WATER MODEL STUDY ON MIXING TIME IN SHAKING LADLE

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ABSTRACT

Most of the previous investigations on shaking ladle have taken the wave height in the bath as a main object of study and defined the critical shaking speed at which the wave height obtained the maximum value. In the present study, the mixing time (T_{mix}) in the shaking ladle bath was experimentally investigated through a water model. Water was used to simulate liquid metal and a NaCl tracer was added during the experiments. The definition and determination of mixing time in gas agitated bath were summarized and a new criterion about shaking ladle, namely derivative criterion was proposed to determine T_{mix} in the present paper, which may be also useful in other vessels. The fluid flow in the shaking ladle bath can be split into active region and dead region and one electrical conductivity probe was set at each region, respectively. The experimental results showed that the values of wave height in the bath could not reflect the mixing efficiency exactly and the mixing time was dependent on the tracer injection positions in shaking ladle. The motion of water in the bath transformed from one type to another with the increase of shaking speed: one is named wave motion while the other is named flow motion, and the latter one performed better in mixing efficiency. A new critical shaking speed of mixing efficiency based on the relationship between mixing time and shaking speed was proposed. Further investigations are necessary to be done in the future, to obtain an empirical equation of the new critical shaking speed as a function of the bath diameter, bath depth, and eccentric distance.

KEYWORDS: *mixing time; shaking ladle; derivative criterion; critical shaking speed.*

1. INTRODUCTION

The efficiencies of many processing operations carried out in metallurgical reactors are related to mixing phenomena. Many bath agitation methods have been proposed in order to promote the reaction rate or bath homogenization, such as gas injection, mechanical stirring, and electromagnetic stirring. In addition to those, another apparatus named shaking ladle, was developed by Bo Kalling [1] in 1958 at the Research Department at Domnarvet, Sweden. The shaking ladle has proved to be an excellent metallurgical tool wherever it is necessary to obtain good mixing, for instance, in desulfurization, recarburization and alloying of pig iron [2], producing low and medium carbon ferromanganese and ferrochrome [3], and processing ferrovanadium [4].

Several investigations have been done to study the mixing phenomena in shaking ladle. Sven Eketorp [1] investigated the phenomena took place when liquid was brought into motion in shaking ladle by model tests. The wave heights in the bath during shaking in different speeds were measured, and a critical shaking speed, n_c, was found, at which a characteristic wave motion was created which looks like a breaker and the wave height in the bath reached a maximum value. Eketorp believed that at a speed which is too high above the critical speed, the mixing effect did not as intensive as closer to the critical speed. Kotaro Ishii [5] proposed a set of empirical equations for the n_c as a function of R (radius of ladle), H (height of bath), g (gravitational constant) and a (eccentricity). The empirical equations were expressed by the following formulae:

$$n_c = 9.5\sqrt{\frac{1}{a}+\frac{5}{R}} \qquad (H/R > 1.2) \tag{1}$$

$$n_c' = \frac{1}{1.08}\left\{(n_c - 15)\lg\frac{H}{R} + n_c + 1.2\right\} \qquad (H/R < 1.2) \tag{2}$$

Chih-Peng Tsai and his co-worker [6] studied the behaviors of three liquids of different viscosities in shaking ladle and found that there were four critical speeds in the shaking ladle, and operation under the conditions of either the second mono-breaker or the multiple-breaker wave state was recommended for production, in order to maintain good stirring and long life of lining. They also demonstrated that the viscosity only effect heights of peaks but critical speed.

Almost all previous investigations paid attentions to the wave height in the shaking ladle and the critical shaking speed was, likewise, defined depending on it. However, the correlation between the mixing efficiency and the wave height has not been confirmed either experimentally or theoretically. Plus, a desulfurization experiment [7] showed that the desulfurization rate attained the desire at 10 rpm (revolutions per minute) over the "critical shaking speed". Therefore, it is uncertain that whether the mixing efficiency at the critical shaking speed is the most desirable.

In the present work, the concept of "mixing time", which has justifiably received considerable attention over the decades in gas stirred liquid bath, was introduced into shaking ladle study. The previous studies about mixing time in gas agitation bath were summarized in the second part of this paper. The mixing process of the tracer in shaking ladle bath was elaborated and a new criterion of mixing time was proposed.

