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Numerical simulation of terrain-induced severe slugging coupled by hydrodynamic slugs in a pipeline–riser system

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ABSTRACT

A numerical study based on a one-dimensional two-fluid model is carried out to describe the transient hydrodynamic slugging and terrain-induced severe slugging in a pipeline–riser system. The system of equations is rendered well-posed by interfacial pressure model for the riser. The selected flow conditions are restricted in the well-posed region for the horizontal and the downward inclined pipes to ensure the hydrodynamic slug characteristics are predicted correctly. The validity of the model is examined by water faucet problem and horizontal slug flow experiments. Simulations with and without slug capturing are conducted to address the effect of hydrodynamic slugs on severe slugging. It has been found that more accurate predictions are obtained by taking hydrodynamic slugs into account. At low superficial gas velocity, the simulation without slug capturing tends to overestimate the severe slugging period. When hydrodynamic slugs are captured, the upstream gas expansion is suppressed by the hydrodynamic slugs. At relatively high superficial gas velocity, the simulation without slug capturing tends to underestimate the severe slugging period. When hydrodynamic slugs are captured, the upstream compressible volume is greatly enlarged by the blowout of the hydrodynamic slugs. In both situations, the influences of the hydrodynamic slugs can reduce the errors of the predicted severe slugging characteristics.

1. Introduction

In many industrial applications, gas and liquid are transported simultaneously in a pipeline system. The transient two-phase flow behavior can be greatly affected by the pipeline geometry. When a downward inclined pipe is followed by a riser, the terrain-induced severe slugging may occur. The terrain-induced slugs in severe slugging flow are much longer than the hydrodynamic slugs. Large fluctuations in flow rate and pressure will arise due to the formation and the blowout of the long liquid slugs. The fluctuations can cause significant damage to the downstream equipment, resulting in an increase in costs due to the replacement and downtime. Therefore, the prediction of severe slugging is of great significance to avoid this flow regime in operation.

Severe slugging occurs when the gas and liquid flow rates are relatively low. A severe slugging cycle consists of four typical steps: slug formation, slug movement into separator, gas blowout and liquid fallback. The four steps and the corresponding pressure fluctuations at the riser base are depicted in Fig. 1. It can be seen that severe slugging is caused by the blockage of the gas passage at the riser base. The gas cannot flow out of the pipe until the upstream gas pressure overcomes the hydrostatic pressure caused by the liquid level in the riser. Therefore, severe slugging characteristics are sensitive to the upstream pressure.

Hydrodynamic slugging may occur in the horizontal and nearly horizontal pipes in a pipeline system due to the interfacial instability. The pressure along the pipe can be greatly influenced by the hydrodynamic slugs. Issa and Kempf (2003) found that two-fluid model can capture the interfacial instability numerically in the well-posed region. The studies of Issa (2009), Kadri et al. (2009), Ansari and Shokri (2011), Cazarez-Candia et al. (2011) and Simões et al. (2014) confirmed the validity of the slug capturing method. Therefore, it can be used for considering hydrodynamic slugging in a pipeline system.

On severe slugging researches, the mixture model is widely used, for example, Fabre et al. (1990), Sarica and Shoham (1991), Baliño et al. (2010), Malekzadeh et al. (2012). Other studies are based on the two-fluid model, like Taitel et al. (1989), Bendiksen et al. (1991), Taitel and Barnea (1998). The mixture model has the advantage of well-posedness for all flow conditions, but it is incapable of predicting hydrodynamic slugging. However, the effect of hydrodynamic slugging on severe slugging is definitely worthy to be addressed and investigated.

As it is known, the standard two-fluid model is not unconditionally well-posed. A system is said to be hyperbolic if the eigenvalues of the coefficient matrix are real and distinct. The hyperbolic system of equations is mathematically well-posed for an initial value

