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Slug initiation and evolution in two-phase horizontal flow

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Abstract

A series of two-phase air–water experiments was carried out in order to study the initiation and the subsequent evolution of hydrodynamic slugs in a horizontal pipeline. Experiments were carried out at atmospheric pressure, 4.0 bar(a) and 9.0 bar(a), and the effects of superficial liquid and gas velocities were investigated. The test section used for these experiments is 37 m in length, with an internal diameter of 0.078 m. To study the interfacial development, measurements of interfacial structures were made at 14 axial locations along the test section, with data acquired at a sampling frequency of 500 Hz. A large number of slugs were initiated within the first 3 m of the test section, with the frequency subsequently reducing towards the fully developed value before the end of the pipe. This reduction in frequency was strongly influenced by the magnitude of the gas and liquid velocities. The frequency of slugging was not strongly affected when the system pressure was changed from 1 atmosphere, to 4.0 and 9.0 bar(a), closely similar values being obtained at the 10 downstream locations. However, higher pressure delayed the onset of slug initiation, with "slug precursors" being formed further downstream as the pressure was increased. The statistical distributions of slug lengths and of the time intervals between slug arrivals were examined in detail and compared to several standard distributions. This showed that slug initiation may be reasonably approximated as an uncorrelated Poisson process with an exponential distribution of arrival times. However, once slugs have developed, there is strong correlation and the arrival time intervals, as well as the lengths, are best represented by the log-normal distribution.

Keywords: Slug initiation; Gas–liquid horizontal flow

1. Introduction

Slug flows can be classified into two main groups: hydrodynamic and terrain slugging. Hydrodynamic slugging is the normal slugging pattern encountered in straight flow lines. Terrain slugging results from liquid accumulation in local dips of flow lines with variable topography. In many experimental studies of hydrodynamic slugging, the entrance to the pipeline is arranged to give a stratified flow, in which the gas flows above the liquid in parallel streams, and slugs originate from waves at the gas–liquid interface that grow to fill the pipe cross-section. An accepted mechanism for this wave growth is the Kelvin–Helmholtz instability; where

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the interface is elevated, the local gas velocity increases so that the gas pressure reduces, and this suction tends to further elevate the interface, increasing the wave amplitude. The wave growth is opposed by gravity, and this gives rise to a criterion for instability, where the gas velocity is sufficient to overcome gravity. Surface tension also opposes wave growth, but acts on a length-scale that is too small to directly influence the formation of slugs.

Once formed, slugs initially grow in length, with their fronts traveling faster than their tails. It is possible for a slug to continue growing all the way along the pipe; this typically occurs for the first slug initiated in a stratified system, since the thickness of the liquid layer in front of it is high enough to sustain growth at the front. As the cycle of wave growth and slug initiation repeats, subsequent slugs can only pick-up the liquid shed by previous slugs, and may approach a constant length in which the front and tail velocities are equal. The tails of short slugs tend to move faster and this may lead to the slugs becoming shorter and ultimately degenerating into large amplitude waves. These residual waves can be overtaken and consumed by subsequent slugs (increasing their growth), so that the number of slugs tends to reduce in the downstream direction. This has been described by Hale et al. (2001) in terms of competition between slugs and survival of the "fittest" (i.e. largest) slugs. The formation, growth, and decay of slugs is thus highly complex, particularly in the entrance region.

Many authors have addressed the mechanisms of slug formation and established approximate criteria for the transition from stratified to slug flow. Other authors have established correlations of experimental data, or heuristic models for the frequency of slugs in "fully developed" flow. The frequency is related to the mean of the distribution of the time intervals between slugs, and other authors have reported details of this distribution, as well as the associated distribution of slug lengths, again for fully developed flow. However, very little is known of the characteristics of slugs in the region where they are initiated and developed. The purpose of the present paper is to report an experimental examination of the statistics of slugs in the initiation region, and the development of these statistics along a pipeline towards fully developed flow. Knowledge of the evolution of slug statistics along a pipeline is important for the assessment of slug initiation and evolution models, such as the slug capturing models (e.g. Issa and Kempf, 2003) and slug tracking models (e.g. Nydal and Banerjee, 1996).

The onset of the wavy flow regime in gas–liquid pipeline flows is often modeled using a form of the long-wave Kelvin–Helmholtz analysis. The classical Kelvin–Helmholtz instability occurs in stratified flow of two incompressible inviscid fluids, of different densities and velocities, in horizontal layers of infinite depth. The inviscid Kelvin–Helmholtz (IKH) analysis of stratified pipeline flow was first reported by Taitel and Dukler (1976). However a viscous Kelvin–Helmholtz (VKH) analysis, including the effects of wall and interfacial shear stress, generally gives better predictions for the onset of slug flow (Lin and Hanratty, 1986; Hall, 1992; Crowley et al., 1992; Barnea and Taitel, 1994a,b; Funada and Joseph, 2001). But if the viscosity difference between the two fluids is very large, this analysis has been found to fail (McCready, 1998). Several other wave generation theories have been proposed, such as those of Jeffreys (1924, 1925), Benjamin (1959), Lighthill (1962) and Belcher and Hunt (1993). The basis of these theories is the transfer of energy from the gas to the liquid across the perturbed surface, which is related to the pressure and shear stress distributions on the surface of a wave. These theories may predict wave growth at lower gas velocities than the Kelvin–Helmholtz approach.

Visual observations of wave growth and slug formation show that the slugs are formed from long waves, when they become large enough to bridge the pipe-cross-section (Taitel and Dukler, 1977; Kordyban, 1985; Lin and Hanratty, 1987; Andritsos and Hanratty, 1987; Woods and Hanratty, 1999). It may be significant that the surface of the long waves tends to be roughened by additional small amplitude short waves. Several models have been proposed for the frequency of slug initiation, one of the first being the model of Taitel and Dukler (1977). This model emphasizes the importance of the rebuilding of the liquid layer left behind by a newly formed slug as it accelerates away after the bridging event. Subsequent models (Woods and Hanratty, 1999; Hale, 2000) have adopted a similar concept of the development of the liquid level to determine the bridging frequency. The Taitel and Dukler (1977) and Hale (2000) models are based on the one-dimensional two-fluid model equations, while the model of Woods and Hanratty (1999) follows a stochastic approach.

Taitel and Dukler (1977) explained the initiation process as follows; long wavelength disturbances on a stratified layer develop into growing waves until eventually one of the waves grows to momentarily block