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Numerical modeling of pseudo-homogeneous fluid flow in a pipe with leaks

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ABSTRACT

This work deals with the numerical modeling of single-phase flow in a pipe with one leak. The mathematical model governing mass, momentum and energy transport was established containing three coupled partial differential equations. These governing equations were numerically solved by discretizing time and space with backward finite differences, leading to one implicit scheme at every time step. The numerical solution was validated with available lab data obtaining good agreement. We present relevant results as the time behavior of upstream and downstream flow and pressure, while varying the leak location. Besides, we also show the temperature, pressure and flow profiles along the pipe when the leak is located near the inlet and outlet of the pipe. The predictive capabilities of the numerical model are remarkable to simulate the transient state of volumetric flow rate and pressure when a single leak is provoked at the pipe. A future application of our numerical scheme is for rapid automatic detection of loss of containment in pipes transporting valuable fluids as, for instance: oil, refined hydrocarbons, fuel, liquid catalysts, etc.

1. Introduction

In the midstream petroleum industry, just a single phase is expected to be present in pipelines for transportation of hydrocarbons. This is true since such products come from separation batteries that have the objective to reduce the water cut and other important functions such as the separation of gas and salt content. Under normal conditions, those objectives are reached, but due to abnormal conditions such as severe slugs coming from production facilities, not all phases are removed completely. Consequently, a little gas could be transported with the liquid phase in the pipe. Another scenario where multiphase flow can happen in pipeline systems is the transportation of refined oil products which are normally composed of one small fraction of light components and a large amount of medium and heavy components [1]. Under certain conditions of pressure and temperature, some light components could flash creating a second phase within the pipeline. In such scenarios, the assumption of just one phase flow is not longer valid. Nevertheless, a multiphase model, for instance the homogeneous formulation, can be used to successfully model those cases. In fact, the homogeneous models treat the mixture of phases as a pseudo single phase, where mixture properties are taken into account [2].

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Nomenclature

A	Cross-section area of pipe (m^2)
$\mathbf{A}$	Matrix given in Eq. (11)
$\mathbf{B}$	Matrix given in Eq. (11)
c	Propagation speed of sound ($m\ s^{-1}$)
$\mathbf{c_n}$	Matrix given in Eq. (23)
C_p	Constant pressure mixture heat capacity ($J\ kg^{-1}\ K^{-1}$)
d	Diameter
e_m	Total convective specific energy ($kJ\ kg^{-1}$)
f	Moody friction factor
H	Liquid volume fraction
h_m	Mixture enthalpy ($kJ\ kg^{-1}$)
I_n	Parameter in Eq. (23)
K_n	Parameter in Eq. (23)
I.D.	Internal diameter of experimental pipe (m)
L	Pipe length (m)
P	Static pressure (kPa)
Q	Volumetric flow rate ($m^3\ s^{-1}$)
Re	Reynolds number
S	Wet perimeter (m)
t	Time coordinate (s)
$\mathbf{u}$	Vector given in Eq. (11)
v	Fluid velocity ($m\ s^{-1}$)
v_L	Leak fluid velocity ($m\ s^{-1}$)
x	Spatial coordinate (m)
$\mathbf{X}$	Matrix given in Eq. (11)

Greek symbols

Λ_n	Parameter in Eq. (23)
ρ_m	Fluid mixture density ($kg\ m^{-3}$)
β	Joule–Thompson coefficient (kPa^{-1})
Γ_L	Leak term ($kg\ m^{-3}\ s^{-1}$)
τ_w	Wall shear stress ($N\ m^{-2}$)
ζ	Auxiliary variable in Eq. (15)

Subscripts

a	Upstream variable
b	Downstream variable
l	Liquid
L	Variable at leak position
g	Gas
0	Dummy variable
i	ith cell

Superscripts

exp	Experimental
sim	Simulated or forecasted by the model
t	Cell at actual time
T	Transpose matrix

On the other hand, a loss of containment in pipelines is one of the main problems for logistics of hydrocarbon transportation. For a single phase flow, the automatic detection and location of leaks in pipes have been studied elsewhere [3], but for multiphase flow cases, there are no precedents in the literature. This paper deals with a homogeneous model with mixture properties for the simulation of one leak in a pipeline. The proposed model is composed of the mass and momentum conservation equations, and additionally, the energy equation is taken into account [4], which is commonly discarded [5]. For each conservation equation, a leak term was incorporated to simulate the loss of containment.

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