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# Experimental Investigations on the Mechanism of Stratified Liquid Mixing in a Cylinder

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***Abstract*—In this paper, the mechanism of stratified liquids' mixing in a cylinder is investigated. It is focused on the effects of Rayleigh-Taylor Instability (RTI) and rotation of the cylinder on liquid interface mixing. For miscible liquids, Planar Laser Induced Fluorescence (PLIF) technique is applied to record the concentration field for one liquid. Intensity of Segregation (IOS) is used to describe the mixing status. For immiscible liquids, High Speed Camera is adopted to record the development of the interface. The experiment of RTI indicates that it plays a great role in the mixing process, and meanwhile the large-scale mixing is triggered, and subsequently the span of the stripes decreases, showing that the mesoscale mixing is coming into being. The rotation experiments show that the spin-down process has a great role in liquid mixing, during which the upper liquid falls down rapidly along the wall and crashes into the lower liquid. During this process, a lot of interface instabilities are excited. Liquids mix rapidly in the spin-down process. It can be concluded that no matter what ways have been adopted to speed up liquid mixing, the fundamental reason is the interface instabilities which increase the area of the interface between liquids and increase the relative velocity of the two liquids.

***Keywords*—Interface instability, liquid mixing, Rayleigh-Taylor Instability, spin-down process, spin-up process.

## I. Introduction

THE process of interface mixing between two stratified liquids with different density usually appears when the interface instability comes into being under some forcing actions, and the study of its mechanism has wide and important application in the fields of petroleum, chemical engineering and pharmaceutical chemistry. For example, injecting water to the oil well during the process of oil production, the problem of fast mixing chamber during the production of chemical industry etc. There are various ways that can lead to liquid mixing, including shake (rock), agitate, impact, accelerate, rotate and other complex forcing ways for enhancing the mixing efficiency. However, the merits and drawbacks of different mixing ways are unclear, the development of liquid mixing technology is constrained. In convention, it is resolved through Navier-Stokes equations and two components diffusion equations, or carried out experimental researches using different agitation equipments to different liquids with different physicochemical properties [1], but the initial forcing action which leads to mixing is usually neglected.

In a container, the different instabilities between the stratified liquid interfaces can lead to different phenomena of liquid mixing. Therefore, liquid interface instabilities generated between stratified liquids have a dominant effect on liquid mixing. According to the difference of the forcing action on the container, some typical interface instabilities are involved. One is the RTI which is generated by the density difference and inertial force whose direction is from lighter liquid to heavier liquid (in other words, the direction of accelerated speed is from the heavier liquid to the lighter liquid) [2]. Another is the Kelvin-Helmholtz Instability (KHI) which is generated by the shearing action between stratified liquids with different tangential velocities [3]. The other liquid instability phenomena are for a rotating liquid system, such as the Centrifugal Instability (CTI) and RTI or KHI in rotating flow field [4].

According to the hydrodynamic theory, there are three stages during the liquid flow in a rotating container. The first is the spin-up process during which the liquid starts to rotate from static state to some definite spinning speed. The second is the rigid body rotation period during which the rotation is stable. The last is the spin-down process during which the spinning speed of the liquid starts to slow down from definite spinning rate. In the spin-up stage, the pumping action of Ekman boundary layer is distinct. The flow field could be divided into three parts, one is the Ekman boundary layer on the upper and bottom end-wall of the cylindrical container, the second is the Stewartson boundary layer where the liquid on the sidewall of the cylindrical container creeps along the sidewall. The third is the central of the container [5]. However, in the spin-down stage, the container stop rotating abruptly which hammer the rigid body rotation of the liquid in the container mightily, which has a nonlinearity effect on the liquid [6]. Therefore, the spin-down process may have a notable effect on the mixing. In 1964, Wedemeyer divided the flow field into two areas and presented the analytic solutions of the spin-up process, where one is the flow of boundary layer, and the other is the flow of central layer [7]. But his work is just for a single liquid in rotating liquid-filled container, not involving two or more liquid components mixing problem.

