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天然气储层裂隙中气-液两相流的流态转变条件数学模型

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摘 要:气-液两相在储层裂隙中流动时可能存在气泡流、段塞流、环雾流等流态,查明流动时流态转变条件能为气-液两相流流态形成机理研究提供依据,有助于天然气井的生产管控。根据气-液两相流不同流态的流动特点,结合连续介质控制理论和动量守恒原理,构建了气泡流-段塞流-环雾状流等流态之间转变的数学模型,确定了各流态间变化的临界条件和主控因素,通过气-液运移产出微观流动物理模拟试验验证了所建数学模型的准确性。结果表明:气-液两相在裂隙中的流态转变是气/液相的物理性质、注气通道孔径、裂隙流动通道孔径、气相流体流速、液相流体流速等因素耦合作用的结果。气泡流与段塞流能否转变主要取决于初生气泡大小、流动通道空间、液相界面波高度;段塞流与环雾流间能否转变取决于气相流体能否击碎液相流体并使之悬浮。不同流态间转变的主要控制因素不同:气泡流与段塞流相互转变的主控因素为裂隙系统的孔径,注气通道孔径越大、流动通道孔径越小,越容易发生段塞流;段塞流与环雾流相互转化的主控制因素为流体流速、气/液相流体的物理性质,气/液相对速度越大、气/液密度差越小、液相表面张力越小,越容易发生环雾流。研究成果能够为天然气储层裂隙中气-液两相流态形成机理和天然气运移产出研究提供理论依据。

关键词:储层裂隙;气-液两相流;流态转化;流体流速;气泡流;段塞流;环雾流

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Mathematical model for flow regime transition conditions of gas-liquid two-phase flow in natural gas reservoir fracture

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Abstract: The flow of gas-liquid two-phase flow in reservoir fractures may exhibit various flow regimes, such as bubble flow, slug flow, and annular mist flow. Identifying the conditions for the transition between these flow regime is essential for understanding the formation mechanism of gas-liquid flow and has significant implications for the production pipeline management of natural gas Wells. Based on the flow characteristics of different flow regimes of gas-liquid two-phase flow, combined with the theory of continuous medium control and the principle of momentum conservation, transformation mathematical models between flow regimes such as bubble flow, slug flow, and annular mist flow were established. The decisive conditions and key controlling variable that govern the transitions between various flow regimes have been precisely identified. Furthermore, the precision of the mathematical model was rigorously validated through microscopic physical simulation experiments focused on gas-liquid transportation. The results indicated that, the flow state transition of gas-liquid two-phase flow in fractures was the result of the coupling effect of factors such as the physical properties of the gas/liquid phase, the pore size of the gas injection channel, the pore size of the fracture flow channel, the gas phase fluid velocity, and the liquid phase fluid velocity. The transition between bubble flow and slug flow mainly depended on the size of the initial bubble, the flow channel space, and the height of the liquid phase interface wave. The transition between slug flow and annular mist flow depended on whether the gas phase fluid can

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break down the liquid phase fluid and suspend it. The main control factors for the transition between different flow states were different. The pore size of the fracture system was one of the most important factors in the mutual transformation of bubble flow and slug flow, when the injection channel aperture was larger and the flow channel aperture was smaller, it was more likely to form slug flow. The mutual transformation between slug flow and annular mist flow was primarily influenced by fluid velocity and the physical properties of gas/liquid phase fluids. A higher relative velocity between the gas-liquid phases, a smaller density difference between the phases, and a lower liquid surface tension all increase the likelihood of forming annular mist flow. These research findings established a theoretical foundation for understanding the mechanism of gas-liquid two-phase flow formation in reservoir fractures and natural gas transport production.

Key words: reservoir fracture; gas liquid two-phase flow; flow state transformation; fluid flow rate; bubble flow; slug flow; annular mist flow

