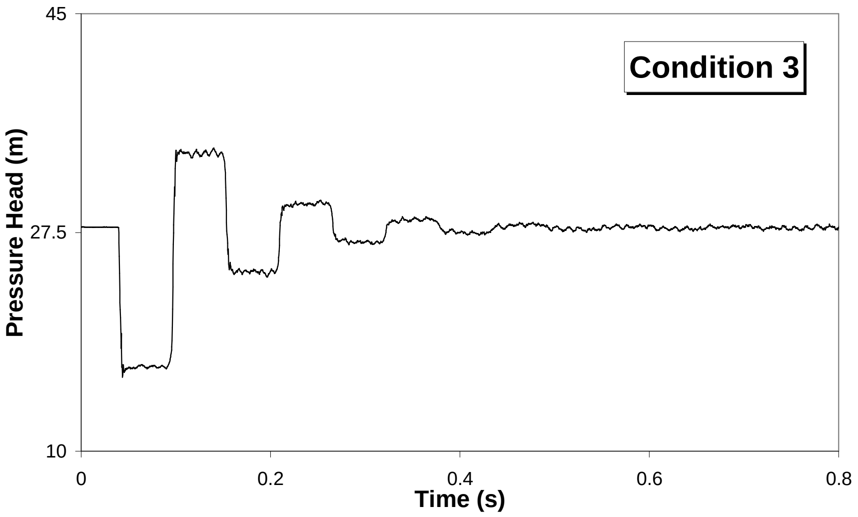
This is the weighting function of the unsteady shear stress for transient turbulent pipe flow in the time domain. The weighting functions are defined in terms of the dimensionless time $\tau = 4\nu_{lam} t / D^2$. A^* and B^* are the coefficients for the weighting function. The values of these coefficients are determined by matching the asymptotic states of Eq. B.6 and Eq. B.7 at large and very small Laplace transform variables.

APPENDIX C

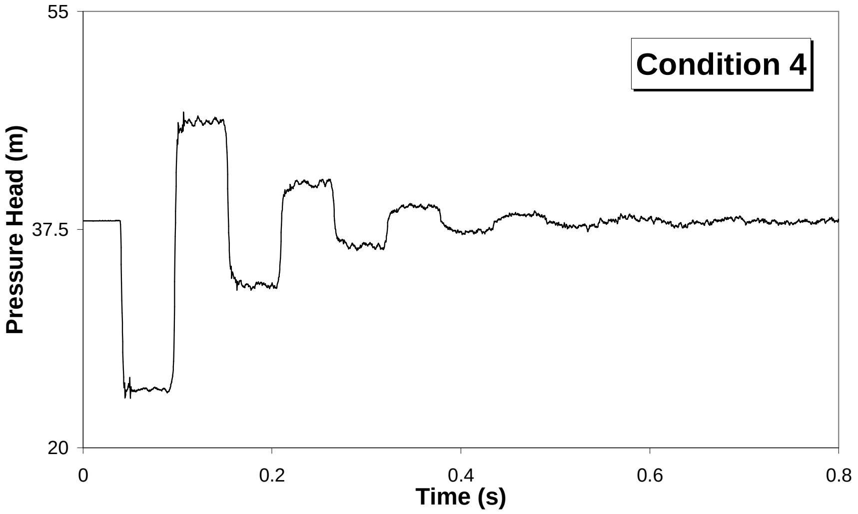
MEASURED TRANSIENT DATA BY A FAST VALVE OPENING EVENT



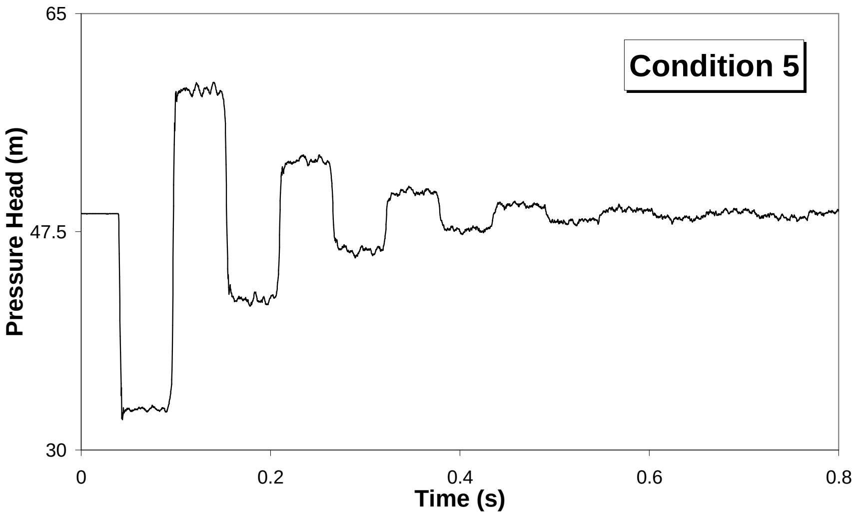




Condition 3
Pressure Head (m)
45
27.5
10
0
0.2
0.4
0.6
0.8
Time (s)



Condition 4
Pressure Head (m)
55
37.5
20
0
0.2
0.4
0.6
0.8
Time (s)



Condition 5
Pressure Head (m)
65
47.5
30
0
0.2
0.4
0.6
0.8
Time (s)

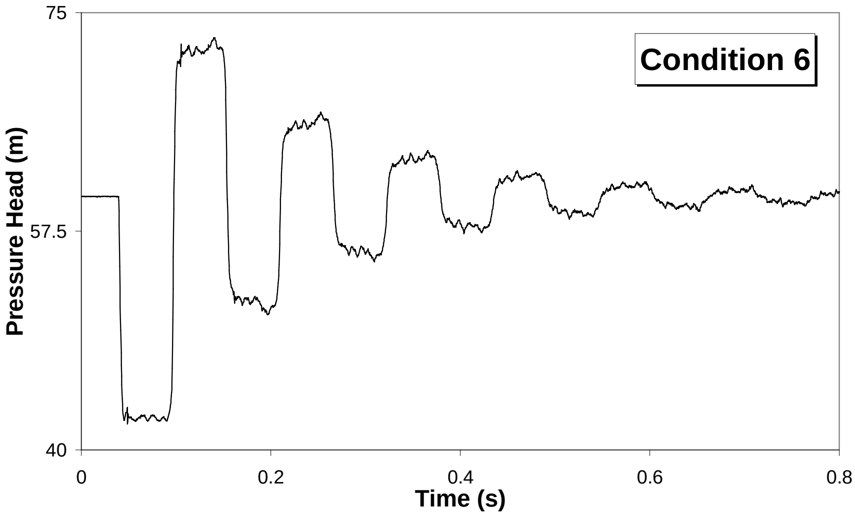
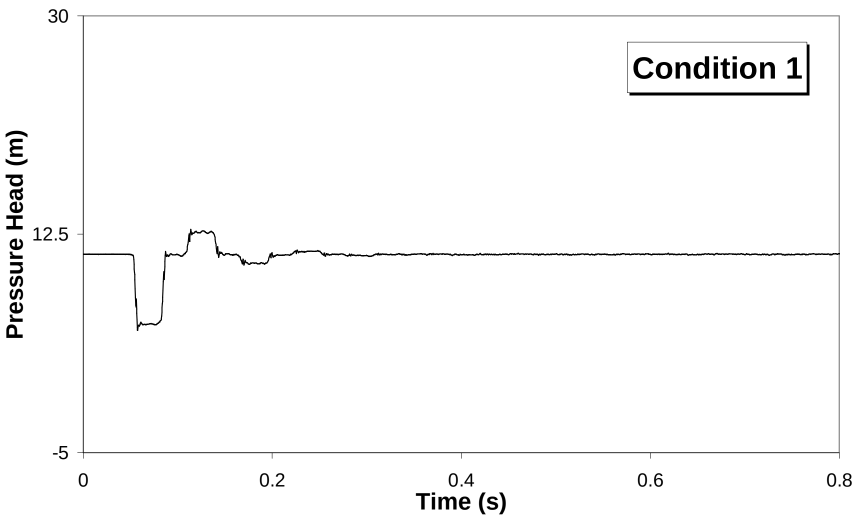
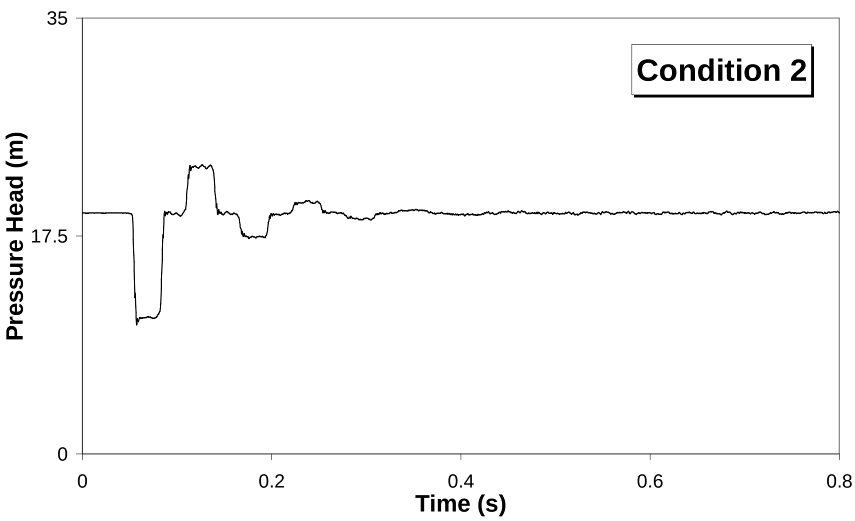
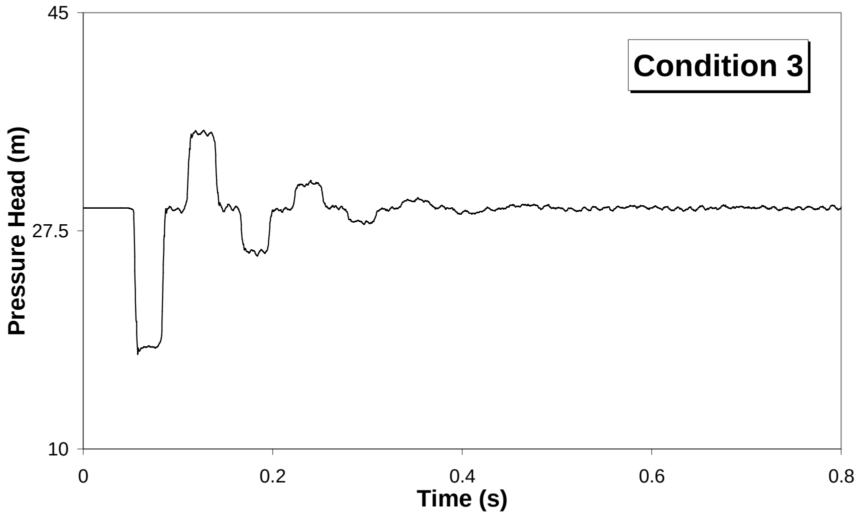


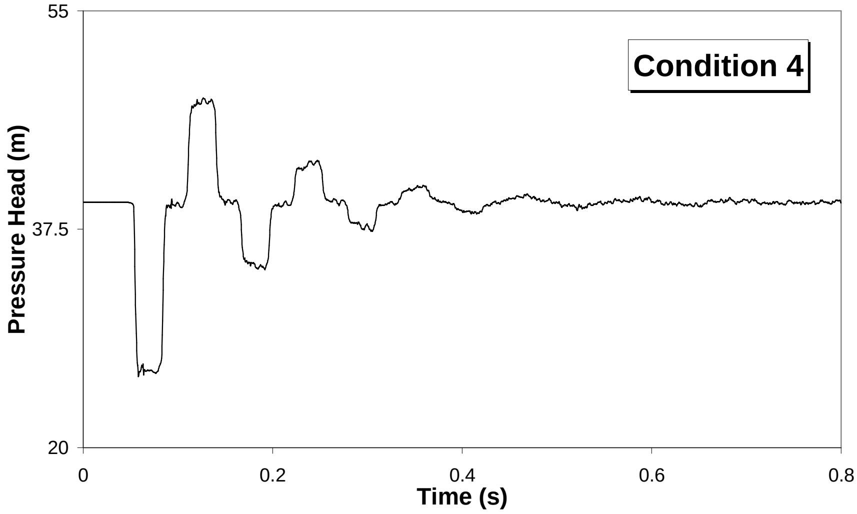
Figure C.1 Measured Transient Data at the Downstream End

