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Original Article

Model of the onset of liquid entrainment in large branch T-junction with the consideration of surface tension

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A B S T R A C T

The T-junction exists widely in industrial engineering, especially in nuclear power plants, which plays an important part in nuclear power reactor thermal-hydraulics. However, the existing prediction models of the liquid entrainment are mainly based on the small branches or small breaks while there are a few researches for large branches (d/D > 0.2). Referring to the classical models about the onset of liquid entrainment of the T-junction, most of previous models regard liquid as ideal working fluid and ignore surface tension. This paper aims to study the effect of surface tension on the liquid entrainment, and develops an improved model based on the reasonable assumption. The establishment of new model employs the methods of force analysis, dimensional analysis. Besides, the dimensionless Weber number is adopted innovatively into the model to show the effect of surface tension. What is more, in order to validate the new model, three kinds of working fluids with different surface tensions are creatively adopted in the experiments: water, silicone oil and ethyl alcohol. The final results show that surface tension has a nonnegligible effect on the onset of liquid entrainment in large branch T-junction. The new model is well matched with the experimental data.

1. Introduction

The T-junction consisting of one primary pipe and one branch is widely adopted in industrial engineering, especially in nuclear power reactors, such as the joint between hot leg and ADS-4 (Fourth Stage Automatic Depressurization System) pipe or PRHRS (Passive Residual Heat Removal System) pipe [1,2]. In addition, when there is a small break in primary loop of reactor, that can also be regarded as a T-junction. The liquid entrainment phenomenon could occur due to the existence of the pressure difference as two-phase flow go through the vertical-up branch of T-junction (see Fig. 1), which could lead to the decrease of reactor coolant inventory. Therefore, the study about the entrainment of T-junction has gained widespread attention in the field of nuclear reactor thermal hydraulic analysis.

As for liquid entrainment phenomenon in vertical-up branch T-junction, it is acknowledged that the existence of Bernoulli effect results in the difference of velocity of upstream and downstream flow, which generates gas drag force and makes droplets be entrained into branch pipe. This moment is called the onset of liquid entrainment (OLE). Furthermore, previous studies of liquid entrainment have shown that the main reason of liquid entrainment has something to do with the gas phase Froude number (*Fr*) of the branch pipe and the dimensionless liquid level height (h_b/d), but they ignore the effect of surface tension. In fact, according to the knowledge of fluid mechanics, when the liquid and gas have an interface and a free surface of the liquid appears, the surface tension of the liquid is an objective force. At this moment, if the surface tension is ignored, the models that are based on the effect of inertial force and gravity may not predict the OLE reasonably.

The previous models are mostly focused on the effect of both gravity and inertial force. At the first, Zuber creatively proposed that liquid entrainment would occur when there is a small LOCA (loss of coolant accident) in nuclear power reactor [3]. The inventory of coolant will be reduced due to the liquid entrainment during LOCA that could disturb the safety of reactor. From then on,

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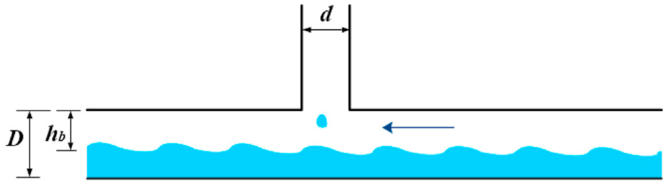


Fig. 1. The liquid entrainment.

many studies related to liquid entrainment in vertical-up branch T-junction have been conducted.

The early studies about entrainment are focused on the small break accidents, then Smoglie et al. [4] improved the OLE model and built a new model to predict the occurrence of entrainment. The liquid is taken as ideal fluid without viscosity and surface tension. Based on this, the model of Smoglie et al. agrees well with the small branch experiment. Furthermore, Moon and No [5] found out that the model of Smoglie et al. could be derived from a more applicable model that could predict the OLE ranged from $h_b/\ d = 1$ to $h_b/d\ =\ 10$. The above models had been adopted in computer program codes, and theoretical research has been widely adopted up to now [7].

Schrock [8] carried out further research with air-water and steam-water applying to small break/branch (d/D = 0.032、0.040、0.059、0.100). Within the range of experimental data, the Schrock's model fitted well. Similarly, Maciaszek et al. [6] also did the experiment with larger branch T-junction (d/D = 0.147、0.149) based on the assumption that distance between liquid surface waves in the horizontal primary pipe was equal to the diameter of branch pipe. In addition to the method of conducting experiments, some researchers have used the Computational Fluid Dynamics (CFD) method to study the theory of the flow mechanism in the T-junction. Wang [9] and Khan [10] used the finite element model to study the flow mechanism, which could be more accurate to describe the flow state of two different phases. Based on their researches of CFD, Feng [11] carried out the experiments on the emergency core cooling safety injection system and validated the results of CFD. This CFD method provides a fundamental guideline for the emergency core cooling safety injection system structure optimization and fatigue aging in the advanced nuclear power plants.

