Splitting Dynamics of Liquid Slugs at a T-Junction

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Abstract

Understanding the mechanisms of liquid movement through fracture intersections is important for prediction of fluid flow and solute transport in unsaturated fractured media. Here we present a quasi-static model to predict the dynamic splitting behavior of liquid slugs at a T-junction, as a simplified representation of a fracture intersection and consisting of a main channel and a branch channel. The proposed model is validated against carefully controlled visualization experiments. We find that there exists a critical initial slug length at which the splitting behavior shifts from flow dominated by the main channel to that dominated by the branch. The influence of key parameters, including the inclination angle of the junction, the channel widths, and the dynamic contact angles, on the splitting dynamics is systematically investigated. We show that the splitting ratio depends non-monotonically on the relative width of the branch channel to the main channel. Furthermore, it is demonstrated that the dynamic contact angles have a profound impact on the splitting ratios and meniscus velocities. It is shown that taking velocity-dependent contact angle into account is essential to predict the meniscus velocities and the dynamic flow process.

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Key points

- A quasi-static model for dynamic splitting of liquid slugs at a T-junction is proposed and validated against experiments
- A critical initial slug length is identified that separate two splitting regimes
- Dynamic contact angles strongly impact meniscus velocities and splitting dynamics
Abstract

Understanding the mechanisms of liquid movement through fracture intersections is important for prediction of fluid flow and solute transport in unsaturated fractured media. Here we present a quasi-static model to predict the dynamic splitting behavior of liquid slugs at a T-junction, as a simplified representation of a fracture intersection and consisting of a main channel and a branch channel. The proposed model is validated against carefully controlled visualization experiments. We find that there exists a critical initial slug length at which the splitting behavior shifts from flow dominated by the main channel to that dominated by the branch. The influence of key parameters, including the inclination angle of the junction, the channel widths, and the dynamic contact angles, on the splitting dynamics is systematically investigated. We show that the splitting ratio depends non-monotonically on the relative width of the branch channel to the main channel. Furthermore, it is demonstrated that the dynamic contact angles have a profound impact on the splitting ratios and meniscus velocities. It is shown that taking velocity-dependent contact angle into account is essential to predict the meniscus velocities and the dynamic flow process.

1 Introduction

Water infiltration through fractured rock vadose zone has received extensive attention owing to its great influence on the application of hydrological cycle, contaminant treatment, geothermal energy production, and radioactive waste disposal (e.g., Berkowitz, 2002; Liu et al., 2003; Salve et al., 2008; Dobson et al., 2012; Essaid et al., 2015; Tsang et al., 2015). Field evidences show that focused, rapid and deep infiltration along preferential pathways within fracture networks commonly occur (e.g., Dahan et al., 1999; Nimmo, 2012). However, owing to the random fracture aperture distribution and complex network structure, the preferential
pathways of water infiltration show a significant spatial and temporal variability, making understanding and accurately predicting the complex behaviors of unsaturated flow a great challenge (e.g., Davidson et al., 1998; Nativ et al., 1995). In the past two decades, detailed investigations have been conducted to identify the fundamental processes of unsaturated flow and transport in fracture networks (e.g., Christensen et al., 2015; Glass et al., 2002, 2003; Huang et al. 2005b). These studies have pointed to the critical role played by the fracture intersections in controlling unsaturated flow in fracture networks.

A number of experimental, theoretical, and numerical studies have investigated the fluid dynamics at fracture intersections of different structural types, such as X-, Y- and T-shaped intersection (e.g., Dragila & Weisbrod, 2004; Huang et al., 2005a; Kordilla et al., 2017; Wood et al., 2005). It has been well demonstrated by experiments that intersections can act as capillary barriers which cause local accumulation of the wetting fluid (Wood et al., 2002). The strength of this barrier effect depends on the combined influence of fracture apertures, intersection geometry, and wetting properties (e.g., Dragila & Weisbrod, 2004; Ji et al., 2006). Once the hydrostatic pressure of the accumulated fluid exceeds the capillary barrier, the liquid will quickly discharge and then the liquid pooling will be reestablished. The cycles of accumulation and discharge not only affect the size and frequency of the infiltrating liquid locally (Wood et al., 2005), but also cause flow pulsation in a fracture network (Glass et al., 2002). During liquid discharging and passing a bifurcating intersection, flow path selection and volume partitioning occur, which lead to flow pathway shifts and structural evolution in the networks (Glass & LaViolette, 2004). To better understand the liquid partitioning process, visualization experiments (Kordilla et al., 2017; Yang et al., 2019) have been performed to examine the fluid splitting behavior under different flow modes, from discrete droplet flows to continuous rivulets. The
splitting process has been shown to exhibit significant dynamic characteristics in the meniscus velocities and the liquid branch lengths (Yang et al., 2019). The splitting dynamics is again influenced by multiple factors, including flow rate, intersection geometry, and hysteretic contact angles (e.g., Noffz et al., 2019; Kordilla et al., 2017). However, most previous experiments have not been designed to have carefully controlled conditions of the above influencing factors to allow for validation of mechanistic models of dynamic splitting at bifurcating junctions. Detailed mechanisms of the dynamic splitting process at fracture intersections remain not fully understood.

