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Positive frictional pressure gradient in vertical gas-high viscosity oil slug flow

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ABSTRACT

The present study describes the wall shear stress and the falling liquid film behavior in upward vertical slug flow of air and high viscosity oil. The frictional pressure gradient is directly related to the wall shear stress, and it is usually negative (opposite to the overall flow direction). However, in vertical slug flow, the average total wall shear stress of a slug unit may be negative (in the same direction of the overall flow), resulting in a positive frictional pressure gradient. However, this does not mean, by any way, generation of additional energy or violation of the second law of thermodynamics.

The positive frictional pressure gradient phenomenon, reasons and required conditions were explained in this paper. A simplified model was developed and validated against recent experimental data of air-high viscosity oil slug flow in a 50.8 mm ID vertical pipe. The oil viscosity was in the range of 127 mPa s to 580 mPa s. Positive frictional pressure gradient appears when the liquid film wall shear stress supersede the wall shear stress in the slug body. The rate of increase of both wall shear stresses (with respect to the mixture Reynolds number) depend, not only, on the mixture Reynolds number but also, highly, on the liquid viscosity.

1. Introduction

In a real piping system the energy dissipated is owing to friction. This is the heat generated by the fluid as it flows through the pipes. The magnitude of this energy lost is definitely positive. For single-phase flow system the frictional pressure drop term is believed to be the only irreversible term generating this energy loss. Consequently, the idea of negative frictional pressure drop is considered to be unrealistic in single phase flow in pipes. However, in two-phase flow, frictional pressure gradient may be positive due to the possibility in some cases of having a negative wall shear stress. The positive pressure gradient values have been noticed in the results of many two-phase flow studies (as it will be explained in the next section) with different or no interpretations. Moreover, Orell and Rembrand (1986) assumed that the pressure within the Taylor bubble is constant. Thus, the pressure drop along the Taylor bubble section of the pipe is zero and then the frictional pressure drop due to the pipe wall shear stress over the entire slug unit is due only to the liquid slug. Therefore, the positive frictional pressure gradient case will never be observed according to Orell and Rembrand (1986) assumption.

1.1. The phenomenon of positive pressure gradient or negative pressure drop

The phenomenon of positive pressure gradient or negative frictional pressure drop was discussed experimentally and theoretically by Liu (2014). The results showed positive pressure gradient at low gas and liquid velocities. Liu used the conservation of mechanical energy for two-phase gas–liquid slug flow to show that even if the frictional pressure gradient is positive, the energy loss due to friction is still positive and the second law of thermodynamics is not violated. He claimed that the energy loss is associated with a buoyancy-like term in addition to the frictional pressure gradient in vertical two-phase flow, and by taking this buoyancy-like term into account (adding it to the frictional pressure drop), the pressure loss or friction loss will be greater than zero.

Fabre and Liné (1992) presented a modeling study on two-phase slug flow in vertical and horizontal pipes. When presenting the momentum equation for calculating the pressure gradient, Fabre and Liné reported that in vertical upward flow the frictional pressure gradient may be positive, as reported by Koeck (1980),

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Souhar (1982), and Fréchou (1986) experimental studies in vertical pipes. Fabre and Liné did not explain the reason for the positive frictional pressure gradient, but declared that although it is contrary to intuitive expectations, it does not violate the second law of thermodynamics. Sujumnong (1998) experimentally studied heat transfer, pressure gradient and void fraction in two-phase vertical flow. For air–water flow in 0.0117 m ID pipe, pressure gradient results showed positive frictional pressure gradient at low superficial gas and liquid velocities. Spedding et al. (1998) evaluated many available pressure gradient data and correlations for air–water vertical flow in a 0.026 m ID pipe. Results showed that calculation of the frictional pressure gradient using only liquid holdup data resulted in positive values in the slug, churn, and semi-annular flow patterns. They claimed that was physically unrealistic and resulted from ignoring the pocket of liquid rising in the wake of the Taylor bubble.

Spedding et al. (2000) studied flow pattern, liquid holdup, and pressure gradient for vertical and near vertical two-phase and three-phase upward flows in a 0.026 m ID pipe. For two-phase air–water flow, the results for both vertical and near vertical (86.5°) showed a positive frictional pressure gradient at low superficial liquid and gas velocities.

Raghunathan et al. (2003) theoretically derived two equations for predicting the total pressure gradient from the momentum and the energy balances for two-phase gas–liquid flow. They showed that the only difference between the pressure gradient calculations from the momentum and the energy balances is the two-phase density used in the gravitational pressure gradient term. In the derivation of the momentum balance, the two-phase density is the mixture density obtained using the liquid holdup, but in the derivation of the energy balance, the two-phase density is the no-slip density obtained using no-slip liquid holdup. It was shown that considering the above mentioned two ways of presenting the density of the two phases, both energy balance and momentum balance gave identical results.