In this paper, the mechanism of stratified liquid mixing in a cylinder is investigated. The macroscopic interface mixing between two miscible liquids and the interfacial evolution between two immiscible liquids are explored experimentally, and the mathematical models of stratified liquid interface mixing are presented under corresponding boundary conditions. It is focused on the effects on liquid interface mixing by RTI and axisymmetrical rotation of cylinder. For

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miscible liquids, PLIF [8] technique is used to record the concentration field, and IOS and Variance of Intensity (VOI) are used to analyze the results. The principle of IOS is the variance of the concentration of one liquid in the total mixture. Using the PLIF techniques, concentration distribution in the flow field is denoted by the induced fluorescence intensity distribution, so that the IOS of the mixture can be measured as long as the differences between the laser induced light intensity and the initial light intensity are measured. The differences between the volume fraction of local solute liquid and the volume fraction of whole liquid under uniform state will be learned, and then the degree of mixing of liquid is obtained. For immiscible liquids, High Speed Camera is adopted to record the variety of the interface.

## II. Experimental System and Analysis Approaches

In the situation of miscible liquid mixing, the experimental system includes cylindrical PMMA container, axisymmetrical rotation turntable, ND-YAG 135-15 laser (which exports light sheet of 532 nm) and HiSense MkII camera, as shown in Fig. 1.

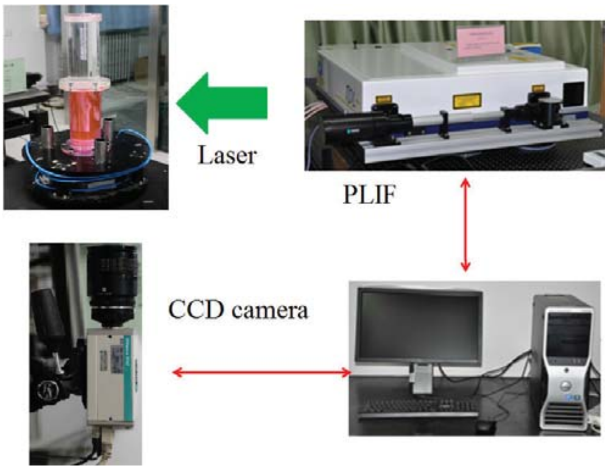



Fig. 1 The sketch of experimental system

The radius of the cylindrical container is $r = 4 \pm 0.1\,\text{cm}$, and the height is $h = 40 \pm 0.1\,\text{cm}$. During PLIF measurement of liquid mixing process, the intensity of the fluorescence recorded by the CCD camera when the light intensity is not saturated shows the proportion of the dyestuff concentration in directly. The expression of the intensity of the fluorescence is $C(X,Y) = A(X,Y) \times (I(X,Y) - 200)$, where $C(X,Y)$ is the concentration of the dyestuff, $I(X,Y)$ is the calibration light intensity recorded by CCD, $A(X,Y)$ is the coefficient which reflects the energy decay of laser and the irregular distribution of the intensity of laser. In general, it is considered that $A(X,Y)$ is constant. Thus, the distribution of the intensity in the photograph represents the concentration field of the dyestuff.

The IOS is a variance of the concentration distribution which is used to describe the degree of mixing in the whole flow field. The principle of IOS is that: adding some tracer agent into the solute or solvent, and measuring the physical content of the tracer in the solution by the recording light intensity; comparing the result of the tracer content at initial standard situation or the equilibrium state with the tracer content during liquid mixing, the degree of deviation can be obtained. The computing formula of IOS is:

$$IOS = \frac{\langle f'^2 \rangle}{\langle f \rangle (1 - \langle f \rangle)}, \quad f' = f - \langle f \rangle$$

where f is the concentration distribution in a designated area in the mixing flow field, <f> represents the mean concentration of the whole flow field. In order to analysis the degree of liquid mixing in detailed, the VOI is defined to describe the mixing degree of discrete point in the field different from the concept of IOS. The definition of VOI is as:

$$VOI = \frac{I'^2}{I_1^2}, I' = I - I_1$$

VOI is the light intensity variance of the two components, I is the light intensity of the liquid measured, $I_1$ is the calibration of the light intensity. The question is how to define the calibration of the light intensity $I_1$. If $I_1$ is defined as the light intensity recording to the balanced concentration, the VOI decreases to 0 when liquid A and liquid B is mixed homogeneously while VOI equaling 1 represents that A and B is completely separated. However, in this condition, the relation between liquid A and liquid B at the discrete point cannot be distinguished. At the same time, because of the destabilization in the light field, it will happen frequently to the situation that the light intensity oversteps the threshold value. Consequently, in this paper $I_1$ is defined as the max light intensity at the initial state in this paper. The final light intensity should be $I'/2$ since the quantities of liquid A and B are equal, and VOI approaches 0.25 during the mixing process, so that the content of liquid A or liquid B and their relation can be distinguished in the discrete point when VOI is larger or smaller than 0.25.