0 引言

天然气是重要的清洁能源^[1-2],开采时常伴随有水的产出^[3-5]。气-液两相流动时,可能会出现气泡流、弹状流、层状流、波状流、段塞流、环雾流等流态^[6-8]。建立合理的气-液两相流的数学模型,有助于深化理解流态形成机理、优化排采工艺^[9]。国内外学者通过理论推导结合物理模拟试验的方法,对气-液两相流体的流态转化条件进行了研究。气-液两相流的物理模拟试验结果表明:当流动通道的直径大于25 mm时,气-液两相流体常以气泡流、弹状流、层状流、波状流、段塞流、环雾流等流态流动^[10-13];当流动通道的直径小于10 mm时,难以发生层状流和波状流^[14-15]。当流动通道中开始出现气泡时,称为气泡流。随着气泡数量的增多,小气泡逐渐汇聚形成气团,形状类似子弹,一些学者把这种流态称为弹状流^[16],这种气泡称为Taylor气泡。关于气泡流与弹状流之间转化的数学模型,比较经典的有Jones and Zuber模型^[17]、Taitel模型^[18]、Mishima-Ishii模型^[19]、Hibiki-Mishima模型^[20],这些数学模型的计算结果与物理模拟试验结果对比表明,误差率均较高^[21]。究其原因,主要是因为弹状气泡的形状和体积的影响因素众多,难以用数学的方法准确界定。气-液两相流体在流动过程中,受气-液流速和通道壁面摩擦力的影响,流动液面发生波动,形成了波状流、段塞流^[22]。部分学者进行了25 mm以上孔径通道内层状流、段塞流物理模拟试验,分析了液体的开尔文-亥姆霍兹不稳定波长^[23]、气-液摩擦力^[24]、壁面剪应力^[25]、液面高度等因素在段塞流形成过程中的变化规律,构建了层状流向段塞流转化的数学模型^[26-27]。当气-液相流体流速差异较大时,液相流体以液滴或液膜的形式被气相流体携带运移,形成环雾流^[28]。研究者分析了液膜的厚度^[29-30]、液滴的体积^[31-33]、气-液界面的剪切力^[34]等因素对环雾流形成的影响,构建了环雾流形成的临界模型^[35-36]。以上研究成果为气-液两

相流的流态划分、流动特性、流动规律的研究奠定了理论及方法基础,但上述研究成果均是建立在流动通道为25 mm以上的尺度,且多为两种流态间的相互转换,针对尺度为10 mm以下的储层裂隙通道内考虑注气通道影响的气-液两相流态连续转变条件的研究鲜有报道。

为了查明气-液两相在10 mm以下储层裂隙中流动时流态转化的条件及主控因素,笔者基于流体力学、湍流力学等理论,结合气-液两相在裂隙运移过程中气泡流、段塞流、环雾状流等流态的流动特点,考虑初始注气通道孔径对流态转化的影响,构建了气-液两相流体在裂隙中流动流态转变的数学模型,通过试验验证数学模型的准确性,并查明气-液相的物理性质、气-液相占比、注气通道孔径、裂隙流动通道孔径、气相流体流速、液相流体流速等因素对流态转变的影响,以期对不同流态形成机理研究提供理论依据。

1 气-液两相在裂隙中流动的主要流态

传统的流态划分方法主要有2种:①采用实验做出流型图,根据流型图分布特点划分流态;②依据流态转化关系式中的流动参数确定流态。随着气相、液相流量的变化,气-液两相在裂隙中流动的主要流态有气泡流、段塞流、环雾流等3种^[37]。

1)气泡流。所谓气泡流,指的是气、液两相在裂隙通道中流动时,液相流中“携带”有气泡流动的现象。随着气相流动速率的逐渐增加,气泡生成速率、初生尺寸越来越大,气泡开始发生聚并,气泡尺寸越来越大。一般认为:当气泡隔断液相流时,气泡流停止^[38]。其演化过程示意如图1a所示。

2)段塞流。所谓段塞流,指的是单个气泡的直径大于裂隙直径,气泡形成气塞,与裂隙通道内的液相形成气、液间隔的现象。随着气-液相相对流速(气相流速与液相流速的差值)的逐渐增加,两相流体中气塞初生尺寸、气泡聚并概率越来越大,气塞长

度与气塞频率逐渐增大,持气率逐渐增大,持液率逐渐减小。一般认为:当持液率减小至液滴最小尺寸分布且两相流体蕴含能量能够致使液滴悬浮时,段塞流停止^[39],其演化过程如图 1b 所示。

3)环雾流。所谓环雾流,指的是在裂隙通道内,气相将液相击碎成小液滴,且在曳力作用下小液滴

悬浮于裂隙通道内流动的现象。随着气相流速增大,液滴尺寸逐渐减小,并在裂隙通道内部的随机性增加,持液率逐渐下降;当气-液相相对流速增大至液相流速可忽略不计时,认为环雾流结束^[35],其演化过程如图 1c 所示。

