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RESEARCH PAPER

Hydraulic model of steady state multiphase flow in wellbore annuli

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Abstract: Based on the classification and flow behaviors of two phase flow in wellbore annuli, the hydraulic models for slug flow and annular flow in annuli for vertical or inclined wells were established, and the flow regime transition criteria were also obtained. Based on the flow behavior research of multiphase flow in wellbore annuli, the liquid film zone was used as the control volume, and the effect of the tubing liquid film, casing liquid film and the droplets in gas core area on the mass and momentum transfers were considered. The mass and momentum conservation equations of slug and annular flows were obtained. Then the evaluation criterion of flow pattern transitions were established, including dispersed flow to slug flow, bubble flow to slug flow and slug flow to annular flow. The model prediction results were compared under the experimental conditions from the previous literatures. The predictions of flow pattern, liquid holdup and pressure gradient were compared between the new model and the pipe flow model modified by using the hydraulic diameter. The results show that the flow pattern, liquid holdup and pressure gradient can be predicted by the new model more accurately, and the prediction of liquid holdup and pressure gradient are better.

Key words: wellbore annuli; multiphase flow; hydraulic model; steady state; tubing liquid film; casing liquid film

Introduction

There will be gas-liquid two phase flow in wellbore annulus in a variety of scenarios during drilling and production, such as gas kick during drilling, underbalanced drilling, and producing through annulus in flowing wells when the production is high. Methods commonly used in the study on two phase flow in wellbores can be divided into two classes: empirical model [1–3] and mechanical model [4–6]. The annular hydraulic models used in empirical models mostly are based on the pipe flow models modified by using the hydraulic diameter [7–14], with big error. In addition, this method ignores the geometric difference between the annulus and pipe, the influence of flow pattern on flow parameters, regards two phase flow as pseudo-single phase flow, or cannot be widely used restricted by experimental conditions. In comparison, considering the flow behavior and property of liquid, the annulus structure and fluid velocity, the mechanical model method establishes a fluid flow equation for each flow pattern separately. Since the 1970s, many researchers have studied the flow pattern transition model [15–18], but there are few models for the prediction of liquid holdup and pressure drop gradient. The tubing and casing liquid film, which changes the applied force on the cell body, and have a great impact on the flow regime transition, liquid holdup and pressure drop gradient prediction, must be considered in the research of the two phase flow in wellbore annulus. In this paper, based on the flow behavior of slug flow, the hydraulic models of slug flow and annular flow were established, and the transition criterion between various flow patterns is studied, taking into account the effect of tubing and casing liquid film, inclined angle and droplets in gas core area. Finally the prediction results are compared with the experimental data from previous literature [16].

1 Flow pattern classification of gas-liquid two phase flow in wellbore annulus

Similar to the pipe flow, the flow patterns of gas-liquid two phase flow in vertical wellbore annulus can be classified into 5 different patterns (Fig. 1): bubble flow, dispersed bubble

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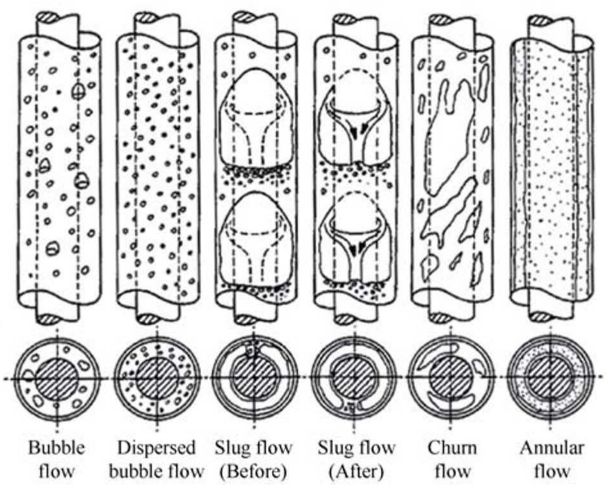

Fig. 1 Flow pattern distribution of gas-liquid two phase flow in an annulus [16]

flow, slug flow, churn flow and annular flow, of which slug flow and annular flow are very different from those in pipe flow.

There are two liquid films in slug flow in annulus, one tubing film, the other casing film. Furthermore, the Taylor bubbles are not axisymmetric any more and there is a high turbulent region behind the Taylor bubble according to the experimental observation of Caetano E F [16].

Annular flow in wellbore annulus occurs when the gas velocity is very high. The gas phase in gas core flows at very high velocity, which may contain liquid droplets. And there is a thin liquid film around the gas core. Due to the annulus structure, there are also two liquid films, the casing and tubing liquid films. The casing liquid film is normally thicker than the tubing liquid film.