## III. Experimental Results for Mixing Induced by RTI

### A. Immiscible Stratified Liquid Mixing Induced by RTI

In the experiment of immiscible stratified liquid mixing induced by RTI, liquid paraffins and water were chosen. The density of liquid paraffins is 0.87g/cm3 and the density of water is 1.0g/cm3. To realize the phenomenon of RTI, the upper layer of the container is filled with the water which is heavier (mixed with red tracer), and the lower layer of the container is filled with the liquid paraffins which is lighter (with bright color). There is rubber membrane to separate the two liquids initially. When the membrane is punctured by an awl in the center, it shrinks to the outer boundary and the mixing begins. High Speed Camera is adopted to record the variation of the interface.

In Fig. 2, the pictures of interface mixing process are recorded at the time of 0s, 0.2s, 0.5s, 1s and 3s respectively. As shown in the pictures, at the beginning, the tiny interfacial disturbance increases and evolves due to RTI, then through the nonlinear increasing of the interface instability. The upper heavy liquid comes into the light liquid rapidly, and meanwhile some entrainment phenomena can be observed. Later, the heavy and light liquids roll-over, and number of vacuoles are visualized directly. The results indicate that the interface instability phenomenon caused by the density difference enlarges the contact area between liquids evidently, and the effect of entrainment also speeds up the flow velocity of liquid in the process. Though it is impossible to reach the complete mixing in this case, abundant information of flow field is obtained, such as interface instability increasing, evolution, entrainment, vacuole emergence and rolling-over of liquid etc., which would help to explore the mechanism of liquid mixing.

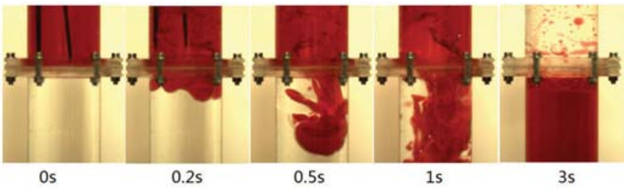
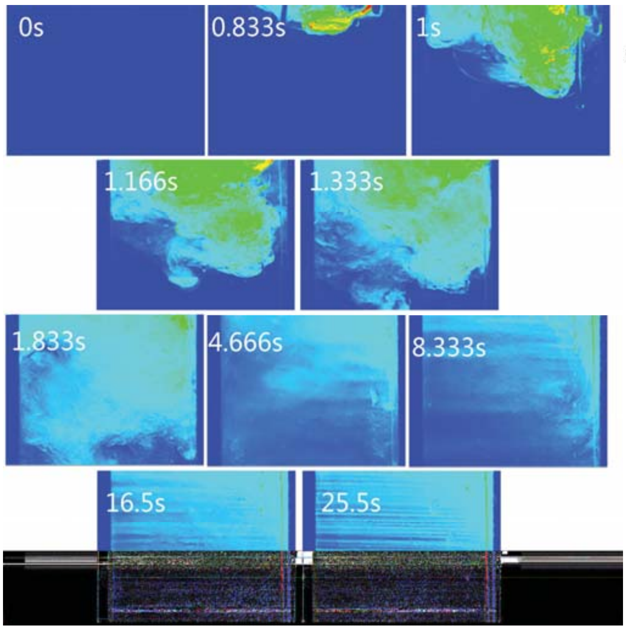



Fig. 2 The pictures of interface mixing process for immiscible liquid induced by RTI

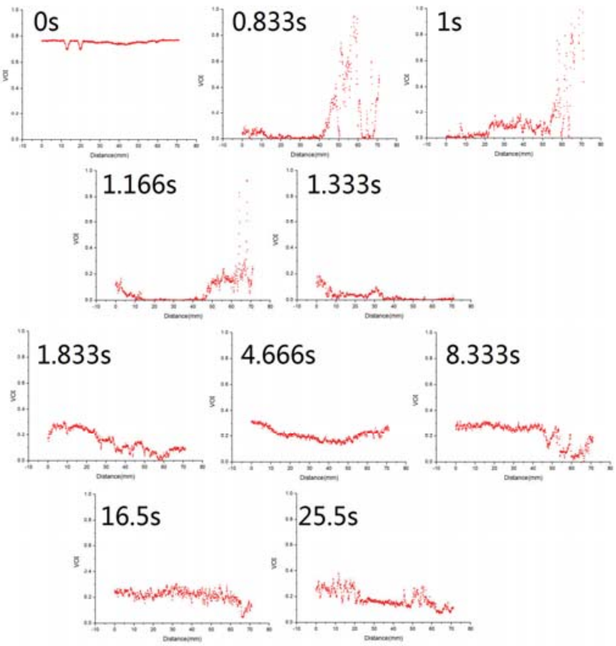
### *B. Miscible Stratified Liquid Mixing Induced by RTI*

