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

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To My Parents
UNG YEOL KIM and SU JEONG PARK

and

To My Wife and Daughter
CHAI YOUNG JEON and EUGENA EUGENE KIM

ABSTRACT

One of the best opportunities to reduce pipeline accidents and subsequent product loss comes from implementing better pipeline condition assessment and fault detection systems. Transient analysis model based condition assessment is the most promising technique because pressure transients propagate through the entire system interacting with the pipe and any devices in the system. Transient measurements embody a large amount of information about the physical characteristics of the system. The performance of this technique has its difficulties because a highly accurate transient model is required. Real systems have numerous uncertainties and flow system components that present a major challenge in the development of precise transient analysis models. To improve transient modelling for the performance of condition assessment, this research undertakes a comprehensive investigation into the transient behaviour of distributed and various local energy loss system components in water and gas pipelines. The dynamic behaviours that have been investigated in this research are the effect of unsteady wall resistance, viscoelasticity effects of polymer pipe, and local energy loss elements including leakages, entrapped air pockets, orifices, and blockages during unsteady pipe flow conditions. The dynamic characteristics of these system components are modelled based on a conservative solution scheme using the governing equations in their conservative form. Use of the conservative form of the equations improves the accuracy and applicability of transient analysis in both liquid and gas pipeline systems. The numerical model results are compared to laboratory experiments in water and gas pipelines to observe the interaction between transient pressure wave and system components and to verify the proposed models.

STATEMENT OF ORIGINALITY

This work contains no material that has been accepted for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

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YOUNG IL KIM

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NOMENCLATURE

A	Pipe cross-sectional area
A_p	Pipe cross-sectional area (in Chapter 8)
A^*	Coefficient for weighting function of unsteady friction
A_L	Area of the leak hole
A_o	Cross-sectional area of the restriction
a	Wavespeed
a	Pipe radius (in Chapter 8)
a^*	Wavespeed at the critical flow state (sonic flow)
a_m	Wavespeed of gas-liquid mixture
a_o	Radius of the orifice
$\mathbf{B}$	Body force vector
B^*	Coefficient for weighting function of unsteady friction
$B_{x,y,z}$	Body forces
C	Correction coefficient for unsteady friction model
C_c	Contraction coefficient
C_d	Discharge coefficient
$C_d A_L$	Lumped leak coefficient
C_N	Courant number for Courant-Friedrich-Levy stability condition
C_p	Specific heat at constant pressure
C_v	Specific heat at constant volume
c_v	Calibrated volumetric constant for the tank
CV	Control volume

CS	Control surface
D	Pipe inside diameter
d	Orifice bore diameter
$dV\!\!\!\!-$	Elemental volume inside the control volume
$d\mathbf{A}$	Vector element representing an surface area of the inflow and outflow
dQ_m	Bound of uncertainty in flow measurement
dL_s	Bound of uncertainty in line pack change over a time interval
E	Young's modulus of elasticity for the pipe wall
E	Flow coefficient (in Chapter 8)
E_T	Total energy of the system
e	Pipe wall thickness
e_t	Internal energy per unit mass
$\dot{e}+V^2/2$	Total energy per unit mass
$\mathbf{F}$	Force vector
F_p	Pressure force
F_s	Shear force
F_{ws}	Gravitational force
f	Darcy-Weisbach friction factor
$\mathbf{f}$	Column vector in conservative equation form (in Section 3.7)
g	Gravitational acceleration
$\mathbf{g}$	Column vector in conservative equation form (in Section 3.7)
H	Piezometric head
$H(s)$	Transfer function for kinetic pressure difference across a restriction
$H'(s)$	Approximated transfer function
H_A	Absolute piezometric head
H_b	Barometric pressure head
H_L	Hydraulic head at the leak
h	Enthalpy per unit mass
h_c	Energy loss due to sudden contraction
h_e	Energy loss due to sudden expansion

h_f	Total energy loss due to pipe wall friction
h_o	Enthalpy through a leak hole
h_{sf}	Quasi-steady energy loss component
h_{uf}	Unsteady energy loss component
I_o	Modified Bessel function of first kind of order 0
I_o	Modified Bessel function of first kind of order 1
I_2	Modified Bessel function of first kind of order 2
i	Unit imaginary number
$J(t)$	Creep compliance function
J_0	Instantaneous elastic creep compliance
J_0	Bessel function of first kind and zero order
J_1	Bessel function of first kind and first order
j	Unit imaginary number
K	Bulk modulus of elasticity of fluid
K_0	Modified Bessel function of second kind and 0^{th} order
K_1	Modified Bessel function of second kind and 1^{th} order
K_g	Bulk modulus of elasticity of gas cavity
K_l	Bulk modulus of elasticity of liquid
K_m	Bulk modulus of elasticity of gas-liquid mixture
k	Thermal conductivity (heat transfer coefficient)
k_c	Compound coefficient of heat transfer coefficient
k_3	Correction coefficient for unsteady friction model
l_o	Axial length of the blockage
M	Mach number
M_g	Mass of gas cavity
M_o	Mach number through a leak hole
$\dot{m}$	Mass flow rate
$\dot{m}_{in}$	Mass inflow to the system
$\dot{m}_{out}$	Mass outflow from the system
$\dot{m}_L$	Mass flow rate by a leak