2. DEFINITION AND DETERMINATION OF MIXING TIME

To obtain a quantitative understanding of mixing in the metallurgical reactors, the tracer dispersion test, which was interpreted in terms of "mixing time", were introduced into the modeling experiment [8]. The addition of the tracer creates a non-homogeneous state of the bath initially, and the agitation makes the non-homogeneous bath homogeneous gradually. When the tracer was injected into the bath, it was broken up into "clumps", which are intermingled. At the same time, molecular diffusion of the tracer occurs across the boundaries of the clumps. The mechanical stirring breaks the tracer into smaller clumps continuously, which speeds up the mixing process. P. V. Dackwerts [9] had precisely described the process in his works. In older to define the "goodness of mixing", P.V. Dackwerts [9] proposed the concept of "intensity of segregation" based on the statistical theory, which reflected the extent to which the concentration in the clumps departs from the mean.

Krishna Murthy [10] expressed the intensity of segregation of the tracer element in the gas agitated bath as

$$I_S = \left|\frac{C_\infty - C_{(t)}}{C_\infty - C_o}\right| \tag{3}$$

Where C_∞ and C_o refer to the tracer final and initial average uniform concentrations, respectively. $C_{(t)}$ is the uniform concentration of tracer at time t. The degree of mixing, "Y", which is the measure of extent of mixing in the bath, is defined as

$$Y = 1 - I_S \tag{4}$$

Krishna Murthy [10] reported that a properly determined value of mixing time would be independent of the locations of the measuring probe or tracer injection. But Mazumdar [11] pointed out that Murthy's conclusion represented an over-extrapolation of their limited experimental observations and it has been demonstrated by many experimental investigations that the mixing time depended on the location of the measuring probe and the tracer injection [12-16]. It is comprehensible that the difference of tracer charge positions makes the initial state of the tracer concentration different in the bath, hence the determined mixing times are variant. It should be noted here that the determined mixing time will also be different for different values of Y as was demonstrated by Krishna Murthy and through extensive experimental trials with in a mixing range of 55% to 99.5% [17]. On the basis of that, most of the previous investigations adapted the 95% criterion [12-14, 16, 18-26]. Since the mixing time in the bath was found to be position dependent, it was defined as the time by which the concentration of the added tracer in the slowest mixing region (dead zone) within the vessel [27].

In addition to the 95% criterion, another criterion of mixing time was proposed by Asai and Okamoto [28]. Two electrical conductivity probes were arranged at the different positions in the bath and the discrepancy in the voltage of the two probes was detected by an alternating bridge circuit and rectified for a pen-recorder. The mixing time was defined as the time in which the concentration difference in vessel is settled to less than 1×10^{-5}% approximately.

In current study, the authors proposed another criterion, which could be named as "derivative criterion". The change rate of the tracer concentration at a measured position, "D", can be expressed as

$$D = \left| \frac{dC_{(t)}}{dt} \right| \tag{5}$$

Where $C_{(t)}$ is the concentration varying with time after the tracer was injected. The mean segregation intensity of the bath, $\overline{I}$, is defined as

$$\overline{I} = \frac{1}{n}\left(D_1 + \cdots D_n\right) = \frac{1}{n}\left(\left|\frac{dC_{1(t)}}{dt}\right| + \cdots + \left|\frac{dC_{n(t)}}{dt}\right|\right) \tag{6}$$

Where $C_{i(t)}$ is the local concentration at position i. $\overline{I} = 0$ means that the concentrations in all determined position are constant, and the bath is homogeneous already. However, theoretically, 100% mixing is only attainable at infinite time and the absolutely mixing is not necessary actually. So the bath was considered to be homogeneous when $\overline{I} < \sigma$, where σ is a constraint factor of the mean segregation intensity. The advantage of the derivative criterion is that it reflects the average mixing efficiency in the bath, which is very important to the actual process.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

Experimental work was carried out in a water model. Figure 1 shows a schematic sketch of the experimental apparatus. The shaking ladle model was fixed to the shaking frame, which was very similar to the one used by Chih-Peng Tsai [6]. Three eccentric crank shafts are driven by an electric motor. Ten liters of water were contained in the vessel, the inner diameter of which was 39 cm. The vessel was filled to a depth of 84 mm.

Aqueous NaCl solution with a concentration of 4.9 mol/L was used as the tracer. A syringe was used to inject the tracer into the bath from the bottom. Approximately 10 mL of tracer was added during each experiment. The changes in the local concentration of tracer at two different positions of the bath were monitored using two electrical conductivity probes, which were supplied with two electrical conductivity meters, respectively. The electrical conductivity signals were collected every 0.11 s by a data acquisition system module (ADAM 4118) that communicated with a personal computer through a RS-485 to RS-232 communications module (ADAM-4520).

