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Experimental model study for separation and dissolution of liquid inclusions at the interface between steel and slag

M. MAGNELÖV*, U. SJÖSTRÖM*, and DU SICHEN†
**Process Metallurgy Department, MEFOS, Luleå, Sweden*
†Royal Institute of Technology, Stockholm, Sweden

An experimental study has been performed to investigate the behaviour and separation of inclusions at the interface between steel and slag. The study has been limited to liquid inclusions because they can be a potential problem in transient situations such as ladle changes in continuous casting of steel.

Model experiments with water and silicon oils have been carried out to study the kinetics of separation of simulated inclusions at an interface. The properties of the inclusions and the slags have been varied by using different oils with different viscosities, densities and surface tensions. The effect of temperature of the liquids has also been examined. Measurements of the terminal velocity, rest time and the behaviour of the liquid inclusions at the interface have been recorded using a video camera.

It has been found that the inclusions reach their terminal velocity early in the vessel and the experimental velocities differ somewhat from the values evaluated using 'intermediate law'. The results from the experiments have shown that the size of the inclusions has no appreciable influence on the rest time. Droplets of AK50 oil have been found to have considerably long rest time. A water film surrounding the droplet has been expected to be the main reason for the long rest time. The present study has also shown that the viscosity of the oil has certain effect on the rest time, but only to some extent, since viscosity has double functions. A higher viscosity provides higher resistance to the droplet entering the oil phase leading to longer rest time and at the same time damps the lateral movement of the droplet along the interface, leading to easier stabilization and shorter rest time. On the other hand, a high viscosity of the oil phase results in slow dissolution process.

It has been concluded that a meaningful model of inclusion separation at the metal-slag interface must take the interfacial phenomena into consideration.

Keywords: Inclusions, terminal velocity, rest time, dissolution.

Introduction

Inclusions can be generated when the steel is transferred from one vessel to another, e.g. from ladle to tundish in continuous casting of steel. When the steel is teemed into a tundish, both the ladle slag and the tundish flux are emulsified in the steel. The emulsification leads to inclusions, which result in surface and internal defects in the products. To avoid and at least reduce the number of this kind of defects, the inclusions must be transported to the interface between steel and slag and there separate to the slag phase.

A number of investigations have been carried out to study the behaviour of inclusions at the steel-slag interface. Chevrier[1] has studied the separation of argon bubbles in both water-oil and metal-slag systems[1]. Misra *et al.*[2] have studied the rest time of inclusions at metal-slag interface and have reported that the rest time depends considerably on the inclusion type and may be quite long in industrial vessels such as ladle, tundish and mould. Study of the separation and dissolution of Al_2O_3 inclusions at the interface between steel and slag has been carried out by Lee *et al.*[3]. They have concluded that liquid inclusions are able to separate across the interface and get dissolved into the slag, while solid inclusions stay at the interface and agglomerate. Sridhar *et al.*[4] have studied the dissolution of Al_2O_3 in slag and have suggested that the boundary layer diffusion is the rate controlling step. The separation of gas bubbles has been investigated by Schwertfeger *et al.*[5]. The authors have observed that material from the lower phase is carried with the gas bubbles into the upper phase in all systems.

The aim of this work is to understand the behaviour of the inclusions. Emphasis is given to the visualization of the movement of the liquid inclusions and their separation as well as dissolution at the slag-metal interface. For this purpose, cold model experiments are performed.

Experimental

Setup and materials

The experimental setup is schematically presented in Figure 1. The dimensions of the vessel are 0.2x0.16x0.4 m. Two sides of the vessel, namely the front side and back side, are made of glass and the other two are made of cupper. The temperature of the liquid can be varied between 20 and 100°C with two heating coils installed on the cupper walls. In order to introduce gas injection, a pipe with an ID of 4.0 mm and OD of 6.0 mm is immersed into the liquid bath. Its orifice is placed 4.0 cm from the front wall, 4.0 cm from the side wall and 3.0 cm above the bottom. Liquid droplets can be injected by a nozzle at the centre of the vessel bottom. The prescribed droplet size was injected into the vessel via syringes.