m_g	Mass of gas cavity per unit volume of mixture
$\dot{m}_{\max}$	Maximum mass flow rate
m_s	Fitted exponential sum coefficient for approximated weighting function
m^*_s	Scaled fitted exponential sum coefficient for approximated weighting function
Δm_{out}	Change in mass from the tank during a test
N	Total amount of some extensive property within the system
N_R	Reynolds number
N_{Rd}	Reynolds number at the orifice bore
n	Polytropic gas process exponent
np	Total number of data points
n_{old}	Number of data points in the earlier part of the data
n_s	Fitted exponential sum coefficient for approximated weighting function
n^*_s	Scaled fitted exponential sum coefficient for approximated weighting function
p	Fluid pressure
$\overline{p}$	Average of the pressure data
p^*	Pressure at the critical flow state (sonic flow) (in Chapter 6)
p^*	Total absolute pressure (in Chapter 7)
p_d	Downstream pressure from the orifice
p^*_g	Absolute partial pressure of gas cavity
p_i	Measured pressure at time i
Δp_t	Variation of tank pressure
p_o	Pressure through a leak hole
p^*_v	Absolute vapour pressure
p_R	Ratio of absolute downstream pressure to absolute upstream pressure
p_u	Upstream pressure from the orifice
Q	Flow rate
Q_H	Energy by heat transfer
Q_{in}	Measured inflow to the system
Q_L	Flow rate of the leak
Q_{out}	Measured outflow from the system

q	Rate of volumetric heat addition externally per unit mass
R	Gas constant
R_p	Radius of Pipe
S	Entropy
s	Laplace variable ($j\omega$)
T	Absolute temperature
T_o	Absolute temperature through a leak hole
T^*	Absolute temperature at the critical flow state (sonic flow)
t	Time (independent variable)
$t_{\Delta z}$	Time for water level change in tank
$\mathbf{u}$	Column vector in conservative equation form (in Section 3.7)
u	x component of velocity
u	Time used in the convolution integral (in Chapter 5)
$\mathbf{V}$	Velocity vector
$\mathbf{v}$	Velocity vector (in Chapter 3)
v	y component of velocity
V_0	Steady state velocity
V_o	Velocity through a leak hole
V^*	Velocity at the critical flow state (sonic flow)
$V^2/2$	Kinetic energy per unit mass
$\cancel{V}$	Volume
$\cancel{V}_a$	Volume of entrapped air pocket
$\cancel{V}_g$	Volume of gas cavity
$\cancel{V}_l$	Volume of liquid
$\cancel{V}_t$	Volume of the tank
W	Energy by work done (in Chapter 3)
W	Weighting function for unsteady friction (in Chapter 5)
w	z component of velocity
W_{app}	Approximated weighting function for unsteady friction
W_{app}^*	Approximated and scaled weighting function

W_o	Weighting function for a restriction
x	Distance in the Cartesian space (independent variable)
Y	Isentropic gas expansion factor
y	Distance in the Cartesian space (independent variable)
z	Distance in the Cartesian space (independent variable)
z	Gas compressibility factor (in Eq. 3.32)
z	Complex number (in Appendix A and B)
z_L	Elevation at the leak
Δz	Change of water level in the tank

α	Time step weighting coefficient (in Chapter 3)
α	Parameter function of pipe constrains (in Chapter 9)
α_v	Void fraction
β	Space step weighting coefficient (in Chapter 3)
β	Beta ratio (orifice bore diameter / pipe diameter)
γ	Ratio of the specific heat
ε	Pipe wall roughness height (in Chapter 5)
ε	Strain (in Chapter 9)
ε_D	Strain in the dashpot
ε_e	Instantaneous elastic strain at the initial state
ε_r	Retarded strain depending on time
ε_S	Strain in the spring
ε_T	Sum of the strains
ε_{Total}	Total strain
ε_0	Fixed strain at initial state
ζ_1	Modified quotient of Bessel function of first order
η	Amount of intensive property per unit mass (in Chapter 3)
η	Reflection time used in the convolution integral (in Chapter 8)
η	Viscosity of the material (in Chapter 9)

η_k	Viscosity of each dashpot
θ	Angle of the pipe from horizontal
λ	The second viscosity coefficient
μ	Absolute viscosity (in Chapter 2)
μ	Poisson's ratio (in Chapter 3 and 9)
ν	Kinematic viscosity
ν_c	Kinematic viscosity at the pipe core region
ν_{lam}	Laminar kinematic viscosity
ν_w	Kinematic viscosity at the pipe wall
ρ	Fluid density
ρ^*	Density at the critical flow state (sonic flow)
ρ_g	Density of gas cavity
ρ_l	Density of liquid
ρ_m	Density of gas-liquid mixture
ρ_o	Density through a leak hole
σ	Stress
σ^2	Variance of the pressure data
σ_D	Stress in the dashpot
σ_S	Stress in the spring
σ_{Total}	Total stress
σ_T	Sum of the stresses
σ_0	Fixed stress at initial state
τ or τ_o	Shear stress between the fluid and pipe wall
τ	Dimensionless time used for unsteady friction model (in Chapter 5)
τ_k	Retardation time of each dashpot
$\tau_{xx,yy,zz}$	Normal stress in a fluid
$\tau_{xy,xz,yz,...}$	Shear stress
φ	Orifice conical angle with pipe axis
Φ	Transfer function for transient turbulent shear stress
ϕ	Transfer function for transient laminar shear stress

ϕ_L	Sign operation for leak equation
ψ	Parameter for the pipe geometry and restraints
ψ_c	Correction factor for different boundary conditions over the restriction
ω	Angular frequency