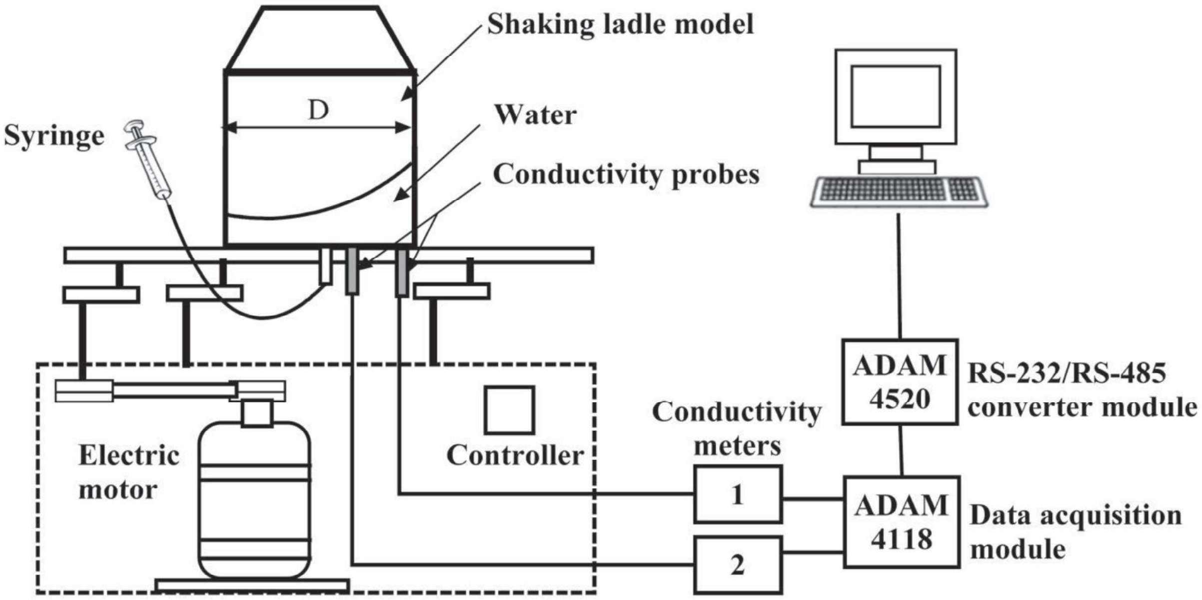
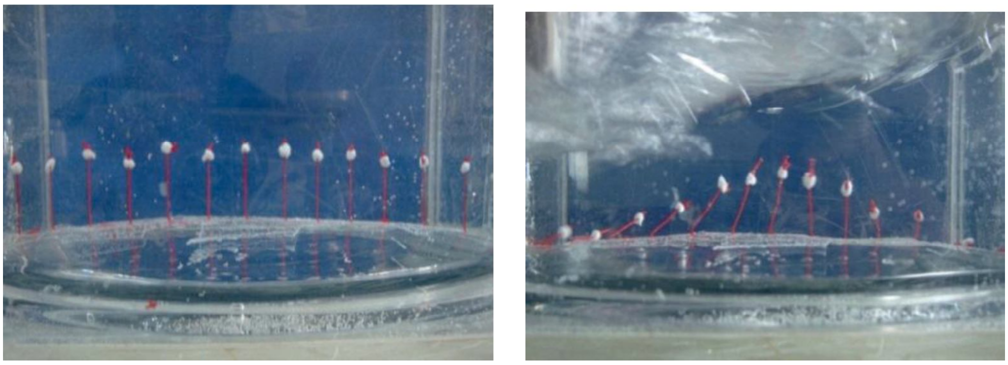


Figure 1: Experimental apparatus

It was shown in figure 2 in a preliminary experiment that the flow field in shaking ladle might be split into two regions, the dead zone near the center of the bath and the active zone near the wall, though the boundary of which was not clearly definite. Therefore, two arrangement modes of probes and tracer injection positions, as shown in figure 3, were employed to observe the influence of the position of the measuring probe, as well as the location of the tracer injection in the bath.