With the development of nuclear power technology, a growing number of researchers [1,14,16] have found that the OLE model for small breaks is not suitable to predict the entrainment phenomenon in larger branches T-junction, which may result from the ignorance of the effect of surface tension. In recent years, some OLE models of large branches have been developed. Welter [14] carried out a droplet entrainment experiment in the ATLATS test facility (ATLATS is an experimental device used to study ADS-4 entrainment phenomenon). The final model showed the influence of the height of gas chamber h_b and Fr number in experimental section. However, Welter did not take the effect of surface tension into consideration.

After that, Sun [16] developed a new model to predict the OLE of large branch T-junction with the effect of surface tension. In the process of modeling, Sun adopted the potential flow theory and innovatively introduced the Bond number into the model to represent the radio of surface tension and inertia force. However, only one working fluid was adopted to do the liquid entrainment experiment, which cannot express how the different surface tension affect the entrainment. The OLE models mentioned above is shown in Table 1.

In a word, the existing models about OLE are mainly suitable for liquid entrainment of small break or small branch T-junction that is mainly influenced by gravity and inertia force, and the existing models have more or less disadvantages to predict the OLE of large branch T-junction due to the effect of surface tension. Thus, this paper aims to study the effect of surface tension on the OLE through the vertical upward large branch T-junction and develops a new model essentially to predict the OLE better.

2. Experimental system

2.1. Experimental content and system

The experiment aims to study the effect of surface tension on the OLE of vertical-up large branch. Therefore, we used a T-junction (d/D = 0.625, the main horizontal pipe with 80 mm inner diameter and the vertical-up branch pipe with 50 mm inner diameter) to conduct visualization experiments. We carried out the experiments with three working fluids (water, ethyl alcohol, silicone oil) with different surface tensions. The gas flows only from one end of the T-junction test section to the other, and there is no symmetrical gas flow condition at both ends.

The whole experimental system is shown in Fig. 2. It mainly includes T-junction experimental section, upstream main pipe, downstream main pipe, gas flow pipelines and data acquisition system. It is stratified flow in the horizontal main pipe of T-junction test section. As for the gas working fluid, there are valves in the gas flow pipeline for controlling the air flow, such as valve 1 and bypass valve shown in Fig. 2. As for the liquid working fluid, a certain amount of liquid is injected into main pipe from the elbow pipe of the downstream main pipe in order to reach a preset water level before experiment.

As for the whole experimental system, the relevant geometrical parameters are shown in Table .2. All of the mentioned experimental sections are made by visualized PMMA (polymethyl methacrylate) so that the phenomenon could be seen clearly during the experiment.

Besides, in order to determine the OLE more accurately, a high-speed camera is used to observe entrainment phenomenon. The main measuring instrumentations are shown in Table .3. They are respectively used to measure the volume flow rate of gas, temperature of working fluids and liquid level height.

The OLE is defined as when the liquid droplets break free from the liquid surface and reach the inlet of branch pipe exactly right. The experimental processes for each kind of working fluid are as follows.

(1) Pour some liquid working fluid (Water, Ethyl alcohol or Silicone) into the horizontal main pipe through the elbow pipe to the preset liquid level.
(2) Turn on the air compressor and adjust the valves of gas flow pipeline and bypass pipeline gradually until liquid entrainment occurs. At the same time, acquire the experimental data for a while.
(3) Turn off the air compressor. Change the liquid level and repeat step (1)–(2).
(4) Change the working fluid and repeat step (1)–(3).

2.2. Data processing

The acquired parameters including air mass flow rate, air and liquid temperature, liquid level in main pipe need to be further processed. Then, they can reflect the influence factors of OLE, including chamber height, size of branch pipe, gas velocity. The first two factors can be reflected in the ratio h_b/d and the later factor is

Table 1
The OLE models of different researchers.

Researchers	d/D	Models
Smoglie et al.[4]	0.029	$h_b = KW_{3b}^{0.4}/[g\rho_b(\rho_L-\rho_G)]^{0.2}$
	0.038	
	0.059	
	0.100	
Schrock et al.[8]	0.032	$Fr_g = 0.395\left(\frac{h_b}{d}\right)^{2.5}$
	0.040	
	0.059	
	0.100	
Moon et al.[5]	0.241	$\frac{h_b}{d} = K^*\left[\frac{v_{3b}^2\rho_b}{gd(\rho_L-\rho_G)}\right]^a$
	0.174	
Maciaszek Micaelli [6]	0.147	$h_b = 0.88\left[\frac{w_{3g}^2}{g\rho_g(\rho_L-\rho_G)d^2}\right]^{\frac{1}{3}}$
	0.149	
Welter [14]	0.330	$\frac{w_{3g}^2}{gd^5\rho_G(\rho_L-\rho_G)} = K\left(\frac{h_b}{d}\right)^3\left[0.22\left(\frac{h_b}{d}\right)+1\right]^2\left[1-\left(\frac{h_b}{D}\right)^2\right]^{-1}$
Sun [16]	0.580	$BoFr^2 = c_1\left(\frac{h_b}{d}\right)^3\left(\frac{D}{d}-\frac{h_b}{d}\right)\tan^2\left[\frac{\pi}{2}\left(0.22+\frac{d}{h_b}\right)\right]$