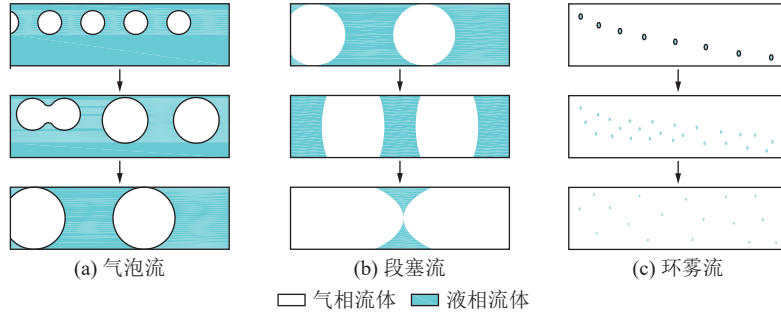


图 1 裂隙中气-液两相典型流态演化过程示意

Fig.1 Schematic diagram of typical flow patterns evolution of gas-liquid two phases flow in fissure

2 气-液两相在裂隙流动时流态转化的数学模型

2.1 基础方程

气-液两相在裂隙中的流动过程非常复杂,选取合适的控制方程来描述游离气-液界面处的受力情况及破碎、聚并行为十分关键。常用的多相流计算模型有 Eulerian-Eulerian 模型、Eulerian-Lagrangian 模型、Mixture 模型等^[40-42]。假设两相流体为气-液两相、互不相溶的混合流体;在流动过程中仅出现气泡流、段塞流、环雾流等流态,且单一类型压力被各相流体共享;介质连续性和动量平衡是分别对气-液相流体独立分析。基于上述假设,本文选用 Eulerian-Eulerian 模型,以连续介质控制方程(质量守恒方程)和动量平衡方程进行分析^[43]。

1)连续介质控制方程。

连续介质控制方程^[44]为

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i v_i) = \sum_{j=1}^n (m_{ji} - m_{ij}) + S_i \quad (1)$$

式中: α_i 为第 i 相的体积分数, %; ρ_i 为第 i 相的密度, kg/m^3 ; v_i 为第 i 相的绝对速度, m/s ; m_{ji} 为从 i 相到 j 相的质量传递, kg ; S_i 为第 i 相的源项。

基于上述假设,式(1)可简化为

$$\frac{\partial}{\partial t}(\alpha_i \rho_i) + \nabla \cdot (\alpha_i \rho_i v_i) = 0 \quad (2)$$

2)动量平衡方程。

动量平衡方程^[45]为

$$\frac{\partial}{\partial t}(\alpha_i \rho_i v_i) + \nabla \cdot (\alpha_i \rho_i v_i v_i) = -\alpha_i \nabla p - \nabla \cdot [\alpha_i \mu_i (\nabla v + \nabla v^T)] + \alpha_i \rho_i g + \vec{F}_{ij} \quad (3)$$

式中: p 为净压力, N ; F_{ij} 为体积力,是作用在流体上的曳力、升力、壁面润滑力、湍流耗散力、虚拟质量力共同作用的合力, N 。即:

$$\vec{F}_{ij} = \vec{F}_d + \vec{F}_l + \vec{F}_{wl} + \vec{F}_{td} + \vec{F}_{vm} \quad (4)$$

式中: \vec{F}_d 为曳力,是由气-液两相之间的相对运动引起的拖拽力, N ; \vec{F}_l 为升力,是由垂直与水平方向上气泡上下表面的压差引起的侧向力, N ; \vec{F}_{wl} 为壁面润滑力,是由壁面附近流体的滑移运动产生的滑动力, N ; \vec{F}_{td} 为湍流扩散力,是由两相流体的湍流运动对某相单一流体的牵引产生的牵引力, N ; \vec{F}_{vm} 为虚拟质量力,是由相对加速度变化而产生的力, N 。

2.2 气泡流发生临界状态数学模型构建

气泡流发生的临界条件为:①初始生成的气泡直径小于裂隙通道直径;②局部持气率小于 30%^[46]。

根据修正的 Tate 模型^[47],初始生成的气泡是直径为 D_c 的球形气泡。即 D_c 为

$$D_c = 1.06 \sqrt[3]{\frac{6D_0 \sigma}{(\rho_l - \rho_g)g}} v_r^{0.036} \quad (5)$$

$$v_r = v_l - v_g \quad (6)$$

式中: D_c 为初始初生气泡的直径, m ; D_0 为注气通道的直径, m ; σ 为液相的表面张力, N/m ; ρ_l 为液相密度, kg/m^3 ; ρ_g 为气相密度, kg/m^3 ; g 为重力加速度, m/s^2 ; v_r

为两相流体的相对速度, m/s; v_l 为液相的流速, m/s; v_g 为气相的流速, m/s。

根据气泡流发生的临界条件①可得:

$$D_f > 1.06 \sqrt[3]{\frac{6D_0\sigma}{(\rho_l - \rho_g)g}} v_r^{0.036} \quad (7)$$

