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The Effect of Slightly Upward and Downward Inclined Pipes on the Stability of Gas-Oil Two-Phase Flow

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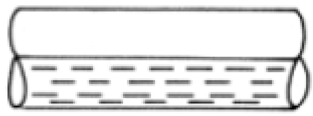
Pipeline inclination has an important effect on the stability of two-phase flow and flow assurance in the pipeline. This inclination may be intentional; it may be inevitable in pipeline installation; or it may be due to an error in pipeline installation. In this situation, even the slight inclination of the pipe plays an important role in the growth or elimination of the instability of the two-phase flow. In this study using a code designed for the analysis of pipelines' two-phase flow, the stability of the two-phase flow for Kerosene oil flow along with methane gas has been compared in downward inclined pipes, upward inclined pipes, and horizontal pipes. Using the mentioned computer code, it has been proved that the pipe's upward inclination results in the increase of two-phase flow instability, while the pipe's downward inclination is helpful in two-phase flow stability. In order to model two-phase flow in the pipe, two-fluid model has been used. This model considers each phase separately and the equations of mass conservation and momentum are written for each phase. The momentum exchange between the two phases and between each phase and the pipe wall has been considered. Conservation equations have been solved using SIMPLE algorithm in a numerical form with finite volume method.

Keywords: Pipes, Two-Phase Flow, Inclined Stability, Two-Fluid Model

INTRODUCTION

Two-phase flow is extensively used in petrochemical, gas, and oil industries (De Henau nd Raithby, 1995). Flow instability may occur in these industries and other engineering industries in which two phases of gas and liquid are flowing simultaneously (Dukler and Fabre, 1994). Different kinds of flow regimes can occur during the simultaneous movement of oil and gas (Lockhart and Martinelli, 1949). The simplest form to be imagined for gas-liquid two-phase flow in horizontal and slightly inclined pipes is that the liquid phase with higher density is placed at the bottom and the one with less density is placed at the top of the pipe and the intersection between these two phases is completely smooth. This flow pattern is known as the stratified smooth flow. There are special reasons which may change the intersection between the phases into a wavy intersection which is known as



Stratified Smooth Flow **(A**

Stratified Wavy Flow **(B**

Fig. 1: The Pipe's Stratified Flow

stratified wavy flow (figure 1) (Ansari, 1998). If the created waves become huge enough, they can vibrate the pipe which is not desirable. The creation of hydrodynamic instability and its growth may result in the occurrence of slug flow (Issa and Kempf, 2003).

If the created wave amplitude at the intersection of the two phases is reduced along the pipe length, the flow is stable; if, however, the created wave amplitude at the intersection of the two phases is increased when the wave moves along the pipe length, the flow is instable and it may result in the change of flow pattern to a slug flow (Woodburn and Issa, 1998; Ansari, 1998). The instability growth mechanism is Kelvin-Helmholtz (K-H) instability (Z Fan and Hanratty, 1993).

Even the slightest change in the pipe inclination from its horizontal position can significantly affect the growth or result in the elimination of these instabilities; this issue has been mentioned in many studies. Taitel, Shoham, Dvora Bernea, and Dukler (1980) studied water-air flow in pipes with upward inclination of 0.25, 0.5, 1, 2, 5, and 10 degrees and in pipes with downward inclination of 1, 2, 5, and 10 degrees. Andreussi and Persen (1987) studied water- air flow in pipes with 5 centimeter diameter and downward inclination of 0.65 and 2.1 degrees, while Kokal, Sranislav, and Nicholson (1986) studied this flow in pipes with upward inclination up to 9 degrees. Grolman, Commandeur, de Baat, and Fortuin (1996) studied water- air and tetradecane-air flows in pipes with 2.6 and 3.1 centimeter diameters in slight upward and downward inclinations. All these researchers have stated that the pipe's downward inclination results in faster elimination of the created instabilities in the stratified flow and helps in flow's stability; the pipe's upward inclination, on the other hand, results in faster growth of the instabilities and also faster conversion of the stratified flow regime to slug flow regime.

