Modeling on Emulsification of Slag and Metal in Shaking Ladle

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Abstract

The shaking ladle is one of the main equipment for producing low & medium carbon ferromanganese with electric furnace-shaking ladle process. The emulsification behaviour of slag and metal in shaking ladle has been studied experimentally using low-temperature oil and water. The entrainment critical shaking speed (ECSS) was defined as the lowest shaking speed at which the entrainment of slag occurs. It was found that the ECSS was decreased with the increasing of ladle diameter, eccentric distance and the density of the lower phase, and was increased with the increasing of lower phase height, the height difference and the density difference of the two phases, the viscosity of the two phases. An empirical equation for the ECSS was proposed as a function of ladle diameter, eccentric distance, the height and physical properties of the liquids.

KEYWORDS: *shaking ladle; emulsification; entrainment critical shaking speed.*

1. Introduction

Low-carbon ferromanganese (LC FeMn) alloys are preferred for the production of low-carbon steel and other special grades of steel. Two principal methods of producing LC FeMn are in commercial operation. The first one is silicothermal reduction and the second is manganese oxygen refining process (MOR)[1]. Because of the high SiO_2 content of Chinese manganese ores, the siliconthermal reduction method is widely used in China [2]. The refining furnace-shaking ladle process is the most popular one for producing LC FeMn nowadays. A flow-chart of the process is shown in Fig. 1.

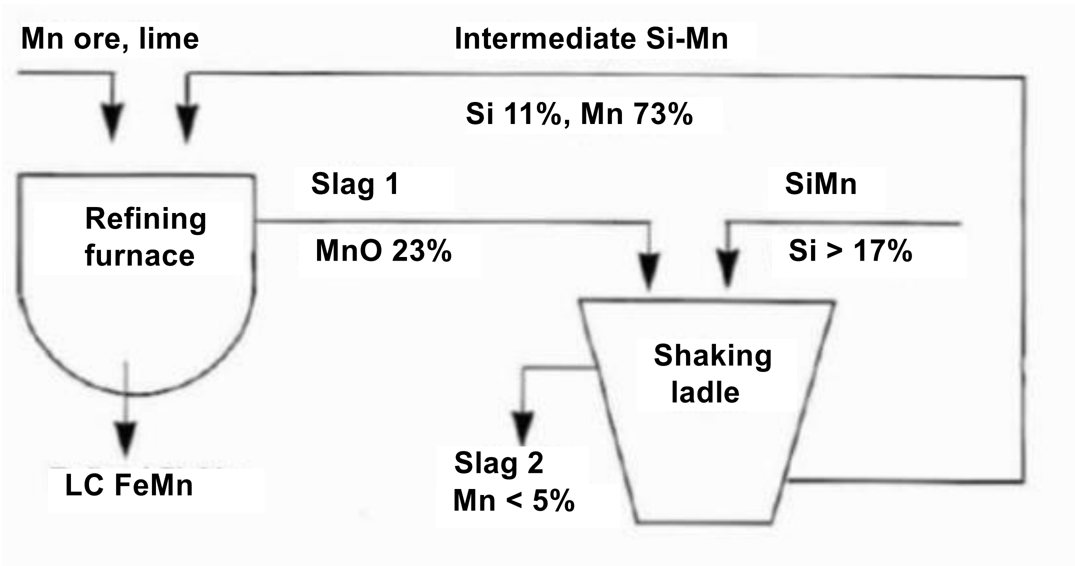

Fig. 1. Flow chart for the refining furnace-shaking ladle process for the production of LC FeMn[2]

The shaking ladle was developed by Kalling[3] at Domnarvet, Sweden in 1958. The shaking ladle has been proved as an excellent metallurgical tool wherever it is necessary to obtain good mixing, for instance, in desulfurization, recarburization and alloying of pig iron[4], production of low and medium carbon ferromanganese and ferrochrome[5], processing of ferrovanadium[6] and stainless steel[7].