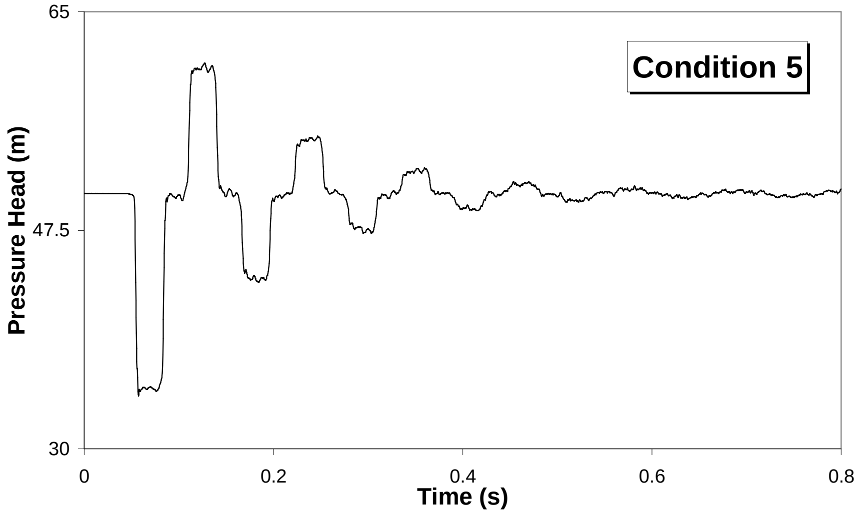
(Flow conditions are shown in Table 5.4)






Condition 3
Pressure Head (m)
Time (s)
45
27.5
10
0
0.2
0.4
0.6
0.8


Condition 4
Pressure Head (m)
Time (s)
55
37.5
20
0
0.2
0.4
0.6
0.8


Condition 5
Pressure Head (m)
Time (s)
65
47.5
30
0
0.2
0.4
0.6
0.8

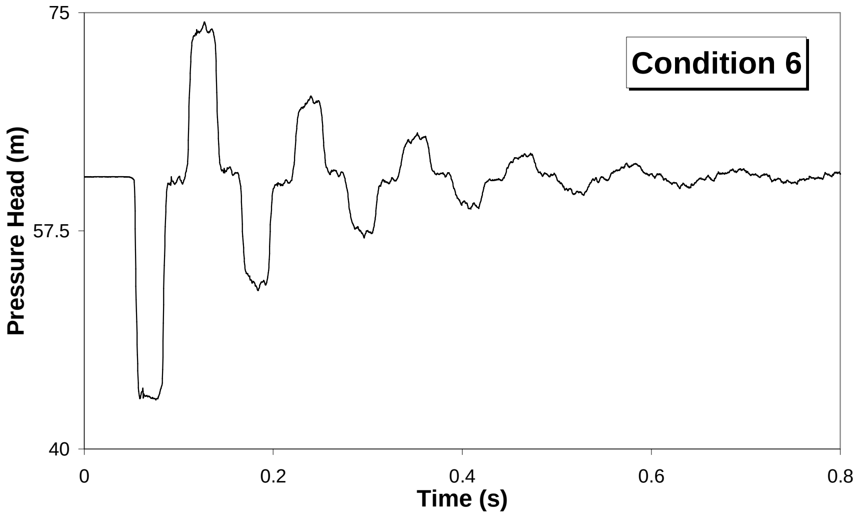


Figure C.2 Measured Transient Data at the Middle of Pipe

(Flow conditions are shown in Table 5.4)

APPENDIX D

THE EFFECT OF JOINTS ON TRANSIENT PIPE FLOWS

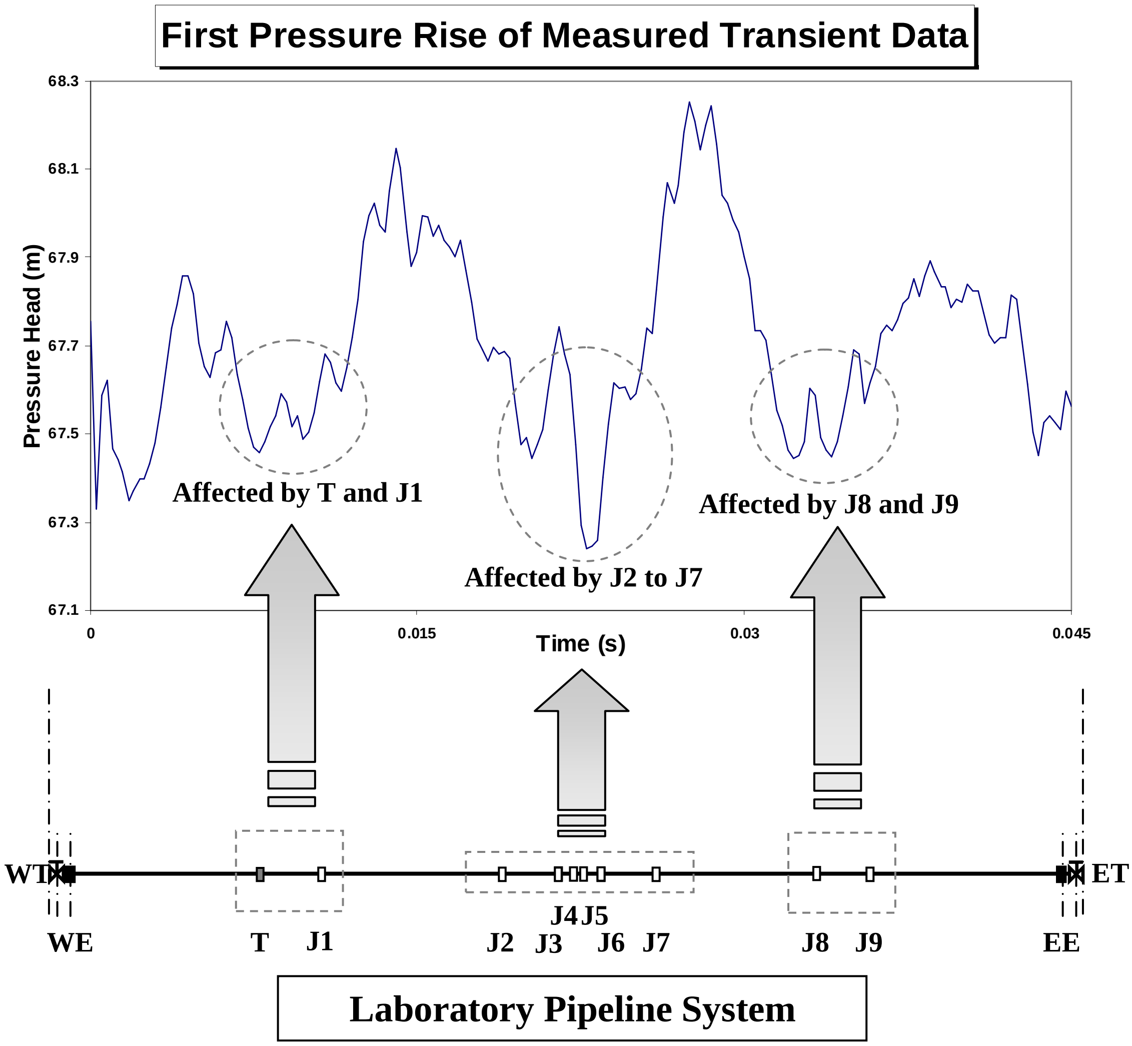


Figure D.1 Effect of Pipe Joints During Transients

APPENDIX E

THE EFFECT OF A VALVE ON TRANSIENT PIPE FLOWS

Laboratory experiments have been executed for the investigation of the effect of a gate valve during transient events. The experimental apparatus described in Chapter 4 is used. The gate valve as shown in Fig. E.2 is inserted between J4 and J5. Transients are generated at the middle of pipe (WM) by a side-discharge solenoid valve with a fast operating time after closing the east flow control valve. The sampling frequency of measured data is 4 kHz and the water temperature is 23^{o}C. Fig. E.1 shows the pipe system layout for gate valve tests.

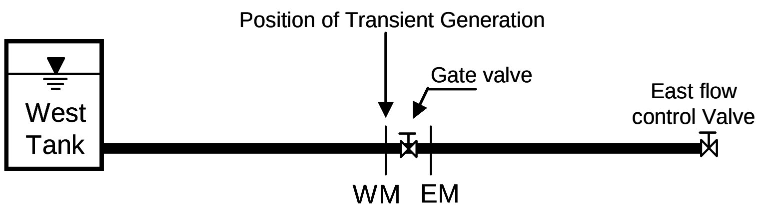


Figure E.1 Pipeline System Layout

The pressure data are collected according to the degree of valve opening or closure by adjusting the hand-wheel of the gate valve as shown in Fig. E.2. The fully open valve position is approximately 9 turns (9×360^o) from the fully closed valve condition. Fig. E.3 shows the measured data. The measured data present the state of transmission and reflection waves by the gate valve. When the gate valve is fully closed, the measured data at the WM shows full transients as a single pipeline composed of west tank, pipeline from west tank to gate valve, and downstream end valve, but the measured data at the EM has no propagation of pressure waves because the fully closed gate valve completely isolates the right-hand part of the gate valve. The situation is similar for valve openings of 1/8 and 2/8 turn opening. When the gate valve is opened to 3/8 opening of the hand-wheel, the pressure waves are very slightly propagated into the right-hand part of the system across the gate valve. The measured data of WM shows a large pressure damping when comparing the Fig. E.3 (a) to (c) but there is no wave reflection from the gate valve. This case is very special because the right-hand pipe of the gate valve can be regarded as a lumped capacitance that severely reduces the pressure wave. From the 4/8 turn open position (Fig. E.3 (e)), as the opening area of the gate valve increases the reflection of pressure wave by the gate valve decreases and the transmission of pressure wave through the gate valve increases. Finally, the measured data of 1 turn open are almost identical with the data of fully open, although the opening area is very small when considering the area of the fully opened condition. It may be noticed that the pressure wave can be easily or fully propagated through a small opening area. Condition assessment for valves uses these kinds of transient data to analyse the dynamic characteristics of valves.

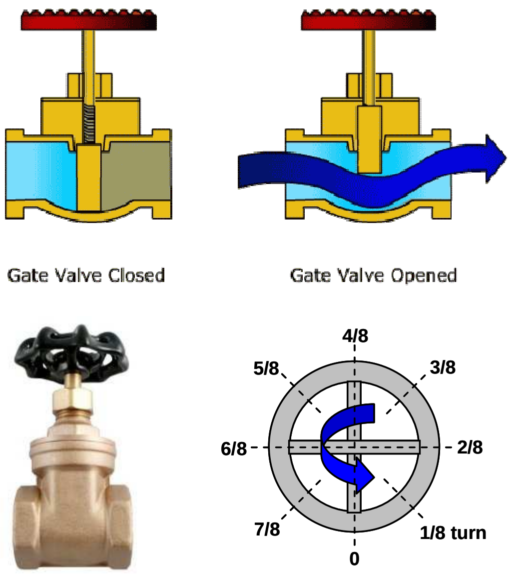
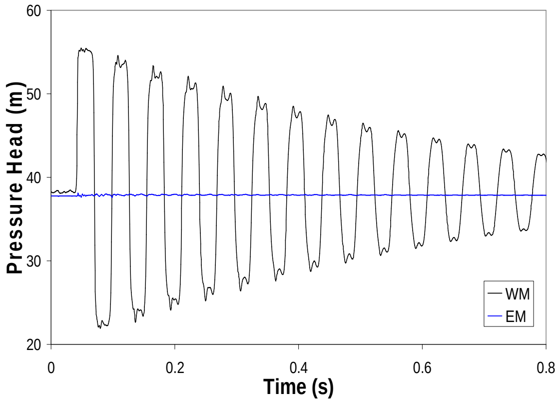
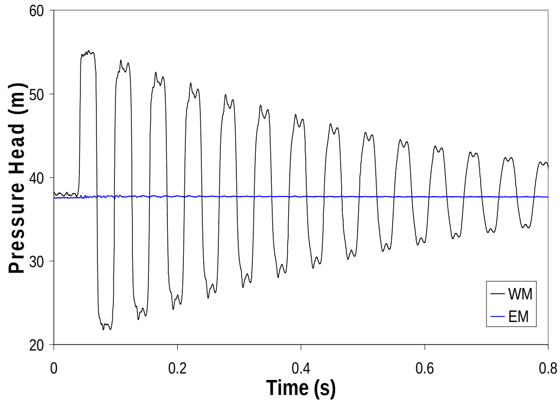