Water was used to simulate the liquid steel, while two different oils, viz. AK50 and AK5000 were employed to simulate top slag. Oils, AK50 and OD40 were used to generate liquid droplets as inclusions. In order to visualize the droplets, trace amount of colour, called Sudan Red, was added into the oils. The addition of Sudan Red would not change the physical properties of the AK50 oil and OD40 oil according to the supplier. The physical properties of water and the oils are listed in Table I and Table II, respectively. In Figure 1, the water level is marked as Hv, and oil level as Ho.

Experimental procedure

When a droplet with pre-determined diameter was released from the nozzle, it was first transported through the water phase. Due to the density difference between the oil and water, the droplet would float up and reach the interface between water and oil. The droplet was found to rest at the water-oil interface and keep its original shape for a certain period of time before it separated and started spreading and dissolving into the oil phase. The whole process was recorded using a digital video camera. The terminal velocity, the rest time and the dissolution time were obtained by image analysis of the video film.

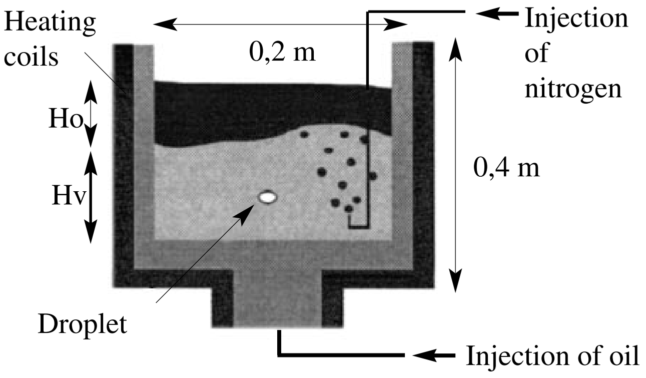

Figure 1. Schematic of the experimental apparatus

In the experiments, the height of the oil layer was kept constant, either 30 or 40 mm. Different water levels varying between 50 and 100 mm were employed to study the effect of the steel level in the tundish on the separation of liquid inclusions. While in most of the experiments, a droplet diameter of 3.4 mm was adopted, different sizes of droplets were also used to examine the impact of the size of the liquid inclusions on their behaviour.

In order to study the effect of temperature, different temperatures were employed. Even experiments with asymmetrical heating (only one of the walls was heated) were performed. In some experiments, nitrogen gas was injected to introduce forced convection.

Each experiment was repeated a number of times to examine the reproducibility. The terminal velocity, the rest time and the dissolution time were taken as the average values over these experiments.

Result

Terminal velocity

When the droplet was released from the nozzle and was transported through the water phase, it behaved in different ways. The motion of the droplet in a stirred fluid was different from its motion in a stagnant fluid. When no heating was applied, the droplet had a straight way up to the interface but when the same experiments were performed at higher temperatures, 50 and 80°C, the droplet moved in all directions on its way up to the interface. This situation is schematically shown in Figure 2. Experiments were performed with asymmetrical heating of the vessel and by gas injection to investigate the effect of local convection. But the droplet did not move differently in the water phase compared to the experiments with symmetrical heating.

Table I
Physical properties of water

Physical properties	Water	Water	Water
Temperature (°C)	20	50	80
Density (kg/m³)	998.2	988.1	971.8
Dynamic visc. (Pa·s)	$1005\cdot10^{-6}$	$549\cdot10^{-6}$	$357\cdot10^{-6}$
Kinematic visc. (m²/s)	$1.004\cdot10^{-6}$	$0.556\cdot10^{-6}$	$0.367\cdot10^{-6}$
Surface tension (mN/m)	72.8		

The velocity of the droplet reaching the water-oil interface is a measure of the kinetic energy of the rising object. In fact, once the forces acting on the droplet reach equilibrium, the droplet will move at a constant velocity known as the terminal velocity[6]. It was found that in all the experiments, the droplets reached their terminal velocity already after a few millimetres transportation through the water phase. Figure 3 shows the terminal velocities of both the AK50 and OD40 droplets in the water-AK50 system. Each experimental point shown in the Figure was taken as the average value over 7–17 measurements. Good reproducibility was observed in all cases. When the water level is increased, the velocity could both increase and