式中: D_f 为裂隙通道的直径, m。

当气相流体相对流速上升时, 局部持气率上升。根据气泡流发生临界条件②可得:

$$\varphi = \frac{V_g}{V_g + V_l} = \frac{v_g}{v_g + v_l} < 30\% \quad (8)$$

式中: φ 为局部持气率, 无量纲; V_g 为局部气相体积, m^3 ; V_l 为局部液相体积, m^3 。

综上所述, 气泡流发生临界状态的数学模型为

$$\begin{cases} v_g > 0 \\ D_f > 1.06 \sqrt[3]{\frac{6D_0\sigma}{(\rho_l - \rho_g)g}} v_r^{0.036} \\ \varphi = \frac{V_g}{V_g + V_l} = \frac{v_g}{v_g + v_l} < 30\% \end{cases} \quad (9)$$

2.3 段塞流发生临界状态数学模型构建

根据段塞流的流动特点可知: 段塞流发生的临界条件为: ①初始生成气泡大于等于裂隙通道直径, 此时气相与液相形成气塞; ②液体在气体的剪切作用下产生界面波, 当界面波高度大于裂隙通道直径; ③液面并未被气体产生曳力击穿, 形成液滴悬浮, 此时两液面间形成液塞^[48]。

由段塞流发生临界状态①与式(5)可得:

$$D_f \leq D_c \quad (10)$$

根据 KH 不稳定效应和“最危险波”理论^[49] 结合段塞流发生临界状态②可得:

$$v_r > C \sqrt{(\rho_l - \rho_g)g \frac{D_f}{\rho_g}} \quad (11)$$

式中: C 为试验拟合常数, 取 0.487^[49]。

根据段塞流临界状态③可知当曳力小于液滴可悬浮力时面并未被气体击穿。气-液两相流动过程中, 气-液两相之间的相对运动引起的拖拽力称为曳力, 曳力的计算公式可表示^[50] 为:

$$F_D = \frac{1}{2} C_D \rho_g v_r^2 A_l \quad (12)$$

式中: F_D 为气相曳力, N; C_D 为曳力系数, 数值与雷诺数有关; A_l 为液滴空间投影面积, m^2 。

C_D 的表达式为

$$\begin{aligned} C_D = & 8 \times 10^{-6} [(Re/6530)^2 + \tanh(Re) - \\ & 8 \ln(Re)/\ln(10)] - 0.4119 e^{-2.08 \times 10^{13}/(Re+Re^2)} - \\ & 2.1344 e^{-[(\ln(Re^2+10.7563)/\ln(10))^2 + 9.9867]/Re} + \\ & 0.1357 e^{-[(Re/1620)^2 + 10.370]/Re} - \\ & 8.5 \times 10^{-3} \{2 \ln[\tanh(\tanh(Re))]/\ln(10) - \\ & 2825.7162\}/Re + 2.4795 \end{aligned} \quad (13)$$

$$Re = \frac{\rho_l D_f v_l}{\mu_l} \quad (14)$$

式中: Re 为雷诺数, 无量纲; μ_l 为液体黏度, $mPa \cdot s$ 。

液滴可悬浮力可表示为

$$F_s = gV(\rho_l - \rho_g) \quad (15)$$

式中: F_s 为液滴可悬浮力, N; V 为液滴的体积, m^3 。

根据韦伯数可知^[51]:

$$We = \frac{v_g^2 \rho_g d}{\sigma} \quad (16)$$

式中: d 为液滴直径, m。

液滴最大直径由韦伯数决定, 对于气流中液滴来说, 临界韦伯数处于 20 ~ 30^[52]。HINZE^[53] 指出, 当韦伯数超过临界值以后, 液滴就会破碎。因此本文取韦伯数为 30。则有

$$d = \frac{30\sigma}{v_g^2 \rho_g} \quad (17)$$

$$\frac{V}{A_w} = \frac{\frac{4}{3}\pi d^3}{\pi d^2} = \frac{4}{3}d = \frac{40\sigma}{v_g^2 \rho_g} \quad (18)$$

因此段塞流临界状态③可表示为

$$\frac{1}{2} C_D \rho_g v_r^2 < \frac{40\sigma g}{v_g^2 \rho_g} (\rho_l - \rho_g) \quad (19)$$