In this experiment, two miscible liquids, ethylene glycol and water, are adopted. The density of the ethylene glycol is 1.132 g/cm$^3$. Similar to 3.1, the upper layer of the container is filled with the ethylene glycol (heavier) mixed with tracer agent (Rhodamine agent), the lower layer is filled with the water (lighter), and there is rubber membrane to separate the two liquids. The PLIF technique is used to record the concentration distribution of ethylene glycol. The light intensity is measured at the middle of the pictures. The flow fields at different times are shown in Fig. 3.

According to the result, after the rubber membrane is ruptured, the interface instability dominates the mixing process, and the mixing in wide area was generated during the time of 0.833s to 1.333s. Some wave-like strips appeared after 8.333s, whose span decreased, showing that the scale of mixing becomes to mesoscale phenomenon. It is found from the graphs of VOI that the rubber membrane is ruptured at 0.833s. The results from 0.833s to 1s indicate that the range of VOI is wide and spread in the interval of 0 to 1, which means that the liquid start to mixing under the action of RTI. Most distribution of VOI are close to 0 from 1.166s and 1.333s, indicates that the action of interface instability speed up the velocity of heavier liquid. From 1.333s to 4.666s, the values of VOI approach 0.25, which showed that the evolution of mixing process become quickly in this period.




(a)




(b)

Fig. 3 Mixing process for miscible liquid induced by RTI and distribution of VOI

## IV. Experimental Results for Mixing Induced by Rotation

### *A. Immiscible Stratified Liquid Mixing Induced by Rotation*

In the experiment of immiscible stratified liquids mixing induced by rotation (Fig. 4), liquid paraffins and water were used. Considering the effect of rotation, the upper layer of the container is filled with the liquid paraffins (lighter), the lower layer is filled with water (heavier), and there is no rubber membrane between the upper and lower liquid. High Speed Camera is also adopted to record the evolution of the interface.

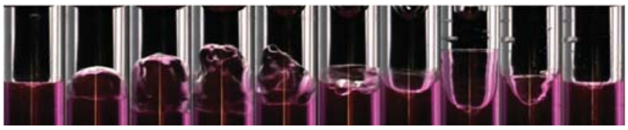


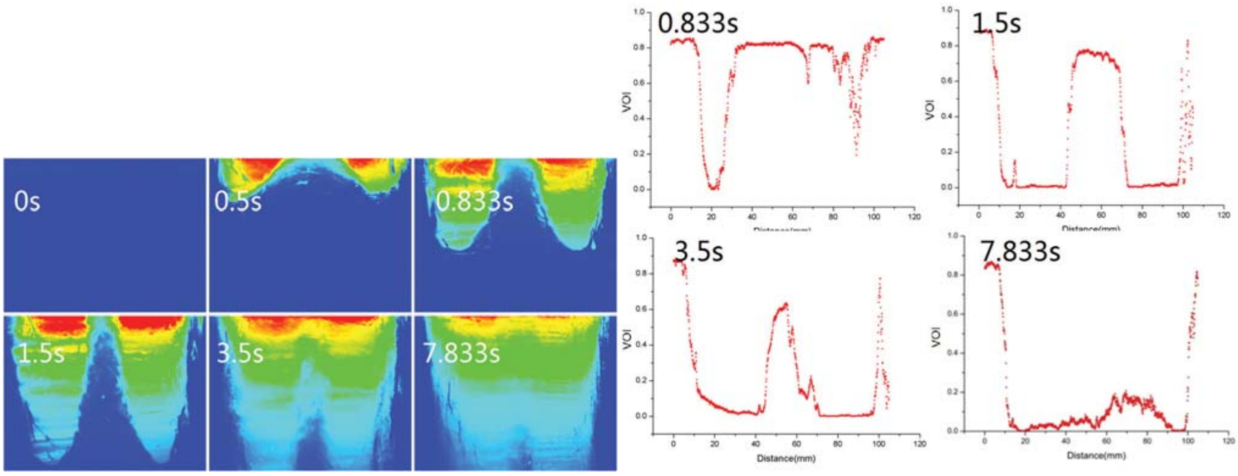
Fig. 4 The pictures of interface for immiscible liquid induced by rotation