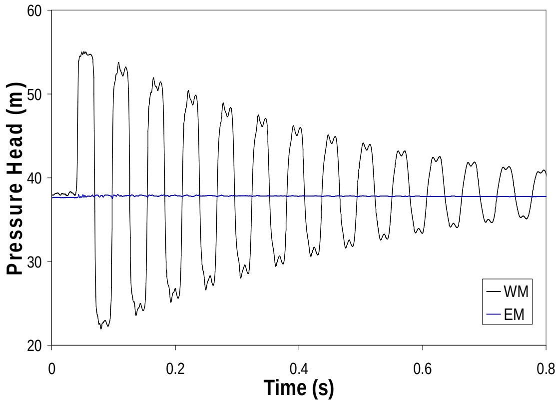
Figure E.2 Gate Valve



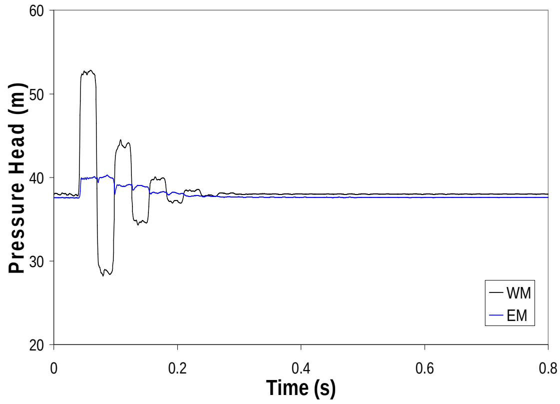
(a) Fully closed



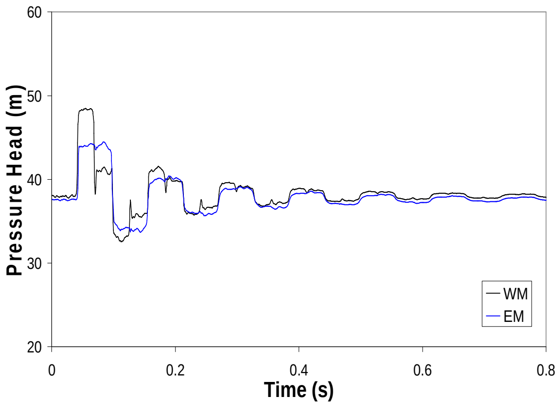
(b) 1/8 Turn Open



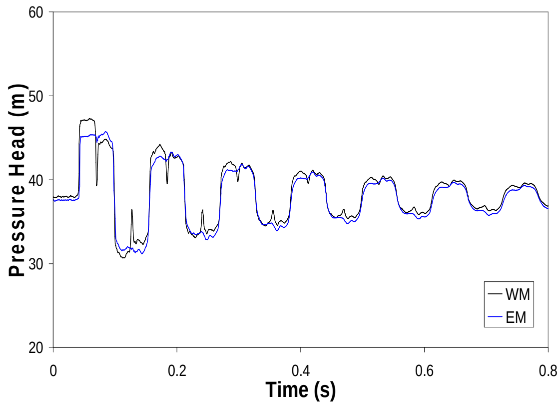
(c) 2/8 Turn Open



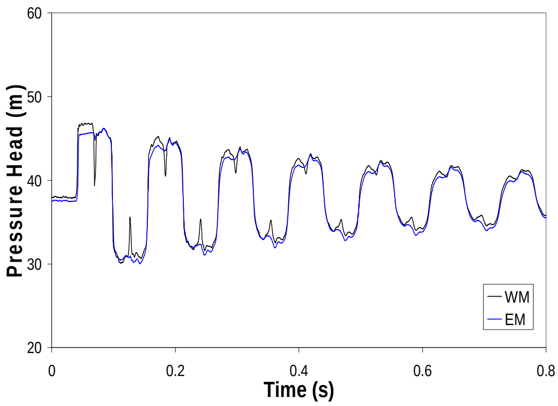
(d) 3/8 Turn Open



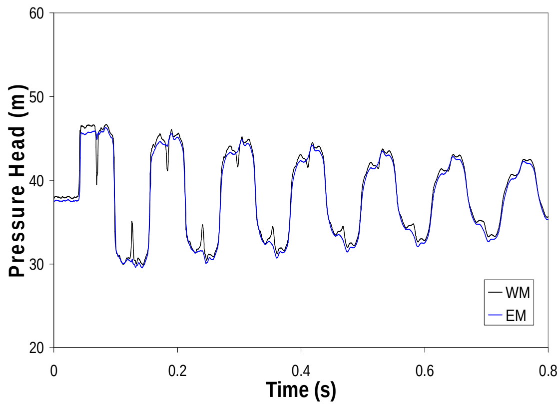
(e) 4/8 Turn Open



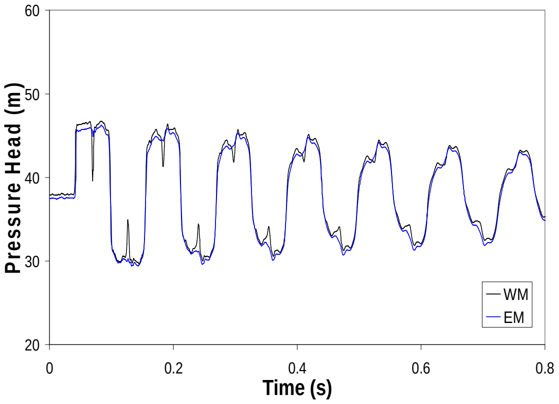
(f) 5/8 Turn Open



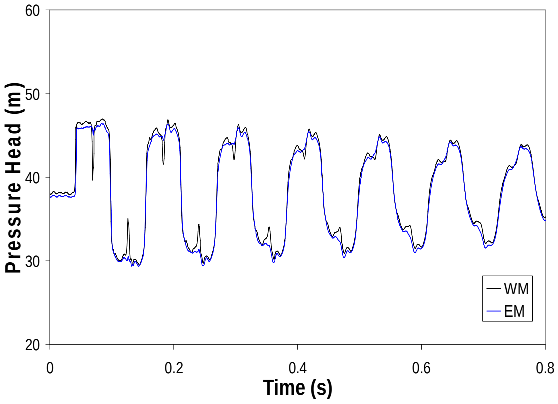
(g) 6/8 Turn Open



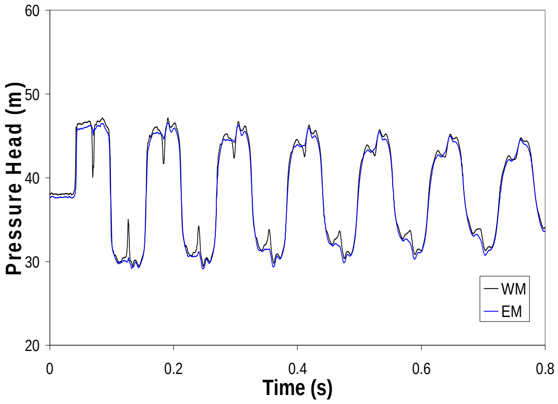
(h) 7/8 Turn Open



(i) 1 Turn Open



(j) 2 Turns Open



(k) Fully open

Figure E.3 Measured Data according to the Degree of Valve Open

APPENDIX F

THE EFFECT OF ROUGH WALL BLOCKAGES ON TRANSIENT PIPE FLOWS

Natural blockages formed by solid deposition or pipe wall corrosion have large roughness height and irregular shape when compared to the pipe wall material. For the natural blockage tests during transients, the surfaces of brass blockages presented in Chapter 8 were artificially cut by a large drill bit to make coarse screw thread on the inside surface of blockage. Fig. F.1 and F.2 shows the comparison of measured transient data between smooth wall blockages used in Chapter 8 and rough wall blockages with a 1 mm screw thread for 5 mm bore blockage and with 2 mm screw thread for 10 mm bore blockage. All blockages have a 153 mm axial length and are installed at the middle of pipeline. Transients are generated at the WE by a side-discharge solenoid valve and pressure waves are also measured at the WE. The results of blockages with rough wall are almost same as the results of blockages with smooth wall. The dominant physical phenomena of blockages still seem to be the eddy inertia effect of the turbulent jet flow because the length of blockage may be too short to affect the transient pressure wave.

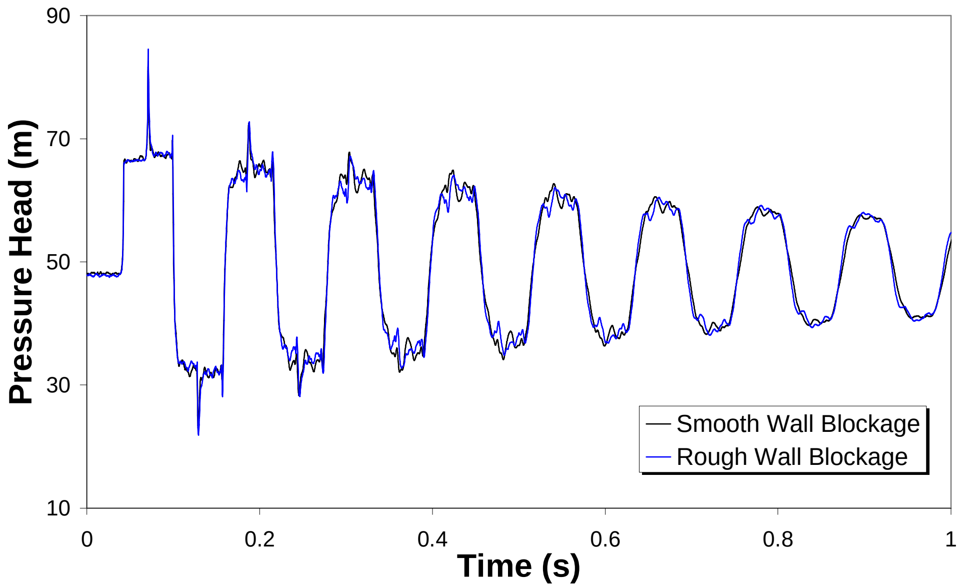


Figure F.1 Comparison between Measured Data with Smooth Wall Blockage (5 mm Blockage Bore) and with Rough Wall Blockage (5 mm Blockage Bore and 1 mm Roughness Height by Screw Thread)

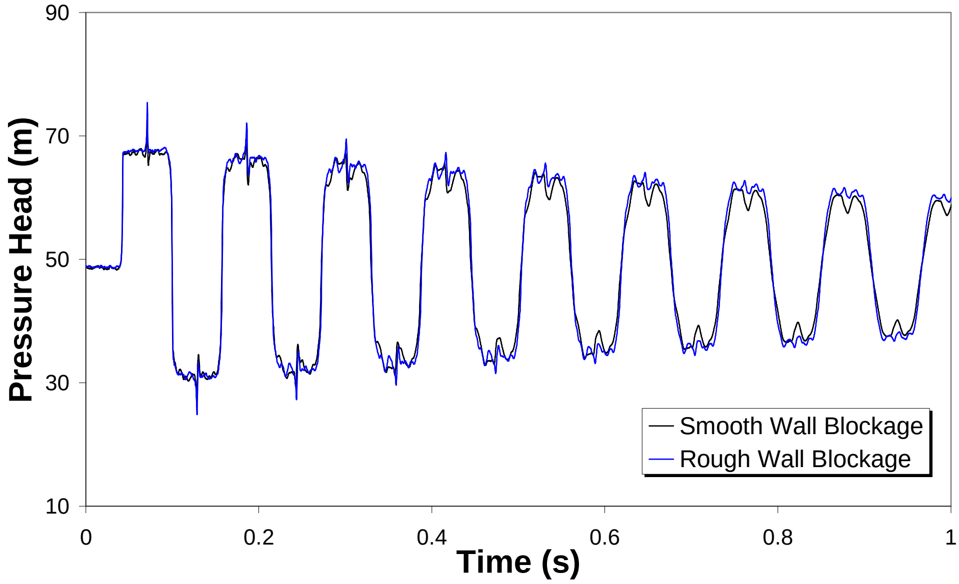


Figure F.2 Comparison between Measured Data with Smooth Wall Blockage (10 mm Blockage Bore) and with Rough Wall Blockage (10 mm Blockage Bore and 2 mm Roughness Height by Screw Thread)

BIBLIOGRAPHY

A

1. Abbott, M.B. and Basco, D.R. (1989). *Computational Fluid Dynamics – An Introduction for Engineers*, Longman Scientific & Technical, copublished in the United States with John Wiley & Sons, Inc., New York.
2. Addison, P.S., Ervine, D.A., Chan, A.H.C., and Williams, K.J. (1997). "An Experimental Investigation into the Breakdown of Low Reynolds Number Pulsed Flows at a Pipe Orifice." Transactions of the ASME, *Journal of Fluids Engineering*, Vol. 119, June, 347-353
3. ADEC (2000). "*Technical Review of Leak Detection Technologies, Volume 1: Crude Oil Transmission Pipelines*." Technical Report, Alaska Department of Environmental Conservation (ADEC).
4. Adewumi, M.A., Eltohami, E.S., and Solaja, A. (2001). "Possible Detection of Multiple Blockages using Transients." *Proceedings of ETCE2001, Engineering Technology Conference on Energy*, February 5-7, Houston, Texas.
5. Adewumi, M.A., Eltohami, E.S., and Solaja, A. (2003). "Possible Detection of Multiple Blockages Using Transients." *Journal of Energy Resources Technology*, Transactions of the ASME, Vol. 125, June, 154-158.
6. AGA (2000). "*Natural Gas Delivery System Materials*." American Gas Association, Technical Report.