In the present study, the stability of two-phase flow of Kerosene oil- Methane gas in horizontal and slightly inclined pipes has been numerically studied and the effect of pipe's upward and downward inclination on flow stability has been demonstrated. There are different methods for modeling two-phase flow; considering the present issue, the proper model is selected (Bruce Stewart and Wendroff, 1984).

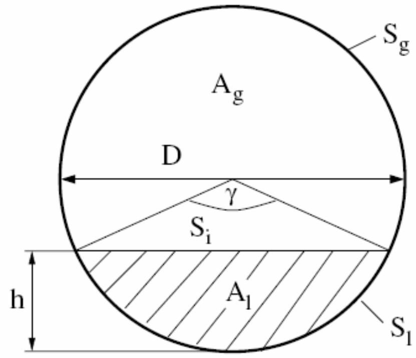


Fig. 1: The Intersection of the Pipe

The Two-Fluid Model

In the two-fluid model, the two-phase flow is divided into two single-phase areas with mobile boundaries. The two-fluid model is based on the separate formulation of mass conservation and momentum equations for each phase. The one-dimensional form of this model is obtained using the interfacial mean of the fluid's properties at the flow's cross-section. The momentum exchange between the pipe wall and each phase of the flow is formulated experimentally and appears as a source term in momentum equations (Issa and Kempf, 2003). The pipe's cross-section for calculations has been shown in figure 2.

In the two-phase flow, the proportion of the void fraction and the proportion of liquid hold-up are resulted from the division of the flow's cross-section of each phase in the pipe over the pipe's total-cross section as below:

$$\alpha_g = \frac{A_g}{A} \quad , \quad \alpha_l = \frac{A_l}{A} \tag{1}$$

Therefore, in each cross-section of the pipe, the result of summing the volumetric proportions of these two phases is equal to one:

$$\alpha_g + \alpha_l = 1 \tag{2}$$

Reynolds' numbers for each phase and for the common intersection of the two phases is defined as below:

$$Re_g = \frac{4A_g u_g \rho_g}{(S_g + S_i)\mu_g} \tag{3}$$

$$Re_i = \frac{4A_g |u_g - u_l| \rho_g}{(S_g + S_i)\mu_g} \tag{4}$$

$$Re_l = \frac{4A_l u_l \rho_l}{(S_l + S_i)\mu_l} \tag{5}$$

Reynolds numbers will be used in calculating the friction coefficient; in Reynolds numbers higher than 2100 the flow is turbulent and in lower Reynolds numbers is laminar.

Equations Governing the Flow

The present study has been based on the numerical solution of momentum and mass conservation equations for each phase separately in one-dimensional and isothermal flow. The equations in the one-dimensional flow will be as below:

$$\frac{\partial(\rho_g \alpha_g)}{\partial t} + \frac{\partial(\rho_g \alpha_g u_g)}{\partial x} = 0 \tag{6}$$

$$\frac{\partial(\rho_l \alpha_l)}{\partial t} + \frac{\partial(\rho_l \alpha_l u_l)}{\partial x} = 0 \quad (7)$$

$$\frac{\partial(\rho_g \alpha_g u_g)}{\partial t} + \frac{\partial(\rho_g \alpha_g {u_g}^2)}{\partial x} = -\alpha_g \frac{\partial P}{\partial x} + \rho_g \alpha_g g \sin\beta + F_{gw} + F_i \quad (8)$$

$$\frac{\partial(\rho_l \alpha_l u_l)}{\partial t} + \frac{\partial(\rho_l \alpha_l {u_l}^2)}{\partial x} = -\alpha_l \frac{\partial P}{\partial x} - \rho_l \alpha_l g \frac{\partial h}{\partial x} + F_{lw} - F_i \quad (9)$$

where the indices of g, l, and I refer to gas phase, liquid phase, and the intersection between these two phases, respectively. The X axis is horizontal axis. The pressure at the intersection of these two phases is considered as P in gas phase, while the pressure in liquid phase is considered as the sum of the intersection pressure and the hydrostatic pressure resultant from the liquid weight; the second term at the right of equation 9 is related to the hydrostatic pressure of the liquid in the pipe (D Barnea and Taitel, 1994).