Wetting fluid flow through unsaturated fractures and fracture intersections involves a complex key process, the motion of liquid–air contact lines. It is well understood that the apparent contact angle is not only influenced by the surface properties (e.g., Bonn et al., 2009; Hirasaki, 1991; Snoeijer & Andreotti 2013) but also the contact line velocities (both direction and magnitude), giving rise to capillarity hysteresis and dynamic contact angles (e.g., Hoffman, 1975; Petrov et al., 2003; Lei et al., 2018). To predict the relationship between dynamic contact angle and contact line velocity, theoretical frameworks have been proposed, including hydrodynamic models (e.g., Cox, 1986; Huh & Scriven, 1971; Voinov, 1976), molecular-kinetic models (Blake & Haynes, 1969), and combined molecular-hydrodynamic models (e.g., Brochard-Wyart & Gennes, 1992; Petrov & Petrov, 1992). Introducing the hydrodynamic theories in flow models has been shown to improve the prediction of wetting droplet flow velocity in a single vertical fracture (e.g., Bico & Quéré, 2001; Dragila & Weisbrod, 2003; Or & Ghezzehei, 2006) over the prediction based on static contact angles. However, the effect of velocity-dependent contact angles on the wetting liquid partitioning behavior at an intersection has not been explored.
A fracture intersection necessarily involves a non-horizontal fracture. This means the wetting liquid flow through a fracture intersection or junction is controlled by the complex interplay between gravity, capillary and viscous forces (Wood et al., 2005). For liquid drops/slugs in a fracture before entering an intersection, when the vertical length of droplets/liquid slugs is larger than the capillary length ($l_c = (\sigma/\Delta\rho g)^{1/2}$, where $\sigma$ is the interfacial tension, $\Delta\rho$ is the density difference, and $g$ is the gravitational constant), gravity or buoyancy becomes important in the droplet flow dynamics. This comparison can be quantified by the dimensionless Bond number, $Bo = \Delta\rho g (L \sin \alpha)^2/\sigma$, where $L$ is the length of the droplet/liquid slug, $\alpha$ is the inclination angle of the fracture containing the droplet/slug. Simple static force balance analysis has been adopted in previous studies to qualitatively explain the flow accumulation and release behavior (e.g., Glass et al., 2002; Wood et al., 2005; Ji et al., 2006). However, the static force balance analysis is unable to describe the splitting dynamics, since the forces vary with time during fluid splitting. Controlling mechanisms of gravity-driven wetting liquid flow at an intersection remains to be elucidated. A comprehensive and quantitative description of dynamic fluid splitting at an intersection is still lacking.

Here we perform carefully controlled experiments of dynamic splitting of liquid slugs at a T-junction as a key representative process for wetting fluids passing a fracture intersection. We propose a quasi-static theory to describe the liquid splitting process at the T-junction. We develop a semi-analytical solution approach to predict the dynamic splitting behavior which is quantified through the evolution of liquid branch lengths, meniscus velocities, and splitting volume ratios. A critical initial slug length is identified that separates the splitting behavior into two types of flow regimes. The key parameters affecting the splitting process are systematically
investigated, including the initial liquid slug length, channel widths, inclination angle of the junction, and the dynamic contact angle.

2 Methods

2.1. Theory and models

We consider a two-dimensional system of flow through a junction, a reasonable simplification for the water infiltration in fractured rocks where localized channel flows usually exist (Su et al., 2004). We present quantitative descriptions of liquid slug motion and splitting at a T-junction. The interplay between gravity, velocity dependent capillary forces, and size of the slug during splitting is detailed. We highlight the important role of capillary hysteresis and dynamic contact angles in the splitting dynamics.

2.1.1 Dynamic contact angles and liquid slug motion within a straight channel

Consider a liquid slug of length $L$ in a single idealized channel (see Figure 1a). The droplet motion is controlled by the capillary, gravity and viscous forces. The slug’s weight acts as a driving force to pull the droplet downward, while the capillary force difference between advancing and receding menisci acts to resist motion. For a stationary liquid slug, the force balance is written as: $L \sin \alpha = \psi_a - \psi_r$, where $\alpha$ is the inclination angle of the channel relative to the horizontal plane, $\psi_a$ and $\psi_r$ are the capillary pressures (in units of hydraulic head) of the advancing and receding menisci, respectively. Ignoring the minor principal curvature, we calculate $\psi_a$ and $\psi_r$ by using the Young–Laplace equation,

\begin{align}
\psi_a &= -2\sigma \cos \theta_a / \rho g w, \quad (1a) \\
\psi_r &= -2\sigma \cos \theta_r / \rho g w, \quad (1b)
\end{align}

where \( \theta_a \) and \( \theta_r \) are the advancing and receding contact angle, respectively, \( \sigma \) is the interfacial tension, \( w \) is the channel width, \( \rho \) is the liquid density, \( g \) is the gravity acceleration. Assuming the contact angles satisfy the relationship: 
\[
\cos \theta_s = \frac{\cos \theta_a + \cos \theta_r}{2} 
\]
(e.g., Andrieu et al., 1994; Decker & Garoff, 1996), where \( \theta_s \) is the static contact angle which can be measured directly. By putting Eq. (1) into the force balance equation, one can obtain the relationship between advancing and receding contact angles and the length of the stationary slug, given a static contact angle.

The receding contact angle decreases with increasing slug length, whereas the advancing contact angle increases. For water–air interfaces the critical contact angles \( \theta^*_a \) and \( \theta^*_r \) exist (e.g., Or & Ghezzehei, 2007; Su et al., 2004). When the advancing contact angle is greater than \( \theta^*_a \) or the receding contact angles less than \( \theta^*_r \), the interface will slip, resulting in slug migration within the channel. Here we define a threshold length \( L^* \) for triggering slug movement as:

\[
L^* = \frac{2\sigma(\cos \theta^*_a - \cos \theta^*_r)}{\rho gw \sin \alpha}. \tag{2}
\]

When the liquid length \( L \) is larger than the threshold length \( L^* \), the slug maintains a steady velocity \( u \), under the balance of capillary, gravity and viscous forces (e.g., Or & Ghezzehei, 2007; Su et al., 2004):

\[
u = \frac{\rho gw^2}{12 \mu} \left[ \sin \alpha - \frac{2\sigma(\cos \theta^*_a - \cos \theta^*_r)}{L \rho gw} \right], \tag{3}
\]

where \( \mu \) is the dynamic viscosity. When the slug is in motion, the values of advancing and receding contact angles vary with the interfacial velocity. Here we adopt the hydrodynamic model for a liquid–air system proposed by Voinov (1976). This model (see Figure 1b) provides a simple scaling relationship between the contact angle and the capillary number \( Ca \).
\[ \theta_s = \theta_s^{\text{static}} + \xi_1 \text{Ca}, \]  
\[ \theta_r = \theta_r^{\text{static}} - \xi_2 \text{Ca}, \]

where \( \text{Ca} = \mu u / \sigma \), \( \xi_1 \) and \( \xi_2 \) are the shape parameters which can be obtained by fitting equation (4) to experimentally measured data of interfacial velocities, and advancing and receding contact angles.

In an idealized channel, the gravity can be eventually balanced by capillary and viscous forces. Given the droplets length and other known parameters, the unknowns, the velocity \( u \) and the dynamic contact angles \( \theta_a \) and \( \theta_r \), can be obtained from equations (3) and (4) by an iterative solution.