Table II
Physical properties of AK50, AK5000 and OD40

Physical properties	AK50	AK50	AK50	AK5000	AK5000	AK5000	OD40
Temperature (°C)	20	50	80	20	50	80	20
Density (kg/m³)	964.6	937.2	909.9	974.5	947.7	920.9	978.5
Dynamic visc. (Pa·s)	$54.0\cdot10^{-3}$	$29.3\cdot10^{-3}$	$19.2\cdot10^{-3}$	$5460\cdot10^{-3}$	$2960\cdot10^{-3}$	$1940\cdot10^{-3}$	$108\cdot10^{-3}$
Kinematic visc. (m²/s)	$56.0\cdot10^{-6}$	$30.5\cdot10^{-6}$	$20.0\cdot10^{-6}$	$5600\cdot10^{-6}$	$3050\cdot10^{-6}$	$2000\cdot10^{-6}$	$110\cdot10^{-6}$
Surface tension (mN/m)	20.8	19.1	17.1	21.4	20.2	18.8	35.0

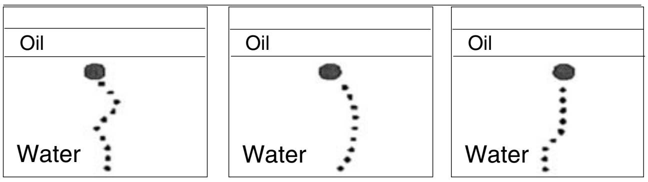

Figure 2. Schematic of the droplet motion in the water phase

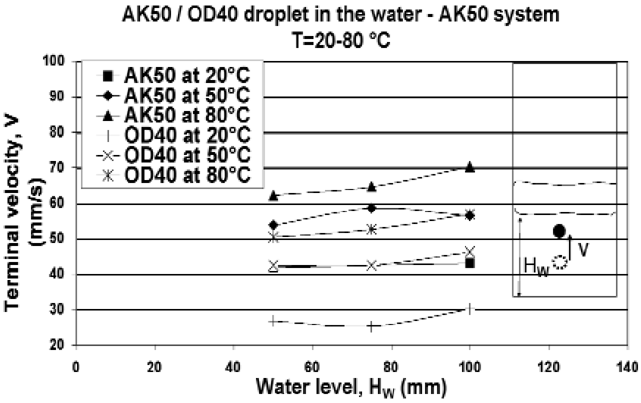

Figure 3. Terminal velocity for AK50 and OD40

decrease. But, the velocity is relatively equal to each other at the different water levels. The terminal velocity of the OD40 droplet is in general lower than the velocity of AK50. It is also seen in Figure 3 that the terminal velocities increase with increasing temperature in the case of both types of droplets. In Figure 4, the terminal velocities of the AK50 droplets with different diameters are compared for the two water-oil systems. Each reported point represents the average value over 70–80 measurements. The velocity of the droplet increases with the increase of the droplet size.

Rest time

The separation of liquid droplets at a steel-slag interface is not instantaneous and these droplets can have a significant rest time before they enter into the slag. When a droplet reaches the interface it first impacts and rebounds from the interface. After the rebounding, the droplet moves to the interface again with lower kinetic energy and is able to stay at the interface for a period of time.

The AK50 droplet in the room-temperature experiments of the water-AK50 system could in some of the trials move laterally along the interface. On the other hand, this behaviour was not observed in the case of the water-AK5000 oil systems with AK50 droplets, and neither in the experiments, wherein OD40 droplets were used.

In the experiments performed at the higher temperatures, both kinds of the droplets were observed to move along the interface before they were stabilized and then separated to the oil phase. When the droplet stayed at the interface, the geometrical shape of the droplet was still spherical. The photograph of a typical droplet resting at the interface is shown in Figure 5. The length of the period, in which the droplet stays at the interface and keeps its original shape, is usually defined as the rest time.