The gravitational acceleration is g; the liquid phase's speed in the pipe is u_1; and the gas phase's speed in the pipe is u_g. β is the inclination angle of the pipe from the horizontal position. The terms of F refer to the friction forces on the fluid's volume unit, between each phase and the pipe's wall, and between the two phases. These forces inquire the closure model's equations.

The overall continuity equation is obtained from the sum of the two phases' continuity:

$$\frac{1}{\rho_g}\left(\frac{\partial(\rho_g \alpha_g)}{\partial t} + \frac{\partial(\rho_g \alpha_g u_g)}{\partial x}\right) + \frac{1}{\rho_l}\left(\frac{\partial(\rho_l \alpha_l)}{\partial t} + \frac{\partial(\rho_l \alpha_l u_l)}{\partial x}\right) = 0 \quad (10)$$

It must be noted that before summation of these two continuity equations, each must be divided over their own phase density in order to make both equations of the same degree; otherwise, it may be possible that the pressure correction equation becomes dominant with the terms related to the heavier fluid and cause some problems in convergence achievement. The pressure correction equation is obtained from the combination of the overall continuity equation with momentum equations of the two phases according to SIMPLE algorithm; since the flow is stratified and isothermal, the two phases are assumed as incompressible.

The Two-Phase Closure Model

The required closure relations in two-fluid model are the shear stresses between liquid phase and the pipe wall, between the gas phase and the pipe wall, and at the intersection between the two phases. The shear stress in one-dimensional flow is written as below:

$$\tau = \frac{1}{2} f \rho |u_r| u_r \quad (11)$$

The term u_r refers to the relative speed between the two phases or between each phase and the pipe wall. The liquid density is used when calculating the shear stress between the liquid phase and the wall and the gas density is used when calculating the shear stress between the gas phase and the wall and the shear stress between the two phases (D Barbea and Taitel, 1994).

The famous relation of Hagen-Poiseulle is used in order to calculate the friction coefficient between the gas phase and the pipe wall and also the friction coefficient of the two phases' intersection in the laminar flow:

$$f_g = \frac{16}{Re_g} \quad , \quad f_i = \frac{16}{Re_i} \tag{12}$$

And Dukler and Taitel (1976) equations are used in turbulent flow:

$$f_g = 0.046\left(Re_g\right)^{-0.2} \quad , \quad f_i = 0.046(Re_i)^{-0.2} \tag{13}$$

The friction coefficient between the liquid phase and the pipe wall is obtained via Hand (1991) equation which is as below for laminar flow:

$$f_l = \frac{24}{Re_l} \quad , \quad f_i = \frac{16}{Re_i} \tag{14}$$

And as below for turbulent flow:

$$f_l = 0.0262(\alpha_l Re_l)^{-0.139} \tag{15}$$

Numerical Solution

The conservation equations 6 to 9 are solved using the finite volume method. These equations have become discrete on a staggered grid in which the speeds are stored in locations between the pressure nodes. In figure 3, the configuration of the staggered grid has been demonstrated; the point P is the control volume center (whether in the continuity or in momentum equations) and the points E and W show the vicinity points, the indices of e and w refer to the control volume dimensions including P. Since the momentum equation only includes the displacement term, first order upwind approximation has been used for location derivations. Besides, Euler implicit approximation has also been used for time derivations.

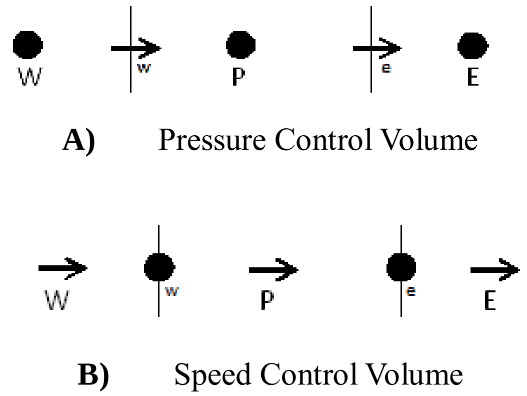


Fig 3: The Configuration of the Staggered Grid

The trial & error method has been used in solving the discrete equation system in each step until convergence achievement and the equations are solved as below:

- Liquid momentum equation from which the liquid speed is resulted;
- Gas momentum equation from which the gas speed is resulted;
- Pressure correction equation to obtain the pressure which is also used in correcting the speed of gas and liquid;
- Gas continuity equation from which the friction void is resulted;
- The proportion of liquid hold-up is calculated using equation 2.