Figure 1. Schematic diagram of droplet flow in channels. (a) An idealized channel for droplet migration. (b) A velocity-dependent dynamic contact angle model. (c) An idealized T-
junction model for liquid slug splitting. (d) Flow in channel C1. (e) Flow in channel C2.

2.1.2 Quasi-static model of liquid slug splitting at a T-junction

Unlike the steady motion of a liquid slug in a single channel, the liquid slug splitting behavior at a T-junction is an unsteady process, involving transient slug lengths and interfacial velocities, as well as the associated velocity-dependent contact angles. Previous work (Yang et al., 2019) suggests that when the width of the branch channel is larger than that of the main channel, no splitting occurs and the wetting fluid bypasses the branch channel, which is a scenario same as that in a straight channel. Therefore, we focus on a geometry where the branch channel width is smaller than that of main channel. It is possible for the liquid slug to be completely diverted into the branch channel (e.g., when the inclination angle is small); we consider this scenario as a special case of splitting with a cumulative splitting ratio (as quantified later in Section 3.1) of 1. Here, we propose a quasi-static model to describe liquid slug splitting at a T-junction. We assume that the motion of menisci during the splitting is completed in discrete steps of a small time interval $\Delta t$, within which a force balance of the deformed (due to the bifurcation) liquid slug is maintained (Figure 1c). It is further assumed that during splitting, the flow velocities within the two individual channels C1 and C2, and the dynamic contact angles can be solved using the solution approach above for equations (3-4).

To describe the liquid motion, we denote the liquid length within channel C1 by $L^{C1}(t)$, the length within the lower part of C1 by $L^{C1,d}(t)$, and the length within channel C2 by $L^{C2}(t)$, see Figures 1c-1e. At the initial time ($t=0$), the liquid is assumed to have just established interface menisci within the C2 and the lower part of C1, $L^{C1}(0) = L$, $L^{C1,d}(0) = w_2/2$, $L^{C2}(0) = w_1/2$, where $w_1$ and $w_2$ are the channel width of C1 and C2, respectively. The splitting ends when the liquid completely passes the T-junction, $L^{C1,d}(t) = L^{C1}(t)$, i.e., no liquid is left above the junction. In an
Within channel C2, the fluid motion is driven by the pressure gradient and gravity. The interface velocity \( u_{C2}^a(t) \) can be expressed by

\[
  u_{C2}^a(t) = \frac{\rho g w_2^2}{12 \mu} \left( \frac{P_w - \Psi_{C2}^a(t)}{L_{C2}^a} + \cos \alpha \right),
\]

where \( \Psi_{C2}^a(t) \) is the capillary pressure in channel C2; \( P_w \) is the fluid pressure (in unit of hydraulic head) at the junction, which is related to the capillary force \( \Psi_{C1}^a(t) \) and the liquid length \( L_{C1,d}^a \) as \( P_w(t) = \Psi_{C1}^a(t) - L_{C1,d}^a(t) \sin \alpha \). The liquid length \( L_{C2}^a(t) \) and \( L_{C1,d}^a(t) \) can be respectively calculated as

\[
  L_{C2}^a(t) = L_{C2}^a(t-\Delta t) + u_{C2}^a \Delta t \quad \text{and} \quad L_{C1,d}^a(t) = L_{C1,d}^a(t-\Delta t) + u_{C1} \Delta t.
\]

Fluid mass conservation provides a closure to the nonlinearly coupled equations to enable a solution. The supplied flow rate at the junction, \( u_{C1}^r w_1 \), is equal to the sum of the flow into channel C2 and the lower part of channel C1. The advancing interface velocity, \( u_{C1}^a \), can be expressed as

\[
  u_{C1}^a(t) = u_{C1}^r - u_{C2}^a w_2 / w_1.
\]

There are six unknowns: \( u_{C1}^r, u_{C1}^a, u_{C2}^a, \theta_{C1}^r, \theta_{C1}^a, \) and \( \theta_{C2}^a \), and six equations: three equations (5-7) and three Voinov equations linking the dynamic contact angles and velocities, i.e., it is a determined system. However, a nested iterative solution strategy is required to solve the system. Here we describe a relatively simple procedure to achieve at a satisfactory solution (Supporting Information Figure S1). At each time step, we first obtain initial guesses of \( u_{C1}^r, u_{C1}^a, \theta_{C1}^r \) and \( \theta_{C2}^a \).
using equations (4-5). Then, $u_{C1}^a$ and $\theta_{C1}^a$ are computed within an internal
iteration scheme to satisfy equations (4, 6) with a pre-set tolerance of 0.1°. Next, we recalculate $u$
according to Eq. (7) and $\theta_{C1}^a$ according to equation (4). Then we check convergence with respect
to $\theta_{C1}^a$: if there is no convergence, we update $\theta_{C1}^a$ and $u_{C1}^a$ and then redo the above steps of the time
step. Upon convergence, we update the slug lengths, obtain the new meniscus locations, and
continue the next time step. The procedure ends when the splitting is finished.

2.2. Laboratory experiment

To test the quasi-static model described above, an experimental setup for liquid breakup at a
T-junction is designed, as shown in Figure 2. The T-junction flow cell consists of three thick (3.0
mm), smooth fused-quartz plates with the polished surface and sharp edges. The quartz plates are
aligned with controlled channel widths and then attached to a piece of acrylic plate by four
spacers (3 mm thick) with UV curing glue. The acrylic plate is then fixed to a support system
which is capable of allowing the T-junction to adjust its inclination angle $\alpha$. The junction divides
channel C1 and C2 into three parts, each being 7 cm in length. The channel widths are carefully
controlled by feeler gauges. The accuracy of channel widths is double-checked with an optic
microscope after the junction assemblage. We set the channel widths $w_1 = 0.83$ mm and $w_2 = 0.33$
mm to ensure the occurrence of liquid splitting and to encourage competition between capillary
force and gravity.

At the top of the main channel C1, dyed water (0.075g capsicum red per liter of pure water)
is injected using a metal capillary tube which is connected to a syringe pump (Harvard Apparatus
703007, 0.25% injection accuracy) through soft silicon tubing. As soon as the injected water
flows out of the capillary tube, the water spans the channel width and forms a liquid slug. We
control the injection volume to acquire liquid slugs of various initial lengths.
Figure 2. The flow visualization system. (a) Experimental apparatus. (b) The front view of the schematic diagram of the T-junction. The upper inset denotes the enlarged view of injection boundary. The lower inset denotes the detailed image of slug splitting behavior at T-junction. (c) The cross-sectional view (A–A’).