The single-phase liquid mixing phenomena in shaking ladle has been investigated by different researchers [3,8-9]. Eketorp [3] measured the wave heights in the bath during shaking in different speeds, and proposed the definition of critical shaking speed, nc, at which a characteristic wave motion was created which looks like a breaker and the wave height in the bath reached a maximum value. Ishii[8]and Tsai [9] continued studies in this field and proposed their empirical equations for the nc as a function of R (radius of ladle, mm), H (height of bath, mm) and a (eccentricity, mm). In the earlier paper[10], the present authors proposed another way to investigate the mixing efficiency in shaking ladle bath by measuring the mixing time, and a new critical shaking speed was defined based on mixing time. In addition, a bioreactor named orbitally shaken bioreactor which is used for the cultivation of mammalian cells has drawn the attention in recent years, and a lot of research results were reported about the single phase liquid behaviour[11-16].

However, the mixing phenomena of two immiscible liquids have not been reported yet, though it is very important for the LC carbon FeMn. In the present work, the mixing process of slag/metal in shaking ladle was studied using low-temperature oil/water analogues. And an empirical equation for the slag entrainment critical shaking speed was proposed.

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic of the experimental apparatus. Water and one of the two oils listed in Tab. 1 were contained in a cylindrical vessel made of transparent acrylic resin. Three vessels were used, with different size (D=0.19 m, 0.24 m, 0.29 m). The vessel was placed on the shaking frame. The eccentricity can be continuously set within the range of 0~50 mm. The liquids behaviours were recorded by a high speed camera with a capture rate of 200 fps.

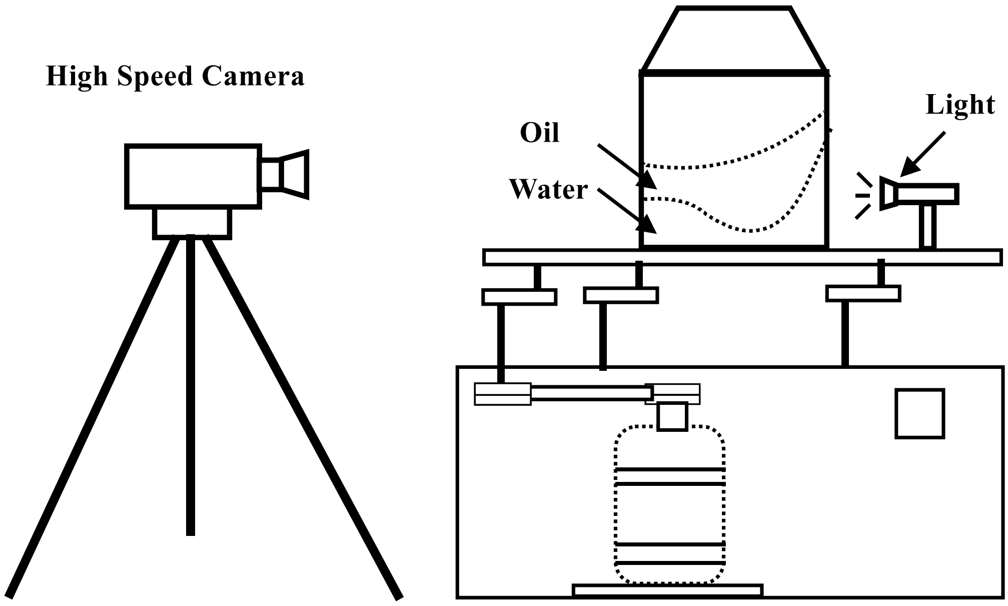

Fig. 2. Experimental apparatus

Tab 1: Operating variables and their ranges of model experiments

Liquid	Density (kg/m^3)	Viscosity (mPa·s)	Surface tension (mN/m)	Interface tension with water (mN/m)
Bean oil	926	71.8	31.2	13.4
Machine oil	933	103.2	32.0	12.0

3. Experimental Phenomena

As described in an earlier paper [17] of the present authors, with the increase in the shaking speed the flow patterns of two liquid phases in shaking ladle could be classified into three types: interface oscillatory pattern, lotus-leaf-like pattern and entrainment pattern (Fig 3). The two layers will maintain stratified status when the shaking speed is low, just as the interface oscillatory pattern and lotus-like pattern shows. However, the lower liquid will be entrained into the upper liquid with the increase in the shaking speed, and the entrainment pattern formed. The lowest shaking speed at which the entrainment of slag occurs is defined as the entrainment critical shaking speed (ECSS).