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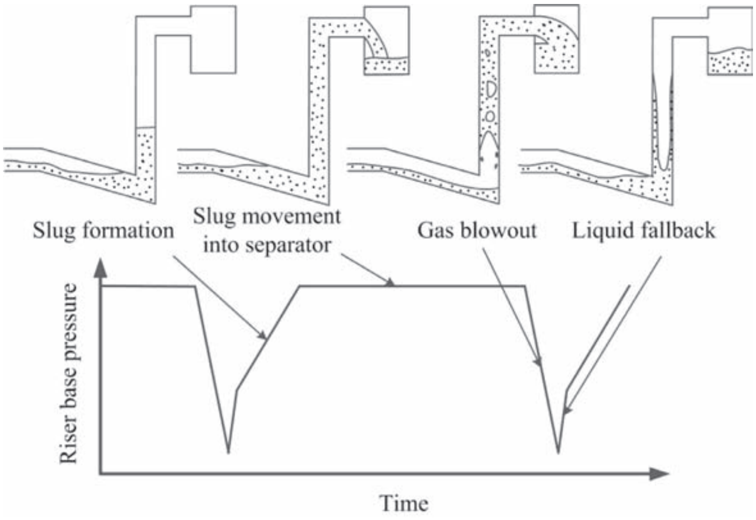

Fig. 1. Description of severe slugging.

Nomenclature

A	pipe cross-sectional area, m^2
C_V	critical wave velocity for the viscous Kelvin–Helmholtz analysis, m/s
C_{IV}	critical wave velocity for the viscous Kelvin–Helmholtz analysis, m/s
D	pipe diameter, m
D_g	gas phase hydraulic diameter, m
f	Fanning friction factor
f_s	slug frequency, Hz
g	gravitational acceleration, m/s^2
h_l	liquid film thickness, m
K	coefficient of Kelvin–Helmholtz analysis
l_s	slug length, m
l_f	liquid film length, m
p	pressure, Pa
Re	Reynolds number
S	wetted perimeter or interfacial contact length, m
t	time, s
T_s	severe slugging period, s
u_l	liquid velocity, m/s
u_g	gas velocity, m/s
u_{sl}	superficial liquid velocity, m/s
u_{sg}	superficial gas velocity, m/s
u_r	relative velocity between gas and liquid, m/s
U	gas or liquid velocity at the mesh cell, m/s
x	the spatial coordinate (distance from inlet), m
y	distance to the bottom of the pipe cross section, m

Greek

α	volume fraction
δ_c	coefficient of interfacial pressure model
Δp	pressure difference between bulk pressure and interfacial pressure, Pa
ΔP_r	riser base pressure difference, Pa
Δt	time step
Δx	mesh spacing
υ	kinetic viscosity, m^2/s
ρ	density, kg/m^3
θ	pipe inclination, rad
τ	shear stress, Pa

Subscripts

g	gas phase
i	interface
l	liquid phase
m	the gas and liquid mixture
w	wall

problem. From a physical point of view, if a model is hyperbolic, the amplification factors are finite for all wavelengths. Moreover, stability requires that the amplification factors must be non-positive for all wavelengths. To model the real flow, stability must be fulfilled for short wavelengths due to the dissipation and the surface tension effect. Numerous studies have been carried out on considering additional physical mechanisms to establish such a model (e.g., viscosity, virtual mass force, surface tension, diffusions and interfacial pressure difference). Holmas et al. (2008) and Issa and Montini (2010) considered that the numerical diffusion can make a system well-posed but the amount of diffusion is difficult to be determined. Building on the hydrostatic pressure effect, Bestion (1990) presented an interfacial pressure model to hyperbolize the two-fluid model. Chang and Liou (2007) indicated that the two-fluid model with interfacial pressure model is well-posed for a large range of flow conditions. Fullmer et al. (2014) showed that the system of equations with interfacial pressure model is unconditionally stable. By using the interfacial pressure and friction models, Ansari and Daramizadeh (2012) found that the interfacial instability can be captured correctly. Therefore, two-fluid model is expected to be capable of simulating hydrodynamic slugging and severe slugging in a pipeline–riser system.

The purpose of the present paper is as follows: When the two-fluid model is ill-posed, the interfacial pressure model is adopted to hyperbolize the system of equations. Severe slugging in a pipeline–riser system is simulated with and without hydrodynamic slugs in the well-posed region for the horizontal and the downward inclined pipes. The simulation results are evaluated through experimental data and the effect of hydrodynamic slugs on severe slugging is investigated numerically.

2. The model

2.1. Governing equations

Two-fluid model is formulated by treating each phase separately through two sets of conservation equations. The one-dimensional