a - Stationary state b - Shaking state

Figure 2: Visualization of the flow field in shaking ladle

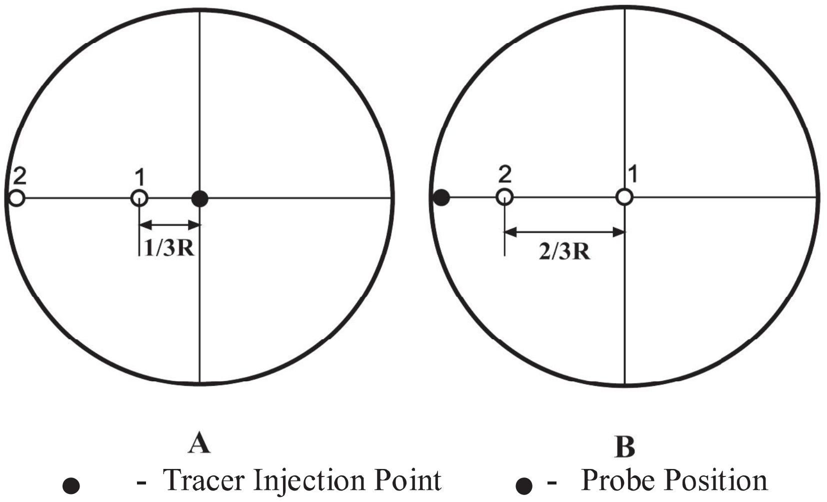


Figure 3: Schematic of the arrangement modes of probes and tracer injection locations in shaking ladle

The height of the wave in the bath was measured at the shaking speeds from 20 rpm to 80 rpm, as shown in figure 4. The mixing times at six typical shaking speeds were determined. Typical examples for curves of electrical conductivity *vs*. time curves are shown in figure 5.

For each experiment, the recording of tracer response was carried out until the concentration of tracer in the bath was considered to reach a homogeneously mixed value. At least three measurements were made for each operating condition, and an average mixing time was thereby calculated through the derivative criterion.

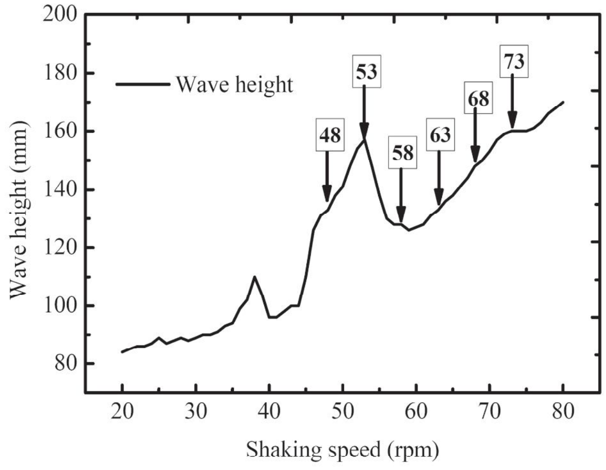


Figure 4: Wave height as a function of shaking speed

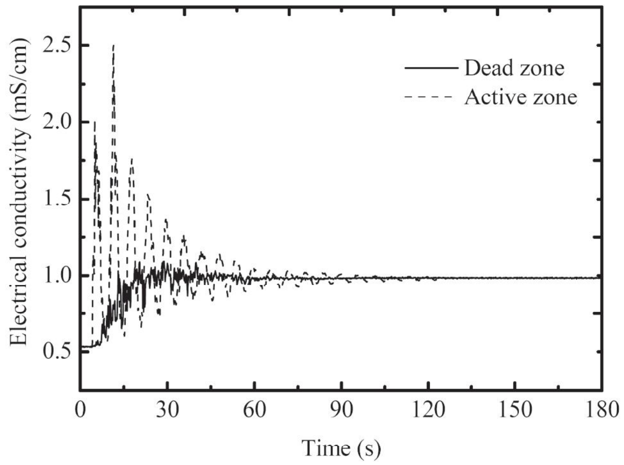


Figure 5: Typical example of electrical conductivity *vs*. time curves

4. RESULTS AND DISCUSSION

4.1 The determination of the mixing time

Two electrical conductivity probes were employed in the experiment. One was located in the dead zone while the other in the active zone. According to the derivative criterion the value of mean segregation intensity could be expressed as following:

$$\overline{I} = \frac{1}{2}\left(\left|\frac{dC_1(t)}{dt}\right| + \left|\frac{dC_2(t)}{dt}\right|\right) \tag{7}$$

Theoretically, $\overline{I}$ would be equal to zero in a homogeneous bath. However, considerable oscillations in the conductivity value were observed because of the system errors. Figure 6 shows the value of $\overline{I}$ as a function of time in a uniform liquid. It can be seen that although $\overline{I}$ has a fluctuation, it always falls into the extent of 0 ~ 0.12 mS·cm^{-1}·s^{-1}. Therefore, 0.12 mS·cm^{-1}·s^{-1} was taken as the criterion of the mixing time. A typical example of definition of mixing time was shown in figure 7.