综上所述, 段塞流发生临界状态的数学模型由式(10)、式(11)、式(19)构成。

2.4 环雾流发生临界状态数学模型构建

环雾流发生的临界状态为: 理想状态下为气、液相混合(以气相为主)在裂隙通道内同时流动, 由于流速、流量的差异致使液滴能够通过气相曳力悬浮^[48], 则有:

$$F_D = \frac{1}{2} C_D \rho_g v_r^2 A_w \geq gV(\rho_l - \rho_g) \quad (20)$$

综上所述, 环雾流发生临界状态的数学模型为

$$\frac{1}{2} C_D \rho_g v_r^2 \geq \frac{40\sigma g}{v_g^2 \rho_g} (\rho_l - \rho_g) \quad (21)$$

3 数学模型试验验证

3.1 试验设备

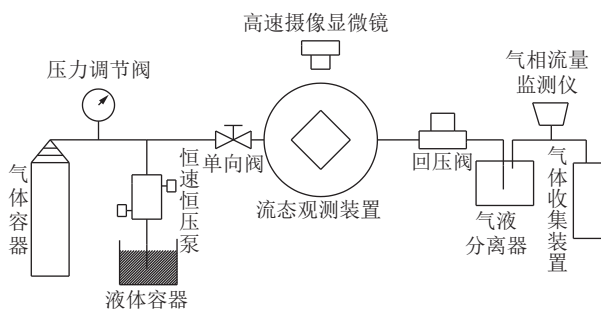
本次采用气-液运移产出微观流动模拟试验装置, 进行了不同孔径注气通道、不同孔径气-液流动

通道以及不同气-液相流速条件下的气-液两相流态转化试验,以验证数学模型的准确性。该装置包括气-液注入装置、流态观测装置、流体回收装置等,如图 2 所示。

试验时将模拟裂隙模型板置入流态观测装置内,通过气-液注入装置将气体和液体以恒压(0~30 MPa)或恒流(0~5 L/min)模式注入流态观测装置,使用高速摄像显微镜对裂隙内的两相流流态进行观测并通过计算机记录试验数据,两相流体通过流态观测装置流出后经气液分离器后分别进行回收。



(a) 实验装置实物



(b) 实验装置连接示意

图 2 实验装置

Fig.2 Diagram of experimental device

3.2 试验方案与步骤

本次试验模拟裂隙模型板采用内置模拟裂隙的高透有机玻璃制成(图 3),内置裂隙直径分别为 0.001, 0.002, 0.003, 0.004, 0.005, 0.006 m, 试验流体采用氮气与活性水, 试验基础参数见表 1。

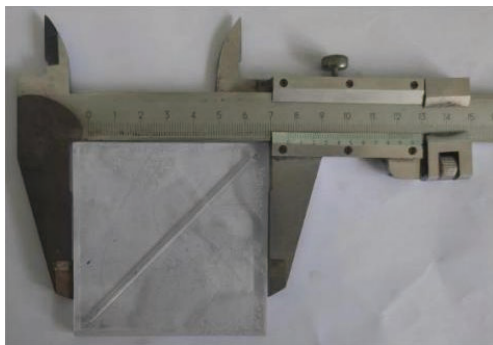


图 3 模拟裂隙模型板

Fig.3 Simulated crack model plate

表 1 试验基础参数

Table 1 Experimental basic parameters

| 类型 | 材料 | 密度/(kg·m ⁻³) | 黏度/(mPa·s) | 表面张力/(N·m ⁻¹) |
|------|-----|--------------------------|------------|---------------------------|
| 气相流体 | 氮气 | 1.25 | 0.016 | — |
| 液相流体 | 活性水 | 1 000 | 1.010 | 0.06 |

为探究气、液相流速、注气通道孔径、流动通道孔径等因素对气液两相流的流态产生的影响,以验证本文所建立数学模型的准确性,分别进行了不同孔径注气通道、流动通道、两相相对流速试验与不同两相流体流速试验,具体试验参数见表 2。试验测试步骤如图 4 所示。

表 2 不同孔径注气通道、流动通道、两相相对流速试验方案

Table 2 Experimental schemes for different pore size gas injection channels, flow channels, and two-phase relative flow rates

| 编号 | 注气通道直径/m | 流动通道直径/m | 流速/(m·s ⁻¹) | | |
|----|----------|--------------|-------------------------|--------|----------------|
| | | | 气相流体 | 液相流体 | 气-液相 |
| 1 | 0.001 | 0.002、0.003、 | — | — | — |
| 2 | 0.002 | 0.004、0.005、 | — | — | 0.001、0.005、 |
| 3 | 0.003 | 0.006 | — | — | 0.01、0.04、0.08 |
| 4 | 0.001 | 0.006 | 0.05~53 | 0.1~16 | — |