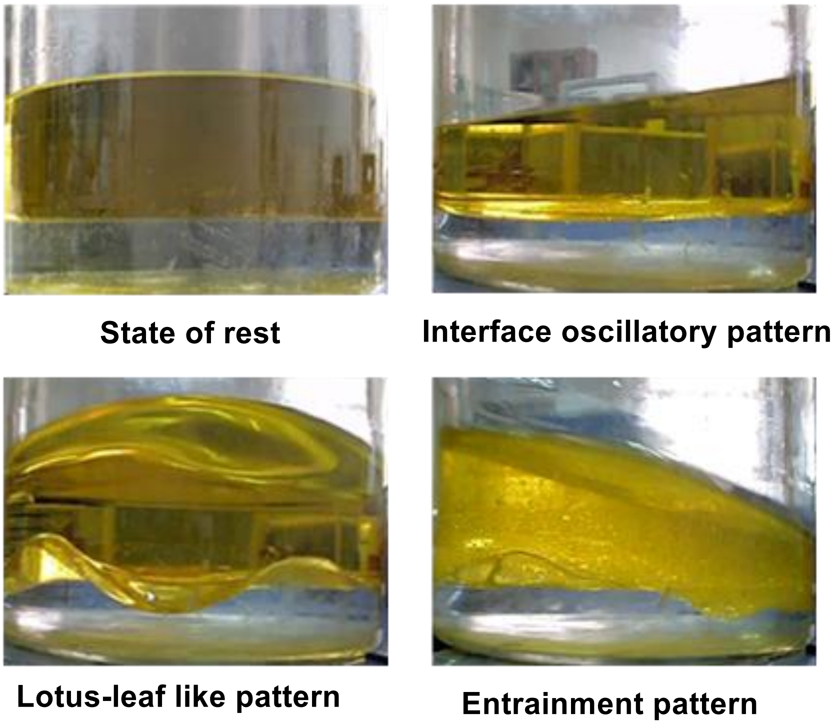

Fig. 3. The flow patterns under different shaking speeds

4. Results and Discussions

4.1 Effect of ladle diameter on ECSS

The effect of ladle diameter on ECSS was studied with 3 different ladles, and the oil used in this experiment was bean oil. The experimental conditions are shown in Table 2. The relationships between ECSS and ladle diameter at four eccentric distances are shown in Fig. 4.

Tab. 2. Experimental conditions

Ladle diameter/m	Oil height/10^{-2}m	Water height/10^{-2}m
0.19	4.4	2.9
0.24	5.5	3.7
0.29	6.7	4.5

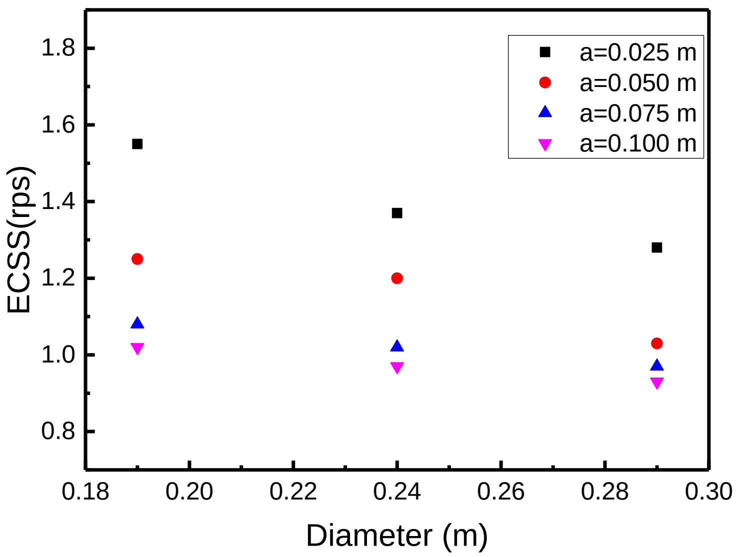

Fig. 4. Effect of shaking ladle diameter on ECSS

As can be seen from Fig. 4, the ECSS decreases with the increase in ladle diameter. It indicates that bigger ladle is more favourable for the mixing of slag and metal in shaking ladle. In addition, the dissipating heat of unit volume molten liquid in a bigger vessel is less than that in a smaller one, which will reduce the heat loss in the process of production.

