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Analysis of Transient Phenomena in Gas and Two-Phase Flow Pipelines

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Abstract:

In designing and planning the operation of pipelines for gases such as natural gas, it is important to know the behavior of the fluid in the pipe in such transient states as operation start and stop and emergency shutdown. Nippon Steel developed a one-dimensional transient phenomenon analysis program for gas and two-phase flow pipeline networks. The functions and configuration of the program are described, and the results of analysis made by the program on examples simulating actual plants are reported.

1. Introduction

In studying the design and operation of pipelines with efficiency, safety, maintenance, and control taken into consideration, it is important to ascertain beforehand the transient effects of starting, stopping, emergency shutdown, and other modes of equipment manipulation on the heat and flow states of the fluid in the pipe. As pipelines have increased in diameter and length in recent years, their heat transfer and fluid flow behaviors during disturbances have gained complexity. Great expectations are entertained in computerized analytical techniques for rational and economical examination of these transient phenomena.

As aid in pipeline design and operation, a one-dimensional transient phenomenon analysis program was developed for gas single-phase and gas-liquid two-phase flow pipeline networks. The program can analyze the transient heat transfer and fluid flow behaviors of pipeline networks, rationally and economically design the pipeline capacity in the basic design stage, and provide data helpful in determining the control parameters and operating conditions of the pipeline.

This report introduces the functions and configuration of the analytical program, presents the results of program verification when applied to basic gas and two-phase flow problems, and describes examples of program application to the analysis of heat transfer and fluid flow in gas and steam-water flow systems simulating actual plants.

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2. Scope of Application

The analytical program can handle the unsteady-state one-dimensional flow of compressible single-component fluids. It can also deal with phase changes between the gas and liquid phases. Unsteady-state heat transfer phenomena between the fluid and the outside boundary, including transient temperature changes of pipe and heat insulating material, can be analyzed, too. Basically, the program can be applied to pipeline networks with arbitrary branch and confluence points, unless restricted by the main storage capacity of the computer, and to those having various control systems (see **Table 1**).

3. Modeling of Pipeline Network

The pipeline network to be analyzed by the program can be easily modeled as described below.

(1) The system configuration of the pipeline network is represented by two basic units: volumes and junctions connecting the

Table 1 Outline of analytical program

Operating environment	Engineering workstation (EWS)
Input	Free format
Output	(1) List output of all physical quantities during transient computation (2) Output of maximum and minimum values (3) Plotting (screen output)
Computation	(1) Steady-state computation (initial value computation) (2) Transient-state computation (3) Restart computation (restart at arbitrary point of time)

volumes.

(2) To assign attributes to the volumes and junctions to suit the functions of the components of the pipeline network, functional units such as valves and pipe are specified, and various parameters are entered.

(3) For heat transfer with the outside boundary, a structural member unit (slab) is specified for each volume, and various parameters are entered.

(4) For each control system loop, control units (CNTMDL) is specified to suit the function of each component, and various parameters are entered.

(5) Boundary conditions at the ends of the pipeline network and the disturbance information of control valves are set for analyzing transient phenomena.

Table 2 summarizes units corresponding to components and their input parameters. **Fig. 1** shows the network end boundary conditions to which the analytical program can be applied.

4. Analytical Methods

4.1 Unsteady-state heat transfer and fluid flow analysis

Table 2 Unit correspondence table

Unit	Classification	Parameter	Corresponding component
VOLUME	PIPE	Pipe length, equivalent diameter, pipe inside surface roughness, angle of inclination	Pipe
	SEPARATOR	Gas-liquid separation efficiency	Separators
	RESERVOIR	Input of temperature, pressure, and dryness fraction (saturated, subcooled, or supersaturated steam) as time-dependent variables	Tanks, holders, pressure-temperature boundaries
JUNCTION	JUNCTION	Resistance coefficients for forward flow and backward flow (input or internal computation), flow channel area	Coupling, confluence, branching, orifice
	VALVE	Input of resistance coefficients for forward flow and backward flow (input or internal computation) as time-dependent variables, valve opening-flow coefficient (C_v value)	Manual valves, control valves, shutoff valves
	RESERVOIR	Input of resistance coefficients for forward flow and backward flow (input or internal computation) and flow rate as time-dependent variables	Compressors, pumps, flow rate boundaries
SLAB		Length, thermally equivalent diameter, initial temperature, outside air temperature, heat transfer efficiency with outside air, and heat capacity, thermal conductivity and heating value of structural materials	Pipe, heat insulating materials, heaters, coolers
CNTMDL		Control element names, control parameters, input items, positions and set points, and output items, positions and set points	PID control, transmission lag, sequential control