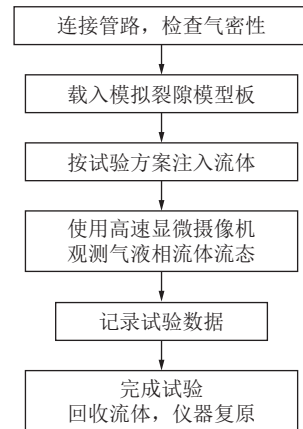


图 4 试验测试步骤流程

Fig.4 Experimental testing procedure flowchart

3.3 试验结果

每次试验结束后,将所记录的流态结果与各流体流速数据进行对照,并制成试验结果流型图,如图 5、图 6 所示。

图 5 为相同的气-液相相对流速(液相流速大于气相流速)、相同孔径气-液相流动通道、不同孔径注气通道条件下的试验流型图。由图 5 可以看出,随着气-液相相对流速的增大、流动通道孔径的减小,

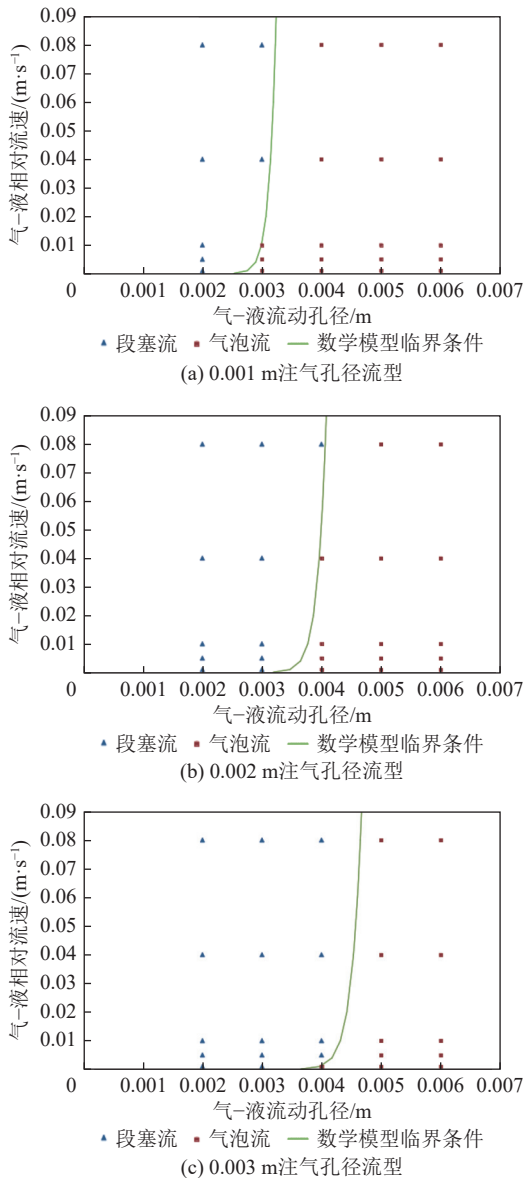


图5 不同孔径注气通道、两相相对流速

Fig.5 Gas injection channels with different apertures and relative flow rates of two phases

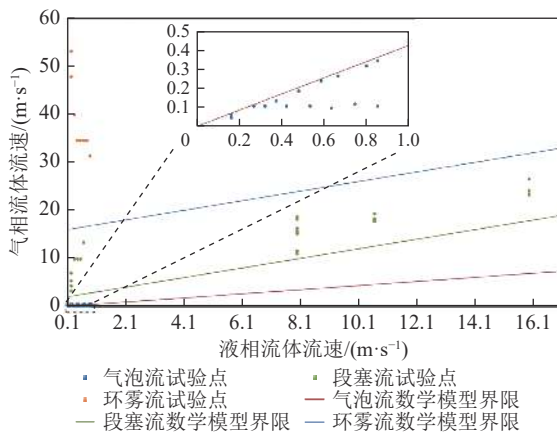


图6 不同两相流体流速

Fig.6 Experimental results of flow rates of different two-phase fluids

气-液两相流动流型逐渐由段塞流转变为气泡流。这是由于受初生气泡直径大小的制约,当初生气泡直径大于流动通道孔径时,在流动通道内无法形成气泡流,从而直接形成段塞流,此规律符合前文气泡流发生临界条件①与段塞流发生临界条件①,试验结果与数学模型计算临界条件相符,验证了所建立的数学模型的准确性。