4.2 Effect of liquid height on the ECSS

The ladle diameter used in this experiment is 0.29 m and the eccentric distance is 1.5 cm. The height of water is 3.4 cm, and the height ratio of oil and water varies with the change of bean oil height. The effect of liquid height ratio on the ECSS is shown in Fig. 5. It can be seen from Fig. 5 that the ECSS increased with the increasing height ratio of the two phases. It indicates that the less slag was better for mixing of slag and metal. When the amount of slag increases, the shaking speed should be increased in order to promote better two-phase mixing.

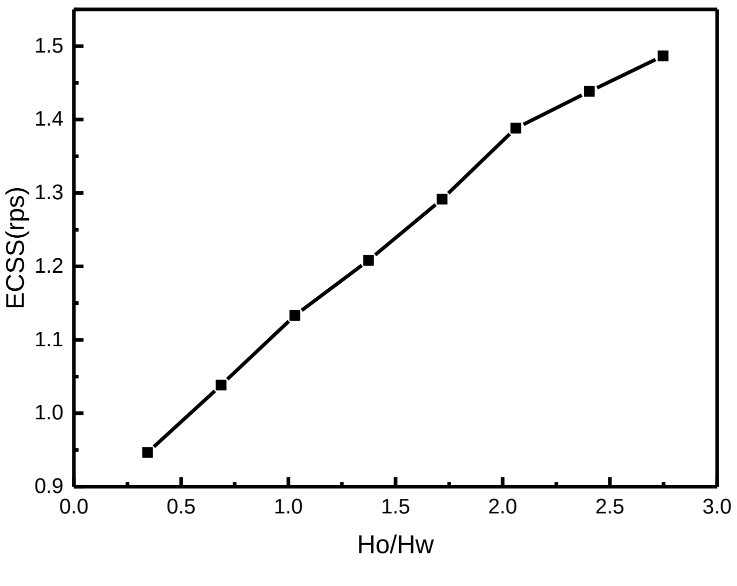

Fig. 5. Effect of height ratio of oil and water volume on ECSS

4.3 Effect of eccentric distance on the ECSS

The value of eccentric distance determines the shaking amplitude of the shaking ladle, which is very important for the emulsification of slag and metal. The effect of eccentric distance on the ECSS was investigated in three ladles with different diameters. The experimental results are shown in Fig. 6. As can be seen from Fig. 6, the ECSS decreases with the increase in the eccentric distance indicating that a larger eccentric distance is favourable for the emulsification of the two phases.

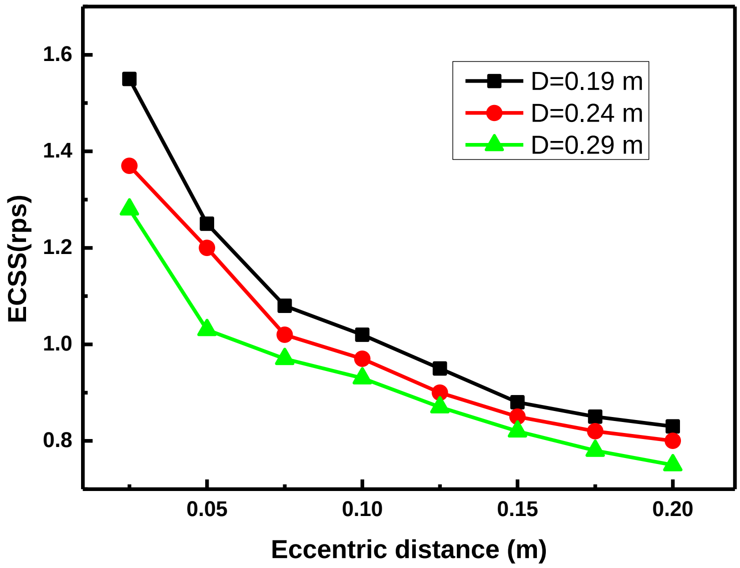

Fig. 6. Effect of eccentric distance on ECSS

4.4 Effect of upper phase property on the ECSS

In actual production, slag phase composition and physical parameters will be different depending on different products. Bean oil and machine oil were used to investigate the effect of upper phase property of ECSS in shaking ladle. The properties of the two oils are listed in Table 1. It can be seen from Table 1 that the main difference between the two oils is the value of viscosity. The experimental result is shown in Fig. 7. As can be seen from Fig. 7, the ECSS for machine oil-water system is lower than that for the bean oil-water system. It indicates that the lower viscosity makes mixing easier.

