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An investigation of highly pressurized transient fluid flow in pipelines

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ABSTRACT

This paper discusses transient processes in natural gas pipelines. The method of characteristics (MOC) is applied for the analysis of two transient categories, where the governing one-dimensional, hyperbolic conservation equations are linearized and solved without neglecting any of their term. First, we present a parametric study of the pressurized flow encountered when pipelines are utilized for the transportation or the temporary storage of natural gas. The non-ideal compressibility of natural gas is included in the model and its impact on the thermo-hydraulic processes is elucidated. Second, we model the hydrodynamics of a pipeline whose downstream boundary is a periodic discharge rate. The results show that, in response to these boundary conditions, the pressure distribution in the pipeline also undergoes periodic variations. Furthermore, our simulation results confirm the usefulness of MOC for numerical simulation of flow phenomena in pipelines.

1. Introduction

Natural gas transportation and distribution often occur in conveyance systems which are designed primarily for steady flow conditions, whereby the transmission to any specific point is to take place at a specific pressure and flow rate. The pipelines in the ideal situation would have quasi-steady flow rates, and the volumetric flow rates of gases delivered at the end of a pipeline would not vary sharply with time. However, the flow rates at boundaries of a pipeline occasionally occur in periodic or pseudo periodic form during a day in response to consumer demand. Highly pressurised flows also occur in pipelines during transients caused by pumps and valves and can cause vibration problems. These flow disturbances, which often generate pressure and mass flow fluctuations, can be slow or rapid. Gato and Henriques [1] associate the slow disturbances to the cyclic variations in the demand for natural gas during the day. To compensate for the uncertainty about the piping system dynamics and the time dependent demand, storage facilities and variable line pack can be utilized. Nevertheless, lack of complete knowledge about the market generated demand transients and the response of the piping systems to these demand transients are the two major sources of uncertainty.

The dynamic behaviour of oil and natural gas pipelines has been studied by several investigators in the recent past. Gato and Henriques [1] studied six types of incidents for pipes formed by assembling three different segments varying in length and in diameter and demonstrated the importance of pipe diameter in the procession of transients.

Streejith et al. [2] performed a finite element analysis of the fluid–structure interaction in pipeline systems, and examined the consequences of time varying flow conditions, in particular the response of liquid filled pipelines to valve closure excitation, which could generate severe vibration problems. Tentis and Margaris [3] developed a system of ordinary differential equations (ODEs) for describing the transport of natural gas in a long pipe bounded at the outlet by a 24-h cyclic variation of the mass flow rate, and applied the Method of Lines (MOL) along with an adaptive grid algorithm. Mekbel [4] attempted to characterize the inertial effects in a pipeline by keeping track of flow phenomena at various locations along a pipeline during transients, and reported that any event that occurs at a point along a pipeline is reverberated in other points at different sections of the pipeline. Kessal and Bennacer [5] developed a model for the fast depressurization that occurs after gas is released from a pipeline. Their numerical method was based on the two step predictor-corrector finite difference scheme and was applied to the interior grid points only, because the method was incapable of treating the boundaries due to the oscillations caused by the valve closure. However, they could avoid this problem by using the method of Characteristics (MOC) at the vicinity of the two boundaries. Wilkinson [6] noted the importance of heat transfer at

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Nomenclature

A	pipe cross section area (m^2)
A(i−1,t), B(i,t), C(i+1,t)	nodal points
A_1, A_2, A_3, A_4, A_5, A_7	constants
C_P	specific heat at constant pressure (J mol K^{-1})
C_v	specific heat at constant volume (J mol K^{-1})
d	pipe diameter (m)
f	friction factor
i	node index
L	pipe length (m)
M(i, t + dt)	nodal point
n	number of nodes
p	pressure (Pa)
q	flow rate (m^3/s)
Q_w	heat transfer rate at the pipe wall (J s^{-1} m^{-3})
R	specific gas constant (J kg^{-1} K^{-1})
T	temperature (K)
T_0	initial temperature (K)
t	time (s)
v	axial fluid velocity (m/s)
v_0	uniform fluid velocity at the pipe's inlet (m/s)
x	axial coordinate (m)
z	compressibility coefficient

Greek symbol

ρ	volume mass (kg/m^3)
γ	the specific heat ratio

the perimeter boundary of a pipeline due to the thermal interaction of the pipelines with the ground.