The discrete form of each of the equations of continuity, momentum, and pressure correction includes a 3-diameter matrix which is solved using SIMPLE algorithm.

Boundary Conditions and the Initial Condition

The used boundary conditions in all the calculations is such that the flow rate of the two fluids is constant at the pipe's inlet and the pipe's outlet pressure in atmospheric standard value is considered constant.

At the time of t = 0, the two fluids flow with a monotonous speed and volumetric proportion without any turbulence at their intersection. In order to model wavy stratified flow, it is assumed that the created waves are sinuous waves at the intersection of the two phases; therefore, the slight turbulences enter the pipe inlet in the form of a continuant sinuous wave in the volumetric proportion of the two phases (figure 4). These turbulences enter the pipe by the two phases. If the flow is stable, the entered turbulence will be eliminated; otherwise, it will grow. The proportion of the created wave amplitude to the wave length is considered as 0.001 due to using a one-dimensional model and assurance of the authenticity of the results.

In order to keep the fluids' flow rate constant at the pipe inlet, it must be noted that the superficial velocity of the two phases which is defined as below, remain constant:

$$u_{sf_i} = \frac{u_i}{\alpha_i} \qquad (16)$$

The accuracy of the calculations have been confirmed by making the computational grid smaller until reaching to an answer which is of several independent computational grids. The computations have been performed such that the time step becomes smaller due to making the computational grid smaller in a way that the Courant number remains constant.

$$C_r = \left(\frac{\delta t}{\delta x}\right) u_g = 0.5 \qquad \left(u_g > u_l\right) \qquad (17)$$

Kelvin-Homholtz Analysis

In order to predict the change of the stratified flow regime in horizontal pipes, D Barnea and Taitel (1994) used K-H analysis and attributed the stability of the two-phase flow in the pipe to the relative velocity of the two phases. The analysis results of applying K-H linear turbulences to the equations of the two-fluid model (equations 6-9) by Barnea and Taitel are as below:

$$u_g < u_l + K\sqrt{\left(\rho_l\alpha_l + \rho_g\alpha_g\right)\frac{\rho_l - \rho_g}{\rho_l\rho_g}\, g\, \frac{A}{\frac{dA_1}{dh}}} \qquad (18)$$