7. Akagawa, K., Fujii, T., Ito, Y., Yamaguchi, T., and Fukuhara, K. (1982). “Studies on Shock Phenomena in Two-Phase Flow.” 2nd Report, Characteristics in Slug Flow Region, *Bulletin of the JSME*, Vol. 25 (201), 387-394.
8. Akagawa, K., Fujii, T., Ito, Y., Hiraki, S., Kitano, T., and Tsubokura, S. (1983). “Shock Phenomena in One-Component Two-Phase Bubbly Flow.” *Proceedings of Nuclear Reactor Thermal Hydraulics*, ANS, Vol. 1, 246-251.
9. Akagawa, K., Fujii, T., Tsubokura, S., Matsushita, H. and Hiraoka, Y. (1986). “Prediction of Pressure Surge in a One-component Two-phase Bubble Flow.” *Nuclear Engineering and Design*, No. 95, 329-341.
10. Aklonis, J.J., MacKnight, W.J., and Shen, M. (1972). *Introduction to Polymer Viscoelasticity*, Wiley-Interscience.
11. Al-Khomairi, A.M. (2005). “Use of the Steady-State Orifice Equation in the Computation of Transient Flow through Pipe Leaks.” *The Arabian Journal for Science and Engineering*, Vol. 30 (1B), 33-45.
12. Almeida, A.B. and Koelle, E. (1992). *Fluid Transients in Pipe Networks*, Computational Mechanics Publications, Southampton Boston, Co-published with Elsevier Applied Science, London, New York.
13. Al-Rafai, W. and Barnes, R. J. (1999). “Underlying the Performance of Real-time Software-based Pipeline Leak-detection Systems.” *Pipes & Pipelines*, November-December, 44-51.
14. Anderson, J.D. Jr. (1995). *Computational Fluid Dynamics: The Basics with Applications*, McGraw-Hill Inc.
15. Anisimov, V., Smogalev, I., and Kriventsev, V. (1999). “TRANSHYD: Computer Program for Transient Flow Analysis in Pipeline Networks.” *28th Biennial Congress, IAHR*, August, Graz, Austria.
16. Arfaie, M. and Anderson, A. (1991). “Implicit Finite-Difference for Unsteady Pipe Flow.” *Mathematical Engineering in Industry*, Vol. 3 (2), 133-151.
17. ASME (1959). *Fluid Meters – Their Theory and Application*, Report of the American Society of Mechanical Engineers Research Committee on Fluid Meters, 5th Ed., New York.

B

18. Barbero, E.J. and Julius, M. (2004). “Time-Temperature-Age Viscoelastic Behavior of Commercial Polymer Blends and Felt Filled Polymers.” *Journal of Mechanics of Advanced Materials and Structures*, Vol. 11 (3), 287-300.
19. Barbero, E.J. and Ford, K.J. (2004). “Equivalent Time Temperature Model for Physical Ageing and Temperature Effects on Polymer Creep and Relaxation.” *Journal of Engineering Materials and Technology*, ASME, Vol. 126 (4), 413.
20. Beauchemin, P. and Marche, C. [1992]. “Transients in Complex Closed-Conduit Systems: Second-Order Explicit Finite Difference Schemes.” *Unsteady Flow and Fluid Transients*, Bettess & Watts, Balkema, Rotterdam.
21. Belsito, S., Lombardi, P., Andreussi, P., and Banerjee, S. (1998). “Leak Detection in Liquefied Gas Pipeline by Artificial Neural Networks.” *American Institute of Chemical Engineers (AIChE) Journal*, Vol. 44 (12), December, 2475-2688.
22. Bender, E. (1979). “Short Note: Simulation of Dynamic Gas Flows in Networks including Control Loops.” *Computers & Chemical Engineering*, Vol. 3
23. Benkherouf, A. and Allidina, A.Y. (1988). “Leak Detection and Location in Gas Pipelines.” *Proceedings of the Institution of Electrical Engineers (IEE)*, Vol. 135 (2), March.
24. Bergant, A. and Simpson, A.R. (1994). “Estimating Unsteady Friction in Transient Cavitating Pipe Flow.” *2nd International Conference on Water Pipeline Systems*, Edinburgh, Scotland, 3-15.
25. Bergant, A. and Simpson, A.R. (1995). “Water Hammer and Column Separation Measurements in an Experimental Apparatus.” *Research Report*, No. 128, School of Civil and Environmental Engineering, University of Adelaide, Australia.
26. Bergant, A. and Simpson, A.R. (1999). “Pipeline Column Separation Flow Regimes.” *Journal of Hydraulic Engineering*, Vol. 125 (8), 835-848.
27. Bergant, A., Simpson, A.R., and Vítkovský, J.P. (1999). “Review of Unsteady Friction Models in Transient Pipe Flow.” *9th International Meeting on the Behaviour of Hydraulic Machinery Under Steady Oscillatory Conditions*, International Association of Hydraulic Research, Brno, Czech Republic.

28. Bergant, A., Tijsseling, A., Vítkovský, J.P., Covas, D., Simpson, A.R. and Lambert, M.F. (2003a). "Further investigation of parameters affecting water hammer wave attenuation, shape and timing. Part 1: Mathematical tools." *11th International Meeting of the Working Group on the Behaviour of Hydraulic Machinery Under Steady Oscillatory Conditions*, Stuttgart, Germany, October.
29. Bergant, A., Tijsseling, A., Vítkovský, J.P., Covas, D., Simpson, A.R. and Lambert, M.F. (2003b). "Further investigation of parameters affecting water hammer wave attenuation, shape and timing. Part 2: Case studies." *11th International Meeting of the Working Group on the Behaviour of Hydraulic Machinery Under Steady Oscillatory Conditions*, Stuttgart, Germany, October.
30. Bergant, A., Simpson, A.R., and Tijsseling, A.S. (2006). "Water Hammer with Column Separation: A Historical Review." *Journal of Fluids and Structures*, Vol. 22, 135-171.
31. Bikai, Z., Yan, H., Tiehua, Z., and Zhuangyun, L. (2002). "Experimental Investigation of the Flow Characteristics of Small Orifices and Valves in Water Hydraulics." *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, Vol. 216, 235-245.
32. Borutzky, W., Barnard, B., and Thoma, J. (2002). "An Orifice Flow Model for Laminar and Turbulent Conditions." *Simulation Modelling Practice and Theory*, Vol. 10, 141-152.
33. Bouazza, Z. and Brunelle, P.E. (2004). "A New Friction Model for Transient Pipe Flows: Development of the Frequency Dependence Approach of Brunone. *9th International Conference on Pressure Surge*, Chester, UK, BHR Group, 391-404.
34. Bratland, O. (1986). "Frequency-Dependent Friction and Radial Kinetic Energy Variation in Transient Pipe Flow." *Proceedings of the 5th International Conference on Pressure Surges*, BHRA, Hannover, Germany, 95-101.
35. Bribiesca, J.L.S. (1981). "A Finite-Difference Method to Evaluate Water Hammer Phenomena." *Journal of Hydrology*, Vol. 51, 305-311.
36. Brown, F.T. (1962). "The Transient Response of Fluid Lines." *Journal of Basic Engineering*, Transactions of the ASME, December, 547-553.
37. Brunone, B., Golia, U.M., and Greco, M. (1991a). "Some Remarks on the Momentum Equation for Fast Transients." *Proceedings of International Conference on Hydraulic Transients with Water Column Separation*, IAHR, Valencia, Spain, 201-209.

38. Brunone, B., Golia, U.M., and Greco, M. (1991b). “Modelling of Fast Transients by Numerical Methods.” *Proceedings of International Conference on Hydraulic Transients with Water Column Separation*, IAHR, Valencia, Spain, 273-280.

39. Brunone, B., Golia, U.M., and Greco, M. (1995). “Effects of Two-Dimensionality on Pipe Transients Modeling.” *Journal of Hydraulic Engineering*, Vol. 121 (12), 906-912.

40. Brunone, B. (1999). “Transient Test-Based Technique for Leak Detection in Outfall Pipes.” *Journal of Water Resources Planning and Management,* September, 302-306.

41. Brunone, B. and Ferrante, M. (2001). “Detecting Leaks in Pressurised Pipes by means of Transients.” *Journal of Hydraulic Research*, IAHR, Vol. 39 (4), 1-9.

42. Brunone, B., Cacciamani, M., Calabresi, F., and Ferrante, M. (2003). “An Investigation on Unsteady-State Friction in Laminar Flow.” *Pumps, Electromechanical Devices and Systems Applied to Urban Water Management*, Valencia, Spain.

43. BSI (1964). *Methods for the Measurement of Fluid Flow in Pipes, Part 1. Orifice Plates, Nozzles and Venturi Tubes*, B.S. 1042, British Standards Institution.

44. Bughazem, M.B. and Anderson, A. (1996). “Problems with Simple Models for Damping in Unsteady Flow.” *7th International Conference on Pressure Surges and Transients in Pipelines and Open Channels*. BHR Group, Harrogate, UK.

45. Bughazem, M.B. and Anderson, A. (2000). “Investigation of an Unsteady Friction Model for Waterhammer and Column Separation.” BHR Group, *Pressure Surges*, 483-498.

46. Burrows, R. and Qiu, D.Q. (1995). “*Effect of Air Pockets on Pipeline Surge Pressure*.” Proceedings of Institution of Civil Engineers Water Maritime & Energy, Vol. 112, 349-361.

C

47. Cabrera, E., Abreu, J., Perez, R., and Vela, A. (1992). “Influence of Liquid Length Variation in Hydraulic Transients.” *Journal of Hydraulic Engineering,* Vol. 118 (12), 1639-1650.

48. Carstens, M.R. and Roller, J.E. (1959). "Boundary-Shear Stress in Unsteady Turbulent Pipe Flow." *Journal of the Hydraulics Division*, *Proceedings of the American Society of Civil Engineers*, Vol. 85 (HY2), 67-81.

49. Chaudhry, M.H. and Hussaini, M.Y. (1985). "Second-Order Accurate Explicit Finite-Difference Schemes for Waterhammer Analysis." *Journal of Fluids Engineering*, Transactions of the ASME, Vol. 107, December, 523-529.

50. Chaudhry, M.H. (1987). *Applied Hydraulic Transients*, 2nd Ed., Van Nostrand Reinhold Company, New York.

51. Chaudhry, M.H., Bhallamudi, S.M., Martin, C.S., and Naghash, M. (1990). "Analysis of Transient Pressures in Bubbly, Homogeneous, Gas-Liquid Mixtures." *Journal of Fluids Engineering*, Transactions of the ASME, Vol. 112, 225-231.

52. Chaudhry, M.H. (1993). *Open Channel Flow*, Prentice Hall, London.

53. Chen, N.H. (1979). "An Explicit Equation for Friction Factor in Pipe." *Industrial and Engineering Chemistry Fundamentals*, Vol. 18 (3), 296-297.

54. Chen, L. (1995). *Pipe Network Transient Analysis – the Forward and Inverse Problems*. PhD Thesis, Cornell University.

55. Chung, W. and Lee, D. (2001). "Real Time Multi-channel Gas Leakage Monitoring System using CPLD Chip." *Sensors and Actuators* B 77, 186-189.

56. Contractor, D.N. (1965). "The Reflection of Waterhammer Pressure Waves from Minor Losses." *Journal of Basic Engineering, Transactions of the ASME,* June, 445-452.

57. Corberan, J.M. and Gascon, M.L. (1995). "TVD Schemes for the Calculation of Flow in Pipes of Variable Cross-Section." *Mathematical and Computer Modelling*, Vol. 21 (3), 85-92.

58. Cosham, A. and Hopkins, P. (2004). "The Effect of Dents in Pipelines – Guidance in the Pipeline Defect Assessment Manual." *International Journal of Pressure Vessels and Piping*, Vol. 81 (2), 127-139.

59. Covas, D., Stoianov, I., Graham, N., Maksimovic, C., Ramos, H., and Butler, D. (2002). "Hydraulic Transients in Polyethylene Pipes." *1st Annual Environmental & Water Resource Systems Analysis Symposium* in Conjunction with ASCE Environmental & Water Resources Institute Annual Conference, Roanoke, Virginia, May.

60. Covas, D., Stoianov, I., Mano, J.F., Ramos, H., Graham, N., and Maksomovic, C. (2004). “The Dynamic Effect of Pipe-Wall Viscoelasticity in Hydraulic Transients. Part 1-Experimental Analysis and Creep Characterization.” *Journal of Hydraulic Research*, Vol. 42 (5), 516-530.

61. Covas, D., Stoianov, I., Mano, J.F., Ramos, H., Graham, N., and Maksomovic, C. (2005). “The Dynamic Effect of Pipe-Wall Viscoelasticity in Hydraulic Transients. Part 2-Model Development, Calibration, and Verification.” *Journal of Hydraulic Research*, Vol. 43 (1), 56-70.

62. Cronje, J.S., Bishnoi, P.R., and Svrcek, W.Y. (1980). “The Application of the Characteristic Method to Shock Tube Data that Simulate a Gas Pipeline Rupture.” *The Canadian Journal of Chemical Engineering*, Vol. 58, 289-294.

D

63. Daily, J.W., Hankey, W.L., Olive, R.W., and Jordaan, J.M. (1956). “Resistance Coefficients for Accelerated and Decelerated Flows Through Smooth Tubes and Orifices.” *Transactions of the ASME*, 1071-1077.

64. Daniels, D.J. (1996). *Surface-Penetrating Radar*, Stevenage, U.K., Institution of Electrical Engineers.

65. Davis, N. and Cheng, R.C. (1972). “Transient Laminar Flow in Ducts of Arbitrary Cross-Section by Finite Element Methods.” *Journal of Biomechanics*, Vol. 5, 485-499.

66. De Bernardinis, B., Graham, J.M.R., and Parker, K.H. (1981). “Oscillatory Flow around Disks and through Orifices.” *Journal of Fluid Mechanics*, Vol. 102, 279-299.