(1) Basic equations

Basic equations for fluid flow analysis in the program are one-dimensional compressible fluid conservation equations given below. A homogeneous thermal equilibrium model is adopted.

Equation of conservation of mass

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial x}=0 \qquad \cdots\cdots(1)$$

Equation of conservation of momentum

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}=-\frac{1}{\rho}\frac{\partial P}{\partial x}-Ku|u|-K_f u|u|-S_u \qquad \cdots\cdots(2)$$

Equation of conservation of energy

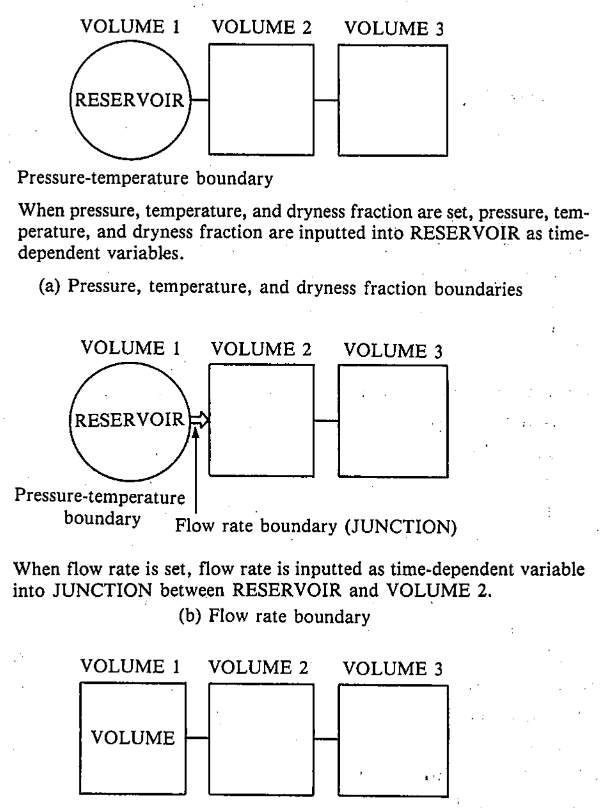
$$\frac{\partial \rho h}{\partial t}+\frac{\partial \rho hu}{\partial x}=\frac{dP}{dt}+q-S_h \qquad \cdots\cdots(3)$$

In the equation of conservation of momentum, pressure, gravitational body force, frictional force from the wall surface, and resistance coefficients for such conditions as flow channel expansion and contraction are considered as forces acting on the fluid. S_u and S_h in Eqs. (2) and (3) are terms indicating flow heterogeneity for the two-phase flow and are omitted in gas flow analysis.

The gas flow analysis uses the following equation as an equation of thermal state considering the compressibility factor z:

Equation of thermal state for gas flow

$$\frac{P}{\rho}=zRT \qquad \cdots\cdots(4)$$



When pressure, temperature, and dryness fraction are set, pressure, temperature, and dryness fraction are inputted into RESERVOIR as time-dependent variables.

(a) Pressure, temperature, and dryness fraction boundaries

When flow rate is set, flow rate is inputted as time-dependent variable into JUNCTION between RESERVOIR and VOLUME 2.

(b) Flow rate boundary

When closed boundary is set, initial quantities of state are inputted into VOLUME.

