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COMPUTATION OF NATURAL GAS PIPELINE TRANSIENTS, INCLUDING FRICTIONAL AND HEAT TRANSFER EFFECTS

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ABSTRACT

To achieve an economical design of natural gas pipeline it is necessary to do a detailed analysis of the transients caused by various operating flow conditions. In this work, unsteady flow in natural gas pipeline was modelled as one dimensional frictional flow with the effect of heat transfer included. The model was used to compute the flow in a ruptured underwater gas pipeline. The predicted mass flow rates out of the pipeline were between 8 and 25 % higher than the results obtained earlier for isothermal unsteady flow.

1. Introduction

Pipelines are commonly used to transport and distribute natural gas in many countries because they are more energy efficient than other methods of transporting natural gas. Transients occur in natural gas pipelines during filling and line pressurization, emergency shut down, gas blow down and line depressurization processes. Unsteady flow can also occur in the pipeline during normal operation when compressors are running or due to fluctuation in demand for natural gas by the consumers. An extreme kind of transient in natural gas pipeline resulting in consic' .rable risk to the environment may occur due to an unexpected sudden break in the pipeline.

It is important to be able to do a detailed analysis of the transients caused by various possible operating conditions to avoid using an unnecessarily high factor of safety and thereby achieve an economical design of the pipeline [1]. In the case of pipeline rupture, it is necessary to know the rate of loss of gas from the break to calculate the dispersion range and ground concentration of the air-gas mixture arising from the rupture. This is necessary in a hazard analysis to determine the area exposed to fire risk.

A break divides the pipeline into two segments: the high pressure segment in which the flow continues in the original direction and the low pressure segment in which flow reversal occurs after the rupture. A more detailed discussion of the flow in a pipeline after rupture can be found elsewhere [2, 3].

Flatt [2] developed a method of characteristics to compute unsteady adiabatic flow of natural gas in a long pipeline following sudden break. Because of the very high gradients of flow variables near the rupture he did not start his computation from the moment the rupture occurred, he allowed the expansion wave to travel a short distance into the pipeline before the computation commenced.

Lang [3] used spectral collocation method to compute unsteady isothermal and adiabatic flows in ruptured natural gas pipeline. His method produced oscillations in the flow rates out of the pipeline at the early times.

Olorunmaiye and Imide [4,5] used a method of characteristics to compute unsteady isothermal flow in natural gas pipelines. In the case of pipeline rupture, their method could handle the flow in the pipeline from the moment the rupture occurred.

With isothermal flow assumption, heat transfer between the gas in the pipeline and the ambient is unlimited and differences in temperature are immediately equalized; whereas adiabatic flow assumption does not allow heat exchange with the environment. The real flow case lies between adiabatic and isothermal flows. The work reported in this paper is an attempt to model the flow more realistically by including the effect of heat transfer on unsteady flow in long natural gas pipeline.

2. Mathematical Model

For one-dimensional flow in a pipeline of uniform diameter, the conservation equations for mass, momentum, and energy are:

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

$$\frac{1}{\rho}\frac{\partial P}{\partial x} + \frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} - F = 0 \qquad (2)$$

$$\frac{\partial h}{\partial t} + u\frac{\partial h}{\partial x} - \frac{1}{\rho}\frac{\partial P}{\partial t} - \frac{u}{\rho}\frac{\partial P}{\partial t} = q + uF \qquad (3)$$

In these equations, $F = 2fu|u|/d$, ρ = density, t = time, u = velocity, x = axial distance, P = pressure, F = frictional force per unit mass, d = internal pipe diameter, f= Darcy's friction factor, h = specific enthalpy, and q = heat transfer rate per unit mass.

For the sake of simplicity, the natural gas in the pipeline is assumed to behave as a perfect gas. It has been found that useful results can be obtained using the perfect gas assumption [3].

For a perfect gas,

$$p = \rho RT \qquad (4)$$

$$and \quad h = c_p T \qquad (5)$$

where R = specific gas constant, C_p = specific heat capacity at constant pressure and T = temperature. It can be shown that the entropic equation of state $p = p(s, \rho)$ is given by

$$p = (\rho RT_o)^{\gamma}\exp(s/c_v)/p_o^{R/c_v} \qquad (6)$$

where p_o, T_o is the datum state at which specific entropy, s is zero, C_v is the specific heat at constant volume and $\gamma = C_p/C_v$.