图6为0.006 m孔径气-液流动通道、0.001 m孔径注气通道、不同气相流速、不同液相流速条件下的试验流型图。从试验结果可以看出,在相同孔径的注气通道与流动通道条件下,随着气-液相流速的增大,两相流体在流动通道内流动流型逐渐由气泡流转变为段塞流再转变为环雾流。产生这种现象的原因为当液相流体流速不变时,随着气相流体的流速的增大,气相流体所产生的曳力逐渐增大,致使液相流体波动,当液相流体受曳力剪切作用而被拉高超过流动通道直径时形成独立完整气-液界面,从而形成段塞流;随着气相流体流速继续增大,气相流体将液相流体击碎成小液滴并使之悬浮,从而形成环雾流。此流动规律与前文气泡流发生临界条件②、段塞流发生临界条件②以及环雾流发生临界条件相符,实验结果均符合前文建立的数学模型所计算的临界条件,验证了数学模型的准确性。

4 讨 论

基于气-液两相流体在裂隙中流动流态转化条件数学模型,分析气/液相的物理性质、气相流体流速、液相流体流速、注气通道孔径、裂隙流动通道孔径对气-液两相流体流动流态的影响。

4.1 流速与裂隙孔径耦合效应影响

气-液两相流体在裂隙中流动流态随着气-液相流体相对流速、裂隙通道孔径等因素的变化过程为:由气泡流逐渐变为段塞流,再转化为环雾流,当气-液相流体相对流速增加速度较快时,可由气泡流之间转化为环雾流。为探究气相流体流速、液相流体流速、注气通道孔径、裂隙通道孔径等各影响因素耦合作用下对气-液两相流体流动流态的影响,以气体密度为 1.25 kg/m^3 ,液体密度为 $1\ 000 \text{ kg/m}^3$,液相表面张力为 0.06 N/m 为基础条件,结合气泡流发生临界条件①与段塞流发生临界条件①,得出气/液相相对速度界限-注气通道管孔径-气-液流动通道孔径流型,如图7所示,结合段塞流发生临界条件②与环雾流发生临界条件,得出气相流度-液相流度-流动通道孔径流型,如图8所示。

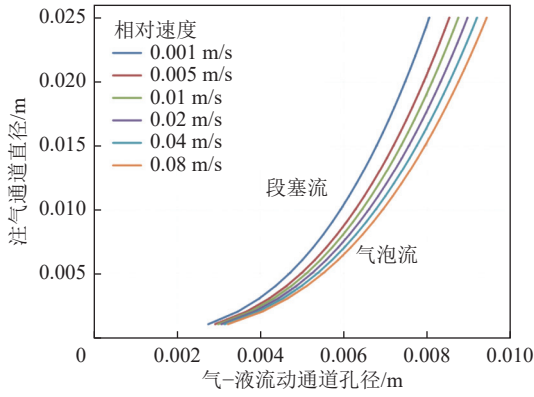


图 7 流态转化相对速度-注气通道管孔径-气-液流动通道孔径流型

Fig.7 Relative velocity of flow transformation - gas injection channel tube aperture - gas-liquid flow channel aperture flow pattern chart

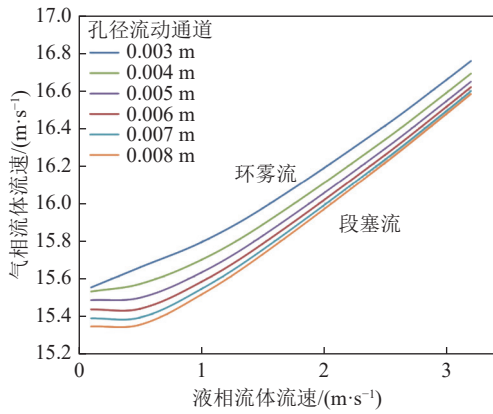


图 8 气相流度-液相流度-流动通道孔径流型

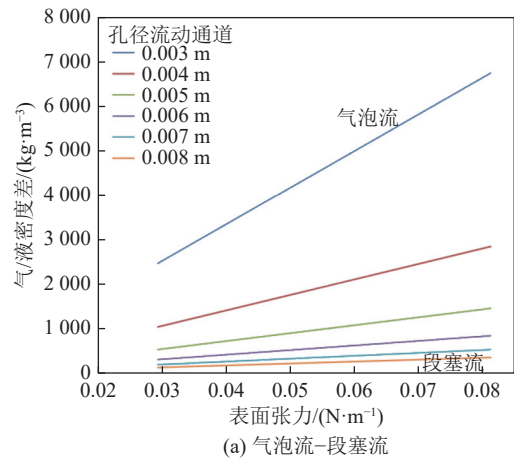
Fig.8 Gas phase fluidity - liquid phase fluidity - flow channel aperture flow pattern chart