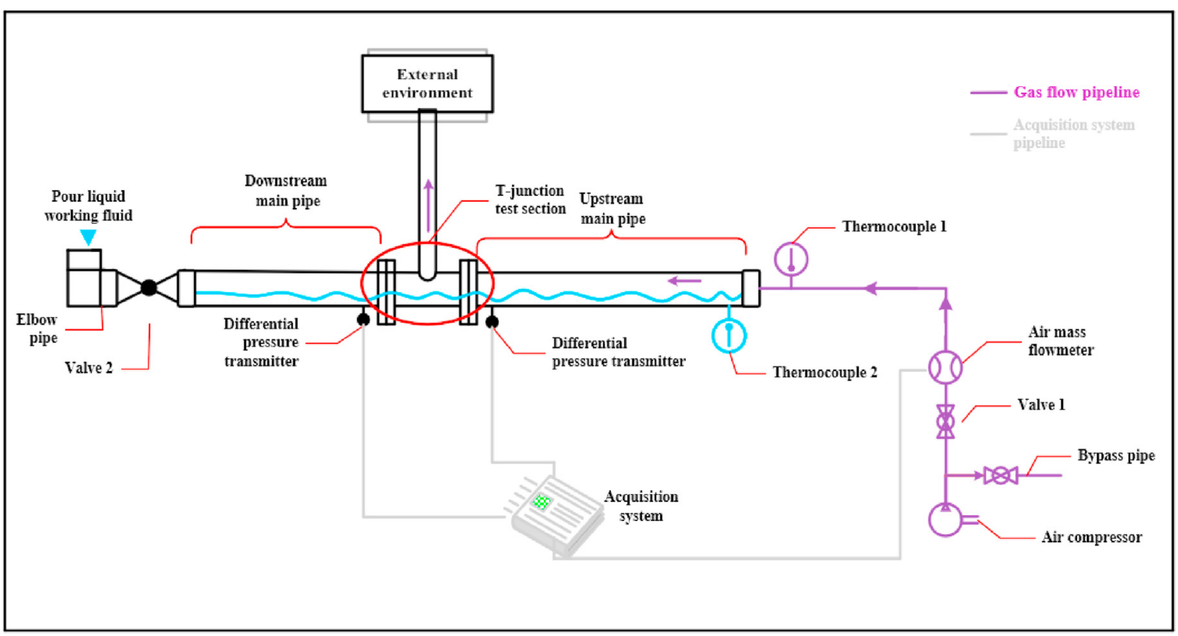


Fig. 2. The schematic diagram of the experiment facility.

Table 2
The main dimensions of experimental section.

Experimental section	Dimensions (mm)
Inner diameter of main pipe D	80
Inner diameter of branch pipe d	50
Upstream length of main pipe	1600
Downstream length of main pipe	710
Main pipe length of T-junction test section	260
Branch length	710

reflected in Fr number that represents the ratio of inertia force to gravity. In this paper, the Fr number can be written as:

$$Fr = \frac{v_{3g}\sqrt{\rho_g}}{\sqrt{\Delta\rho g d}} \tag{2-1}$$

where v_{3g} is the air velocity in the vertical-up branch, ρ_g is the gas density, $\Delta\rho$ is the density difference between gas and liquid phase.

Table 3
Main instrumentations and measured parameters.

Instrumentation	Range	Unit	Accuracy	Function
Air volume flowmeter	0–307	m^3/h	±0.50%	Air volume flow rate
Thermocouple	0–350	°C	±0.5 °C	Air and liquid temperature
Differential pressure transmitter	0–1000	Pa	±0.05%	Liquid level in main pipe

3. Model about onset of liquid entrainment

3.1. The effect of surface tension

Surface tension is like an elastic film covering the gas-liquid interface which tends to minimize the surface shrinkage of droplets. From the point of force analysis, the inertial force is motive power while both gravity and surface tension are resistance. The inertial force needs to overcome the resultant force of the gravity and surface tension when the OLE is occurring. Therefore, it is necessary to analyze magnitude about them quantificationally.

In this paper, assuming liquid droplet is hemispherical when the OLE occurs. Furthermore, we can employ this hemispherical droplet model to study the relative magnitude of these forces quantitatively. When the OLE occurs, we could see the droplet in part "C" (see Fig. 5) is much smaller than the size of branch in Fig. 5. According to the observation of entrainment phenomenon, the droplets have a radius of millimeters when the OLE occurs in large branch T-junction. Thus, we have studied the orders of magnitude about gravity and surface tension which are shown in Table .4. We can conclude that the gravity and surface tension have closer orders of magnitude which means they play the same role as resistance in the OLE. Hence, the surface tension could not be ignored in the OLE.

Relevant research results [12] show that surface tension and viscosity are two different manifestations of intermolecular forces, and they are one-to-one correlations for the same work liquid. Therefore, when we consider the effect of surface tension on the OLE, it also represents the effect of viscosity.

Table .5 is about the physical properties of water, silicone and ethyl alcohol in the experimental condition.

