Model Study on Shaking Ladle*

By Chih-Peng TSAI** and Zhan-Min QIAN**

Synopsis

This paper deals with the behavior of liquid in the shaking ladle as revealed in model experimental study. A series of experiments have been made by the use of four size models with different liquids, by varying eccentricity, rotational speed and the amount of charge. Four critical states of liquid motion in the shaking ladle have been discovered: oscillatory motion, the 1st and 2nd monobreaker wave motions, multiple breaker motion and rotational paraboloid motion. The 2nd and the multiple breaker wave motions as well as the rotational paraboloid critical states are of practical importance to metallurgical production. The stirring action strongly promotes the chemical reaction in the liquid bath. Some empirical formulas for calculating these critical rotational speeds have been established from experiments. The results obtained by the use of a 10-ton commercial shaking ladle with liquid iron at above 1 200 °C, are in good agreement with those of laboratory scale investigations. Consequently, optimal shaking parameters have been proposed for production operation.

I. Introduction

The shaking ladle has been widely applied in metallurgy for eliminating P, S, Cr, V, Nb, Si, C, etc. during metal processing. In desulfurization, the concentration of sulfur can be reduced to as low as 0.01 %, ¹⁾ thus providing a more favorable condition for smelting high-quality steel in oxygen top-blown converter. In South Africa, a good result has been achieved in a 60-ton shaking ladle for processing ferrovanadium, ²⁾ and it is also used to smelt high-grade cast iron ^{2,3)} and nodular cast iron and to adjust the chemical composition of iron in the casting process. It is also employed to smelt simple ferro-chrome and other special ferro-alloys in ferro-alloy works. ⁴⁾ Therefore, further investigation on the behavior of liquid in the shaking ladle is of great importance to optimal design of the shape of the shaking ladle, its geometrical dimensions, eccentricity, rotational speed, driving horsepower, etc., and of practical significance, too, for selecting optimal operation parameters in production.

II. Experiments and Measuring Apparatus

1. Shaking Frame

Three adjustable eccentric crank shafts are driven by a DC-motor through a worm-gear-reducer with a velocity ratio of 1/24, and the shaking ladle fixed on the triangular shaking frame is shaking but without autorotation at the same time. Its eccentricity can be continuously adjusted within the range of 0~50 mm.

2. Adjuster

The shaking frame can shake at a continuously

variable rate in the range of 0~125 rpm through a TYPE ZTD-20 SCR adjuster.

3. Apparatus for Measuring Rotating Speed

Measurement of revolution speed of the shaking ladle is made through a disc with 25 holes which is mounted on a coupler connecting the motor and reducer. A small lamp is fixed on one side of the disc, and a photodiode, with its impulse-amplifier circuit fixed on the other side. When a small hole on the disc passes the photodetector, and impulse signal inputs to the TYPE PS-25 digital frequency meter, and the rotational speed of the shaking ladle (rpm) is displayed automatically. The shaking states of liquid in the ladle were observed by means of flow-visualization with a special bubbling-polymerized styrene particles.

4. Shaking Ladle Models

Four models were used, all made of Plexiglass with different sizes ($D=38.6$ cm, 28.6 cm, 24.0 cm, and 18.4 cm). The shaking state of the liquid surface at different revolutions is shown by a ruler stuck on the model. The experimental equipment of the shaking ladle is shown in Fig. 1.

Fig. 1. Model experimental equipment of shaking ladle.

* Manuscript received on May 27, 1985; accepted in the final form on October 11, 1985. © 1986 ISIJ

** Institute of Chemical Metallurgy, Academia Sinica, Beijing, China.

III. Experimental Results

A series of experiments has been made with the models, using as water, aqueous potassium iodide, carbon tetrachloride, mercury, aqueous glycerin, transformer oil and a low-melting alloy. The physical properties of the various liquids are as shown in Table 1.

The experiments were made under different conditions, such as variable radius R , eccentricity a , and the height of liquid charge H_0 . The variation of liquid surface wave height has been recorded as

Table 1. Physical properties of the experimental liquids.