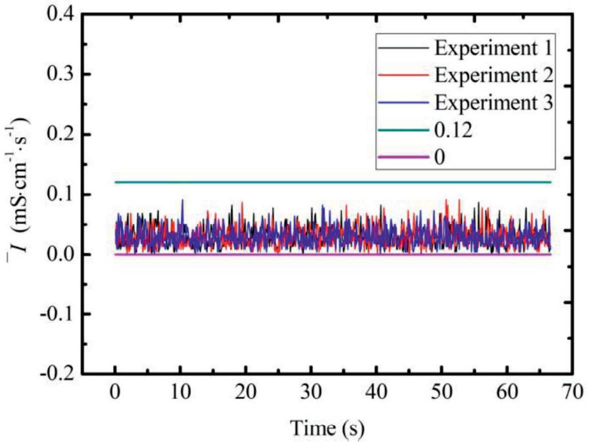


Figure 6: The definition of σ

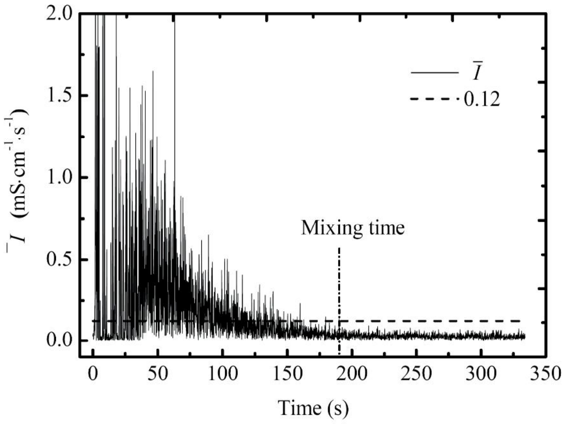


Figure 7: Typical example of mixing time

4.2 Relationship between mixing time and shaking speed

Figure 8 shows the relationship between mixing time and wave height at different shaking speeds. According to Ektorp's definition [1], the critical shaking speed is 53 rpm for the present experiment. However, the shortest mixing time was obtained at 63 rpm for both A and B conditions, rather than the "critical shaking speed". The result indicates that the values of wave height in the bath can not reflect the mixing efficiency exactly and the "critical shaking speed" is only for the wave height, not the mixing efficiency.

The relationship between the mixing time T_{mix} and shaking speed n could be fitted with the following formula:

$$T_{\text{mix, A}} = 73622e^{-0.1131n} \tag{8}$$

$$T_{\text{mix, B}} = 2902e^{-0.0671n} \tag{9}$$

Where $T_{\text{mix, A}}$ is the mixing time when the tracer is injected in dead zone and $T_{\text{mix, B}}$ is in the active zone.

It is shown in figure 8 that, the mixing time is obviously shorter as soon as the speed is over 63 rpm. Chih-Peng Tsai [6] classified the motion behaviors of liquid in shaking ladle into three states: surface wave state, transition state and rotating state, with the increase of shaking speed, which is shown in figure 9. As was observed in the experiment, both transition state and rotating state may be substituted for one, namely flow motion state. Figure 10 shows that the mixing times are shorter in the flow motion state than that in the wave motion state. The flow motion is more efficient than wave motion for bath agitation. Therefore, the critical shaking speed may be defined as the shaking speed at which the wave motion transforms into the flow motion. Further investigations will be carried out to obtain an empirical equation of the new critical shaking speed as a function of the bath diameter, bath depth, and eccentric distance.