(c) Closed boundary

Fig. 1 Boundary conditions

For a two-phase flow, the above equation (4) is differentiated by pressure as in Eq. (5):

Equation of thermal state for two-phase flow

$$\frac{d\rho}{dP}=\left.\frac{\partial\rho}{\partial P}\right|_h+\left.\frac{\partial\rho}{\partial h}\right|_P\frac{dh}{dP} \qquad \cdots\cdots(5)$$

For the water-steam system, the partial differential term in Eq. (5) is calculated from a thermodynamic relation equation and a steam table similar to the JSME steam table published by the Japan Society of Mechanical Engineers. For other single-component systems, it can be arbitrarily set by user subroutines.

(2) Slip velocity model

The terms S_u and S_h that indicate the dissipation of momentum and energy by the slip velocity between the gas and liquid phases in two-phase flow are expressed by a slip velocity model as follows:

$$S_u=\frac{\partial}{\partial x}\left\{\frac{\alpha(1-\alpha)(\rho_f-\rho_g)}{\alpha\rho_g+(1-\alpha)\rho_f}uV_s\right\} \qquad \cdots\cdots(6)$$

$$S_h=\frac{\partial}{\partial x}\{(h_g-h_f)\alpha(1-\alpha)(\rho_f-\rho_g)V_s\}-\frac{\alpha(1-\alpha)(\rho_f-\rho_g)V_s}{\alpha\rho_g+(1-\alpha)\rho_f}\frac{\partial P}{\partial x} \qquad \cdots\cdots(7)$$

If V_g and V_f are the gas-phase velocity and liquid-phase velocity, respectively, the slip velocity V_S is given by

$$V_S=V_g-V_f \qquad \cdots\cdots(8)$$

According to the drift flux model[1], V_g and V_f are expressed as follows:

$$V_g=C_oJ-V_{gj} \qquad \cdots\cdots(9)$$

$$V_f=\frac{J-\alpha V_g}{1-\alpha} \qquad \cdots\cdots(10)$$

Table 3 Drift velocity model for vertical flow

Average velocity j (m/s)	Pressure P (ata)	Pipe diameter D (m)	Drift velocity V_{gj}
j≦0.24	P≦180	D≦0.61	$a_1\left[\frac{\sigma\cdot g\cdot(\rho_f-\rho_g)}{\rho_f^2}\right]^{1/4}$
j≧0.24	P≦15	D≦0.05	$a_1\left[\frac{\sigma\cdot g\cdot(\rho_f-\rho_g)}{\rho_f^2}\right]^{1/4}$
		0.05≦D	$a_2\left[\frac{g\cdot D\cdot(\rho_f-\rho_g)}{\rho_f}\right]^{1/2}$
	15≦P≦180	D≦0.02	P≦15ata V_{gj}*
		0.02≦D≦0.24	$V_{gj}^*+\left[a_3\left(\frac{0.24g(\rho_f-\rho_g)}{\rho_g}\right)^{1/2}-a_1\left[\frac{\sigma\cdot g\cdot(\rho_f-\rho_g)}{\rho_f^2}\right]^{1/4}\right]\times a_4\left[\left(\frac{D}{0.02}\right)^{1/2}-1\right]$
		0.24≦D≦0.46	$a_3\left[\frac{g\cdot D\cdot(\rho_f-\rho_g)}{\rho_g}\right]^{1/2}$

Average velocity j (m/s)	Distribution parameter C_0
j≦−3.5	$a_5-a_6\ \rho_g/\rho_f$
−3.5≦j≦−2.5	$a_7+a_8\ \rho_g/\rho_f\ -0.3(1-\rho_g/\rho_f)(2.5+j)$
−2.5≦j≦0	$a_7+a_8\ \rho_g/\rho_f$
0≦j	$a_5-a_6\ \rho_g/\rho_f$

σ = surface tension
V_{gj}* when P≦15 ata
a_1 to a_8 = constant

If ρ, ρ_g, and ρ_f are average density, gas-phase density, and liquid-phase density, respectively, the void fraction α is obtained from the following relation:

$$\rho=\alpha\rho_g+(1-\alpha)\rho_f \qquad \cdots\cdots(11)$$

Using the pressure and enthalpy obtained by flow calculation, ρ_g and ρ_f can be determined by equations of state for the gas phase and the liquid phase as given by

$$\rho_g=\rho_g(P, h) \qquad \cdots\cdots(12)$$

$$\rho_f=\rho_f(P, h) \qquad \cdots\cdots(13)$$

For the drift velocity V_{gj}, drift velocity models for vertical flow and horizontal flow are used to suit specific flow patterns.