Experimental medium	Temperature (°C)	Density (g/cm)	Surface tension (dyn/cm)	Viscosity (g/cm·s)
Water	20	0.998	72.75	0.01
Aq. potassium iodide	20	1.6		
Mercury	20	13.545	471.60	0.0163
Low-melting alloy	65~70	7		
Liquid iron	1 300	7	800	0.075
Liquid iron	1 400	7	800	0.070
Carbon tetrachloride	20	1.594	26.8	0.0097
Aqueous glycerin	20	1.027		0.0318
Aqueous glycerin	20	1.07		0.123
Aqueous glycerin	20	1.129		0.710
Transformer oil	20	0.9		2.32

follows:

IV. Behavior of Liquid in the Shaking Ladle

Figure 2 shows the motion of the liquid in the ladle while shaking eccentrically without rotating about the vessel axis. It can be seen from Fig. 2 that the liquid surface waves move up and down at relatively low revolution speeds (left hand side in Fig. 2) and the particles in the liquid are free from relative motion with one another of any kind.

This is called the surface wave region. In this region, at a certain speed, such as point A_0 , surface oscillatory motion appears, at a frequency of once a circle, and at other point A_1 the 1st peak of wave appears on account of the overlapping or resonance of surface waves, similar to the sea breakers rising and falling. This critical point is called the 1st mono-breaker wave motion status.

At the region of relatively higher revolution speed (right hand side in Fig. 2 from point A_3), mainly rotational motion of the liquid appears along the inner wall of the vessel, and this is called the rotating motion region. The second peak A_3 appears at a certain revolution speed in this region. This critical point is called the 2nd mono-breaker wave motion status. From the view point of stirring effect of metal, it is favorable for production practice. Because the particle tracer in the liquid moves up and down

Fig. 2. The wave state of liquid in shaking ladle.

Fig. 3. Comparison of waves for high viscosity liquid.

sharper than before. When the revolution speed increases continuously again to a certain point, the rotating paraboloid motion state will occur at the liquid surface, point A_4 , then although the revolution speed is further increased, the rotating paraboloid motion state is maintained, only the liquid rotates much faster along the inner wall of the vessel with increase of revolution speed. If the revolution speed increases still higher, the liquid would stick to the wall of the vessel without relative motion, due to the centrifugal action.

There is a transition region from the former to the latter region (cross-hatched area in Fig. 2). In this region, not only the liquid surface moves up and down but also all the liquid rotates in the vessel. Therefore the multiple-breaker wave (2 or 3 waves) motion along the inner wall of the vessel occurs at the surface, but the waves refuse to fall down and its surface is lower than the previous one. Then all particles in the inner part of the bath move vigorously up and down. It can also be seen from Fig. 3 that another special phenomenon for liquid of high viscosity (*e.g.*, basic slag) appears, that is, the wave peak separates from the wall of the vessel and forms a stepped curve in Fig. 3. It not only gives good stirring effect but also greatly reduces erosion and impact on the wall of the furnace. It is thus favorable to increasing the life of the equipment and decreasing the cost of production.

Figure 4 shows a comparison of the wave forms for three liquids of different viscosities at the same value of H_0/R . It proves that the viscosity gives an effect only on heights of peaks but critical points.

Critical Revolution Speed N_{cr}

The second (mono-breaker wave motion) and fourth (rotating paraboloid motion) critical motion

Fig. 4. Comparison of waves for different liquid viscosities.

states, as well as the multiple-breaker wave state, have relevance to practical production. The 1st and 2nd critical revolution speeds of mono-breaker wave motion N_{cr} caused by resonance and rotating paraboloid motion have bearings on the radius of the vessel R , eccentricity a , height of liquid surface in static state H_0 , density of liquid ρ , viscosity of liquid μ , and gravitational acceleration g . Its functional relation is as follows:

$$f(N_{cr}, R, a, H_0, \rho, \mu, g) = 0 \quad \dots\dots\dots(1)$$

The functional relation of the dimensionless numbers has been obtained by the dimensional analysis as follows:

$$\phi\left(\frac{RN_{cr}^2}{g}, \frac{R^2N_{cr}\rho}{\mu}, \frac{R}{H_0}, \frac{R}{a}\right) = 0 \quad \dots\dots\dots(2)$$

where, RN_{cr}^2/g : a Froude number of shaking liquid motion in the ladle.