It is seen from Fig. 3 that the experimental data of three working fluids with different surface tensions can reflect the influence of surface tension of OLE. It shows that, at the same dimensionless gas chamber height, the larger the surface tension is, the greater the gas mass of OLE is needed, which indicates that the OLE tends to occur more difficultly with the larger surface tension.

3.2. Modeling on onset of liquid entrainment

There are the waves appearing in stratified flow in the horizontal pipe beneath the branch inlet, which are formed with the effect of Kelvin-Helmholtz instability [16]. Some previous researches take these waves flow as the regular flow and use the wave equations (i.e. cosine wave) to describe the wave at the gas-liquid interface, such as the researches of Welter [15] and Sun [16]. However, the regular flow can not be observed during the OLE, whether in the engineering prototype or in the relative experiments. The liquid entrainment study is usually based on gas-liquid two phase flow coming from the same end of the horizontal main pipe, which causes the existence of pressure difference between upstream and downstream. Thus, it is unreasonable to describe the wave with regular wave equations.

Under the effect of drag force of gas phase, the wave of gas-liquid interface is dragged into deformed wave, when the liquid entrainment occurs, as is shown in Fig. 4.

We were inspired by Al-Wahaibi [13] who had modeled the liquid-liquid entrainment with the deformed wave and assumed the wave of gas-liquid interface is a kind of deformed wave as shown in Fig. 5. As the gas phase flows, the wave at upstream "a" becomes longer and downstream wave "b" becomes shorter, which can be viewed as two sides of a triangle. So, we can express the complex and deformed wave in a specific geometric form when the OLE occurs.

Therefore, some hypotheses are introduced into the modeling in order to establish the entrainment theoretical model. First of all, the deformed wave mentioned above is obtained by regular wave deformation (i.e. cosine wave) and only the geometric shape of the wave changes while both wavelength and wave amplitude are unchanged. Besides, when the onset of liquid entrainment occurs, there is only one wave crest below the inlet of the branch with a liquid droplet broken free from the wave crest.

The droplet is taken on hemispherical in this modeling. What is more, we only take three forces into consideration, i.e. gas phase drag force, gravity and surface tension. The gas phase drag force caused by the pressure difference will promote the wave growth while the gravity and surface tension prevent the wave from growing. Meanwhile, the surface tension acts along the gas-liquid interface with the effect of making wave surface tend to shrink. The OLE occurs when the balance between these three forces is broken. At this time, a liquid droplet will jump off the gas-liquid interface and then be entrained into branch pipe (i.e. OLE). The hypotheses above are described in Fig. 6.

The following treatment for this wave form is performed, assuming that the amplitude of the deformed wave is a_0 and the wavelength is λ (see Fig. 7). Therefore, the deformed wave can be expressed by the specific mathematical function. As assumed above, the deformed wave is transferred into a wave like triangle and the force analysis on the wave has changed on the basis of the deformed wave.

For the whole deformed wave, gas phase drag force and gravity still play a role in the vertical direction, but the surface tension which acts along the surface of the liquid has changed direction (i.e. Fig. 8).

Furthermore, the forces on the hemispherical droplet need to satisfy Eqs. (3)-1) when the OLE occurs.

$$F_D \geq F_G + F_\sigma \tag{3-1}$$

where F_G, F_D, F_σ is gravity, gas phase drag force, surface tension. As for the gravity and gas phase drag force, their expressions are as followed:

$$F_D = \frac{1}{2} C_d \rho_g A v_r^2 \tag{3-2}$$

$$F_G = \rho_l g V \tag{3-3}$$

C_d is drag coefficient. ρ_g, ρ_l is the density of the gas and liquid phase. A is the cross section of the droplet. V is the volume of droplets in the hemisphere. Moreover, we also know that the expression of the surface tension is:

Table 4
The comparison of gravity and surface tension.

Force	Property	The radium of droplets(m)	Expression	The forces' orders of magnitude(N)
Gravity	Resistance	10^{-3}	$F_G = \frac{2}{3}\pi R^3 \rho_l g$	10^{-5}
Surface tension			$F_\sigma = 2\pi R\sigma$ (see *Table*.5 about σ)	10^{-5}

Table 5
The physical properties of working fluids.

Working liquid	Surface tension mN/m	Density kg/m^3	Viscosity mm^2/s	Dynamic viscosity mPa•s
Water (20 °C)	72	998	1.0	1.0
Ethyl alcohol (20 °C)	18.3	800	1.3	1.1
Silicone (5cst) (25 °C)	19.7	915	5.0	4.6

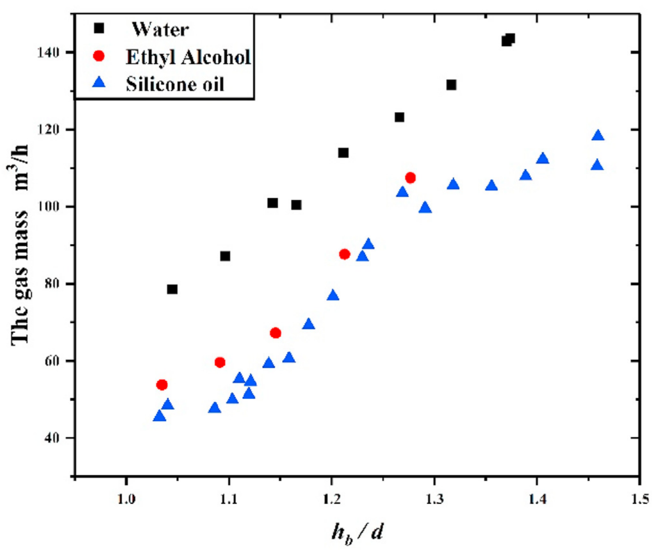


Fig. 3. Relationship between the gas mass flow rate and dimensionless gas chamber height.