Many drift velocity models are proposed for vertical flow by Ishii, Zuber, and other workers. Among them, the model[2] (see **Table 3**) of Hirano et al. is adopted in consideration of its high accuracy for vertical downflow and large diameter. This analysis takes bubble flow, slug flow, and froth flow into account.

The flow pattern map of Mandhane et al.[3] shown in **Fig. 2** is used for horizontal flow. The drift velocity models[4] used in the nuclear engineering field and shown in **Table 4** are adopted for specific flow patterns.

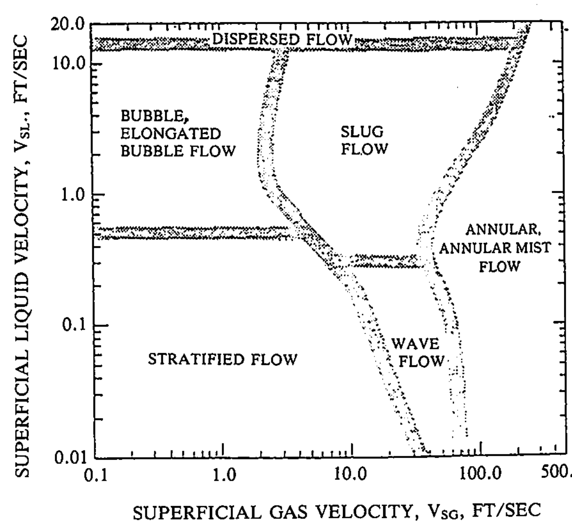


Fig. 2 Flow pattern map of Mandhane et al.

Table 4 Drift velocity model for horizontal flow

Flow pattern	Distribution parameter C_0	Drift velocity V_{gj}
Bubble flow	$C_o=b_1-b_2\ \rho_g/\rho_f\times(1-e^{-18\alpha})$	$V_{gj}=0$
Slug flow	$C_o=b_3$	$V_{gj}=b_4\ g\Delta\rho D/\rho_f$
Annular flow Annular mist flow	$C_o=1+\frac{(1-\alpha)(1-E_d)}{\alpha+4\ \rho_g/\rho_f}$	$V_{gj}=0$
Stratified flow Wavy flow	$C_o=\frac{1}{\alpha(\rho_g/\rho_f)^{4/9}(\mu_g/\mu_f)^{1/9}g(\alpha)^{10/9}}$ where g(α) is reverse function of following equation $\alpha=f(Y)=1-(1-\frac{21}{Y}+\frac{1}{Y^2})^{-0.5}$ where Y = Lockhart-Martinelli parameter	$V_{gj}=0$

E_d = droplet flow rate ratio
b_1 to b_4 = constant

(3) Finite difference method and time integration method

The equations of conservation of mass, momentum and energy are discretized by the control volume method, and the staggered grid shown in **Fig. 3** is adopted as the computational grid. The upstream difference method is applied to the convection term.

The time integration method can be selected from between the Euler semi-implicit method and the stability enhancing two-step (SETS) method[5].

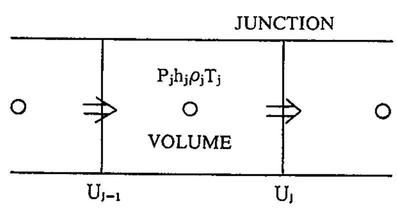
The Euler semi-implicit scheme is an explicit method that basically needs no iterative computation. The pressure term in the equation of conservation of momentum and the convection terms in the equations of conservation of mass and energy are implicitly treated. The time step size of this technique is limited by the Courant stability condition.