图 7 中各相对速度界限为对应孔径注气通道下产生初始气泡的直径,从图中可知当以此为流态转化判别条件时,注气通道孔径、气-液流动通道孔径、气-液两相流体相对流速等因素对气泡流与段塞流之间相互转化的条件有较大影响。气泡流向段塞流转化的相对流速界限随注气通道孔径的增大而减小,随气-液流动通道孔径而增大,当气-液两相流体相对流速一定时,气泡流向段塞流转化通道界限呈幂指数正相关关系。

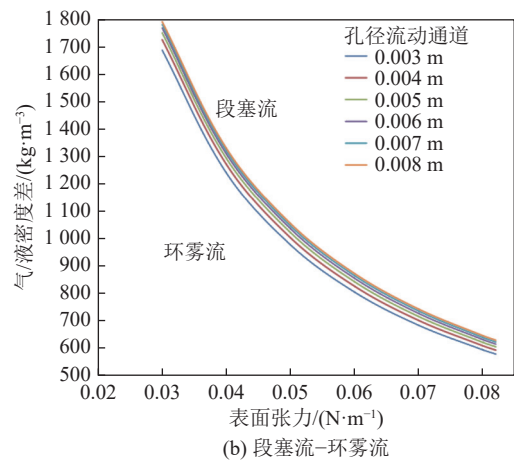
从图 8 可以看出:在气-液两相流体流动过程中,由段塞流向环雾流转化的临界条件的主要影响因素有:气相流体流速、液相流体流速与气-液两相流动通道孔径。当流动通道孔径一定时,由段塞流向环雾流转化的气相流体流速、液相流体流速临界条件呈正相关关系;当液相流体流速不变时,由段塞流向环雾流转化的气相流体流速与流动通道孔径临界条件呈负相关关系。

4.2 流体物理性质与裂隙孔径耦合效应影响

为探究气/液相物理性质与流动通道孔径相互作用下对气-液两相流体流动流态的影响,分别以气/液相相对流速为 0.01 m/s、注气通道为 0.005 m 与气相流体流速为 15 m/s、液相流体流度为 1 m/s,气相流体密度为 1.25 kg/m^3 为基础条件,结合前文 3 种流态发生临界状态数学模型,得出气/液密度差-流动通道孔径-液相表面张力流型图版,如图 9 所示。



(a) 气泡流-段塞流



(b) 段塞流-环雾流

图 9 气/液密度差-流动通道孔径-液相表面张力流型

Fig.9 Gas/liquid density difference - flow channel aperture - liquid phase surface tension flow pattern chart

从图 9 可知当气/液相对流速恒定时,气泡初生直径随着液相流体表面张力、气/液相流体密度差的增大而增大,因此由气泡流向段塞流转化的流动通道孔径临界值与液相流体表面张力、气/液相流体密度差呈正相关关系,且流动通道孔径对于气泡流与段塞流间的转化起主要控制作用;当处于段塞流与环雾流相互转化阶段,由段塞流相环雾流转化的流动通道孔径临界值与液相流体表面张力、气/液相流体密度差呈负相关关系,较低的流体表面张力与气/液相流体密度差的情况下,液相流体更容易被击碎

为小液滴悬浮,从而形成环雾流,在段塞流与环雾流相互转化阶段,液相流体表面张力与气/液相流体密度差对于流态间的转化器主要控制作用。

5 结 论

1)根据气-液两相在裂隙中流动流态特点,结合流体力学、湍流力学等理论建立了气-液两相流流态转化临界状态数学模型,并通过室内物理模拟试验验证了本模型的准确性。

2)气-液两相流体在裂隙通道中的流态转化是/液相的物理性质、注气通道孔径、裂隙流动通道孔径、气相流体流速、液相流体流速等因素耦合作用的结果。

3)不同的流态间转化的主要控制因素不同,气泡流与段塞流间的相互转化主要控制因素为裂隙系统的孔径,段塞流与环雾流间的相互转化主要控制因素为流体流速与两相流体物理性质。

4)裂隙中气泡流与段塞流相互转化过程中,注气通道孔径越大、流动通道孔径越小、相对速度越小、气/液密度差越小、液相表面张力越大,越容易发生段塞流;段塞流与环雾流相互转化过程中,流动通道孔径越小、气/液相对速度越大、气/液密度差越小、液相表面张力越小,越容易发生环雾流。

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