Uniform and stable static contact angle is a key to ensure the experimental repeatability. Before each experiment, we clean the T-junction cell through plasma cleaning and subsequent repeated cycles of vacuum drying and ultrapure water immersion (Yang et al., 2019). We find that the static contact angle of the channel surface eventually reaches a stable state at 49.2°±3.5° (Supporting Information Figure S2). Besides, we also measure the dynamic contact angles and find that with increasing interface velocity from 0.2 cm/s to 1.5 cm/s, the receding contact angle decreases from about 30° to 25° and the advancing contact angle increases from about 75° to 90° (Supporting Information Figure S3). These data allow us to obtain the shape parameters in equation (4).
Three different inclination angles ($\alpha = 90^\circ, 70^\circ, 50^\circ$) are controlled in the experiments to investigate the influence of gravity on slug splitting behavior. In each case, we also accurately control the injected volumes ($V = 25, 30, 35, 40, 45, 50 \mu\text{L}$) and the corresponding initial slug lengths ($L = 1.05, 1.25, 1.45, 1.65, 1.85, 2.05 \text{ cm}$). The experimental processes are recorded by a camera at a frequency of 5 frames/s. Experiments for each slug length and each inclination angle are repeated 5 times. The Bond number ($\text{Bo} = \Delta \rho g L^2 / \sigma$) ranges between 15 and 58.

3 Results

In this section, experimental results are presented together with the results from the quasi-static model described in section 2.1. The comparison between experiments and model also serves as a validation of the theory. Then, using the model, we systematically investigate the impact of slug length $L$, channel width ratio $w_2/w_1$, inclination angle $\alpha$, and dynamics contact angles $\theta_i$ and $\theta_a$ on the splitting behavior.

3.1. Characteristic behaviors of liquid splitting at the T-junction

3.1.1 Splitting characteristics

When the liquid front arrives at the junction, splitting occurs under the influence of capillary force in channel C2, resulting in part of water invading channel C2 and the rest entering the lower part of channel C1. After completely passing the T-junction, the liquid slug is divided into two daughter slugs. We experimentally find that the initial slug length $L$ has a strong influence on the volume ratio of the daughter slugs. When $L = 1.25 \text{ cm}$, most liquid enters C2 (Figures 3a-3d). When $L = 1.65 \text{ cm}$, most water prefers to enter the lower part of C1 (Figures 4a-4d). According to the volume ratio of the two daughter slugs, the splitting behavior can be generally divided into two typical patterns: (1) type I for small $L$, flow dominated by channel C2; (2) type II large $L$, flow dominated by channel C1.
The detailed evolution of liquid lengths and interface velocities for the case of initial length $L = 1.25$ cm is shown in Figure 3e, f. We reproduce the experiments by the quasi-static model. The basic parameters used in the model are $w_1=0.83$ mm, $w_2=0.33$ mm, $\sigma = 0.072$ N/m, $\rho = 1000$ kg/m$^3$, $g = 9.8$ N/kg, $\mu =1\times10^{-3}$ Pa·s, $\theta_s = 50^\circ$, $\xi_1 = 12000$, $\xi_2 = 500$, $L^* = 7$ mm. As can be seen, the modeling results of liquid lengths well match the experimental observations in terms of the overall trends. The maximum deviation of slug lengths from experiments for $L = 1.25$ cm is about 0.2 cm, which is an acceptable error. For $L = 1.05$ cm, the maximum deviation is comparable.

The modeling results also show that velocities $u_{C1}^a$, $u_{C1}^r$ and $u_{C2}^a$ all rapidly decline due to fluid partitioning into the side branch. The ratio between $u_{C2}^a$ and $u_{C1}^r$ continuously increases from 1.25 at $t = 0$ to 2.52 (which equals to $w_1/w_2$) at $t = 1.36$s, indicating that the capillary force of channel C2 dominates the splitting process. According to the evolution of the velocity $u_{C1}^a$, the splitting process can be divided into two stages. During the first stage, the fluid arriving at the junction flows through both exits with velocities $u_{C1}^a$ and $u_{C2}^a$, since the flow rate in channel C2 is less than the supplied flow rate above the junction, $u_{C1}^aw_1 > u_{C2}^aw_2$. The separation between the first and the second stage is marked by the velocity $u_{C1}^a = 0$. In the second stage, the liquid no longer enters the lower part of C1, and the receding interfacial velocity $u_{C1}^r$ is controlled by the advancing interfacial velocity $u_{C2}^a$ in C2.
Figure 3. Dynamic splitting of a liquid slug with an initial length of 1.25 cm. (a-d) Snapshots of the dynamic splitting process at different times. (e) Evolution of slug lengths with time. (f) Evolution of interface velocities. The dots and the lines denote experimental data and model calculations, respectively. The dashed line marks the time at which the meniscus in C1 stops advancing.

The evolution of the type II splitting for large $L = 1.64$ cm is presented in Figure 5. In this scenario, most of the liquid arriving at the junction enters the lower part of C1. The splitting process is excellently captured by the model (Figure 4e). The deviation between predictions and experimental observations is smaller than that in the cases of $L = 1.25$ cm. During the splitting process, the interface velocities also decrease continuously until the fluid completely passes the junction. The advancing interface velocity $u_{C1}^C$ is always smaller than the receding velocity $u_{C1}^R$, indicating that the gravity of the liquid in C1 dominates the splitting behavior. Different from the
type I flow pattern, velocities $u_{C1}$ and $u_{C1}'$ slowly converge with time, which is another indication of the flow dominance in C1. This result implies that the more water entering the lower part of channel C1, the more unfavorable the capillary dominated flow in channel C2 is.

Figure 4. Dynamic splitting behavior with initial liquid slug length of 1.64 cm. (a-d) Snapshots of the dynamic splitting process at different times. (e) Evolution of liquid lengths with time. (f) Evolution of interface velocities. The dots and the lines denote experimental data and model calculations, respectively.