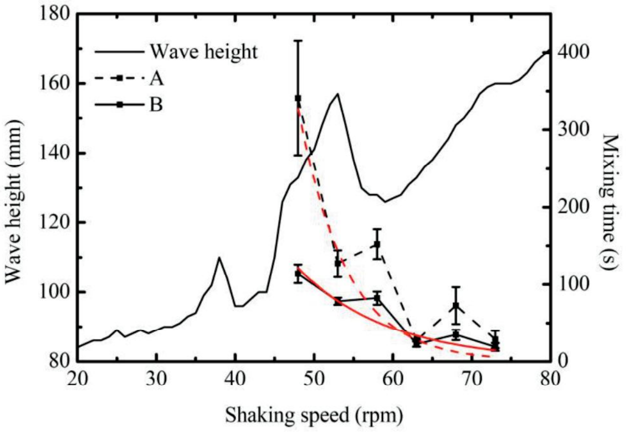


Figure 8: Mixing times and wave height as functions of shaking speed

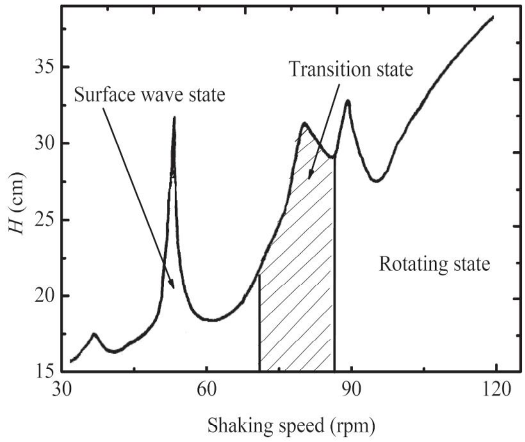


Figure 9: The classification of motion behavior in shaking ladle (reproduced from [6]

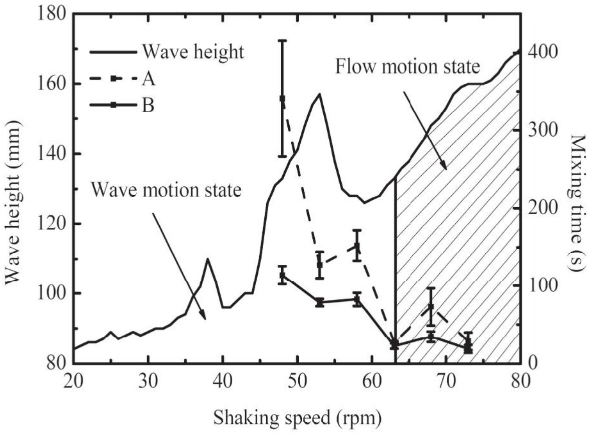


Figure 10: Mixing times for different liquid motion states

4.3 The influence of tracer injection position to mixing time in shaking ladle

As was shown in figure 8, the values of mixing time are dependent on the tracer injection positions in shaking ladle. The mixing time that determined with the tracer injected in dead zone (condition A) is greater than that in the active zone (condition B). This indicates that the mixing times determined by different tracer injection positions are uncomparable. Furthermore, the differences decreased with the increase of shaking speed. The reason may be that the increase of mixing intensity makes the dead zone more active.

5. CONCLUSIONS

The experiment to investigate the mixing time as a function of shaking speed in shaking ladle was performed by means of tracer dispersion test. A new concept, mean segregation intensity, $\overline{I}$, based on the derivative of concentration with respect to time, was employed to determine the mixing time in shaking ladle. Following conclusions can be drawn from the present work:

(1) The flow field in shaking ladle can be split into two regions, the dead zone near the center of the bath and the active zone near the wall.

(2) The mixing time is dependent on the tracer injection position in shaking ladle. This suggests that only the mixing times determined with the same tracer injection position are comparable.

(3) The mixing efficiency at the critical shaking speed based on the wave height is not desirable. The wave height can not reflect the mixing efficiency exactly. A new critical shaking speed at which the mixing efficiency is desirable, is defined as the shaking speed at which the wave motion transforms into the flow motion.

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7. LIST OF SYMBOLS

a	Eccentric distance, cm
C_∞	The tracer final average uniform concentrations, $\mathrm{mS\cdot cm^{-1}}$
C_0	The tracer initial average uniform concentrations, $\mathrm{mS\cdot cm^{-1}}$
$C_{(t)}$	The uniform concentration of tracer at time t, $\mathrm{mS\cdot cm^{-1}}$
D	The change rate of the tracer concentration with respect to time, $\mathrm{mS\cdot cm^{-1}\cdot s^{-1}}$
g	Gravitational constant, $\mathrm{m/s^2}$
H	Height of the bath, m
$\overline{I}$	Mean segregation intensity of the bath, $\mathrm{mS\cdot cm^{-1}\cdot s^{-1}}$
n_c	Critical shaking speed, rpm
R	The radius of the bath, m
σ	The constraint factor of the mean segregation intensity, $\mathrm{mS\cdot cm^{-1}\cdot s^{-1}}$
T_mix	Mixing time, s
Y	The extent of mixing

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