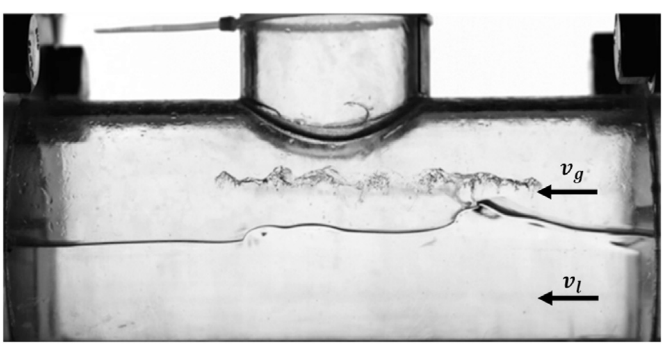


Fig. 4. The wave of gas-liquid interface.

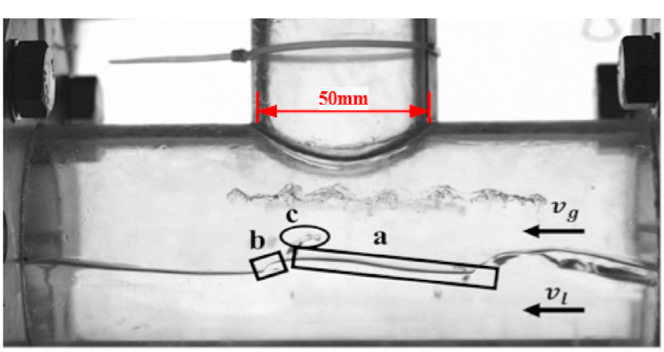


Fig. 5. The wave of the OLE in experiment.

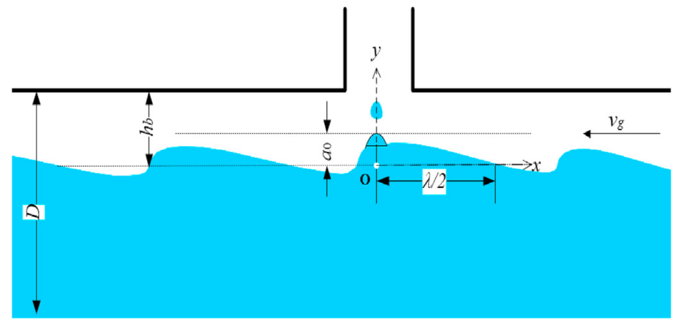


Fig. 6. The schematic diagram of liquid entrainment.

$$F_\sigma = \sigma L \tag{3-4}$$

L is the perimeter of the droplet contacting with the gas phase. However, the value of L may be indeterminate due to the deformed wave. According to what have been assumed, a hemispherical droplet (Fig. 9) is produced from the deformed wave.

The “ABC” is the surface of the hemispherical droplet and it determines the value of L. Specifically, we divide “ABC” into two parts: “AB” and “BC”. Decompose “AB” in the direction parallel to “a” and decompose “BC” in the direction parallel to “b”. The surface tension acts along the surface of droplet: because the forces F_1 and F_2 cancel each other in the direction “O'D” which is perpendicular to the direction of “a”. They have a strong effect only in the direction parallel to “a”. The same effect could be produced by “BC”. Thus, the surface tension of the hemispherical droplet is decomposed in the direction of parallel to “a” and “b”. As what have been analyzed above, we only take the surface tension in the vertical direction into consideration. Finally, we can get the final expression of the surface tension in the vertical direction. We could also get the same result by the symmetry of the droplet.

$$F_\sigma = 2R \cdot \sigma \tag{3-5}$$

Referring to the work of Al-Wahaibi[13], it is assumed that the droplet radius is related to the geometric factors of deformed wave:

$$R = k(a_0\lambda)^{1/2} \tag{3-6}$$

According to the theory of Welter[15], the wavelength is closely related to the diameter of branch pipe:

$$\frac{\lambda}{d} = 0.22\frac{h_b}{d} + 1 \tag{3-7}$$

Using the conservation of energy, we can solve the wave amplitude a_0 at the origin of coordinates:

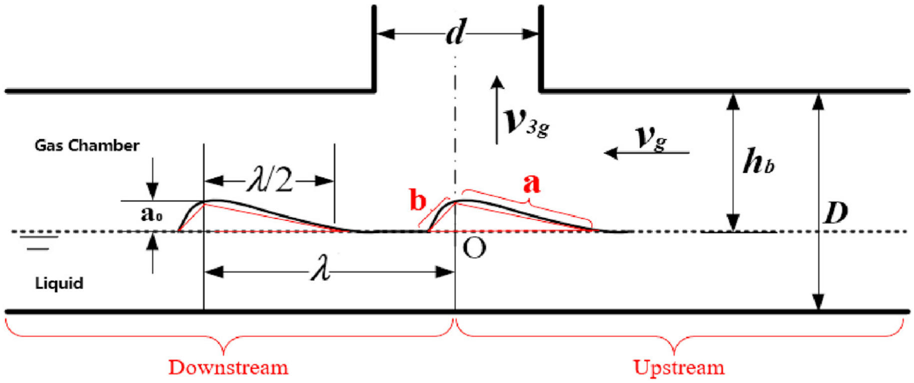


Fig. 7. The schematic diagram according to assumption.

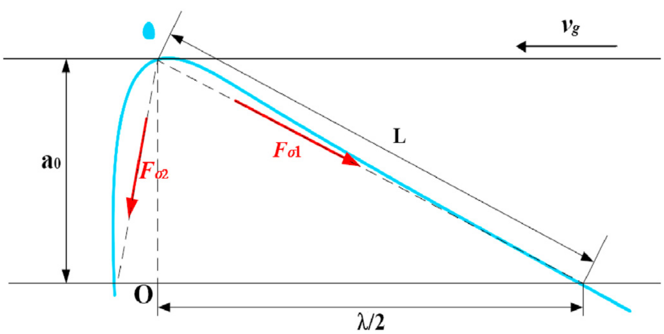


Fig. 8. The force analysis about deformed wave.

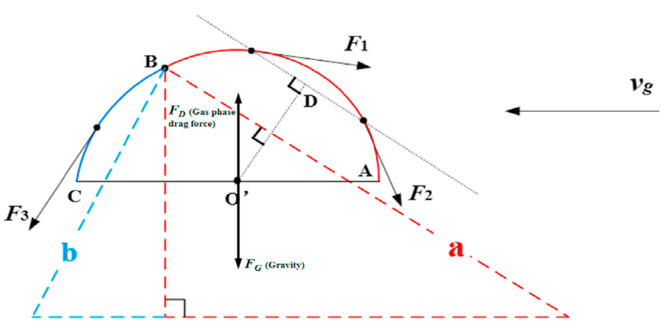


Fig. 9. The force analysis of the droplet.

$$\varDelta\rho g a_0 = \frac{1}{2}\rho_g v_g^2 \tag{3-8}$$

By combining the above Eqs (3-6), (3-7), and (3-8), we can get:

$$R = k\left(\frac{\rho_g v_g^2(0.22h_b + d)}{2\varDelta\rho g}\right)^{1/2} \tag{3-9}$$

It can be seen from Eqs. (3)-9) that all the factors affecting entrainment are attributed to the expression of radius. Furthermore, we can get equation of critical point when the OLE occurs:

$$C_1\left[\frac{\rho_g v_g^2(0.22h_b + d)}{\varDelta\rho g}\right]^{\frac{1}{2}} = C_2\left[\frac{\rho_g v_g^2(0.22h_b + d)}{\varDelta\rho g}\right]\rho_l g + 2\sigma \tag{3-10}$$

where C_1, C_2 are constant. We have defined the Froude number:

$$Fr = \frac{v_{3g}\sqrt{\rho_g}}{\sqrt{\varDelta\rho g d}} \tag{3-11}$$

Therefore, Eq. (3-11) can be written as:

$$C_1 Fr\sqrt{0.22\frac{h_b}{d} + 1 \cdot \frac{v_r^2}{gd}} = C_2 Fr^2 \cdot \left(0.22\frac{h_b}{d} + 1\right) \cdot \frac{\rho_l}{\rho_g} + \frac{\sigma}{\rho_g g d^2} \tag{3-12}$$

In this study, the relative velocity v_r between gas and liquid phase in equation (3-12) can be regarded as the gas phase velocity v_{3g}. Eq. (3-12) can be further written:

$$C_1 Fr^3\sqrt{0.22\frac{h_b}{d} + 1} = C_2 Fr^2 \cdot \left(0.22\frac{h_b}{d} + 1\right) \cdot \frac{\rho_l}{\varDelta\rho} + \frac{\sigma}{\varDelta\rho g d^2} \tag{3-13}$$

Furthermore, take the right side of Eqs. (3)-7) as a whole and replace it with H.

$$H = 0.22\frac{h_b}{d} + 1 \tag{3-14}$$

Therefore, Eq. (3-13) can be expressed as:

$$C_1 Fr^3 \cdot H = C_2 Fr^2 \cdot H^2 + \frac{\sigma}{\varDelta\rho g d^2} \tag{3-15}$$

where we can see it as a quadratic equation of one variable and we can use the root formula of the quadratic equation of one variable to solve it. Then, we can get:

$$H = a \cdot Fr + \sqrt{b \cdot Fr^2 + c \cdot \frac{\sigma}{\varDelta\rho g d^2 \cdot Fr^2}} \tag{3-16}$$

where a, b, c are constants determined by experiment. We can deal with item containing σ further:

$$\frac{\sigma}{\varDelta\rho g d^2 \cdot Fr^2} = \frac{\sigma}{\varDelta\rho g d^2 \cdot \frac{v_g^2\rho_g}{(\rho_l - \rho_g)gd}} = \frac{\sigma}{\rho_g v_g^2 d} \tag{3-17a}$$