3.1.2 Splitting ratio

We use the dimensionless parameters $t^*$ and $\eta$ to quantify the dynamic splitting process. The dimensionless time $t^*$ is defined as the volume ratio of water passing the junction to the initial
The splitting ratio $\eta(t^*)$ is a transient variable defined as the flow rate of water entering channel C2 to the total flow rate (as measured at the receding meniscus) at time $t^*$,

$$t^* = \int_0^t u^C_1 \, dt / L_3, \quad (8)$$

$$\eta(t^*) = u^C_2(t^*) w_2 / u^C_1(t^*) w_1. \quad (9)$$

The evolution of splitting ratio against time for initial liquid slug lengths from 1.05 to 2.05 cm is shown in Figure 5a. The splitting processes show a stark contrast between type I ($L \leq 1.25$ cm) and type II flow regimes ($L \geq 1.45$ cm), as suggested by both the model and the experiments. For the type I flow pattern (flow dominated by branch channel C2), the splitting ratio $\eta$ is initially at its minimum and grows with time until reaching 1. For the type II flow pattern (dominated by flow in channel C1), $\eta$ decreases steadily with time. According to the quasi-static calculations, we find that there is a critical initial length ($L_{\text{crit}} = 1.41$ cm) at which the splitting ratio maintains a stable value. The critical length can be used as a criterion to determine the flow regimes of dynamic splitting at the T-junction. However, a fully analytical expression for $L_{\text{crit}}$ is difficult to obtain due to the strong nonlinearity of system.

The cumulative splitting ratio $\eta^*$ is also analyzed, $\eta^* = V^C_2 / V$; i.e., $\eta^*$ is defined as the volume ratio of the daughter liquid slug within channel C2 to the total volume. The relationship between $\eta^*$ and the initial length $L$ is presented in Figure 5b. Generally, the cumulative splitting ratio is smaller for longer liquid slugs. Consistent with $\eta-t^*$ data in Figure 5a, the critical liquid slug length is at the inflection point of the obtained $\eta^*-L$ relationship, separating the two flow regimes (see Figure 5b). Within the type I flow regime, $\eta^*$ is strongly sensitive to the variation of $L$, indicating that the key controlling force of the splitting behavior is gravity. When $L$ is much larger than $L_{\text{crit}}$, $\eta^*$ is insensitive to the change of $L$. This is because in the type II splitting regime,
the flow in the branch channel is limited by the capillary force in C2. The dynamic contact angle acts as a flow regulator: the higher the flow rate, the smaller the capillary force in channel C2.

3.2. Effect of inclination angle

Previous studies have shown that the inclination angle is an important parameter in the wetting fluid flow in a conduit (Su et al., 2004). When the T-junction is inclined, gravitational effects are present in the liquid flow of both channels C1 and C2. Note here the inclination angle of 90° means channel C1 is vertical. Our experimental results of liquid splitting with different inclination angles ($\alpha = 70°, 50°$) for $L = 1.65$ cm are shown in Figure 6. The model calculations are again in excellent agreement with the experimental data (Figure 6a). As expected, reducing the inclination angle $\alpha$ leads to more water invading channel C2. As the inclination angle $\alpha$ lowers from 70° to 50°, the initial velocity $u_{C1}$ drops from 1.3cm/s to 0.8cm/s (Figure 6b), giving more time for the water to enter channel C2. When $\alpha = 50°$, the velocity $u_{C2}$ in C2 first remains constant before the meniscus in C1 stops advancing, and then rises as the liquid in the upper C1 continue to feed C2 (Figure 6b).

Figure 5. (a) Evolution of the transient splitting ratio $\eta$. (b) Relationship between the cumulative splitting ratio $\eta^*$ and initial liquid slug length $L$. The dashed lines denote the critical liquid slug length.
The evolution of splitting ratio $\eta$ with time $t^*$ for the T-junction with different inclination angles are presented in Figures 6c-6d. Decreasing the inclination angle $\alpha$ leads to a larger critical liquid slug length: when $\alpha = 70^\circ$, $L_{\text{crit}} = 1.75$ cm (compare with 1.41 cm at $\alpha = 90^\circ$). When $\alpha$ further decreases to $50^\circ$, the splitting behavior completely shifts to the type I flow regime for $L$ between 1.05 and 2.05 cm. As a result, given an initial liquid slug length $L$, the splitting ratio is higher for a smaller inclination angle.

Figure 6. (a) Evolution of liquid slug lengths with splitting time. (b) Evolution of interface velocities with time. (c, d) The evolution of splitting ratio $\eta$ with time. (c) $\alpha = 70^\circ$. (d) $\alpha = 50^\circ$. The symbols represent experimental data with the error bars. The solid lines denote the model predictions.
3.3. Effect of channel widths

In addition to the inclination angle, the channel widths $w_2$ and $w_1$ also have a strong impact on the splitting behavior. The flow capacity in channel C2 is determined by the meniscus advancing velocity $u^{C2}_a$ and the conductivity or permeability. On the one hand, when $w_2$ decreases, $u^{C2}_a$ is expected to rise as the capillary force in C2 becomes stronger, which is favorable to a higher flow rate in C2. On the other hand, the permeability of the channel C2 decreases with $w_2$ as $k^{C2} = \frac{w_2}{12}$, resulting in a reduction of flow. In other words, there exist two competing effects of the channel width. Thus, one would expect a non-monotonic dependence of the splitting ratio on the channel width $w_2$. Here, because no experimental data is available, we only use the developed model to quantitatively explore the influence of the channel width ratio $w_2/w_1$ on the splitting ratio $\eta$ and the cumulative ratio $\eta^*$ by varying $w_2$. The inclination angle $\alpha$ is set to $90^\circ$.

As shown in Figures 7a, 7b, when $w_2/w_1$ changes from 0.2 to 0.4, the transient splitting ratio generally becomes higher for a given initial liquid slug length, especially for the Type I splitting regime (small $L$). However, as $w_2/w_1$ increases from 0.4 to 0.6 (compare Figures 7b and 7c), $\eta$ is noticeably smaller for $L$ between 1.25 and 1.45 cm. When $w_2/w_1$ is large enough (Figure 7d), the transient splitting ratio $\eta$ even drops to 0 (i.e., the fluid no longer invades C2) before the slug completely penetrate the T-junction.