Its physical meaning is the ratio of inertial force to gravitational force. It shows the effect of gravitational force. The number $R^2N_{cr}\rho/\mu$ is a Reynolds number of shaking liquid motion in the ladle. Its physical meaning is the ratio of inertial force to viscous force, showing the effect of viscosity. The terms of R/H_0 and R/a are the geometrical numbers of the shaking ladle. They show the effects of the geometry of shaking ladle and the size of eccentricity.

Experiments indicate that, when the mono-breaker wave motion or rotating paraboloid motion state happens, the Froude number plays an important role, but the effect of Reynolds number is very little. Therefore, it can be neglected in studying the problems of breaker-wave motion. Thus the functional relation of dimensionless numbers mentioned above can be simplified as follows:

$$\frac{RN_{cr}^2}{g} = A\left(\frac{R}{H_0}\right)^m \cdot \left(\frac{R}{a}\right)^n \quad \dots\dots\dots(3)$$

where, A, m, n : the constants obtained from the experiments

$$\frac{RN_{cr}^2}{g} = 38.8 \left(\frac{R}{H_0} \right)^{-0.311} \cdot \left(\frac{R}{a} \right)^{0.03} \dots\dots\dots(4)$$

for the critical revolution speed of the first mono-breaker wave motion

$$\frac{RN_{cr}^2}{g} = 100 \left(\frac{R}{H_0} \right)^{-0.452} \cdot \left(\frac{R}{a} \right)^{0.124} \dots\dots\dots(5)$$

for the critical revolution speed of the second mono-breaker wave motion; and

$$\frac{RN_{cr}^2}{g} = 38 \left(\frac{R}{H_0} \right)^{-0.298} \cdot \left(\frac{R}{a} \right)^{0.562} \dots\dots\dots(6)$$

for the critical revolution speed of rotating paraboloid motion state. These equations are plotted in Figs.

○: Liquid iron Others: Aqueous glycerin
Fig. 5. Relation between dimensionless analogous numbers for the first mono-breaker wave motion.

○: Liquid iron Others: Aqueous glycerin
Fig. 7. Relation between dimensionless numbers for the rotating paraboloid motion.

5 to 7.

It has been found in the experiments that when $R/H_0 > 2.5$ under the conditions of constants R and a , liquid motion is different from the above statements, because the friction at the bottom of vessel becomes larger due to the less volume of liquid in the ladle. But when $R/H_0 < 0.833$ it hardly influences the critical revolution speed (see Fig. 8). It is in good agreement with the values found in Refs. 3) and 7).

It has been shown from the above experiments, that the radius of vessel R has the greatest influence, and the depth of charge H_0 has only secondary influence, on the critical revolution speed. The eccentricity, a , has a small influence on the first and second mono-breaker wave motion, but has larger influence on the paraboloid motion.

V. Experiments on 10-ton Shaking Ladle

Seven hot model experiments on the critical revolution speed were made with 10-ton shaking ladle in

Shanghai 1st steel work. After charging liquid iron into the 10-ton dechromization shaking ladle ($R=78$ cm, $a=10$ cm) and measuring its temperature (1 200 °C), the operation began. The revolution speed of the shaking ladle was measured by the use of a stop watch and the readouts from the operation room. The motion states of the liquid iron and the variation of the surface wave are observed and filmed at the lance frame. The experimental results with liquid iron on 10-ton shaking ladle are in good agreement with the results calculated from the empirical formula obtained in laboratory scale studies as shown in Table 2.

VI. Discussion

Eketorp and Kalling³⁾ first investigated the liquid motion in the shaking ladle and proposed the following relationship, $RW^2/g = f(H_0/R, a/R)$, but it is not specific enough. Then Ishii *et al.*^{5,6)} investigated this problem by the model experimentation, and obtained

Fig. 8. The relation between H_0/R and the first critical revolution speed N_{cr} .

Table 2. Experimental results on critical revolution speed on 10-ton shaking ladle.