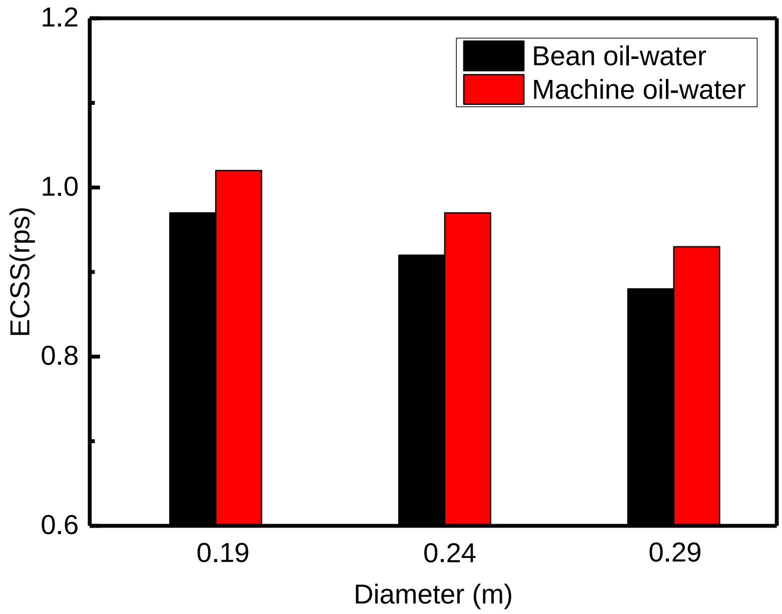

Fig. 7. Effect of upper phase property on ECSS

4.5 Effect of lower phase density on the ECSS

Gravity is the main force to stabilize the interface of two phases in shaking ladle. A NaCl aqueous solution was used to investigate the effect of lower phase density on ECSS. The densities of the three liquids are listed in Table 3. The experimental results are shown in Fig. 8. It can be seen that the bean oil-NcCl aqueous solution system, for which the density difference is bigger, is easier to mix with each other in shaking ladle when the height ratio of the two-phase is small. However, with the increase in the ratio, the effect of the lower phase density decreased and could be ignored.

Tab. 3. The density differences between the two systems

	Bean oil-water	Bean oil-NaClaqueous solution
Lower phase density（kg/m^3）	1000	1190
Upper phase density（kg/m^3）	926	926
Density difference（kg/m^3）	74	264

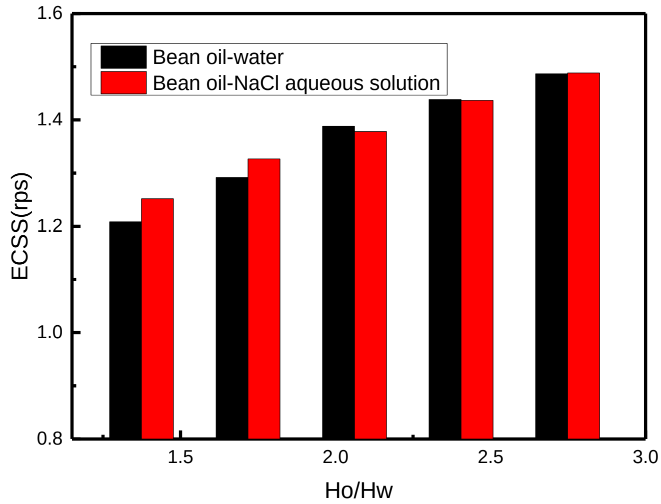

Fig. 8. Effect of lower phase density on ECSS

4.6 Dimensional analysis

Based on experimental results and the preceding discussion, one can carry out a preliminary dimensional analysis by assuming that the ECSS is dependent on the variables listed in the following correlation:

$$N_{ce} = f(D, a, H_w, \Delta H, \mu_o, \mu_w, \rho_w, \Delta\rho, \sigma_{ow}, g) \quad (1)$$

where N_{ce} (rps) is the ECSS; D (m) is the ladle diameter; a is the eccentric distance; H_w (m) is the lower phase height; ΔH (m) is the height difference of lower and upper phases; μ_w (Pa·s) is the viscosity of water andμ_o(Pa·s) is the viscosity of oil; ρ_w (kg/m^3) is the density of lower phase and $\Delta\rho$ (kg/m^3) is the density difference of lower and upper phases; σ_{ow} is the interfacial tension between the two liquids; g is the gravitational constant.