Furthermore, we find, by the quasi-static model, that the critical length $L_{\text{crit}}$ depends non-monotonically on $w_2/w_1$ (Figure 7f). At about $w_2/w_1 = 0.4$, $L_{\text{crit}}$ reaches the maximum, about 1.43 cm, for $\alpha = 90^\circ$ (vertical C1). The relationship between $w_2/w_1$ and $L_{\text{crit}}$ can be fitted by a parabola (Figure 7f). When $w_2/w_1 < 0.4$, $L_{\text{crit}}$ increases with $w_2/w_1$, indicating that the hydraulic conductivity of C2 is the main limiting factor for water partitioning into C2. When $w_2/w_1 > 0.4$, $L_{\text{crit}}$ declines with the width ratio, which is a sign that the capillary force in C2 is taking control of
the dynamic splitting. When \( w_2/w_1 > 0.7 \), the splitting behaviors for \( L \) between 1.05 and 2.05 cm all belong to the type II regime. The cumulative splitting ratio \( \eta^* \) for different \( w_2/w_1 \) values is presented in Figure 7e. A marked non-monotonic dependence \( \eta^* \) on \( w_2/w_1 \) can be observed for all initial lengths except for \( L = 2.05 \) cm (in which case the splitting is dominated by gravity-driven flow in C1). The shorter the initial length, the stronger the non-monotonicity. This also manifests the salient non-linearity caused by the complex interplay between gravity and velocity-dependent capillarity during liquid splitting.
Figure 7. The evolution of splitting ratio $\eta$ with dimensionless splitting time. (a) $w_2/w_1 = 0.2$. (b) $w_2/w_1 =0.4$. (c) $w_2/w_1 = 0.6$. (d) $w_2/w_1 =0.8$. In panels (a-d), the lines from red to purple represent $L = 1.05, 1.15, 1.25, 1.35, 1.45, 1.65, 2.05$ cm. (e) Dependence of the cumulative splitting ratio on the channel width ratio for different initial lengths $L$. (f) The relationship between initial critical liquid slug length and the channel width ratio. The dots denote the predicted $L_{\text{crit}}$. The solid line denotes fitting by a parabola.

3.4. Effect of dynamic contact angles

The influence of dynamic contact angles on the splitting behavior is studied by varying the critical contact angles, $\theta^*_a, \theta^*_r$, and the shape parameters, $\xi_1, \xi_2$ (see equation 4). Since these parameters cannot be controlled independently in experiments, here we only present a modeling analysis. Here we set $\alpha$ to 90°, and the channel widths to $w_1 = 0.83$ mm, $w_2 = 0.33$ mm.

3.4.1 The receding contact angle

To investigate the effect of the receding contact angle, we set the Voinov theory based advancing contact angle as $\theta^*_a = 60^\circ$ and $\xi_1 = 12000$ (see dashed line in the inset of Figure 8a). Different values of $\theta^*_r$ ranging from 10° to 40° and of $\xi_2$ between 50 and 1000 are tested (Figures 8a-8b, insets). The results show that with the decrease of the critical contact angle $\theta^*_r$ (with $\xi_2$ fixed at 250), the cumulative splitting ratio $\eta^*$ increases obviously, especially for small slugs (Figure 8a). This is attributed to the fact that a smaller $\theta^*_r$ leads to a significant decrease of the velocity $u^{C_1}_C$ compared with $u^{C_2}_C$, which favors liquid partitioning into the branch C2 (Figure 8c). This conclusion can be also supported by the variation of the initial splitting ratio $\eta(t \to 0)$ at a small $L = 1.25$ cm (Figure 8c). The higher the initial splitting ratio $\eta$ is, the higher the cumulative splitting ratio for type I regime becomes. However, as the initial slug length $L$ increases to above 1.7 cm, the effect of $\theta^*_r$ gradually diminishes, overshadowed by the gravity effect.
The shape parameter $\xi_2$ dictates the relationship between the contact angle and the capillary number (Eq. 4b). It can be seen from Figure 8b that $\eta^*$ appears to be insensitive to changes in $\xi_2$. This is because as the parameter $\xi_2$ increases from 50 to 1000, the contact angle shows a significant change only for interfacial velocity $u > 1 \text{ cm/s}$, while the interfacial velocities, given the splitting scenario and the parameter space considered in this study, are mostly $< 1 \text{ cm/s}$. Besides, the influence of $\xi_2$ can also be explained by the evolution of the initial splitting ratio $\eta(t \to 0)$. With $\xi_2$ increasing from 50 to 1000, $\eta$ only increase from 0.46 to 0.56 (Figure 8d).

Figure 8. The relationship between cumulative splitting $\eta^*$ and initial length $L$ for different receding contact angle curves. (a) The influence of critical contact angle $\theta_r^c$. (b) The influence of the shape parameter $\xi_2$. The insets display the relationship between the dynamic contact angle and velocity. (c) The influence of critical receding contact angle $\theta_r^c$ on the initial interface
velocities and splitting ratio at $L = 1.25$ cm. (d) the influence of shape parameter $\xi_2$ on the initial interface velocities and splitting ratio at $L = 1.25$ cm.

3.4.2 The advancing contact angle

The impact of the advancing contact angle on the cumulative splitting ratio $\eta^*$ is investigated by using different values of $\theta^*_a (= 40^\circ, 50^\circ, 60^\circ, 70^\circ)$ and the shape parameter $\xi_1 (= 1000, 11000, 21000, 31000)$. With increasing advancing contact angle, both the velocities $u^{c1}_a$ and $u^{c2}_a$ decrease. On the one hand, it is favorable for liquid splitting into channel C2 with $u^{c1}_a$ decreases. On the other hand, the decrease of $u^{c2}_a$ is unfavorable for the splitting behavior. Thus, the cumulative splitting ratio depends on the relative change of $u^{c1}_a$ and $u^{c2}_a$.