The SETS method is characteristic in that it solves a stabilized version of each equation of conservation before and after the semi-implicit scheme. It can perform computation at time steps exceeding the limitation of the Courant stability condition, and its stability of analysis is good. The computational time can be drastically shortened by adopting the SETS method.

This analytical program has the function of automatically setting the time step size and can automatically compute an appropriate time step size.

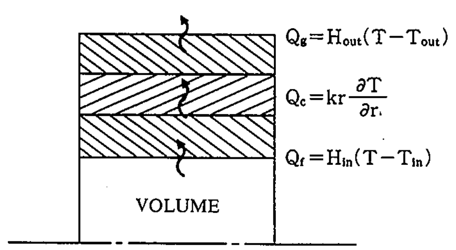
4.2 Unsteady-state heat transfer analysis between fluid and outside boundary

Unsteady-state heat transfer phenomena between the fluid and the outside boundary are analyzed as combination of heat transfer at the boundary and heat conduction within the structural material (such as pipe, heat insulating material or soil) as shown in **Fig. 4**. Assuming that the shape and temperature distribution of the structural material are axisymmetrical and that temperature is independent in the axial direction, one-dimensional unsteady-state heat conduction in the radial direction of the structural material is given by



1. P_j, h_j, ρ_j, T_j = pressure, enthalpy, density, and temperature in j-th VOLUME, respectively
U_j, U_{j-1} = velocity in j-th and j−1-th JUNCTIONS, respectively

Fig. 3 Staggered grid



Q_g, Q_f = amount of heat passing through outside and inside surfaces of pipe, respectively
Q_c = amount of heat passing through pipe structural material
H_{out}, H_{in} = heat transfer coefficients on inside and outside surfaces of pipe, respectively
T_{out}, T_{in} = pipe outside and inside surface temperatures, respectively

Fig. 4 Heat transfer in structural materials

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right) + Q = \rho C\frac{\partial T}{\partial t} \quad \cdots\cdots(14)$$

Next, the boundary condition for the fluid side (between the fluid and structural material) is expressed as follows:

Boundary condition for fluid side

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=R1} = H_{in}(T - T_{in}) \quad \cdots\cdots(15)$$

The heat transfer coefficient H_{in} for the gas flow is obtained by using a forced convection heat transfer equation for turbulent flow in circular pipe, and for steam-water two-phase flow by using the WREM evaluation model[6] that considers heat transfer in various boiling conditions such as film boiling. For other single-component two-phase flow systems, the heat transfer coefficient H_{in} can be arbitrarily defined by user subroutines.

As the outside boundary condition (between the structural material and the outside boundary), the necessary heat transfer coefficient H_{out} for the outside boundary is given, and its value is assumed to be constant without computation.

Outside boundary condition

$$-k\left.\frac{\partial T}{\partial r}\right|_{r=R2} = H_{out}(T - T_{out}) \quad \cdots\cdots(16)$$

4.3 Control system model

Control units are incorporated to model the control system. The control system is composed of the following elements that can be freely given by input:

First-order lag element	Second-order lag element	Lead-lag element
Integral element	Derivative element	Proportional-integral-derivative (PID) element
Additional element	Multiplication element	Maximum element
Trip unit element	Minimum element	Nonlinear element
Trip delay element		

4.4 Critical flow model

Gas flow analysis determines the critical flow rate by a critical pressure ratio equation.

Gas theories cannot be applied to two-phase flow under the influence of evaporation or condensation in flow channels and gas-liquid slip velocity, and so forth. Various models are built for the water-steam system according to channel geometry and flow condition. Here is used the homogeneous equilibrium model (HEM)[7] that is extensively applied to analysis in the nuclear reactor field.

Other two-phase systems can be arbitrarily modeled by user subroutines.

4.5 Initial value setup function

The analytical program has an automatic initial value setup function. The three conservation equations of mass, momentum, and energy with the time term omitted can be solved by iteration by the Newton method, and the initial values of pressure, velocity, density and enthalpy can be set. At the same time, the degree of control valve opening can also be set automatically. The work load of initial value setting can thus be lessened during transient computation.