67. De Salis, M.H.F. and Oldham, D.J. (2001). “The Development of a Rapid Single Spectrum Method for Determining the Blockage Characteristics of a Finite Length Duct.” *Journal of Sound and Vibration*, Vol. 243 (2), 625-640.

68. Doebelin, E.O. (1990). *Measurement Systems – Application and Design*, 4th Ed., McGraw-Hill Publishing Company.

69. Druck (1997). *PDCR 800 SERIES*, Druck Limited.

70. D’Souza, A.F. and Oldenburger, R. (1964). “Dynamic Response of Fluid Lines.” *Journal of Basic Engineering*, Transactions of the ASME, Septemper, 589-598.

71. Dukhovnaya, Y. and Adewumi, M.A. (2000). "Simulation of Non-Isothermal Transients in Gas/Condensate Pipelines using TVD Scheme." *Powder Technology*, Vol. 112, 163-171.

E

72. Earles, S.W.E. and Zarek, J.M. (1963). "Use of Sharp-Edged Orifices for Metering Pulsating Flow." *Proceedings of the Institution of Mechanical Engineers., Thermodynamics and Fluid Mechanics Group*, Vol. 177 (37), 997-1024.
73. Echavez, G. (1997). "Increase in Losses Coefficient with Age for Small Diameter Pipes." *Journal of Hydraulic Engineering*, Vol. 123 (2), 157-159.
74. Eichinger, P. and Lein, G. (1992). "The Influence of Friction on Unsteady Pipe Flow." *International Conference on Unsteady Flow and Fluid Transients*, Bettess and Watts eds., Balkema, Rotterdam, 41-50.
75. Eiswirth, M., Heske, C., Burn, L.S., and DeSilva, D. (2001). "New Methods for Water Pipeline Assessment." *IWA 2. World Water Congress*, 15-19, October, Berlin, Germany.
76. Ellis, J. (1986). "Prediction of Pressure Surge in Plastic Pipes." *5th International Conference on Pressure Surges*, Hannover, Germany, 103-111.

F

77. Ferrante, M. and Brunone, B. (2003a). "Pipe System Diagnosis and Leak Detection by Unsteady-State Tests – 1. Harmonic Analysis." *Advances in Water Resources*, Vol. 26, 95-105.
78. Ferrante, M. and Brunone, B. (2003b). "Pipe System Diagnosis and Leak Detection by Unsteady-State Tests – 2. Wavelet Analysis." *Advances in Water Resources*, Vol. 26, 107-116.
79. Ferry, J.D. (1970). *Viscoelastic Properties of Polymers*, 2nd Ed., Wiley.
80. Fietz, T.R. (1988). *An Aid to the Design of Orifice Plates according to ISO CODE 5167*, Research Report No. 173, Water Research Laboratory, The University of New South Wales.

81. Fox, J.A. (1977). *Hydraulic Analysis of Unsteady Flow in Pipe Networks*, Macmillan Press LTD.

82. Fox, J.A. (1989). *Transient Flow in Pipes, Open Channels and Sewers*, Ellis Horwood Limited, Halsted Press; a Division of John Wiley & Sons.

83. Fox, L. (1961). *Numerical Solution of Ordinary and Partial Differential Equations*: Based on a Summer School held in Oxford, Pergamon Press.

84. Franke, P.G. and Seyler, F. (1983). "Computation of Unsteady Pipe Flow with Respect to Visco-Elastic Material Properties." *Journal of Hydraulic Research*, Vol. 21 (5), 345-353.

85. Fuertes, V.S., Cabrera, E., Izquierdo, J., and Iglesias, P.L. (1999). "Peak Pressure Evaluation in Pipelines with Entrapped Air Pockets." *Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference*, July 18-23, San Francisco, California.

86. Fujii, T. and Akagawa, K. (1993). "Water Hammer Phenomena in a One-component Two-phase Bubbly Flow." *Nuclear Engineering and Design*, No. 141, 101-110.

87. Fujii, T. and Akagawa, K. (2000). "A Study of Water Hammer Phenomena in a One-component Two-Phase Bubbly Flow." *JSME International Journal*, Series B, Vol. 43 (3), 386-392.

88. Fujimoto, T. and Usami, M. (1984). "Rarefied Gas Flow Through a Circular Orifice and Short Tubes." *Journal of Fluids Engineering*, Vol. 106, 367-373.

89. Fukushima, K., Maeshima, R., Kinoshita, A., Shiraishi, H., and Koshijima, I. (2000). "Gas Pipeline Leak Detection System using the Online Simulation Method." *Computers and Chemical Engineering*, 24, 453-456.

90. Funk, J.E., Wood, D.J., Chao, S.P. (1972). "The Transient Response of Orifices and Very Short Lines." *Journal of Basic Engineering*, Transaction of the ASME, 483-491.

91. Funk, J.E., Wood, D.J., vanVuuren, S.J., LeChevallier, M., and Friedman, M. (1999). "Pathogen Intrusion into Water Distribution Systems due to Transients." *Proceedings of the 3rd ASME/JSME Joint Fluids Engineering Conference*, July 18-23, San Francisco, California.

92. Furness, R.A. and van Reet J.D. (1998). *Pipe Line Rules of Thumb Handbook*, Gulf Publishing Company, Houston, Texas.

G

93. Gally, M., Guney, M., and Rieutord, E. (1979). "An Investigation of Pressure Transients in Viscoelastic Pipes." *Journal of Fluid Engineering, Transaction of the ASME*, Vol. 101, 495-499.

94. Germanopoulos, G. (1985). "A Technical Note on the Inclusion of Pressure Dependent Demand and Leakage Terms in Water Supply Network Models." *Civil Engineering Systems*, Vol. 2, 171-179.

95. Ghilardi, P. and Paoletti, A. (1986). "Additional Viscoelastic Pipes as Pressure Surges Suppressors." *5th International Conference on Pressure Surges*, Hannover, Germany, 113-121.

96. Ghidaoui, M.S. and Karney, B.W. (1994). "Equivalent Differential Equations in Fixed-Grid Characteristics Method." *Journal of Hydraulic Engineering*, Vol. 120 (10), 1159-1175.

97. Ghidaoui, M.S., Mansour, G.S., and Zhao, M. (2002). "Applicability of Quasi-Steady and Axisymmetric Turbulence Models in Water Hammer." *Journal of Hydraulic Engineering*, ASCE, Vol. 128 (10), 917-924.

98. Ghidaoui, M.S. and Mansour, S. (2002). "Efficient Treatment of the Vardy-Brown Unsteady Shear in Pipe Transients." *Journal of Hydraulic Engineering*, Vol. 128 (1), 102-112.

99. Ghidaoui, M.S., Zhao, M., McInnis, D.A., and Axworthy, D.H. (2005). "A Review of Water Hammer Theory and Practice." *Applied Mechanics Reviews*, Transactions of the ASME, January, Vol. 58, 49-76.

100. Gibson, A.H. (1908). *Water Hammer in Hydraulic Pipe Lines*, Archibald Constable & Co., LTD, London.

101. Goldberg, D.E. and Wylie, E.B. (1983). "Characteristics Method Using Time-Line Interpolations." *Journal of Hydraulic Engineering*, Vol. 109 (5).

102. Goldstein, R.J. (1983). *Fluid Mechanics Measurements*, Hemisphere Publishing Corporation.

103. Greco, M. (1990). "Some Recent Findings on Column Separation during Water Hammer." *Excerpia*, Vol. 5, 261-272.

104. Greyvenstein, G.P. (2002). "An Implicit Method for the Analysis of Transient Flows in Pipe Networks." *International Journal for Numerical Methods in Engineering*, Vol. 53, 1127-1143.

105. Guney, M.S. (1983). "Waterhammer in Viscoelastic Pipes Where Cross-section Parameters are Time Dependent." *4th International Conference on Pressure Surges*, the University of Bath, England, 189-204.

H

106. Han, S.M. (1983). "A Generalized Implicit Finite Difference Method for Transient Analysis of Compressible and Incompressible Fluid Flows." ASME, *Fluids Engineering Division, FED*, V4, 17-21.

107. Hayase, T., Cheng, P, and Hayashi, S. (1995). "Numerical Analysis of Transient Flow through a Pipe Orifice (Time Constant for Settling Flow)." *Japan Society of Mechanical Engineers (JSME) International Journal*, Series B, Vol. 38 (2), 157-163.

108. Hoeijmakers, J. (2002). "Real Time Statistical Leak Detection on the RRP Crude Oil Network, Holland." *Proceedings of ICP02, International Pipeline Conference 2002*, September 29-Octorber 3, Calgary, Alberta.

109. Holly, F.M. and Preissmann, A. (1977). "Accurate Calculation of Transport in Two Directions." *Journal of Hydraulic Engineering*, Vol. 103 (11), 1259-1277.

110. Holmboe, E.L. and Rouleau, W.T. (1967). "The Effect of Viscous Shear on Transients in Liquid Lines." *Journal of Basic Engineering*, Transactions of the ASME, March, 174-180.

111. Hunt, A. (1996). "Fluid Properties Determine Flow Line Blockage Potential." *Oil & Gas Journal*, 94(29), 62-66.

112. Hwang, N.H.C. and Houghtalen, R.J. (1996). *Fundamentals of Hydraulic Engineering Systems*, 3rd Ed., Prentice Hall, New Jersey.

113. Hwang, Y. and Chung, N. (2002). "A Fast Godunov Method for the Water-hammer Problem." *International Journal for Numerical Methods in Fluids*, Vol. 40, 799-819.

I

114. International Association of Hydraulic Engineering and Research (IAHR). (2000). "*Hydraulic transients with water column separation.*" IAHR working group 1971-1991 Synthesis report.

115. Islam, M.R. and Chaudhry, M.H. (1998). “Modeling of Constituent Transport in Unsteady Flows in Pipe Networks.” *Journal of Hydraulic Engineering*, Vol. 124 (11), 1115-1124.

116. Issa, R.I. and Spalding, D.B. (1972). “Unsteady One-Dimensional Compressible Frictional Flow with Heat Transfer.” *Journal Mechanical Engineering Science*, Vol. 14 (6), 365-369.

117. Izquierdo, J., Fuertes, V.S., Cabrera, E., Iglesias, P.L., Garcia-Serra, J. (1999). “Pipeline Start-up with Entrapped Air.” *Journal of Hydraulic Research*, Vol. 37 (5), 579-590.

J

118. Jaeger, C. (1977). *Fluid Transients in Hydroelectric Engineering Practice*, Blackie & Sons, Ltd., London.

119. Jitschin, W. (2004). “Gas Flow Measurement by the Thin Orifice and the Classical Venturi Tube.” *Vacuum*, Vol. 76, 89-100.

120. Jones Jr. E.H. and Bajura, R.A. (1991). “A Numerical Analysis of Pulsating Laminar Flow through a Pipe Orifice.” *Journal of Fluids Engineering*, Vol. 113, June, 199-205.

121. Jönsson, L. (2001). “Interaction of a Hydraulic Transient with a Leak in a Pipe Flow.” *14th Australasian Fluid Mechanics Conference*, University of Adelaide, Adelaide, Australia, December 10-12.

K

122. Kagawa, T., Lee, I., Kitagawa, A., and Takenaka, T. (1983). “High Speed and Accurate Computing Method of Frequency-Dependent Friction in Laminar Pipe Flow for Characteristics Method.” *Transactions of the Japanese Society of Mechanical Engineering*, Vol. 49 (447), 2638-2644.

123. Karney, B.W. and Ghidaoui, M.S. (1997). “Flexible Discretization Algorithm for Fixed-Grid MOC in Pipelines.” *Journal of Hydraulic Engineering*, Vol. 123 (11), 1004-1011.

124. KEMBLA (2006). *The Plumbers Handbook*, 7th Ed., KEMBLA Australia.

125. Kessal, M. (2000). "Simplified Numerical Simulation of Transients in Gas Transients." Institution of Chemical Engineers (IchemE), *Transaction of the IchemE* Vol. 78, Part A, 925-930.

126. Kim, Y. (2002). *Development and Verification of Leak Detection Program for Water Distribution System using Transients and Genetic Algorithms.* Master dissertation, Department of Civil and Ocean Engineering, Dong-A University (in Korean).

127. Kim, Y., Simpson, A.R., and Lambert, M.F. (2005). "Unsteady Friction Models for Conservative Solution Schemes in Transient Pipe Flows." *Computing and Control in the Water Industry (CCWI) Conference*, Exeter, UK.

128. Kiuchi, T. (1994). "An Implicit Method for Transient Gas Flows in Pipe Networks." *International Journal of Heat and Fluid Flow*, Vol. 15 (5), 378-383.

L

129. Lai, C. (1989). "Comprehensive Method of Characteristics Models for Flow Simulation." *Journal of Hydraulic Engineering*, Vol. 114 (9), 1074-1097.

130. Lai, L. and Bakker, A. (1995). "Analysis of the Non-linear Creep of High-Density Polyethylene." *Polymer*, Vol. 36 (1), 93-99.