Interestingly, we find that $\eta^*$ presents the opposite evolution for type I regime (flow dominated by channel C2) and type II regime (flow dominated by channel C2) (Figure 9a). When $L < \sim 1.45$ cm, $\eta^*$ increases with $\theta^*_a$; otherwise, $\eta^*$ decreases with $\theta^*_a$. Qualitatively, this can also be explained by the evolution of initial interface velocities, $u^{c1}_a$ and $u^{c2}_a$, and the corresponding initial splitting ratio $\eta(t\to0)$. When $L$ is small (type I regime), with increasing $\theta^*_a$, $u^{c1}_a$ will decrease significantly compared with $u^{c2}_a$ (Figure 9c), resulting a larger $\eta(t\to0)$, which is in favor of liquid entering channel C2. This is owing to the fact that the variation of advancing contact angle is more sensitive to the smaller velocity (Figure 9a inset). Conversely, when $L$ is large (type II regime, $u^{c1}_a > u^{c2}_a$), $\eta(t\to0)$ decreases with the increase of $\theta^*_a$.

The shape parameter $\xi_1$ regulates the relationship between the advancing contact angle and the interfacial velocity. We study the influence of $\xi_1$ on the splitting with $\theta^*_a = 60^\circ$ and $\theta^*_r = 30^\circ$. The results show that $\xi_1$, compared with $\theta^*_a$, has a much less appreciable impact on $\eta^*$ (Figure 9b), even though the meniscus velocities show a strong dependence on $\xi_1$ (Figure 9b inset). Furthermore, we find that when $\xi_1 = 1000$, the advancing contact angle approaches a constant for
interface velocity between 0 cm/s and 5 cm/s, resulting in increase of $u_{C1}^r$ and $u_{C2}^a$ by near an order of magnitude. This result implies that the shape parameters $\xi_1$ and $\xi_2$ play an important role in controlling the interface velocities.

Figure 9. The relationship between cumulative splitting $\eta^*$ and initial length $L$ for different advancing contact angle curves. (a) The influence of critical contact angle $\theta_a^*$. (b) The influence of the shape parameter $\xi_1$. The insets display the relationship between the dynamic contact angle and velocity. (c) The influence of critical advancing contact angle $\theta_i^*$ on the initial interface velocities and splitting ratio at $L = 1.25$ cm. (d) The influence of shape parameter $\xi_1$ on the initial interface velocities and splitting ratio at $L = 1.25$ cm.
4. Discussion

4.1. Slugs splitting at the junction

When a liquid slug passes a dry fracture intersection, there exist two different flow behaviors: splitting and bypass. Here, bypass means the liquid flows only in the main channel and ignores the branch channel, i.e., the cumulative $\eta^* = 0$. The criterion for separating the two behaviors can be determined using the interface velocity $u_c^{C2}$. When the interface velocity $u_c^{C2} > 0$, slug splitting occurs; otherwise, bypass occurs. According to equation (6), the critical condition, $u_a^{C2} > 0$, for the splitting behavior can be expressed as:

$$\frac{2\sigma \cos \theta_c^{C2}}{w_2} + \rho g L^{C2} \cos \alpha > \frac{2\sigma \cos \theta_c^{C1}}{w_1} + \rho g L^{C1,d} \sin \alpha.$$  \hspace{1cm} (10)

This equation means that the flow behavior is controlled by the competition between channel $C2$ and the lower part of $C1$. Consider an initial status: $L^{C1,d} = 0$ and $L^{C2} = 0$, and assuming $\theta_c^{C1} = \theta_c^{C2}$, we find that the wetting liquid invades channel $C2$ only when the widths (apertures) satisfy $w_2 < w_1$. This is consistent with previous experimental studies (e.g., Ji et al., 2006; Yang et al., 2019).

However, it should be noted that the competition between the two exits at the intersection is also mediated by the velocity-dependent contact angles. In addition, the lengths $L^{C1,d}$ and $L^{C2}$ may not be initially zero due to preexisting liquids. Thus, the condition $w_2 < w_1$ for the occurrence of splitting may not always be applicable.

When splitting occurs, the transient splitting ratio is determined by the relative magnitude of interface velocities $u_c^{C1}$ and $u_c^{C2}$, which are dependent on and, at the same time, alter the capillary and gravitational forces. As shown in Equation (5), the interface velocity $u_c^{C1}$ is related to the channel width, inclination angle, and slug length in channel $C1$. Longer slugs tend to have higher velocity $u_c^{C1}$, which is in favor of flow dominated by channel $C1$. On the other hand, Equation (6)
indicates that the interface velocity \( u_{c2} \) is not only affected by channel C2 but also by the pressure at the junction, \( P_w \). During the splitting process, the more liquid enters the lower part of the main channel, the lower the pressure \( P_w \) is, which leads to a smaller velocity \( u_{c2} \) in C2. This explains the observation that a preexisting hanging column of water in C1 inhibits the invasion of the channel C2 (Glass et al., 2002). Additionally, according to equation (7), the liquid is completely diverted into channel C2 when \( u_{c1}(t) = 0 \). This special behavior with a cumulative splitting ratio of 1 tends to occur for small initial slug lengths and small inclination angles (see Supporting Information Table S1).

Two types of splitting flow regimes are distinguished: the branch channel-dominated flow and the main channel-dominated flow, which are found to be separated by a critical initial slug length \( L_{\text{crit}} \). This length \( L_{\text{crit}} \) is important as it gives us a criterion to determine the main flow direction at junctions/intersections and even in simple networks. This length is a function of the inclination angle, the wetting parameters, and the channel widths/apertures. In Figure 7f, we present a fitted function of the dependence of \( L_{\text{crit}} \) on \( w_2/w_1 \). However, it is currently difficult to derive an analytical expression of the dependence considering all influencing factors. Further investigations are thus needed in this regard.

It is important to further clarify the role of viscous forces in liquid splitting at an intersection. The viscous pressure drop \( \Delta P \) can be estimated as \( \Delta P = 12\mu uL/w^2 \); given \( u = 2.0 \) cm/s, \( w = 0.033\) mm, and \( L = 1 \) cm, \( \Delta P = 22 \) Pa. This is about one order of magnitude smaller than the capillary pressure \( 2\sigma \cos \theta/w \) (= 280 Pa for \( \theta = 50^\circ \) and \( w = 0.033\) mm). In this sense, the viscous force seems to play an insignificant role for the widths considered in this study; this is also suggested by previous analyses (e.g., Wood et al., 2005; Ji et al., 2006). However, our work here also draws attention to a previously overlooked issue: the effect of visco-capillary balance at
the contact region, as embedded in the Voinov (1976) theory, on wetting liquid flow through intersections. Through the model calculations, we find that ignoring the velocity dependence of the apparent contact angle can overpredict the interface velocities by over one order of magnitude (see Figure 9d).