Making use of equations (4) - (6) in (3) and using the resulting equation in (1), the equations obtained from (3) and (1) and equation (2) can be non-dimensionalized choosing ambient pressure and temperature (p_o, T_o), speed of sound ($a_o = (\gamma RT_o)^{1/2}$), length of the pipeline segment (L_o), and specific gas constant (R) as reference parameters to get the following equations:

$$\frac{1}{\gamma D}\frac{\partial P}{\partial X} + \frac{\partial U}{\partial Z} + U\frac{\partial U}{\partial X} - F' = 0 \qquad (7)$$

$$\frac{\partial S}{\partial Z} + U\frac{\partial S}{\partial X} = \frac{\gamma D}{P}(Q + UF') \qquad (8)$$

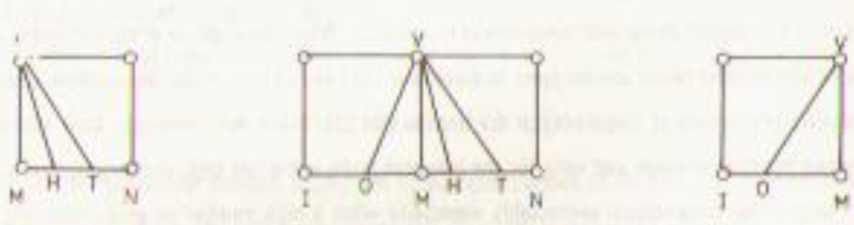
$$\frac{\partial P}{\partial Z} + U\frac{\partial P}{\partial X} + \gamma A^2 D\frac{\partial U}{\partial X} = \frac{\gamma R}{C_v}D(Q + UF') \tag{9}$$

where $P = p/p_o$, $Z = ta/l_o$, $U = u/a_o$, $X = x/l_o$, $F' = Fl_o/a_o^2$, $Q = ql_o/a_o^3$,
$D = \rho RT_o/p_o$, $S = s/R$ and $A = a/a_o$.

3. Numerical Method

Choosing P, U and S as dependent variables, equations (7) - (9) can be solved using a numerical method of characteristics described in earlier works [4, 5].

The three characteristics curves of equations (7) - (9) have reciprocal slopes (U + A), (U - A) and U in the X-Z plane. The characteristics reaching a grid point are shown in Figure 1.



(a) LEFT BOUNDARY GRID POINT (b) INTERNAL GRID POINT (c) RIGHT BOUNDARY GRID POINT

FIGURE 1: CHARACTERISTICS REACHING INTERNAL AND BOUNDARY GRID POINTS FOR SUBSONIC/SONIC FLOW TO THE LEFT.

The characteristics having reciprocal slopes (U+A), (U-A) and U are labelled OV, TV, and HV respectively. The finite difference approximation of the compatibility equations along characteristics OV, TV, and HV are respectively:

$$U_V - U_O + \left(\frac{1}{\gamma AD}\right)_{OV}(P_V - P_O) = -\left(F' - \frac{E}{\gamma AD}\right)_{OV}\Delta Z \tag{10}$$

$$U_V - U_T - \left(\frac{1}{\gamma AD}\right)_{TV}(P_V - P_T) = -\left(F' + \frac{E}{\gamma AD}\right)_{TV}\Delta Z \tag{11}$$

$$S_V - S_H = Y_{HV}\Delta Z \tag{12}$$

where $E = \gamma RD(Q + UF')/C_v$ and $Y = \gamma D(Q + UF')/P$

In equations (10) - (12), double subscripts on a term indicates that the term is taken to be the mean of its value at the end points indicated by the two subscripts (see Figure 1).

4. Boundary Conditions

Assuming the changes causing unsteady flow occur at the left end, for instance in the case of pipeline rupture, choked flow occurs there for sufficiently high pressures.

$$U_V = -A_V \tag{13}$$

When the flow becomes subsonic the condition used is

$$P_V = P_A \tag{14}$$

where P_A = dimensionless ambient pressure.

Equation (13) or (14) is solved along with equations (11) and (12). When the outflow at the left end is sonic, the heat transfer and friction terms are dropped in equations (11) and (12) to make the outflow isentropic and thereby avoid the problem of singularity at the broken end [2]. Since this isentropic flow assumption applies only when the flow is sonic and only for the last grid node at the left end, the assumption will not affect the accuracy of the computation appreciably especially when a high number of grid points are used.