5. Verification of Analytical Program

The results of analysis performed by the program were checked for validity against pertinent experimental results and numerical analysis results.

For one-dimensional gas flow, the analytical program was validated by comparison with the analytical solution of shock wave tubes, and with the results of analysis by the published code Topaz[8]. Good results were obtained on the whole.

For one-dimensional two-phase flow, the program verification was made through comparison with the experimental results of Edward's pipe problem[9], with the results of the PHOENICS code applied to the problem of boiling in horizontal pipe, and with the results of another code applied to the problem of steam removal from subcooled water in vertical pipe. **Fig. 5** shows the verified results of the analytical model for the problem of boiling in horizontal pipe, as compared with the PHOENICS code.

6. Examples of Analysis

Introduced here are examples of analysis conducted by the analytical program simulating an actual plant.

6.1 One-dimensional gas flow

Analysis of transient phenomena in a long-distance natural gas pipeline is presented here as an example for one-dimensional gas flow. The model configuration and analytical conditions are as shown in **Fig. 6**.

(1) Model characteristics and analytical conditions

(i) Natural gas is supplied from the production base CPP and transported over about 420 km to the power plant GRE.

(ii) Natural gas is supplied at a constant flow rate from the upstream production base.

(iii) The downstream power plant has large variations in the natural gas consumption between the daytime and nighttime.

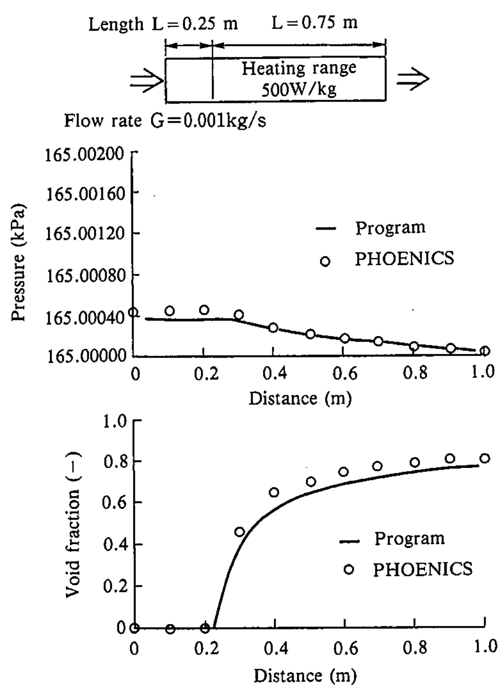


Fig. 5 Model and verification results

(iv) The intermediate station ORF of the pipeline has a control valve installed to control not the flow rate but the downstream pressure for the purpose of reducing the downstream design pressure. The natural gas consumption at the power plant is varied in two steps of about ±5% at 12-h intervals. The effect of varying the natural gas consumption on the upstream and downstream pressures, as well as the operation of the station control valve ORF, are analyzed.

(2) Results of transient computation

Fig. 7 shows the pressure distribution of the pipeline in the initial steady state.

As results of transient effect analysis, changes in the flow rate and pressure at the respective sites and in the degree of control valve opening are shown in **Fig. 8**.

The following can be known from these results of analysis:

(i) The upstream pressure of the pipeline varies little compared with the change of flow rate on the downstream side.

(ii) The downstream pressure at the pressure control valve does not rise above the set point.

Even when the downstream flow rate steeply increases, the pipeline itself serves as a tank, and the intermediate pressure control valve slowly opens while controlling the downstream pressure at the set point until it becomes full open. Thereafter, the pressure downstream the control valve falls below the set point. When the downstream flow rate decreases, the pressure control valve remains fully open until the downstream pressure reaches the set point. As soon as the downstream pressure reaches the set point, the pressure control valve is throttled to return the downstream pressure to the set point.

Since the model covers a very long laying distance, the pipeline plays the role of a sufficient buffer tank. The pressure change is small for the flow rate change. There is no problem when the design pressure is changed by the pressure control valve (class break).