The results show that a clear interface exists between the two stratified liquids for the reason that liquid paraffins and water are immiscible, and the phenomenon of RTI did not happen. However, due to the Ekman pumping action, heavy liquid is pumping up to the center of the container, until the KH instability on the interface happens because of the circumferential speed difference of liquids. Then the interface of the two liquids becomes to tortuosity and breakup, and is thrown to the sidewall of the container. In the rigid rotation process, the interface evolves into a paraboloid. Actually, the density of liquid paraffins is smaller than water, the viscosity of liquid paraffins is larger than water, so that the spin-up time of liquid paraffins is shorter than water. Therefore, there is a difference of flow velocity between the liquid interface (it means that the velocity of liquid paraffin is larger than water velocity) during spin-up, and it is the reason for the KHI excitation. However, during spin-down, the circumferential velocity of liquid paraffins is less than water circumferential velocity. As a result, water will climb up along the sidewall, meanwhile there is another KHI along the circumference. It indicates that KHI generated during rotation can induce the liquid with larger circumferential velocity crashing into the other liquid with smaller circumferential velocity.

Above experimental results indicate that the Ekman pumping action has a strong effect during spin-up, and the impact of liquid which has smaller viscosity to the other liquid will lead to interface instability phenomenon during spin-down.

### *B. Miscible Stratified Liquid Mixing Induced by Rotation*

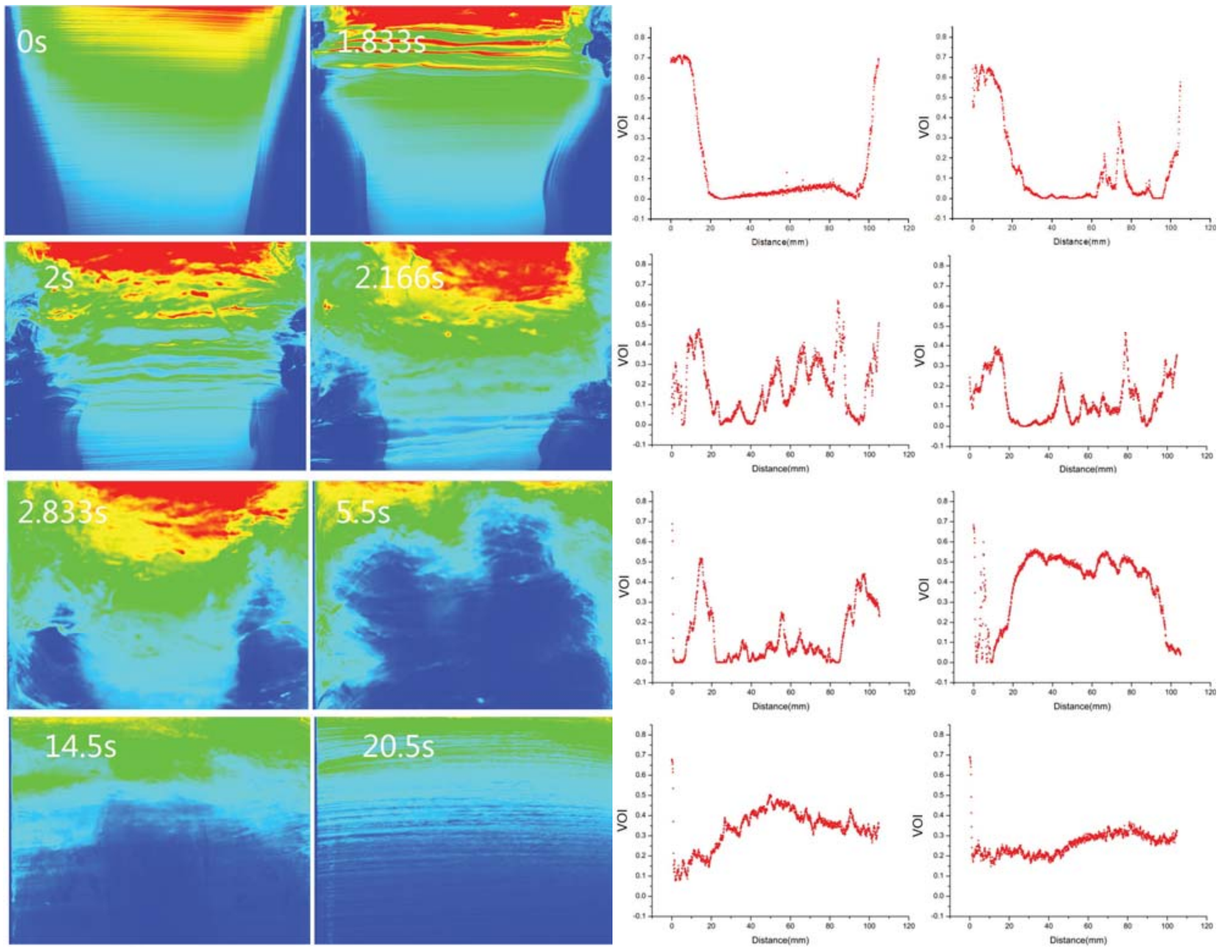
In the experiment of miscible stratified liquid mixing induced by rotation (as shown in Fig. 5), ethylene glycol and water are used. The upper layer of the container is filled with the water (lighter) mixed with tracer agent (Rhodamine agent), while the lower layer is filled with the ethylene glycol (heavier). There also is rubber membrane separating two liquids. The PLIF technique is used to record the concentration field.