The dependent variables at the right end are not affected until time Z^* when the wave arrives there. Hence,

$$U_V\,(Z \le Z^*) = U_R\,(Z = 0) \tag{15}$$

$$P_V\,(Z \le Z^*) = P_R\,(Z = 0) \tag{16}$$

$$S_V\,(Z \le Z^*) = S_R\,(Z = 0) \tag{17}$$

where U_R, P_R and S_R are the flow variables at the right end at the initial condition. The valve at the right end of the pipeline segment is assumed to be shut immediately the wave reaches this position. Therefore,

$$U_V\,(Z > Z^*) = 0 \tag{18}$$

Other boundary conditions which may be used at either end of the pipeline are prescription of the static pressure or velocity as function of time. The latter may be used to simulate gradual valve closure or variation in demand of natural gas by consumers. The other dependent variables not specified can be obtained using the appropriate compatibility equations.

5. Initial Conditions

The initial condition used is the steady isothermal flow in the pipeline prior to the initiation of unsteady flow. The initial distributions of pressure and velocity in steady isothermal flow are given approximately by

$$P(X, Z = 0) = P_{IN}\left(1 - \frac{4fU_{IN}^2 X}{D^*}\right)^{\frac{1}{2}} \tag{19}$$

$$U(X, Z = 0) = D_{IN}U_{IN}/P(X, Z = 0) \tag{20}$$

where subscript "IN" refers to initial conditions at the left end of the pipeline, and dimensionless pipe diameter $D^* = d/d_o$.

6. Heat Transfer and Wall Friction

The rate of heat transfer by convection from wall to a grid node is

$$q^i = h_{cin}\alpha_{in}(T_w - T_g) \tag{21}$$

where h_{cin} = convective heat transfer coefficient at the inner surface of the pipe, α_{in} = inner lateral surface area of the pipe cell, T_w = the wall temperature and T_g = gas temperature.

Dittus-Boelter equation [6] for convective heat transfer for steady flow in smooth tubes was used to calculate h_{cin}.

$$h_{cin}d/k = 0.023\ Re_d^{0.8}Pr^{0.4} \tag{22}$$

where d = inner diameter of the pipeline, k = thermal conductivity of the gas, Re = Reynolds number and Pr = Prandtl number.

A constant friction factor f = 0.0018 which was used by earlier workers [2, 5] for unsteady flow in natural gas pipeline was also used in this work.

The wall temperature was calculated using the equation

$$T_w^{t+\Delta t} = T_w^t + \frac{\Delta t}{mc}\left[h_{cex}\alpha_{ex}(T_A - T_w) - h_{cin}\alpha_{in}(T_w - T_g)\right]^t \tag{23}$$

where T_A = ambient temperature, h_{cex} = convective heat transfer coefficient at the external surface of the pipe cell, α_{ex} = external surface area of the pipe cell, mc = heat capacity of the pipe cell, and superscripts t and t + Δt refer to the time steps of computation.

The h_{cex} was calculated from the empirical relation for free convection from horizontal pipe [6]

$$h_{cex}d_{ex}/k = 0.53\ (GrPr)^{0.25} \tag{24}$$

where Gr = Grashof number, d_{ex} = external diameter of the pipe and k = thermal conductivity of water or air surrounding the pipeline.

7. Stability and Accuracy Criteria

The time step chosen was

$$\Delta Z = 0.9\ \Delta X/(A + |U|) \tag{25}$$

to ensure that the CFL stability criterion is not violated.

The mass balance error which was used to check how well the global conservation of mass is satisfied in the flow in the pipeline which was suggested by Flatt [2] and used by the author earlier [5] is given by

$$e = 1.0 - \frac{(\textit{Rate of mass outflow at both ends of pipeline})(t_2 - t_1)}{(\textit{Mass in pipeline at time } t_1) - (\textit{Mass in pipeline at time } t_2)} \tag{26}$$

The ideal value of this error is zero.

8. Results and Discussion

The FORTRAN programmes written were run on SWAN 286/12 and 486/25 IBM compatible personal computers with math co-processors using WATFOR 77 compilers.