131. Larson, M. and Jonsson, L. (1991). "Elastic Properties of Pipe Materials during Hydraulic Transients." *Journal of Hydraulic Engineering*, Vol. 117 (10), 1317-1331.

132. Lauchlan, C.S., Escarameia, M., May, R.W.P., Burrows, R., and Gahan, C. (2005). *Air in Pipelines – A Literature Review*, Report SR 649, HR Wallingford Limited.

133. Lee, P.J., Vítkovský, J.P., Lambert, M.F., Simpson, A.R., and Liggett, J.A. (2002). "Leak Detection in Pipelines Using an Inverse Resonance Method." *1ST Annual Environmental & Water Resources Systems Analysis Symposium in Conjunction with ASCE Environmental & Water Resources Institute Annual Conference*, Virginia, USA.

134. Lee, P.J., Vítkovský, J.P., Lambert, M.F., Simpson, A.R., and Liggett, J.A. (2003). "Frequency Response Coding for the Location of Leaks in Single Pipeline Systems." *Pumps, Electromechanical Devices and Systems Applied to Urban Water Management*, Vol. 1, Valencia, Spain, 371-378.

135. Lee, T.S. (1998). “A Numerical Method for the Computation of the Effects of an Air Vessel on the Pressure Surges in Pumping Systems with Air Entrainment.” *International Journal for Numerical Methods in Fluids*, Vol. 28, 703-718.

136. Lee, T.S. (1999). “Air Influence on Hydraulic Transients on Fluid System with Air Valves.” *Journal of Fluids Engineering*, Transactions of the ASME, Vol. 121, 646-650.

137. Lee, T.S. (2000). “Effects of Air Entrainment on the Ability of Air Vessels in the Pressure Surge Suppressions.” *Journal of Fluids Engineering*, Vol. 122, 499-504.

138. Lee, T.S. and Leow, L.C. (2001). “Numerical Study on Effects of Check Valve Closure Flow Conditions on Pressure Surges in Pumping Station with Air Entrainment.” *International Journal for Numerical Methods in Fluids*, Vol. 35, 117-124.

139. Lienhard, J.H. IV and Lienhard, J.H. V. (2004). *A Heat Transfer Textbook*, 3rd Ed., Phlogiston Press, Cambrige, Massachusetts.

140. Liepmann, H.W. and Roshko, A. (1957). *Elements of Gasdynamics*, John Wiley & Sons, Inc. New York.

141. Liggett, J.A. and Cunge, J.A. (1975). “Numerical Methods of Solution of Unsteady Flow Equations.” In *Unsteady Flow in Open Channels*, edited by Mahmood, K. and Yevjevich, V., Water Resources Publications, Fort Collins, Colorado, USA.

142. Liggett, J.A. (1994). *Fluid Mechanics*, McGraw-Hill Book Company.

143. Liggett, J. A. and Chen, L. C. (1994). “Inverse Transient Analysis in Pipe Networks.” *Journal of Hydraulic Engineering*, Vol. 120 (8), 934-955.

144. Liou, C.P., and Tian, J. (1995). “Leak Detection – Transient Flow Simulation Approaches.” *Journal of Energy Resource Technology*, Transactions of ASME, September, Vol. 117, 243-248.

145. Liou, C.P. and Hunt, W.A. (1996). “Filling of Pipelines with Undulating Elevation Profiles.” *Journal of Hydraulic Engineering*, Vol. 122 (10), 534-539.

146. Liou, J.C. (1996). “Leak Detection by Mass Balance Effective for Norman Well Line.” *The Oil & Gas Journal*, April 22, Vol. 94 (17), 69.

M

147. MacLaren, J.F.T., Tramschek, A.B., Pastrana, O.F., and Sanjines, A. (1976). "Research Note: An Alternative Scheme to Solve the Equations for Unsteady Gas Flow." *Journal Mechanical Engineering Science*, Vol. 18 (3), 161-163.

148. MacLean, A., Moran, C., Johnstone, W., Culshaw, B., March, D., and Andrews, G. (2001). "Distributed Fiber Optic Sensors for the Detection of Liquid Spills." *2nd International Symposium and Workshop on Time Domain Reflectometry for Innovative Geotechnical Applications*, September.

149. Makar, J. and Chagnon, N. (1999). "Inspecting Systems for Leaks, Pits, and Corrosion." *Journal of American Water Works Association*, Vol. 91 (7), 36-46.

150. Mano, J.F., Sousa, R.A., Reis, R.L., Cunha, A.M., and Bevis, M.J. (2001). "Viscoelastic Behavior and Time-Temperature Correspondence of HDPE with Varying Levels of Process-Induced Orientation." *Polymer*, Vol. 42, 6187-6198.

151. Martin, C.S. (1976). "Entrapped Air in Pipelines." *2nd International Conference on Pressure Surges*, London, England.

152. McCloy D. (1966). "Effects of Fluid Inertia and Compressibility on the Performance of Valves and Flow Meters Operating under Unsteady Conditions." *Journal of Mechanical Engineering Science*, Vol. 8 (1), 52-61.

153. McCrum, N.G., Buckley, C.P., and Bucknall, C.B. (1997), *Principles of Polymer Engineering*, 2nd Ed., Oxford, New York, Oxford University Press.

154. Measurement Computing (2006). *USB-1608FS: USB-based Analog and Digital I/O Module User's Guide*, Measurement Computing Corporation.

155. Meiβner, E. and Franke, (1977). "Influence of Pipe Material on the Damping of Water Hammer Oscillations." *Proceedings of the 17th International Association for Hydraulic Research (IAHR) Congress*, Vol. 5, Baden-Baden, German, 177-183.

156. Meyers, M.A. and Chawla, K.K. (1998). *Mechanical Behavior of Materials*, Prentice Hall.

157. Mezger, T.G. and Westphal, E. (2006). *The Rheology Handbook*, 2nd Ed., Vincentz Network.

158. Miller, E. (1996). *Introduction to Plastics and Composites: Mechanical Properties and Engineering Applications*, New York, M. Dekker.

159. Mitosek, M. (2000). "Study of Transient Vapor Cavitation in Series Pipe Systems." *Journal of Hydraulic Engineering*, Vol. 126 (12), 904-911.

160. Miwa, T., Sano, M., and Yamamoto, K. (1989). "Experimental Studies on Waterhammer Phenomenon including Vapor Column Separation." *Water Nagoya 89*, ASPAC IWSA, 430-438.

161. Modisette, J.L. (2000). "Equation of State Tutorial." *Pipeline Simulation Interest Group (PSIG)*, No. 0008.

162. Mohapatra, P.K., Chaudhry, M.H., Kassem, A.A., and Moloo, J. (2006). "Detection of Partial Blockage in Single Pipelines." *Journal of Hydraulic Engineering*, Vol. 132 (2), 200-206.

163. Moseley, D.S. (1966). "Measurement Errors in the Orifice Meter on Pulsating Water Flow." ASME, Flow *Measurement Symposium*, 103-123.

164. Mpesha, W., Gassman, S., and Chaudhry, M. (2001). "Leak Detection in Pipes by Frequency Response Method." *Journal of Hydraulic Engineering*, Vol. 127 (2), 134-147.

165. Mulpuru, S.R. (1983). "A Flux Splitting Method for the Numerical Simulation of One-Dimensional Compressible Flow." *Mathematics and Computers in Simulation* XXV, North-Holland, 309-320.

166. Munson, B.R., Young, D.F., and Okiishi, T.H. (2002). *Fundamentals of Fluid Mechanics*, 4th Ed., John Wiley & Sons, Inc.

167. Murayama, T. (1978). *Dynamic Mechanical Analysis of Polymeric Material*, Elsevier Scientific Pub. Co.

168. Murdock, J.W. (1976). *Fluid Mechanics and Its Applications*, Houghton Mifflin Company, Boston, USA.

N

169. Nakagawa, M. and Takenaka, T. (1995). "Damping and Peak Period Shortening of a Water Hammer in Collapse of a Cooling Cavity." *Japan Society of Mechanical Engineers (JSME) International Journal*, Series B, Vol. 38 (2), 300-307.

170. Nakayasu, H., Markovitz, H., and Plazek, D.J. (1961). "The Frequency and Temperature Dependence of the Dynamic Mechanical Properties of a High Density Polyethylene." *Transactions of the Society of Rheology*, V, 261-283.

171. Nash, G.A. and Karney, B.W. (1999). "Efficient Inverse Transient Analysis in Series Pipe Systems." *Journal of Hydraulic Engineering*, ASCE, 125(7), 761-764.

O

172. Ohmi, M., Kyomen, S., and Usui, T. (1985a). "Numerical Analysis of Transient Turbulent Flow in a Liquid Line." *Bulletin of the Japanese Society of Mechanical Engineers*, Vol. 28 (239), 799-806.

173. Ohmi, M., Iguchi, M., Kawabata, H., and Takano, M. (1985b). "Velocity Distribution and Reattachment Length in an Oscillatory Pipe Flow through a Plate Orifice." *Bulletin of Japan Society of Mechanical Engineers (JSME)*, Vol. 28 (235), 54-61.

174. Oke, A., Mahgerefteh, H., Economou, I., and Rykov, Y. (2003). "A Transient Outflow Model for Pipeline Puncture." *Chemical Engineering Science*, Vol. 58, 4591-4604.

175. Onorati, A., Perotti, M., and Rebay, S. (1997). "Modelling One-Dimensional Unsteady Flows in Ducts: Symmetric Finite Difference Schemes versus Galerkin Discontinuous Finite Element Methods." *International Journal of Mechanical Science*, Vol. 39 (11), 1213-1236.

176. ORNL (2002). "Gas Pipeline Safety: ORNL's Role." *Oak Ridge National Laboratory (ORNL) Review*, Vol. 35 (2).

177. Osiadacz, A. (1983). "Optimal Numerical Method for Simulating Dynamic Flow of Gas in Pipelines." *International Journal for Numerical Methods in Fluids*, Vol. 3, 125-135.

178. Osiadacz, A.J. and Chaczykowski, M. (2001). "Comparison of Isothermal and Non-Isothermal Pipeline Gas Flow Models." *Chemical Engineering Journal*, Vol. 81, 41-51.

P

179. Parmakian, J. (1955). *Waterhammer Analysis*, Prentice-Hall, INC., New York.

180. Pejovic, S. and Boldy, A.P. (1992). *Guidelines to hydraulic transient analysis of pumping systems*, P & B Press.

181. Perotti, M. (1999). "Speed-up of a DFEM Code for Unsteady Gas Dynamics in Pipes." *International Journal of Mechanical Science*, Vol. 41, 793-813.

182. Pezzinga, G. and Scandura, P. (1995). "Unsteady Flow in Installations with Polymeric Additional Pipe." *Journal of Hydraulic Engineering*, Vol. 121 (11), 802-811.

183. Pezzinga, G. (1999). "Quasi-2D Model for Unsteady Flow in Pipe Networks." *Journal of Hydraulic Engineering*, ASCE, Vol. 125 (7), 676-685.

184. Pezzinga, G. (2000). "Evaluation of Unsteady Flow Resistances by Quasi-2D or 1D Models." *Journal of Hydraulic Engineering*, ASCE, Vol. 126 (10), 778-785.

185. Pezzinga, G. (2002). "Unsteady Flow in Hydraulic Networks with Polymeric Additional Pipe." *Journal of Hydraulic Engineering*, Vol. 128 (2), 238-244.

186. PPI (2006). *Handbook of Polyethylene Pipe*, 1st ed., Plastic Pipe Institute.

187. Prenner, R.K. (1998). "Design of Throttled Surge Tanks for High-head Plants. Pressure Wave Transmission and Reflection at an In-line Orifice in a Straight Pipe." Technical Papers, *Hydro Vision 98*, 529-538.

188. Prenner, R.K. (2000). "Calculation of the Transient Response of Small In-line Orifices in a Straight Pipe." *International Conference on Hydrodynamics 2000*, Yokohama, Japan.

189. Press, W.H., Teukolsky, S.A., Vetterling, W.T., and Flannery, B.P. (1997). *Numerical Recipes in Fortran 77-The Art of Scientific Computing*, 2nd Ed., Cambridge University Press.

190. Pudar, R.S. and Liggett, J.A. (1992). "Leaks in Pipe Networks." *Journal of Hydraulic Engineering*, Vol. 118 (7), July, 1031-1046.

Q

191. Qunli, W. and Fricke, F. (1989). "Estimation of Blockage Dimensions in a Duct Using Measured Eigenfrequency Shifts." *Journal of Sound and Vibration*, Vol. 133 (2), 289-301.

R

192. Raabe, J. and Olbrich, S. (1992). "The Role of Turbulence on Maximum Water Hammer due to 2D Theory in Axial Symmetric Pipe Flow and Corresponding LD Measurement." *16th Symposium of the International Association of Hydraulic*

Research (IAHR), Section on Hydraulic Machinery and Cavitation, Sao Paulo, Brazil.