Sakharov and Mokhov (2004) conducted experimental tests on vertical two-phase flow with high viscosity oils. They observed a positive frictional pressure gradient region at low superficial liquid velocity, and noticed that the region increased with the increase of liquid viscosity.

Liu et al. (2005) studied the two-phase gas–liquid flow in vertical capillaries using air as the gas phase and water, ethanol, or oil mixture as the liquid phase. Flow pattern, bubble rise velocity, liquid slug length, and pressure gradient were measured in the experiments. Pressure gradient results showed that at lower liquid flow rates, the frictional pressure gradient values were positive and for higher liquid flow rates, the frictional pressure gradient increased with liquid and gas velocities.

Akhiyarov et al. (2010) used oil viscosity of 120–510 mPa s and Tulsa City Natural gas to experimentally study the effect of high oil viscosity on two-phase flow behavior in vertical pipes. Total pressure gradient and average liquid holdup were measured in the experiments. The experimental results showed a positive frictional pressure gradient at low liquid velocities.

Tang et al. (2013) studied the effect of void fraction on pressure gradient in upward vertical two-phase flow. Results for air–water vertical upward flow in 0.0127 m ID pipe showed a positive pressure gradient for the lowest superficial liquid velocity, $V_{SL} = 0.08$ m/s, and range of superficial gas velocity from 0.35 to 2 m/s. However, for the same V_{SL} and for V_{SG} higher than 3 m/s the pressure gradient sign was switched. No explanation was made on the negative pressure drop values.

The phenomenon of negative pressure drop is reported in many public literatures in vertical gas–liquid flows with different explanations or with no explanations at all and worth to be investigated more. This phenomenon usually appears and reported for slug and churn flow in vertical pipes.

1.2. Wall shear stress measurements of the falling film flow

One of the oldest study mentioned about the negative wall shear stress is that of Hewitt and Hall Taylor (1970). They explained the effect of gravitational force in annular type flow as follows: the shear stress in the film decreases from the interface to the wall. Thus, when the gas velocity decreases, the interfacial shear stress also decreases resulting in a lower shear stress on the wall of the pipe. Additional reduction in the gas velocity, will eventually cause the wall shear stress to fall to zero. More reduction in the gas velocity below the zero wall shear stress point will result in a negative value of wall shear stress, or a downward movement of the liquid film adjacent to the wall.

Kashinsky et al. (2006) measured the wall shear stress in an upward slug flow in a vertical stainless steel tube with 20 mm-I.D. and 4.5-m length. Thin platinum plates of 0.07×0.9 mm separated by a thin dielectric film were used to measure the alternating wall shear stress and determine the time moments of the flow direction change. The distribution of instantaneous shear stress on a wall obtained via the treatment of currents recording from the doubled shear stress probe, was shown in this study. The behavior showed extensive pulsations of shear stress caused by passing a gas pocket (Taylor bubble) followed by a liquid slug. It was mentioned that when a gas pocket passes by, the shear stress value decreases drastically, then it becomes negative, and the flow near the wall is directed downward. The region of a negative shear corresponds to the downward flow of a liquid film, streamlining a gas pocket upward. It was also explained that at the beginning of a liquid slug (slug body) following a gas pocket, shear stress increases significantly because of breaking the near-wall liquid jet flowing from under a gas pocket. As a result, a circulation flow is formed, which significantly deforms the velocity profile along a liquid slug which is also mentioned in Kashinsky et al. (2004). Moreover, the averaged over ensemble values of wall shear stress of a slug for different slug lengths was shown. It is was shown clearly that shear stress decreases with a distance from a slug nose and can take negative values for large slug lengths. It was also indicated that an increase in the volumetric gas flow rate provides a rise of wall shear stress under the slug. For slugs with different lengths and gas flow rates, the character of wall shear stress alteration stays almost constant with a distance from the slug beginning.

Laborie and Cabassud (2005) measured shear stress for a slug flow inside a capillary using electrochemical method and found a negative wall shear stress near the bubble (gas slug) and positive shear stress near the liquid slug.

Zabaras et al. (1986) conducted experimental study in a 0.0508 m ID vertical pipe to investigate the upward concurrent gas–liquid annular flow. The fluids used are air and a solution of sodium hydroxide mixed with potassium ferricyanide and potassium ferrocyanide. The solution viscosity is 1.04 mPa s. The film flow was studied by measuring instantaneous local film thickness, wall shear stress, and pressure gradient. The wall shear stress was measured by diffusion-controlled electrolysis as described by Reiss and Hanratty (1962) with some modification to produce the direction of the shear stress in addition to the magnitude. Analysis of the obtained data revealed that at low gas flow rates the film motion is controlled by a switching mechanism, where the film changes direction and the measured instantaneous wall shear stress changes between positive and negative values. The pressure gradient results show that at low flow rates the gravitational pressure gradient is larger than the total pressure gradient, which indicates positive frictional pressure gradient.