In Eq. (1), there are 11 variables and three fundamental dimensions; therefore, eight dimensionless groups are to be obtained:

$$\pi_1 = \frac{D}{H_w} \quad (2)$$

$$\pi_2 = \frac{a}{H_w} \quad (3)$$

$$\pi_3 = \frac{\Delta H}{H_w} \quad (4)$$

$$\pi_4 = \frac{\rho_w^2 g H_w^3}{\mu_o^2} \quad (5)$$

$$\pi_5 = \frac{\rho_w^2 g H_w^3}{\mu_w^2} \quad (6)$$

$$\pi_6 = \frac{\Delta\rho}{\rho_w} \quad (7)$$

$$\pi_7 = \frac{\rho_w g H_w^2}{\sigma_{ow}} \quad (8)$$

$$\pi_8 = \frac{N_c^2}{gH_w} \quad (9)$$

Through dimensional analysis, the Eqs. (2) to (9) lead to the functional relationship that

$$\pi_8 = f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7) \quad (10)$$

or, for the first memeber of a polynomial series, that

$$\pi_8 = K\pi_1^{\alpha_1}\pi_2^{\alpha_2}\pi_3^{\alpha_3}\pi_4^{\alpha_4}\pi_5^{\alpha_5}\pi_6^{\alpha_6}\pi_7^{\alpha_7} \quad (11)$$

By applying multiple regression analysis to the experimental results, the following relationship between the ECSS and other independent variables was obtained:

$$N_{ce} = 2.36\times10^4 D^{-0.83} a^{-0.27} H_w^{0.51} \Delta H^{0.07} \mu_o^{0.05} \mu_w^{0.74} \rho_w^{-0.80} \Delta\rho^{0.12} \quad (12)$$

Fig. 9 compares the measured values and calculated values of the ECSS at different experimental conditions. The measurement is approximated by Eq. (12) with a scatter of ±10%.

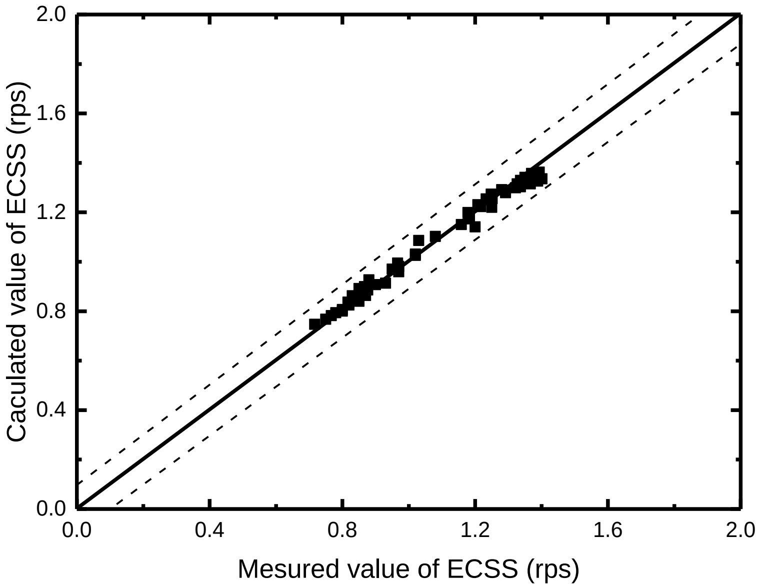

Fig. 9. Relation between measured and calculated values of ECSS

5. Conclusion

The entrainment critical shaking speed has been studied experimentally using bean oil-water system and machine oil-water system. From the present work, the following conclusions can be drawn:

(1) The ECSS was decreased with the increase in the ladle diameter, eccentric distance and the density of the lower phase, and was increased with the increase in lower phase height, the height difference and the density difference of the two phases, the viscosity of the two phases;

(2) Dimensional analysis was used to express the empirical equation of ECSS. With the present modelling study, the empirical equation can be expressed as follows: $N_{ce} = 2.36\times10^4 D^{-0.83} a^{-0.27} H_w^{0.51} \Delta H^{0.07} \mu_o^{0.05} \mu_w^{0.74} \rho_w^{-0.80} \Delta\rho^{0.12}$.

Acknowledgements

The authors gratefully acknowledge research funding from the National Natural Science Foundation of China (Nos. 51274030 and 51204001).

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