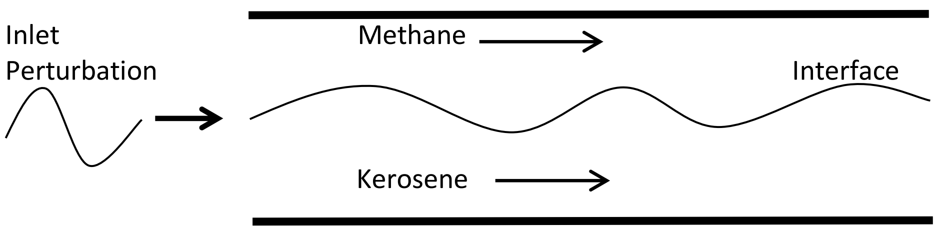


Fig. 4: The Entered Turbulence at the Intersection of the Two Fluids

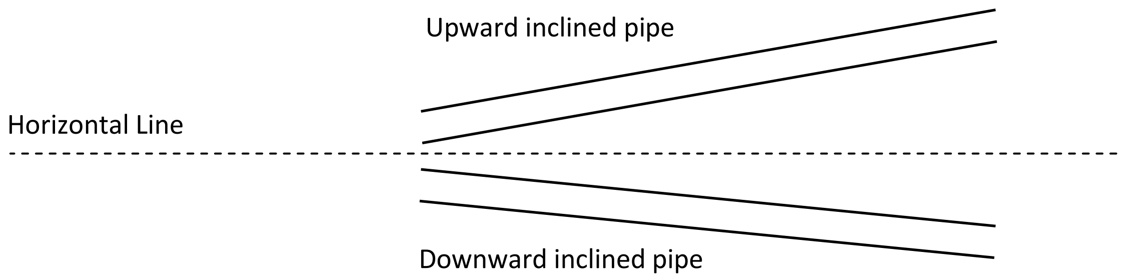


Fig. 5: The Entered Turbulence at the Intersection of the Two Fluids

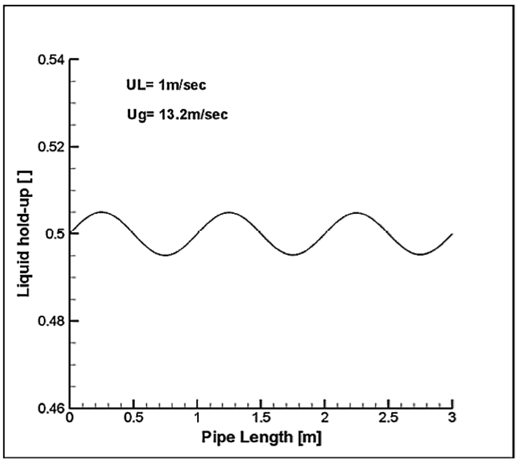


Fig. 6: The Created Wave in the Horizontal Pipe at the Intersection of the Two Phases at the Critical Speed of Methane

$$K = 1 - \frac{h}{D} \tag{19}$$

Equation 19 refers to the stability condition of gas-liquid stratified flow; it means that if the speed of the gas phase is less than the amount of the right side of equation 18, the flow is stable, while if the speed of the gas phase is equal to this amount, the flow is about to become instable; and if the speed of the gas phase is more than this amount, the flow will be instable (it must be noted that the speed of the gas phase is more than that of the liquid phase in the two-phase flow).

DISCUSSION

Here, the results of the numerical analysis of methane-oil two-phase flow in the horizontal and inclined pipes are presented. In figure 5, the upward and downward inclinations have been shown. The diameter of the pipe containing the flow has been considered as 0.2 meter in all computations.

At first, a situation is considered in which the pipe is in a horizontal position and a half of the pipe is filled with oil and the other half is filled with methane; i.e. the initial height of the oil in the pipe (h) is 0.1 meter and the speed of oil is considered as 1 m/s. According to figure 6,

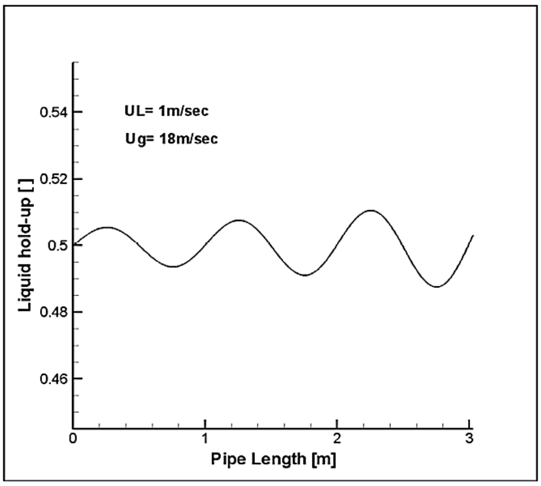


Fig. 7: The Wave Growth in the Horizontal Pipe at Methane's Speeds higher than the Critical Speed

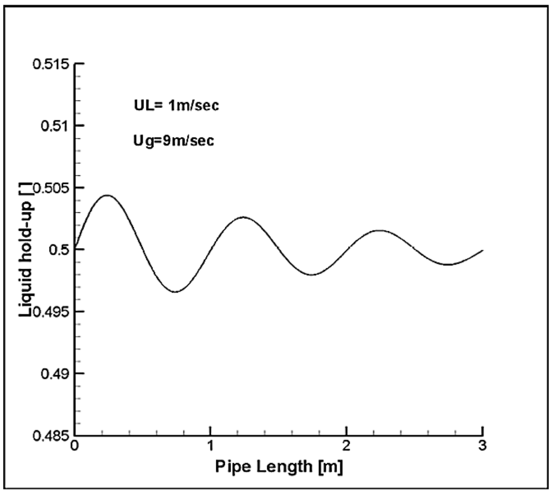


Fig. 8: The Wave Elimination in the Horizontal Pipe at Methane's Speed Less than the Critical Speed

it is observed that the created wave at the intersection between the two phases has not grown and has not been eliminated when the speed of methane is 13.2 m/s; it means that the flow is about to become instable and this speed of methane is methane's speed in making the flow in a pipe with the mentioned properties instable.