Dimensionless number We is introduced into Eq. (3-17a) to express the surface tension.

$$We^{-1} = \frac{\sigma}{\rho_g v_g^2 d} \tag{3 -17b}$$

Moreover, the final form of Eq. (3-15) is:

$$H = a \cdot Fr + \sqrt{b \cdot Fr^2 + \frac{c}{We}} \tag{3-18}$$

where Eq. (3-18) contains components of dimensionless gas chamber height, *Fr* number and *We* number. The software Origin was used to fit the model and data. The results were as follows:

$a = 1.49, b = -0.05, c = 32.37$

Bring the above figures of a, b, c into the theoretical model Eq. (3-18) and the concrete model forms are as follows:

$$\frac{h_b}{d} = 6.77Fr + \left(666.74We^{-1} - 1.03Fr^2\right)^{0.5} - 4.55\left(We \cdot Fr^2 \le 647.32\right) \tag{3-19}$$

Eq. (3-19) is the final theoretical model which is developed to study the effect of surface tension on the onset of liquid entrainment.

4. Model analysis and comparison

The data obtained in the experiment is used to fit the theoretical model above and the result is shown in Fig. 10. From the figure, it can be seen that the experimental data are uniformly distributed on both sides of the prediction model surface. The error between the most experimental data and the predicted figures of the model is within ±20%.

Sun [16,17] established a model to predict the OLE of large branch T-junction with considering surface tension. Sun's model is following:

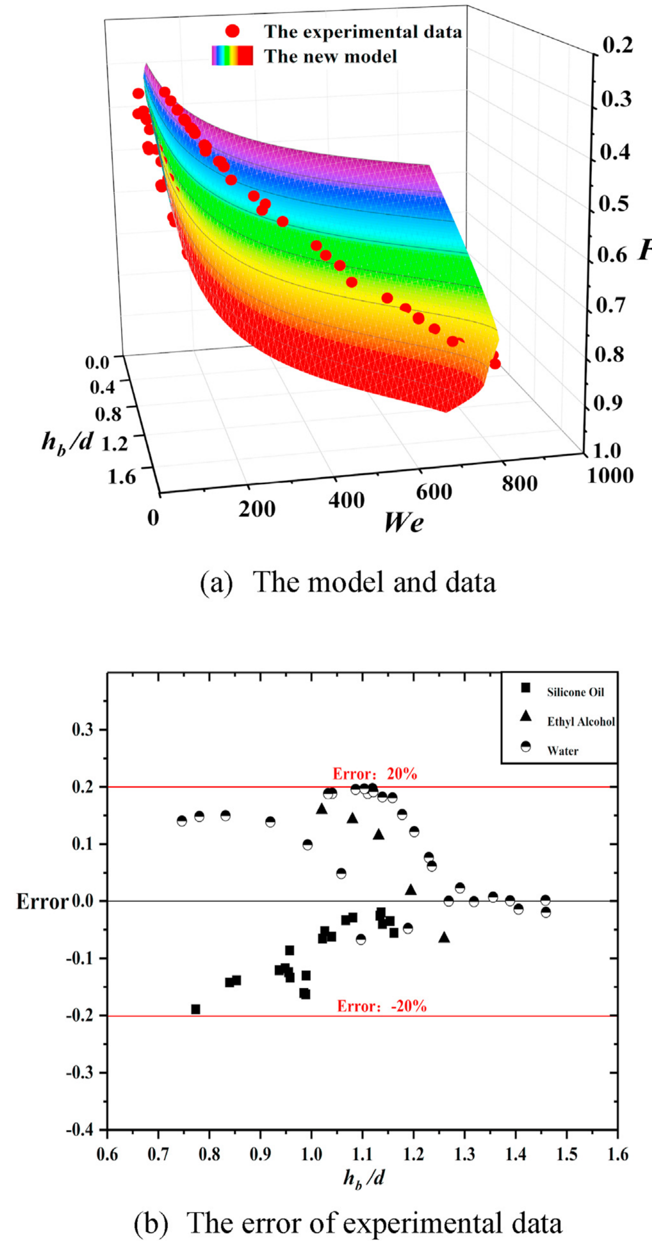
$$BoFr^2 = c_1\left(\frac{h_b}{d}\right)^3\left(\frac{D}{d} - \frac{h_b}{d}\right)\tan^2\left[\frac{\pi}{2}\left(0.22 + \frac{d}{h_b}\right)\right] \tag{4-1}$$

where $Bo = \frac{\Delta\rho g d^2}{\sigma}$, $c_1 = 601.0$, $c_2 = 1.12$.