193. Rachford, H.H. and Dupont T. (1974). "A Fast, Highly Accurate Means of Modeling Transient Flow in Gas Pipeline Systems by Variational Methods." *Society of Petroleum Engineers Journal*, Vol. 14, 165-178.
194. Rajtar, J.M. and Muthiah, R. (1997). "Pipeline Leak Detection System for Oil and Gas Flowlines." *Journal of Manufacturing Science and Engineering*, February, Vol. 119, 105-109.
195. Ram, A. (1997). *Fundamentals of Polymer Engineering*, New York, Plenum Press.
196. Ramamurthi, K. and Nandakumar, K. (1999). "Characteristics of Flow through Small Sharp-Edged Cylindrical Orifices." *Flow Measurement and Instrumentation*, Vol. 10, 133-143.
197. Ramos, H. and Almeida, A.B. (2001). "Dynamic Orifice Model on Waterhammer Analysis of High or Medium Heads of Small Hydropower Schemes." *Journal of Hydraulic Research*, Vol. 39 (4), 429-436.
198. Ramos, H. and Almeida, A.B. (2002). "Parametric Analysis of Water-Hammer Effects in Small Hydro Schemes." *Journal of Hydraulic Engineering*, Vol. 128 (7), 689-696.
199. Rao, P.V. and Sridharan, K. (1996). "Discussion: Inverse Transient Analysis in Pipe Networks." *Journal of Hydraulic Engineering*, ASCE, 122 (5).
200. Riande, E., Diaz-Calleja, R., Prolongo, M.G., Masegosa, R.M., and Salom, C. (2000). *Polymer Viscoelasticity – Stress and Strain in Practice*, Marcel Dekker Inc.
201. Rich, G.R. (1951). *Hydraulic Transients*, McGraw-Hill Book Company, Inc.
202. Rieutord, E. and Blanchard, A. (1979). "Pulsating Viscoelastic Pipe Flow-Waterhammer." *Journal of Hydraulic Research*, Vol. 19 (3), in French, 217-229.
203. Rieutord, E. (1982). "Transient Response of Fluid Viscoelastic Lines." *Journal of Fluids Engineering, Transactions of the ASME*, Vol. 104, 335-341.
204. Rodriguez, F. (1982). *Principles of Polymer Systems*, 2nd Ed., Washington, D.C: Hemishere Pub. Corp; New York: McGraw-Hill.
205. Rouse, H. (1978). *Elementary Mechanics of Fluids*, New York, USA, Dover Publications Inc.
206. RS Components (2005). *Thermocouples Data Sheet*, RS Component Company.

S

207. Saad, M.A. (1985). *Compressible fluid flow*, Prentice Hall

208. Salgado, R., Zenteno, J., Twyman, C., and Twyman, J. (1994). "A Hybrid Characteristics-Finite Difference Method for Unsteady Flow in Pipe Networks." *Integrated Computer Applications in Water Supply, Vol. 1: Methods and Procedures for Systems Simulation and Control*, John Wiley & Sons, Inc., New York, 139-150.

209. Samani, H.M.V. and Khayatzadeh, A. (2003). "Transient Flow in Pipe Networks." *Journal of Hydraulic Research*, Vol. 40 (5), 637-644.

210. Samuels, P.G. and Skeels, C.P. (1990). "Stability Limits for Preissmann's Scheme." *Journal of Hydraulic Engineering*, Vol. 116 (8), 997-1011.

211. Schohl, G.A. (2003). "Transient Flow Modeling of Networks with Both Implicit and Explicit Components." *4th ASME/JSME Joint Fluids Engineering Conference*, FEDSM03, Honolulu, Hawaii, July 6-11.

212. Schwarzl, F.R. (1970). "On the Interconversion between Viscoelastic Material Functions." *Pure & Applied Chemistry*, Vol. 23 (2), 219-234.

213. Scott, S.L. and Yi, J. (1999). "Flow Testing Methods to Detect and Characterize Partial Blockages in Looped Subsea Flowlines." *Journal of Energy Resources Technology*, September, Vol. 121 (3), 154-160.

214. Selcuk, N., Tarhan, T., and Tanrikulu, S. (2002). "Comparison of Method of Lines and Finite Difference Solutions of 2D Navier-Stokes Equations for Transient Laminar Pipe Flow." *International Journal for Numerical Methods in Engineering*, Vol. 53, 1615-1628.

215. Seth, H.S. (1973). "Pressure Wave Transmission at an Orifice Surge Tank." *Water Power*, August.

216. Shapiro, A.H. (1953). *The Dynamics and Thermodynamics of Compressible Fluid Flow*, The Ronald Press Company, New York.

217. Sharp, B.B. (1981). *Water Hammer – Problems and Solutions*, Edward Arnold Ltd.

218. Shuy, E.B. (1996). "Wall Shear Stress in Accelerating and Decelerating Turbulent Pipe Flows." *Journal of Hydraulic Research*, Vol. 34 (2), 173-183.

219. Sibetheros, I.A., Holley, E.R., and Branski, J.M. (1991). "Spline Interpolations for Water Hammer Analysis." *Journal of Hydraulic Engineering*, Vol. 117 (10), 1332-1351.

220. Silva-Araya, W.F. and Chaudhry, M.H. (1997). “Computation of Energy Dissipation in Transient Flow.” *Journal of Hydraulic Engineering*, ASCE, Vol. 123 (2), 118-115.

221. Silva-Araya, W.F. and Chaudhry, M.H. (2001). “Unsteady Friction in Rough Pipes.” *Journal of Hydraulic Engineering*, ASCE, Vol. 127 (7), 607-618.

222. Simpson, A.R. and Wylie, E.B. (1987). “Column Separation Experiments with Large Pressure Pulses.” *Pressure Vessel and Piping Conference*, San Diego, California.

223. Simpson, A.R. and Wylie, E.B. (1991). “Large Water-Hammer Pressures for Column Separation in Pipelines.” *Journal of Hydraulic Engineering*, Vol. 117 (10), 1310-1316.

224. Simpson, A.R. and Bergant, A. (1994a). “Developments in Pipeline Column Separation Experimentation.” *Journal of Hydraulic Research*, Vol. 32 (2), 183-194.

225. Simpson, A.R. and Bergant, A. (1994b). “Numerical Comparison of Pipe-Column-Separation Models.” *Journal of Hydraulic Engineering*, Vol. 120 (3), 361-377.

226. Singh, S.N., Gandhi, B.K., Seshadri, V., and Chauhan, V.S. (2004). “Design of a Bluff Body for Development of Variable Area Orifice-Meter.” *Flow Measurement and Instrumentation*, Vol. 15, 97-103.

227. Smith, L. A., Field, K. A., Chen, A. S. C., and Tafuri, A. N. (2000). *Options for Leak and Break Detection and Repair for Drinking Water Systems.* Battelle Press, Columbus, Ohio, USA.

228. Sondh, H.S., Singh, S.N., Seshadri, V., and Gandhi, B.K. (2002). “Design and Development of Variable Area Orifice Meter.” *Flow Measurement and Instrumentation*, Vol. 13, 69-73.

229. Sparks, C.R. (1966). “A Study of Pulsation Effects on Orifice Metering of Compressible Flow.” *ASME, Flow Measurement Symposium*, 124-138.

230. Spitzer, D.W. (1991). *Flow Measurement-Practical Guide for Measurement and Control*, Instrument Society of America.

231. Stephens, M.L., Simpson, A.R., Lambert, M.F., Vítkovský, J.P., and Nixon, J.B. (2003). “The Detection of Pipeline Blockages Using Transients in the Field.” *Ozwater Convention & Exhibition, AWA 20th Convention*, April, Perth, Australia.

232. Stephens, M., Simpson, A.R., Lambert, M.F., and Vítkovský, J. P. (2005) “Field Measurements of Unsteady Friction Effects in a Trunk Transmission Pipeline.” *7th Annual Symposium on Water Distribution Systems Analysis*, American Society of Civil Engineers, 15–19 May, Anchorage, Alaska, USA.

233. Stephenson, D. (1986). “Depiction of Friction Damping in Numerical Flow Modelling.” *Advances in Engineering Software*, Vol. 8 (4), 211-216.

234. Stoner, M.A. (1969). “Analysis and Control of Unsteady Flows in Natural Gas Piping Systems.” *Journal of Basic Engineering*, Transaction of ASME, 331-340.

235. Streeter, V.L. and Wylie, E.B. (1985). *Fluid Mechanics*, 8th ed., McGraw-Hill Book Company.

236. Suo, L. and Wylie, E.B. (1990a). “Hydraulic Transients in Rock-Bored Tunnels.” *Journal of Hydraulic Engineering*, Vol. 116 (2), 196-210.

237. Suo, L. and Wylie, E.B. (1990b). “Complex Wavespeed and Hydraulic Transients in Viscoelastic Pipes.” *Transaction of the ASME, Journal of Fluids Engineering*, Vol. 112, 496-500.

238. Suzuki, K., Taketomi, T., and Sato, S. (1991). “Improving Zielke’s Method of Simulating Frequency-Dependent Friction in Laminar Liquid Pipe Flow.” *Journal of Fluids Engineering*, Transactions of the ASME, Vol. 113, 569-573.

239. Swaffield, J.A., Gasiorek, J.M., and Johal, K.S. (1978a). “Mathematical Models to Predict the Celerity of Pressure Waves in two Component Gas/Liquid Flow.” Proceedings of the ASME. *Symposium on Fluid Transients and Acoustics in the Power Industry*, San Francisco.

240. Swaffield, J.A., Gasiorek, J.M., and Johal, K.S. (1978b). “Measurements of the Speed of Propagation of Pressure Transients in Two Component Gas/Liquid Mixture.” Proceedings of the ASME. *Symposium on Fluid Transients and Acoustics in the Power Industry*, San Francisco.

241. Swaffield, J.A. and Boldy, A.P. (1993). *Pressure surge in pipe and duct systems*, Avebury Technical; Brookfield, Ashgate Publisher.

242. Swagelok (2006). *Gaugeable Tube Fittings and Adapter Fittings*, Swagelok Company.

243. Swamee, P.K. and Jain, A.K. (1976). “Explicit Equations for Pipe-Flow Problems.” *Journal of Hydraulic Division*, ASCE, May, 657-664.

244. Szymkiewicz, R. (1995). “Method to Solve 1D Unsteady Transport and Flow Equations.” *Journal of Hydraulic Engineering*, Vol. 121 (5), 396-403.

245. Szymkiewicz, R. and Mitosek, M. (2005). “Analysis of Unsteady Pipe Flow using the Modified Finite Element Method.” *Communications in Numerical Methods in Engineering*, Vol. 25, 183-199.

T

246. Theakston, J. and Larnaes, G. (2002). “Selecting and Installing a Software Based Leak Detection System.” *Pipeline & Gas Journal*, October, 52-53.

247. Thorley, A.R.D. and Tiley, C.H. (1987). “Unsteady and Transient Flow of Compressible Fluids in Pipelines – A Review of Theoretical and Some Experimental Studies.” *Heat and Fluid Flow*, Vol. 8 (1), 3-15.

248. Thorley, A.R.D. (2004). *Fluid Transients in Pipeline Systems – A guide to the Control and Suppression of Fluid Transients in Liquids in Closed Conduits*, 2nd Ed., Professional Engineering Publishing Limited, UK.

249. Thurston, G.B. and Martin, Jr. C.E. (1953). “Periodic Fluid Flow through Circular Orifices.” *The Journal of the Acoustical Society of America*, Vol. 25 (1), 26-31.

250. Thurston, G.B. and Wood, J.K. (1953). “End Corrections for a Concentric Circular Orifice in a Circular Tube.” *The Journal of the Acoustical Society of America*, Vol. 25 (5), 861-863.

251. Thurston, G.B., Hargrove, Jr. L.E., and Cook, B.D. (1957). “Nonlinear Properties of Circular Orifices.” *The Journal of the Acoustical Society of America*, Vol. 29 (9), 992-1001.

252. Trengrouse, G.H., Imrie, B.W., and Male, D.H. (1966). “Comparison of Unsteady Flow Discharge Coefficients for Sharp-Edged Orifices with Steady Flow Values.” *Journal of Mechanical Engineering Science*, Vol. 8 (3), 322-329.

253. Trikha, A.K. (1975). “An Efficient Method for Simulating Frequency-Dependent Friction in Transient Liquid Flow.” *Journal of Fluids Engineering*, Transactions of the ASME, March, 97-105.

254. Tubb, M. (2001). “International Pipeline Construction Outlook – Oil & Gas Infrastructure.” *Pipeline & Gas Journal*, August, 16-32.

255. Tullis, J.P. and Govindarajan, R. (1973). “Cavitation and Size Scale Effects for Orifices.” *Journal of Hydraulic Division, Proceedings of the American Society of Civil Engineers*, Vol. 99 (HY3), 417-430.

256. Tullis, J.P. (1989). *Hydraulics of Pipelines – Pumps, Valves, Caviation, Transients*, John Wiley & Sons.

V

257. Vaculik, J., Lambert, M.F., and Vítkovský, J. (2002). "Modelling Fluid Transients using Water-Hammer Equations in the Conservative Form." *Research Report* (unpublished), School of Civil and Environmental Engineering, The University of Adelaide, Australia.