Heats No.	Weight (t)	Temp. (°C)	N_{cr} 1		N_{cr} 2		N_{cr} 3	
			M*	C**	M*	C**	M*	C**
5041	7.80	1 190	no	20.2	29~32	30.9	42	41.0
5055	10.00	1 220	no	21.0	29~32	32.9	42	42.3
5224	8.50	1 220	no	20.2	29~33	30.9	42	41.0
5225	8.50	1 220	no	19.7	29~33	30.2	41	40.4
5291	9.57	1 250	18~22	19.5	29~32	30.2	41	40.6
5310	9 69	1 200	18~23	18.8	29~32	29.0	40	39.5
5312	9.75	1 200	18~22	19.2	29~31	29.5	41	40.0

N_{cr} 1: Critical revolution speed of the 1st mono-breaker wave
 N_{cr} 2: Critical revolution speed of the 2nd mono-breaker wave
 N_{cr} 3: Critical revolution speed of rotating paraboloid motion

M*: Measured
C**: Calculated

Fig. 9. Comparison between present investigation and previous authors.

the following empirical formula for the critical revolution speed:

$$N_{cr} = 9.5 \sqrt{\frac{1}{a} + \frac{5}{R}} \quad (\text{when, } H_0/R > 1.2)$$

$$N'_{cr} = \frac{1}{1.08} \left[(N_{cr} - 15) \log \frac{H_0}{R} + N_{cr} + 1.2 \right] \quad (\text{when, } H_0/R < 1.2)$$

According to them, there is only one critical point. But four critical motion states have been found in the present work by repeating experiments with different liquids. In Fig. 9 the results obtained by the present investigation are compared with those of the other authors. There is an average error of about 10 rpm between the curves calculated by Eketorp and Kalling and their experimental values. The effect of eccentricity was neglected in their calculations. But the calculated curves proposed by Ishii is in good agreement with his own experimental data. One can see that all the experimental values obtained by both Eketorp and Kalling and Ishii are only in good agreement with the curve of the second mono-breaker wave motion of our present investigation.

VII. Conclusions

(1) Four critical revolution speeds in the shaking ladle have been found by experiments with water, aqueous potassium iodide, carbon tetrachloride, mercury, aqueous glycerin, transformer oil and an alloy of low-melting point in the present work. Experiments with liquid iron (1 200~1 400 °C) in a 10-ton shaking ladle showed that the results of laboratory scale experiments are in good agreement with those of production scale.⁷⁾

(2) Operation under the conditions of either the second mono-breaker or the multiple-breaker wave state, is recommended for production, in order to maintain good stirring and long liner life.

(3) For the furnace with $D/H_0=1$, the amount of charge should be controlled so as to be $H_0/R=0.8 \sim 1.0$ in order to prevent overflow, as was proved by both model experiments and practice on a 10-ton shaking ladle.

(4) The present experiments are made according to the theory of similarity, the present results may be taken as a reference in shaking ladle design for the range of $H_0/R=0.4 \sim 1.6$ and $R/a=14.3 \sim 2.04$.

Nomenclature

- a : eccentricity (cm)
- D : diameter of the vessel (cm)
- H_0 : height of the liquid surface in static state (cm)
- g : acceleration of gravity (cm/s^2)
- N_{cr} : critical revolution speed (rpm)
- R : radius of the vessel (cm)
- μ : viscosity of liquid ($\text{g/cm} \cdot \text{s}$)
- ρ : liquid density (g/cm^3)

Acknowledgements

The authors would like to express their appreciation to Professor Kwauk, Director of the Institute of Chemical Metallurgy, for his guidance and useful comments throughout this study. They are also grateful to Professor Ryuzo Ito, Department of Chemical Engineering, Osaka University, Japan, for his valuable advice on data processing.

REFERENCES

- 1) *Tetsu-to-Hagané*, **51** (1965), 376.
- 2) B. Rohrman and A. G. Raper: *JISI*, **208** (1970), 336.
- 3) S. Eketorp and B. Kalling: *Giesserei*, **46** (1959), 905.
- 4) Lu Zhixiang: *Ferroalloy*, **4** (1981), 29~34.
- 5) K. Ishii: *Suiyo Kaishi*, **15** (1964), 253.
- 6) H. Shindo, Y. Nagoya and K. Ishii: *Suiyo Kaishi*, **14** (1962), 481.
- 7) C. P. Tsai, A. W. Xia and Z. M. Qian: *Iron Steel*, **14** (1979), June, 23~27.