(a) (b)

Fig. 5 The pictures of interface mixing process for miscible liquid induced by rotation and distribution of VOI during spin-up

Fig. 6 shows pictures of the mixing process of liquids in the lower part of cylinder during Spin-up stage, which were recorded at 0s, 0.5s, 0.833s, 1.5s, 3.5s and 7.833s respectively. During the experiment, the planar laser passes through the cross section along axisymmetry of the cylinder. The distribution of VOI along the line at 0.833s, 1.5s, 3.5s and 7.833s are calculated respectively. It is shown from the pictures that an open side-down concavity generates, performing like two parabolas on the 2-D picture at 0.5s after the cylinder rotating, which should be two paraboloids in the 3-D space. Then the two paraboloids converge together, and the interface becomes indistinct, and it shows that the two liquids are mixing. During the rigid rotation, the shape of the interface and the distribution of VOI keep invariant (See the first picture in Fig. 6 (a)and the first picture of distribution of VOI in Fig. 6 (b)), which shows that the rigid rotation has little effect on mixing process. According to the theory of KHI, there are two reasons for the open side-down concavity. One is the centrifugal force of container rotation and the other one is the KHI generated due to the difference of circumferential velocity of the two stratified liquids. The two effects have co-rotation function on the paraboloids, and the force of KHI is stronger than centrifugal force in this experiment. During spin-down stage, the paraboloid becomes shaking and breaking, the upper liquid falls down rapidly along the wall, and crashes into the lower liquid, and at last a lot of interface instability effects appear. As shown in the VOI distribution, the mixing process of two liquids completes during spin-down (Fig. 6).




(a) (b)

Fig. 6 The pictures of interface mixing process for miscible liquid induced by rotation and distribution of VOI during spin-down

## V. Conclusion

Based on the experiment of RTI, it could be concluded that: Interface instabilities between liquids provide the primary driving force for mixing. Without interface instability, it is hard for liquids to mix well.

In the experiment of rotation, phenomena in the three stages of rotation indicate that the pumping action and the broken interface of the immiscible liquids in spin-up stage provide power for mixing. Although the spin-up stage provides axial movement of liquids, it cannot enhance the instability between liquids. Therefore, spin-up process has limited effect on liquid mixing. In the process of rigid body rotation, the interface between liquids keeps stable, which has little effect on mixing. On the contrary, in the spin-down stage, the interface instability is comparatively strong. It brings about available fragmentation effect which promotes mixing. Secondly, the direction of density gradient and viscosity gradient at the interface are critical for mixing in the process of rotation, which decides the impact sequence of the above and below liquid in the process of spin-up and spin-down. When the two directions are opposite, pumping action is generated in spin-up process, and the liquid level breaks during the process of reaching rigid body rotation. On the contrary, when they are the same, pumping will not happen, and two paraboloids are generated after the container starts rotating and then the two paraboloids converged together.

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