4.2. Experimental and conceptual limitations

To reveal the essential mechanisms of fluid splitting at an intersection, we make some necessary simplifications in this study. Our experimental and model scenarios correspond to the droplet flow mode of unsaturated flow (Kordilla et al., 2017). However, in natural fractures, other flow patterns, such as rivulet and film flow, can also occur, which can lead to alternative splitting behaviors at fracture intersections (e.g., Dragila & Weisbrod, 2004; Kordilla et al., 2017; Yang et al., 2019). In addition, we use a two-dimensional system in this study to investigate wetting liquid flow through fracture intersections, while in reality water infiltration in fractured media presents a three-dimensional flow problem. Nevertheless, this simplification can be considered reasonable as localized, channeling behavior has been recognized to be commonplace in unsaturated flows (Su et al., 2004).

During the calculation of the interface velocity, we have assumed the receding meniscus to be in a stable state without slip. In fact, when the droplet velocity is high, the droplet slip will occur, leaving a macroscopic film separated from the receding interface (Zhao et al., 2018). This film will increase the droplet/slug velocity and should be considered in the calculation of capillary pressures (Bico & Quéré, 2001). Additionally, only the scenario of initially dry intersections is considered here, while in natural conditions preexisting fluid either as pooling water or as residual droplets/liquid bridges can make the problem more complex. Future work is needed to address the above limitations.
4.3 Extensions and applications of the model

In this study, the idealized case of liquid slug motion in smooth channels is considered, while in nature channels can have rough surfaces and be non-straight (Shigorina et al., 2019). Rough surfaces can significantly enhance the effect of contact angle hysteresis (Bonn et al., 2009), resulting in a smaller interface velocities of the liquid slug (Su et al., 2004). In this respect, the effect of roughness on slug motion and splitting can be possibly accounted for by adjusting the parameters \( \theta_a^*, \theta_r^*, \xi_1, \xi_2 \) in equation (4). To fully address this effect, more experimental and modeling work is needed. For non-straight channels, the slug length in the gravity force terms can be replaced by its projection length in the gravity direction. Additionally, by changing the angle in the pressure gradient term (\( \cos \alpha \)) in equation (6), the model can be straightforwardly extended to predict slug splitting at non-perpendicular junctions, i.e., the model is not limited to T-shaped geometries.

In subsurface environmental and engineering applications, such as underground waste isolation, it is important to be able to predict seepage into or flow diversion around natural cavities and excavated openings (Finsterle et al., 2003; Ghezzehei, 2005). The unsaturated flow mechanism in the fractured rocks surrounding the cavities is the key in this prediction. Under low flow conditions, the droplet/slug flow mode commonly prevails, giving rise to spatially and temporally discontinuous flows (Wood et al., 2005). The resulting complex flow diversion and fluctuation behaviors may not be well captured by continuum unsaturated flow models with effective parameters (e.g., Finsterle et al., 2003). Under this circumstance, our mechanistic model of fluid splitting can be particularly useful in predicting the flow diversion through fractures around the cavities. The liquid splitting ratio as a function of initial slug length (see, e.g., Figure 5b) can also be incorporated into network models to study macroscopic flow features (e.g., flow
convergence/divergence) in fracture networks, which may provide insights for understanding field-scale infiltration and contaminant transport problems in the vadose zone.

5. Conclusions

In this work, the splitting dynamics of liquid slugs at a T-junction has been studied. A quasi-static model and a semi-analytical solution approach are proposed to predict the dynamic splitting behavior. The model is shown to well reproduce the liquid splitting process as observed in visualization experiments. Combining model predictions and experimental data, we find that there is a critical initial slug length dividing the splitting process into two different regimes: flow dominated by the main channel, and flow dominated by the branch channel. We systematically investigate the influence of key parameters on the splitting dynamics, including the inclination angle of the junction, the channel widths/apertures, and the dynamic contact angles. It is shown that the splitting ratio depends non-monotonically on the relative width of the branch channel to the main channel. Furthermore, it is demonstrated that the dynamic contact angles have a profound impact on the splitting ratios and meniscus velocities. We highlight the important, previously overlooked role of velocity-dependent contact angle in the splitting dynamics. Ignoring the velocity dependence of contact angles can lead to overprediction of interface velocities by over an order of magnitude.

This work sheds light on the mechanisms of two-phase flow driven by gravity/buoyancy in fractured media. The improved understanding on the liquid splitting dynamics at a junction is also of direct relevance to applications of controlling bifurcation of liquid slugs/plugs in microfluidics. This work has important implications in hydrological and environmental applications, where the mechanisms of liquid splitting at channel intersections in a complex network need to be elucidated in order to mechanistically predict unsaturated flow and
contaminant transport behavior in the subsurface. Splitting dynamics of liquid flow in channel networks composed of a series of junctions/intersections remains to be explored in future work.

Notation

\( \alpha \) inclination angle

\( Bo \) Bond number

\( Ca \) capillary number

\( g \) gravitational constant

\( L \) initial liquid slug length

\( L^* \) threshold length

\( L^{C1} \) liquid length within channel C1

\( L^{C1,d} \) liquid length within the lower part of C1

\( L^{C2} \) liquid length within channel C2

\( L_{\text{crit}} \) critical initial length of slug

\( \mu \) dynamic viscosity

\( \Psi_a \) capillary pressure of advancing meniscus

\( \Psi_r \) capillary pressure of receding meniscus

\( \sigma \) interfacial tension

\( \theta_s \) static contact angle

\( \theta_a \) advancing contact angle
θ_r receding contact angle

θ_a critical advancing contact angle

θ_r' critical receding contact angle

V initial liquid slug volume

V^{C2} liquid volume within channel C2

u interface velocity

u^{C1}_r receding interface velocity in channel C1

u^{C1}_a advancing interface velocity in channel C1

u^{C2}_a advancing interface velocity in channel C2

P_w fluid pressure at the junction point

w channel width

w_1 channel width of C1

w_2 channel width of C2

ρ density

Δρ density difference

ξ_1 shape parameter of hydrodynamic model

ξ_2 shape parameter of hydrodynamic model

t time

Δt time interval
610 \( t^* \) dimensionless time
611 \( \eta \) transient splitting ratio
612 \( \eta^* \) cumulative splitting ratio

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