Use Sun's model to predict the data of ethyl alcohol in this experiment and the results of the comparison are shown in Fig. 11.

It can be seen from Fig. 11 that when the dimensionless liquid height h_b/d is smaller, the prediction results of Sun's model and new model are close, but when the h_b/d is larger, the Sun's model gives much larger result. Sun [16,17] adopted the method of conformal transformation to develop a new model, which introduced the tangent function into the model and neglected the condition that the value of tangent function may not be exist (i.e. the working condition satisfies "$0.22 + \frac{d}{h_b} = 1$" in Sun's model). Besides, Sun carried out the experiment on the model of ADS-4 and searched for the OLE by using the method of searching for invariant liquid level signal. The experiment is so close to the actual working condition that the fluctuation of liquid level is intense and it is difficult to find the constant ideal signal. Only by gradually reducing entrainment Sun can find the liquid level signal which changes slowly in a long period of time as the judgment basis of the OLE. However, there is already liquid droplets entrained into the branch by visualization study. Therefore, at a certain Froude number, a lower critical chamber height will be obtained by this method. Besides, even though the model is about the effect of surface tension on OLE, Sun just took water as liquid working fluid without different surface tension working fluids, which made the effect of surface tension cannot be studied clearly.

By contrast, when considering the effect of surface tension, this experiment uses three working fluids with different surface tensions to find out how surface tension affects the OLE of large branch T-junction. In this experiment, the Froude number varies from 0.2 to 1.1, where the orders of magnitude of surface tension is equal to gravity and it should be considered.



(b) The error of experimental data

Fig. 10. The fitting model and error.

5. Conclusion

In this paper, in order to establish the model about the effect of surface tension on the OLE of large branch T-junction, the fundamental mechanism of the OLE is analyzed and how the surface tension affects the OLE is concluded by conducting the experiment with three kinds of different working fluids. Then, the theoretical model was modified with experimental data to establish a more suitable model to predict the OLE. The main conclusions are summarized as follows:

As for the OLE, the *Fr* number and dimensionless gas chamber height h_b/d are related to the liquid entrainment. It is innovatively determined by quantitative analysis that surface tension has the closer orders of magnitude with gravity in the OLE of large branch

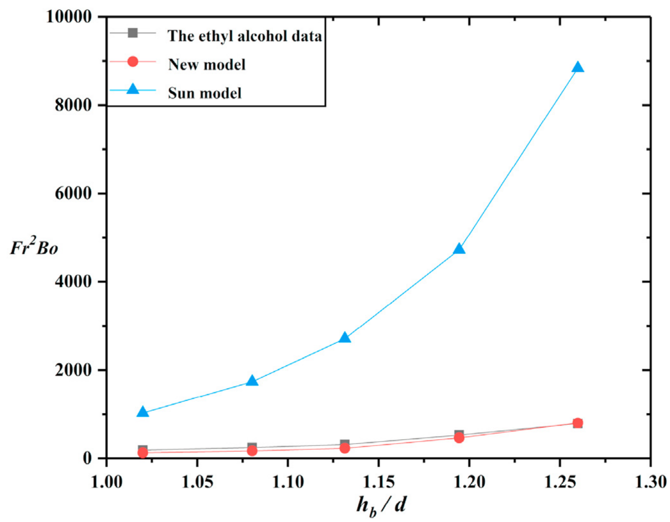


Fig. 11. The experimental data of ethyl alcohol.

T-junction. Therefore, the surface tension cannot be ignored when it is related to the OLE of the large branch T-junction. The surface tension performs that it tends to shrink the surface area of droplets, which requires greater gas phase drag force if the liquid working fluid has larger surface tension.

Moreover, by carrying out the experiment of three working fluids, the result shows when the gas chamber is the same, the larger the surface tension is, the larger the *Fr* number of the OLE has, that is, the greater the surface tension is, the more difficult the OLE occurs.

Based on wave equation theory, force analysis and dimensional analysis, a theoretical model is established, and the new hypothesis is put forward according to the experimental phenomenon, that is, the change of gas-liquid interface when liquid entrainment occurs is based on the deformation wave. Thus, this model can reflect the actual working condition of the OLE more exactly. Compared with previous research conclusions of the OLE, such as the small branch T-junction of Smoglie, the *Fr* number of small branch T-junction is often larger and the gas phase drag force is much larger than gravity. At this time, the effect of surface tension which is relative to gas phase drag force can be neglected. As for the model of large branch T-junction, such as Sun's model, there are some limitations to predict the OLE as analyzed above. Compared with the previous models, the new model is well fitted with the existing data with the error less than 20%.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

d	branch diameter
D	main pipe diameter
Fr	Froude number
We	Weber number
g	gravitational acceleration
v	velocity
h	distance between interface and branch centerline

Greek symbols

ρ	density
$\Delta\rho$	density difference
λ	wavelength

Subscripts

g	gas
l	liquid

Abbreviations

ADS-4	Automatic Depressurization System-Stage Four
OLE	Onset of liquid entrainment
CFD	Computational Fluid Dynamics
PRHRS	Passive Residual Heat Removal System
PMMA	Polymethyl methacrylate

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