As can be seen in figure 7, when methane's speed is 15 m/s, the created wave amplitude at the intersection between the two phases has been increased while moving through the pipe length and the wave has grown. In this situation, it is stated that the two-phase flow is instable.

In figure 8, the speed of methane is 9 m/s (the speed less than the critical speed) and the wave amplitude has been decreased while moving through the pipe; it means that at the speeds less than the critical speed of methane, the flow is stable.

In all cases, the numerical method was independent of the number of

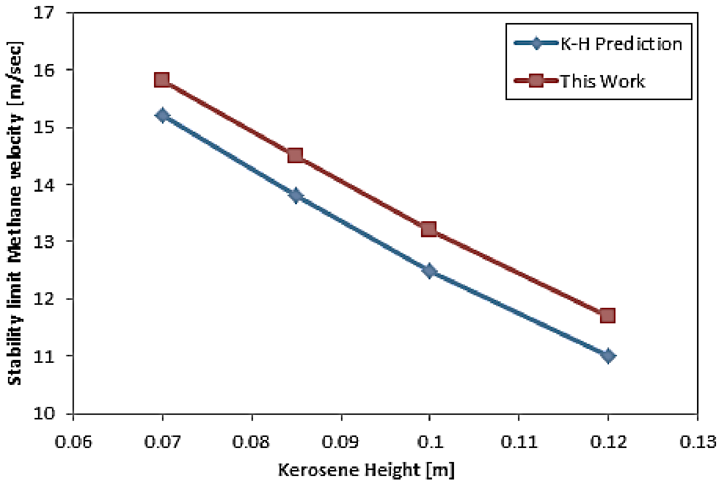


Fig. 9: The Effect of the Initial Height of Oil on the Critical Speed of Methane in Making the Flow in the Horizontal Pipe with Diameter of 0.2 Instable

computational grids and the results have been presented on the basis of 600 computational grids in the unit of length.

The critical speed of methane to make the flow instable highly depends on the initial height of oil in the pipe; the more the oil's initial height in the pipe, the less methane's speed is required to make the flow instable; on the other hand, the less the oil's initial height in the pipe, the more methane's speed is needed to make the flow instable. In figure 9, the critical speed of methane required to make the flow instable has been shown in terms of the initial height of oil. The results of the present work have been compared with the analysis results obtained by Barnea and Taitel in order to investigate the authenticity of the solutions. It is observed that the public behaviors of the solutions have been in harmony; the reason of the slight difference between the numerical and analytical solutions is that Barnea and Taitel has used the linear analysis theory of turbulences' stability to reach to equation 18, while the present work is based on the numerical solution of the nonlinear equations dominating the flow. Besides, Barnea and Taitel have experimentally presented k coefficient in equation 19 for fluids with low viscosity.

Figure 10 shows the diagram of oil volumetric proportion in terms of the pipe length in the oil speed which is 1 m/s and the methane's speed which is 13.2 m/s per the three downward inclinations of 2, 4, and 6 degrees (β= -2, -4, -6). It can be seen that in this state the amplitude of the created waves at the intersection between the two phases has been reduced while moving through the pipe and the increase of downward inclination has resulted in the decrease of the severity of the wave amplitude, while figure 6 has shown that the speed of 13.2 m/s is the critical speed of methane to make the flow in the horizontal pipe instable and at this speed the flowing methane in the horizontal pipe is about to become instable.

The results of the comparison of figures 6 and 10 showed that the downward inclination of the pipe results in the increase of flow's tendency to stability.