To assess the model, it was used to compute transient flow in a pipeline of length 63.8 km linking two reservoirs, one at the left end, the other at the right end. The pressure everywhere in the pipeline was 22.17 (P_o = 6 bar) being the same as pressure in the reservoir at the right end to which the pipeline is open. The left end of the pipeline was separated by a diaphragm from the reservoir there which was at a pressure of 17.64. The wall and gas temperature were 281 K and the gas in the pipeline was initially at rest. The diaphragm at the left end was punctured suddenly at time t= 0. After the transients would have died out, the flow in the pipeline should settle to a steady flow from the right to the left. By the time the programme ran till t= 1000 s, the flow had become steady with the pressure and velocity distributions shown in Figure 2. The results agree remarkably well with the isothermal steady flow pressure and velocity distributions given in equations (19) and (20) as can be seen in Figure 2.

The gas and wall temperatures obtained at t = 1000 s varied from 0.994 - 1.003, and 0.995 - 1.004 respectively (T_o = 281 K). These results show that the assumption of steady isothermal flow in long natural gas pipeline (dimensionless wall and gas temperature = 1) is quite good.

The physical case to which the programme was applied was an underwater pipeline of length 143 km, internal diameter 0.87 m, inlet pressure at the left end of 133 atm., outlet pressure 55 atm., gas temperature T_o = 281 K, and flow rate of about 650 kg/s. The outside pressure P_o = 6 atm (corresponding

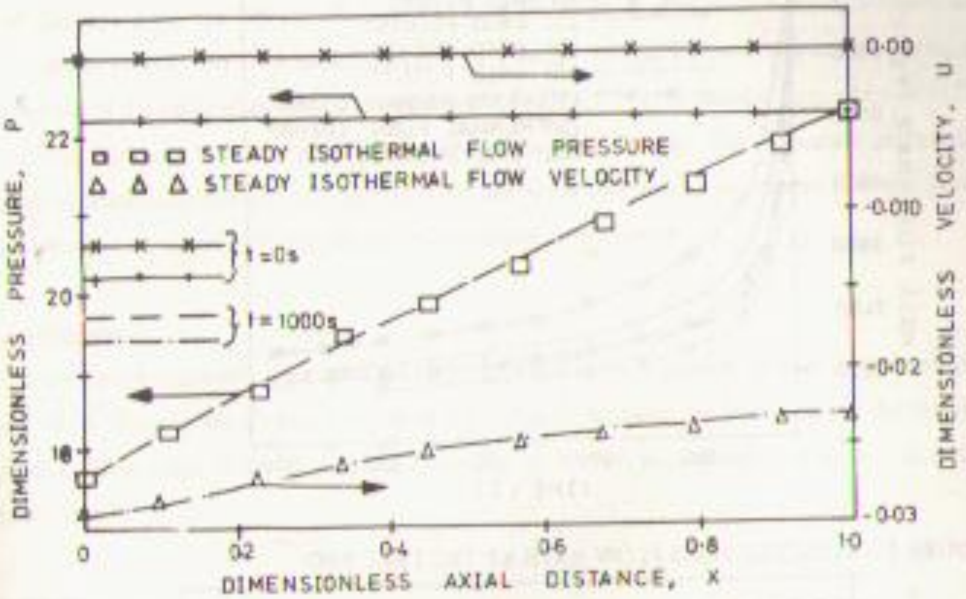


FIGURE 2: PRESSURE AND VELOCITY DISTRIBUTIONS AT t = 0 AND t = 1000 s COMPARED WITH THOSE FOR STEADY ISOTHERMAL FLOW IN A PIPELINE LINKING TWO RESERVOIRS.

to 50 m depth). For the natural gas, R = 518.3 J/kg.K and $\gamma = 1.33$. The flow in the pipeline was initially steady and isothermal until time t = 0 when the pipe was completely broken suddenly at the high pressure end. This was also the case considered in the earlier work on unsteady isothermal flow in natural gas pipelines [4, 5].

Figure 3 shows the mass flow rate out of the ruptured end versus time for the first 500 seconds using different number of grid points. Also shown is the result obtained earlier for isothermal unsteady flow [5]. The flow rates predicted using the isothermal model are lower than results predicted using the present model (401 grid points) by between 8 % and 25 %. This is so because of higher densities (due to higher pressures and lower temperature) at the exit plane in the present model, and adiabatic sonic velocities being higher than isothermal sonic velocities, when the flow is choked at the left end.