258. Van Deen, L.K. and Reintsema, S.R. (1983). "Modelling of High-Pressure Gas Transmission Lines." *Applied Mathematical Modelling*, Vol. 7, 268-273.

259. Van Duyne, D.A., Semprucci, L.B., and Jaycox, N. (2003). "Pump Start Transients in Closed Loop System Solved with Restriction Orifices." *Pressure Vessels and Piping Division*, Vol. 454, Problems Involving Thermal-Hydraulics, Liquid Sloshing, and Extreme Loads on Structures, 1-6.

260. Vandevoorde, M., Vierendeels, J., Dick, E., and Sierens, R. (1998). "A New Total Variation Diminishing Scheme for the Calculation of One-Dimensional Flow in Inlet and Exhaust Pipes of Internal Combustion Engines." *Proceedings of the Institution of Mechanical Engineers, Part D, Journal of Automobile Engineering*, Vol. 212 (5), 437-448.

261. Vardy, A.E. (1976). "On the Use of the Method of Characteristics for the Solution of Unsteady Flows in Networks." *Proceedings of 2nd International Conference on Pressure Surges*, Cranfield, England.

262. Vardy, A.E. and Hwang, K.L. (1991). "A Characteristics Model of Transient Friction in Pipes." *Journal of Hydraulic Research*, IAHR, Vol. 29 (5), 669-684.

263. Vardy, A.E., Hwang, K., and Brown, J.M.B. (1993). "A Weighting Function Model of Transient Turbulent Pipe Friction." *Journal of Hydraulic Research*, Vol. 31 (4), 533-548.

264. Vardy, A.E. and Brown, J.M.B. (1995). "Transient, Turbulent, Smooth Pipe Friction." *Journal of Hydraulic Research*, Vol. 33 (4), 435-456.

265. Vardy, A.E. and Brown, J.M.B. (1996). "On Turbulent, Unsteady, Smooth Pipe Friction." *7th International Conference on Pressure Surges and Fluid Transients in Pipelines and Open Channels*, Harrogate, UK, 289-311.

266. Vardy, A. and Pan, Z. (1997). "Quasi-Steady Friction in Transient Polytropic Flow." *Computer & Fluids*, Vol. 26 (8), 793-809.

267. Vardy, A. and Pan, Z. (2000). "Numerical Accuracy in Unsteady Compressible Flows." *BHR Group 2000 Pressure Surges*, 205-224.

268. Vardy, A.E. and Brown, J.M.B. (2003). "Transient Turbulent Friction in Smooth Pipe Flows." *Journal of Sound and Vibration*, Vol. 259 (5), 1011-1036.

269. Vardy, A.E. and Brown, J.M.B. (2004a). "Efficient Approximation of Unsteady Friction Weighting Functions." *Journal of Hydraulic Engineering*, Vol. 130 (11), 1097-1107.

270. Vardy, A.E. and Brown, J.M.B. (2004b). "Transient Turbulent Friction in Fully Rough Pipe Flows." *Journal of Sound and Vibration*, Vol. 270, 233-257.

271. Varma, V.K. (2001). "*State-of-the-art Natural Gas Pipe Inspection*." Oak Ridge National Laboratory, Technical note.

272. Venutelli, M. (2002). "Stability and Accuracy of Weighted Four-Point Implicit Finite Difference Schemes for Open Channel Flow." *Journal of Hydraulic Engineering*, Vol. 128 (3), 281-288.

273. Verwey, A. and Yu, J.H. (1993). "A Space-Compact High-Order Implicit Scheme for Water Hammer Simulations." *Vol. 5 of Proceedings of the XXVth IAHR Congress*, Tokyo, Japan, 363-370.

274. Vítkovský, J., Simpson, A.R., and Lambert, M.F. (2000a). "Leak Detection and Calibration using Transients and Genetic Algorithms." *Journal of Water Resources Planning and Management*, ASCE, 126(4), 262-265.

275. Vítkovský, J.P., Lambert, M.F., Simpson, A.R., and Bergant, A. (2000b). "Advances in Unsteady Friction Modelling in Transient Pipe Flow." *The 8th International Conference on Pressure Surges*, BHR, Hague, Netherlands, 471-482.

276. Vítkovský, J. (2001). *Inverse analysis and modeling of unsteady pipe flow*. Doctoral thesis, Dept. of Civil & Environmental Eng., University of Adelaide.

277. Vítkovský, J.P., Lee, P.J., Stephens, M.L., Lambert, M.F., Simpson, A.R., and Liggett, J.A. (2003). "Leak and Blockage Detection in Pipelines via an Impulse Response Method." *Pump, Electromechanical Devices and Systems Applied to Urban Water Management*, Vol. I, April, Valencia, Spain, 423-430.

278. Vítkovský, J.P., Stephens, M.L., Bergant, A., Simpson, A.R., and Lambert, M.F. (2004). "Efficient and Accurate Calculation of Vardy-Brown Unsteady Friction in Pipe Transients." *9th International Conference on Pressure Surges*, Chester, UK, 405-419.

279. Vítkovský, J.P., Bergant, A., Simpson, A.R., and Lambert, M.F. (2006). "Systematic Evaluation of One-Dimensional Unsteady Friction Models in Simple Pipelines." *Journal of Hydraulic Engineering*, Vol. 132 (7), 696-708.

W

280. Wakes, S.J., Holdo, A.E., and Meares, A.J. (2002). "Experimental Investigation of the Effect Orifice Shape and Fluid Pressure has on High Aspect Ratio Cross-Sectional Jet Behaviour." *Journal of Hazardous Materials*, A89, 1-27.

281. Wang, J.L. (2003). *Global Phase Diagrams and Critical Phenomena of Binary Mixtures*. PhD Thesis, Swinburne University of Technology, Victoria, Australia.

282. Wang, X.J. (2002). *Leakage and Blockage Detection in Pipelines and Pipe Network Systems Using Fluid Transients*. PhD dissertation, August, Department of Civil & Environmental Engineering, University of Adelaide, Australia.

283. Wang, X.J., Lambert, M.F., Simpson, A.R., Liggett, J.A., and Vítkovský, J.P. (2002). *"Leak Detection in Pipelines using the Damping of Fluid Transients"*, Journal of Hydraulic Engineering, Vol. 128 (7), 697-711.

284. Wang, X., Lambert, M.F., and Simpson, A.R. (2005). "Detection and Location of a Partial Blockage in a Pipeline Using Damping of Fluid Transients." *Journal of Water Resources Planning and Management*, Vol. 131 (3), 244-249.

285. Washio, S., Takahashi, S., Yu, Y., and Yamaguchi, S. (1996). "Study of Unsteady Orifice Flow Characteristics in Hydraulic Oil Lines." *Journal of Fluids Engineering*, 118, 743-747.

286. Watanabe, K. and Himmelblau, D.M. (1986). "Detection and Location of a Leak in a Gas-Transport Pipeline by a New Acoustic Method." *American Institute of Chemical Engineers (AIChE) Journal*, October, Vol. 32 (10), 1690-1701.

287. Watanabe, K. and Koyama, H. (1990). "Location and Estimation of a Pipeline Leak." *Electrical Engineering in Japan*, Vol. 110, No. 7, *Translated from Denki Gakkai Ronbunshi*, Vol. 110c (5), May 1990, 310-317.

288. Watt, C.S., Boldy, A.P., and Hobbs, J.M. (1980). "Combination of Finite Difference and Finite Element Techniques in Hydraulic Transient Problems." *3rd International Conference on Pressure Surges*, Canterbury, England, March, 43-62.

289. Webb, T. and Gould, B.W. (1978). *Water Hammer*, New South Wales University Press Limited, James Hardie & Coy. Pty. Limited.

290. Wesseling, P. (2001). *Principles of Computational Fluid Dynamics*, Springer.

291. Whaley, R.S., Nicholas, R.E., and Van Reet, J.D. (1992). “Tutorial on Software Based Leak Detection Techniques.” *Pipeline Simulation Interest Group*, October.

292. Williams, D.J. (1977). “Waterhammer in Non-Rigid Pipes: Precursor Waves and Mechanical Damping.” *Journal Mechanical Engineering Science*, IMechE, Vol. 19 (6), 237-242.

293. Wood, D.J., Dorsch, R.G., and Lightner, C. (1966). “Wave Plan Analysis of Unsteady Flow in Closed Conduits.” *Journal of Hydraulics Division*, ASCE, Vol. 92 (2), 83-110.

294. Wood, D.J. and Funk, J.E. (1970). “A Boundary-Layer Theory for Transient Viscous Losses in Turbulent Flow.” *Journal of Basic Engineering*, ASME, 865-873.

295. Wood, D.J., Lingireddy, S., Boulos, P.F., Karney, B.W., and Mcpherson, D.L. (2005). “Numerical Methods for Modeling Transient Flow.” *Journal of American Water Works Association (AWWA)*, Vol. 97 (7), 104-115.

296. Wood, D.J. (2005). “Waterhammer Analysis – Essential and Easy (and Efficient).” *Journal of Environmental Engineering*, Vol. 131 (8), 1123-1131.

297. Wu, D., Burton, R., Schoenau, G., and Bitner, D. (2003). “Modelling of Orifice Flow Rate at very small openings.” *International Journal of Fluid Power*, Vol. 4 (1), 31-39.

298. Wylie, E.B., Streeter, V.L., and Stoner, M.A. (1974). “Unsteady-State Natural-Gas Calculations in Complex Pipe Systems.” *Society of Petroleum Engineers Journal*, 35-43.

299. Wylie, E.B. (1984). “Simulation of Vaporous and Gaseous Cavitaition.” *Journal of Fluids Engineering*, Vol. 106, September, 307-311.

300. Wylie, E.B., Streeter, V.L., and Suo, L. (1993). *Fluid Transients in Systems*, Prentice Hall, Englewood Cliffs, NJ.

Y

301. Yamaguchi, A. (1976). “Non-steady Characteristics of Orifices.” *Bulletin of the JSME*, Vol. 19 (131), 505-512.

302. Yang, J. and Hsu, E. (1990). “Time-line Interpolation for Solution of the Dispersion Equation.” *Journal of Hydraulic Research*, Vol. 28 (4), 504-520.

303. Yow, W. (1972). “Numerical Error on Natural Gas Transient Calculations.” *Journal of Basic Engineering*, Transaction of ASME, June, 422-428.

Z

304. Zhang, C. and Moore, I.D. (1997). “Nonlinear Mechanical Response of High Density Polyethylene. Part 1: Experimental Investigation and Model Evaluation.” *Polymer Engineering and Science*, Vol. 37 (2), 404-413.

305. Zhang, J. (1993). “Statistical Leak Detection in Gas and Liquid Pipelines.” *Pipes & Pipelines International*, July-August, 26-29.

306. Zhang, J. (1996). “Designing a Cost Effective and Reliable Pipeline Leak Detection System.” *Pipeline Reliable Conference*, Houston, USA, November 19-22.

307. Zhang, J. and Mauro, E.D. (1998). “Implementing a Reliable Leak Detection System on a Crude Oil Pipeline.” *Advances in Pipeline Technology*, Dubai, UAE.

308. Zhang, J. and Xu, L. (1999). “Real Time Pipeline Leak Detection on Shell’s North Western Ethylene Pipeline.” *Institution of Mechanical Engineers (ImechE)*, C571/025, 69-77.

309. Zhang, J. and Twomey, M. (2000). “Statistical Pipeline Leak Detection Techniques for All Operating Conditions.” *26th Environmental Symposium & Exhibition*, California, March 27-30, 286-290.

310. Zhang, J. (2001). “Statistical Pipeline Leak Detection for All Operating Conditions.” *Pipeline & Gas Journal*, February.

311. Zhang, Q.Y. and Chai, B.Q. (2001). “Hydraulic Characteristics of Multistage Orifice Tunnels.” *Journal of Hydraulic Engineering*, Vol. 127 (8), 663-668.

312. Zhao, M. and Ghidaoui, M.S. (2003). “An Efficient Quasi-Two-Dimensional Model for Water Hammer Problems.” *Journal of Hydraulic Engineering*, ASCE, Vol. 129 (12), 1007-1013.

313. Zhao, M. and Ghidaoui, M.S. (2004). “Godunov-Type Solutions for Water Hammer Flows.” *Journal of Hydraulic Engineering*, Vol. 130 (4), 341-348.

314. Zhou, J. and Adewumi, M.A. (2000). “Simulation of Transients in Natural Gas Pipelines using Hybrid TVD Schemes.” *International Journal for Numerical Methods in Fluids*, Vol. 32, 407-437.

315. Zhou, F., Hicks, F.E., and Steffler, P.M. (2002). "Transient Flow in a Rapidly Filling Horizontal Pipe Containing Trapped Air." *Journal of Hydraulic Engineering*, Vol. 128 (6), 625-634.

316. Zhou, F., Hicks, F.E., and Steffler, P.M. (2004). "Analysis of Effects of Air Pocket on Hydraulic Failure of Urban Drainage Infrastructure." *Can. J. Civ. Eng.*, Vol. 31, 86-94.

317. Zielke, W. (1968). "Frequency-dependent Friction in Transient Pipe Flow." *Journal of Basic Engineering*, Transactions of the ASME, 109-115.