6.2 One-dimensional two-phase flow

Analysis of transient phenomena in a downstream pipeline

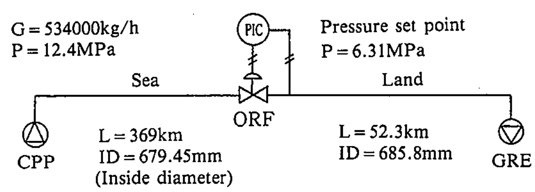


Fig. 6 One-dimensional gas flow analysis

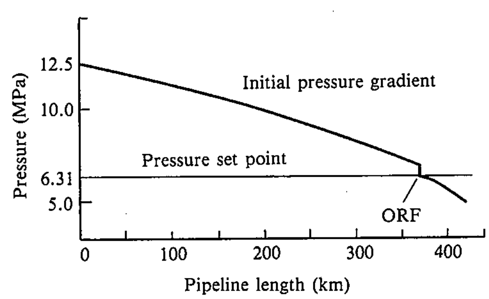


Fig. 7 Initial pressure distribution

when hot water is discharged from a tank is taken as an example of application for one-dimensional two-phase flow. **Fig. 9** shows the analytical model.

(1) Model characteristics and analytical conditions

(i) An instantaneous-opening blowdown valve is provided between the upstream tank and the downstream pipeline.

(ii) The upstream tank is filled with high-pressure hot water, and the downstream pipeline after the blowdown valve is filled with water saturated under the atmospheric pressure.

(iii) The quick opening of the blowdown valve discharges the hot water from the upstream tank and brings about a sudden change in the flow condition of the fluid in the downstream pipeline.

The flow state of the hot water in the downstream pipeline when the blowdown valve is quickly opened is analyzed in two cases of hot-water temperature in the upstream tank under the pressure of 350 kPa. The hot-water temperature is 406.7 K in case A (steam generated after discharge of hot water) and is 373.2 K in case B (no steam generated after discharge of hot water).

(2) Results of transient state computation

Fig. 10 shows transient pressure changes in respective points in cases A and B. **Fig. 11** in for transient flow rate changes downstream the blowdown valve in the two cases.

The following can be known from the results of analysis:

(i) In case A, the sudden discharge of hot water generates steam on the downstream side of the blowdown valve, and the gas-liquid two-phase flow thus produced changes pressure and flow rate in a complicated manner.

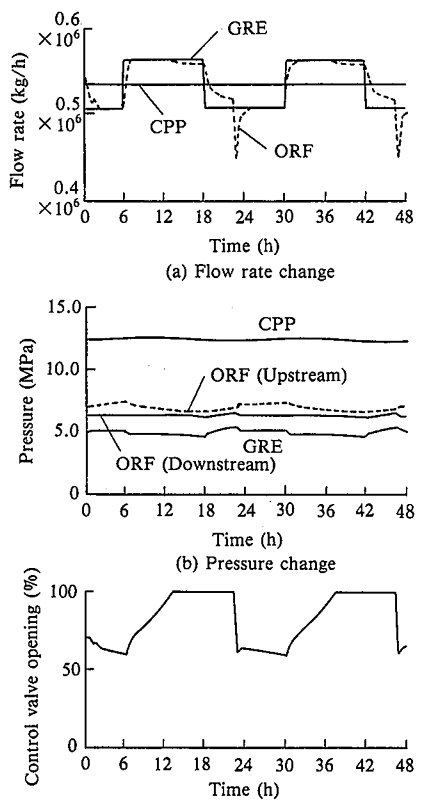
(ii) In case B, pressure and flow rate downstream the blowdown valve change in a simple manner after the hot water discharge and soon reach the steady state.

(iii) The flow rate in case A where the flow is gas-liquid two-phase flow is smaller than in case B where the flow is liquid single-phase flow.

In case A, the flow pattern changes to two-phase flow and increases in pressure variation. Sharp pressure variation should be kept under control lest it should vibrate the pipeline depending on the pipe geometry.