Figure 11 shows the diagram of oil's

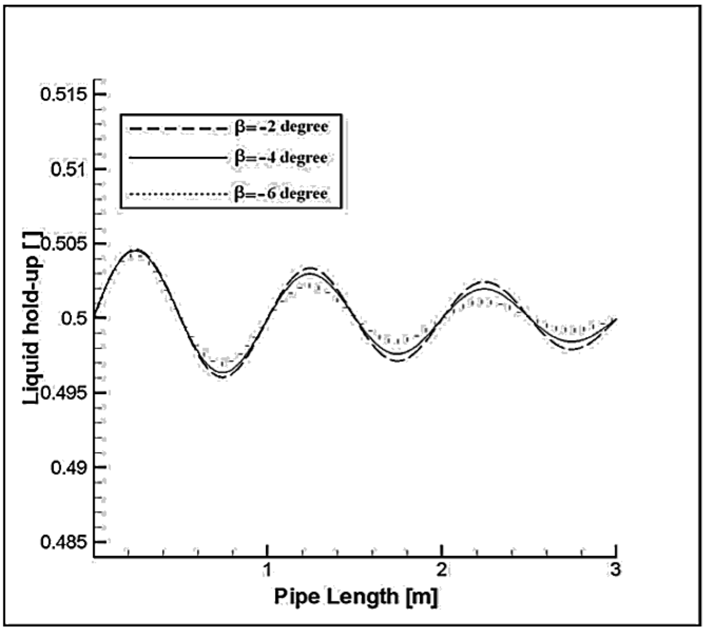


Fig. 10: The Effect of the Pipe's Downward Inclination on the Wave Amplitude's Reduction

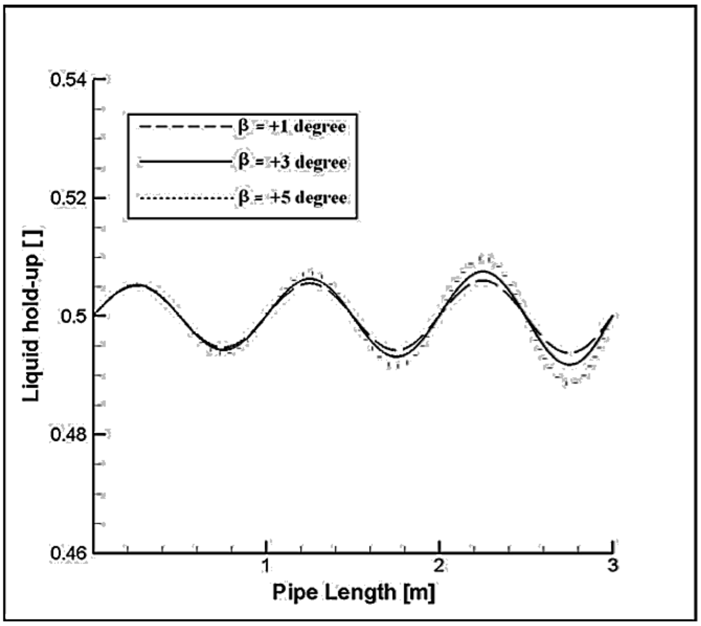


Fig. 11: The Effect of the Pipe's Upward Inclination over the Increase of Wave Amplitude

volumetric proportion in terms of the pipe length over the oil's speed which is 1 m/s and methane's speed which is 13.2 m/s per each three upward inclinations of 1, 3, and 5 degrees (β= +1, +3, +5). As was mentioned, the flow with these properties in the horizontal pipe is about to become instable; it is observed, however, that the upward inclination of the pipe from the horizon has resulted in the growth of waves and the flow is instable. Besides, the increase of inclination has resulted in the increase of waves' amplitude growth. Therefore, the pipe's upward inclination helps in making the flow instable; the more the upward inclination, the more the instabilities will be.

CONCLUSION

The growth of hydrodynamic instabilities in the pipe which has been modeled in the present article as sinuous waves depends on several factors such as the initial height of the liquid phase in the pipe and the pipe's inclination. The more the height of the liquid phase in the pipe, the less speeds of the gas phase will be able to make the flow instable. The upward inclination of the pipe results in the more growth of the instabilities, while the downward inclination helps in the flow's remaining stable. Consequently, when installing the pipeline, the possibility of the pipe's becoming upwardly inclined must be decreased to some extent and downward inclination must be applied in order to become sure of the stability of stratified two-phase flow, if possible. The numerical results of the present work are in harmony with the analysis results of Barnea and Taitel.

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