Makino and Sugie [7] investigate the decompression of a highly pressurized natural gas in pipelines, addressing the fracture propagation process in such pipelines. Operation at high pressure is of interest because pipelines are operated at increasingly higher pressures for economic reasons, and pipeline networks are often utilized for storage of natural gas. Ke and Ti [8] investigated the transient flow in pipeline networks in response to daily changes of the load, using the electrical analogy technique. In other studies [9,10] the method of characteristics has been shown to be also efficient for solving unsteady flow equations.

The purpose of the present study is to provide examine the flow evolution in pipelines in response to transients under operational scenarios that require effective control of the flow rate, the pressure drop, and the temperature distribution in pipelines for their safe and reliable operation. A horizontal pipe of constant diameter with one input and one output, representing the most common system element in the integrated gas delivery systems, is modelled. Assuming one-dimensional flow, the conservation equations are cast in the form of a closed set of coupled partial differential equations (PDEs). The hyperbolic systems of PDEs, which represent a compressible fluid in transient flow, are solved by MOC. The discretization for the unsteady numerical analysis is based on the finite difference technique with constant time and spatial steps. Two transient types will be investigated. The first type deals with the pressurized flow encountered when pipelines are utilized for the transportation or the temporary storage of natural gas. The second type is concerned with the flow field inside a pipeline when the downstream boundary is a periodic discharge rate.

2. Basic formulation for one-dimensional compressible flow

Following Mekbel [4], the one-dimensional transient flow in a pipe is represented by the forthcoming set of coupled PDEs. The system of PDEs describes the compressible unsteady natural gas flow in a horizontal pipeline where it is assumed that the pipeline's radius of curvature is much larger than its diameter (see Fig. 1).

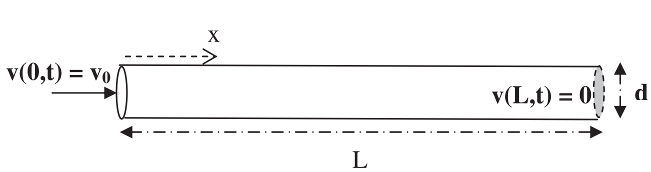

Fig. 1. Schematic of a pipe and its boundary conditions.

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{2d}v^2 = 0 \tag{2}$$

$$v\frac{\partial v}{\partial t} + v^2\frac{\partial v}{\partial x} + \delta v C_p\frac{\partial p}{\partial x}\beta C_p\frac{\partial p}{\partial t} + vC_p\frac{\partial T}{\partial x} + C_p\frac{\partial T}{\partial t}\frac{Q_w}{\rho} = 0 \tag{3}$$

where

$$\delta = \frac{1}{C_p}\left[\frac{1}{\rho} - T\left(\frac{\partial(1/\rho)}{\partial T}\right)_p\right]$$

It is assumed, at this point, that $z = 0.99$. The equation of state for the fluid will therefore be $\rho = \frac{p}{zRT}$.

The parameter a represents the speed of sound, $a^2 = \gamma\frac{p}{\rho}$, and

$$\beta = \frac{T}{C_p}\left(\frac{\partial}{\partial T}(1/\rho)\right)_p$$

$$\gamma = \frac{C_p}{C_v} = 1/\left(1 - \frac{p}{T}\beta\right)$$

The aforementioned set of PDEs is now transformed into the following set of equations in accordance with the method of characteristics (MOC) (see Zucrow and Hoffman [11], for a discussion). Fig. 2displays a schematic representation of MOC.

Characteristic C^0

$$\text{(II)}\quad \begin{cases} \left[\dfrac{dx}{dt}\right] = v \\ \left[\dfrac{dp}{dt}\right]_{(0)} - \dfrac{\gamma}{\gamma - 1}\dfrac{p}{T}\left[\dfrac{dT}{dt}\right]_{(0)} = -E_0 \end{cases} \tag{4}$$

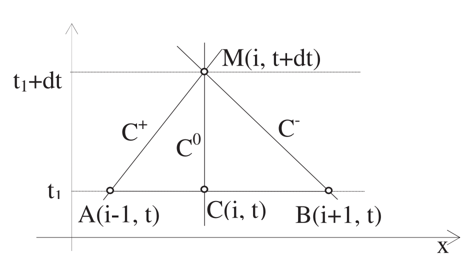

Fig. 2. Schematic representation of MOC.