7. Conclusions

A one-dimensional transient analysis program was developed to analyze transient heat transfer and fluid flow in gas single-



(a) Flow rate change
(b) Pressure change
(c) Control valve opening change

Fig. 8 Results of gas analysis

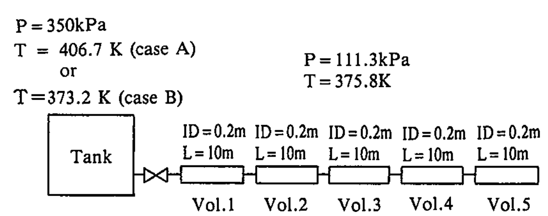
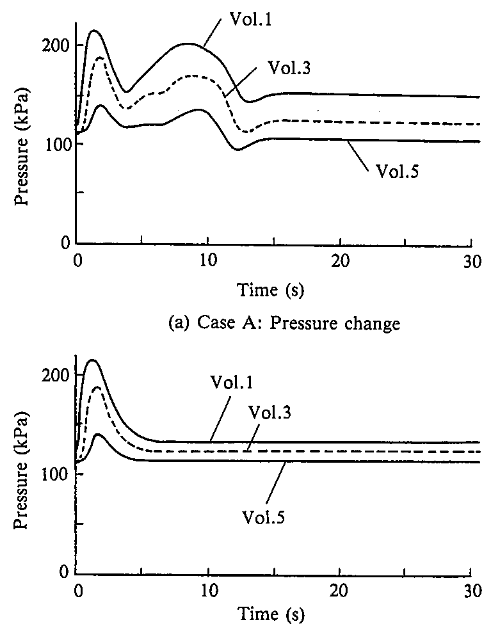


Fig. 9 One-dimensional two-phase flow analysis model



(a) Case A: Pressure change
(b) Case B: Pressure change

Fig. 10 Results of two-phase flow analyses (example)

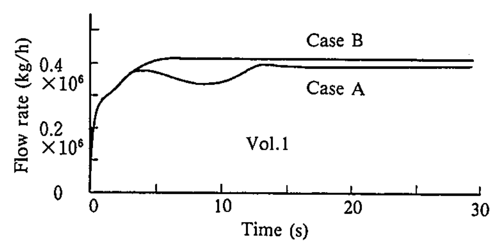


Fig.11 Downstream flow rates in cases A and B

phase flow and gas-liquid two-phase flow pipeline networks. The validity of the program has been established by the results of analyses made of the basic problems of gas flow and two-phase flow. Examples of the application of the program to the analysis of heat transfer and fluid flow in gas single-phase flow and steam-water two-phase flow systems simulating actual plants have been reported.

The authors intend to apply the analytical program to actual projects with a view to expanding its scope of application with improving accuracy of analysis.

The authors would like to express gratitude to Mr. Toshiharu Mitsuhashi and Mr. Katsumasa Ishii of Fuji Research Institute Corporation for their cooperation in the preparation of this paper.

Nomenclature

t = time (s)
x = x-coordinate (m)
ρ = density of fluid (kg/m^3)
u = velocity of fluid (m/s)
P = pressure of fluid (Pa)
z = compressibility factor (−)
K = representative resistance coefficient for fitting (1/m)
K_f = friction factor for pipe (1/m)
$g \cos\theta$ = gravitational body force (m/s^2)
h = enthalpy of fluid (J/kg)
q = heating value ($J/m^3 \cdot s$)
S_u, S_h = Change in momentum or energy with slip velocity
r = radial coordinate (m)
T = temperature (K)
R = gas constant (J/kg·K)
C = specific heat (J/kg·s)
k = thermal conductivity (W/m·K)
H = heat transfer coefficient ($W/m^2 \cdot K$)
Q = heating value per unit volume (W/m^3)
$R1$ = inside diameter of structural material (m)
$R2$ = outside diameter of structural material (m)
α = void fraction (−)
V = velocity (m/s)
V_S = slip velocity (m/s)
j = average velocity of mixture (m/s)
C_0 = distribution parameter (−)
V_{gj} = drift velocity (m/s)
f = liquid phase
g = vapor phase

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