2 Hydraulic model of slug flow in wellbore annulus

In 2003, Zhang H Q et al [6, 19] established a unified hydrodynamic model (Zhang Model) for the prediction of flow pattern transition, pressure gradient, and liquid holdup and slug characteristics in gas-liquid pipe flow based on the dynamics of slug flow. He found any other flow patterns could be transited from slug flow, when the liquid slug section did not exist, the slug flow would transit to annular flow; when the liquid film area didn't exist, the slug flow would transit to bubble or dispersed bubble flow.

In this paper, based on the slug flow dynamics, considering the effect of tubing liquid film, casing liquid film and droplets in gas core area on the mass and momentum transfer, the liquid film zone is used as the control unit and the hydraulic model of slug flow in wellbore annulus is established.

2.1 Mass conservation equation

As shown in Fig. 2, the entire casing and tubing liquid film zone of a slug unit is used as the control unit. There are liquid droplets in the Taylor bubble area. It is assumed the liquid

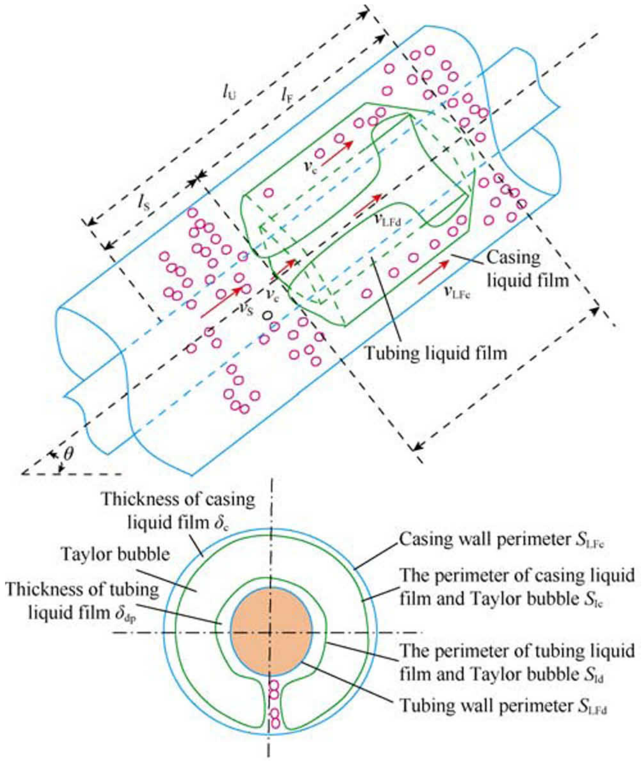

Fig. 2 Slug flow in wellbore annulus

droplet velocity is equal to the slug translational velocity and the liquid is incompressible.

For a stable slug flow, the input mass flow rate should equal to the output mass flow rate,

$$H_{LS}(v_T - v_S) = H_{LFc}(v_T - v_{LFc}) + H_{LFd}(v_T - v_{LFd}) + H_{Lc}(v_T - v_c) \quad (1)$$

For the gas phase, the input mass flow rate at the bottom boundary is equal to the output mass flow rate at the top boundary of the film zone, and can be written as:

$$(1 - H_{LS})(v_T - v_S) = (1 - H_{LFc} - H_{LFd} - H_{Lc}) \times (v_T - v_c) \quad (2)$$

The sum of Eqs.(1) and (2) gives,

$$v_S = H_{LFc}v_{LFc} + H_{LFd}v_{LFd} + (1 - H_{LFc} - H_{LFd})v_c \quad (3)$$

If it takes Taylor bubble Δt_{TB} to pass the cross section, the liquid volume change in the liquid film during Δt_{TB} is,

$$V_{LF} = v_{LFc}H_{LFc}A_c\Delta t_{TB} + v_{LFd}H_{LFd}A_c\Delta t_{TB} + v_cH_{Lc}A_c\Delta t_{TB} = (v_{LFc}H_{LFc} + v_{LFd}H_{LFd} + v_cH_{Lc})A_c\frac{l_F}{v_{TB}} \quad (4)$$

If it takes the liquid slug Δt_{LS} to pass the same cross section, the liquid volume change in the liquid film during Δt_{LS} is,

$$V_{LS} = v_SH_{LS}A_c\Delta t_{LS} = v_SH_{LS}A_c\frac{l_S}{v_{TB}} \quad (5)$$

The liquid volume change in the slug unit during Δt_{TB}+Δt_{LS} is,

$$V_{SU} = v_{SL}A_c(\Delta t_{TB} + \Delta t_{LS}) = v_{SL}A_c\frac{l_F + l_S}{v_{TB}} \quad (6)$$

According to the mass conservation law:

$$V_{SU} = V_{LF} + V_{LS} \quad (7)$$