Figure 4 shows the pressure distributions in the pipeline at various times. The point at which pressure did not change for a long time was found to be at a dimensionless distance of 0.79 from the broken end. In the isothermal flow simulation this point was found to be a dimensionless distance of 0.75 [5]. A dimensionless gas temperature as low as 0.741 (-65°C) was observed at the rupture end shortly after the rupture and it gradually increased to 0.852 (-33.7°C) by time t = 500 s.

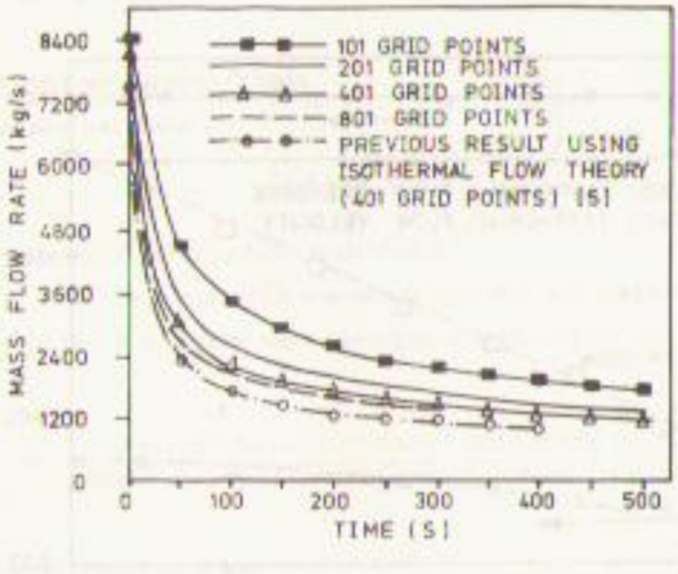


FIGURE 3: PREDICTED MASS FLOW RATE AT THE LEFT END.

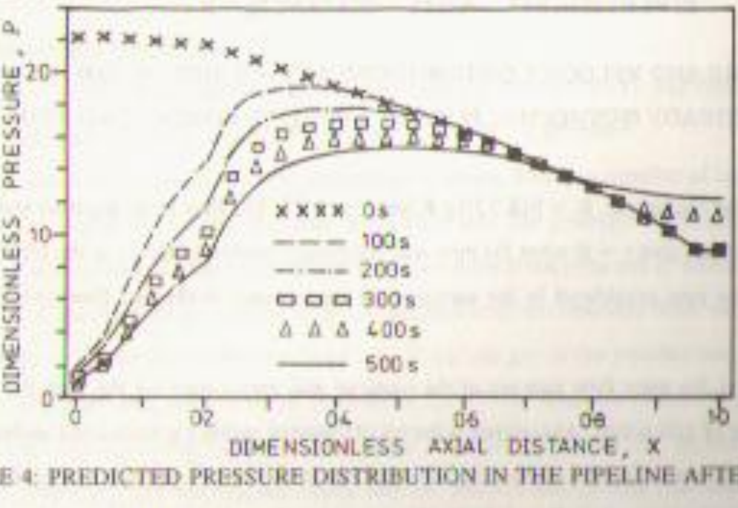


FIGURE 4: PREDICTED PRESSURE DISTRIBUTION IN THE PIPELINE AFTER RUPTURE.

The values of errors obtained in the computation for 201, 401 and 801 grid points were 18%, 3% and 1% respectively. This shows that results of the present model are far more accurate than results obtained using isothermal simulation in which 1601 grid points were used to obtain an error of about 7% [5]. However, the higher accuracy is at the expense of much higher computer time for the present model than for isothermal model.

9. Conclusions

A model of unsteady flow in a long natural gas pipeline in which the effect of friction and heat transfer were included has been presented. The mass flow rates at the ruptured end of an underwater natural gas pipeline during the first 500 seconds predicted using the model were between 8 and 25% higher than those predicted in an earlier work using isothermal flow model. The gas temperature predicted during the time interval, at the ruptured end varied between -65°C and -33.7°C in an ambient temperature of 21°C.

This work can be easily extended and applied to study unsteady flow in natural gas pipeline subjected to heating environment such as may occur due to fire outbreak on an offshore platform. In that case it would be necessary to include the effects of radiative heat transfer.

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