Figures 6–8 show the rest times of the AK50 and OD40 droplets at 20, 50 and 80°C with different water levels. The rest time of the AK50 droplet varies with the water level. It should be mentioned that each experimental point represents the average value over 7–17 measurements. Carrying out so large number of experiments was to obtain a representative value. As shown in these Figures, the uncertainties are considerably high. This uncertainty level was caused by many factors, such as the oscillation of the droplet and fluctuation of the interface. Even the surroundings would have affected the rest times of the droplets. Nevertheless, the experimental results in Figures 6–8 are still able to show trends. The rest time of the AK50 droplet lies in the interval of 12.4–48.9 s. The OD40 droplet has a much shorter rest time, in the interval of 0.61–2.29 s. Water level has very little effect on the rest time of the OD40 droplets.

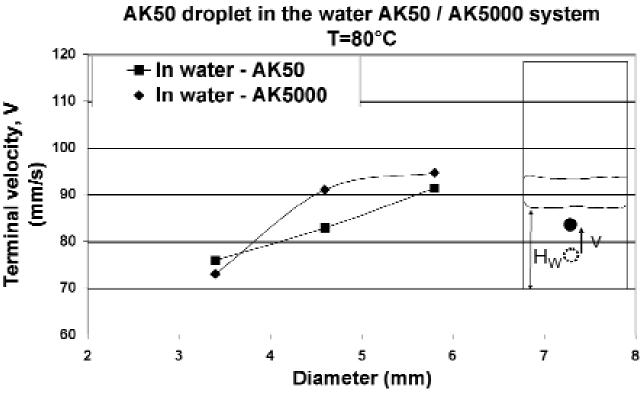

Figure 4. Terminal velocity for the different drop sizes

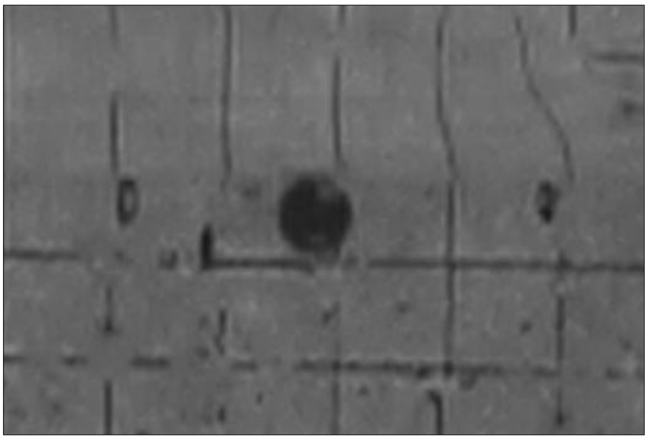

Figure 5. Droplet shape at the interface

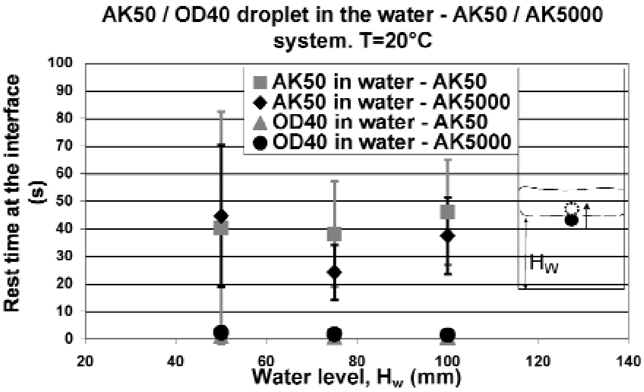

Figure 6. Rest time at 20°C

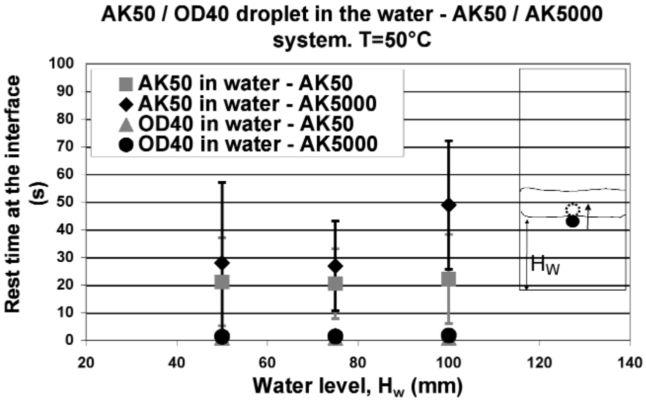

Figure 7. Rest time at 50°C

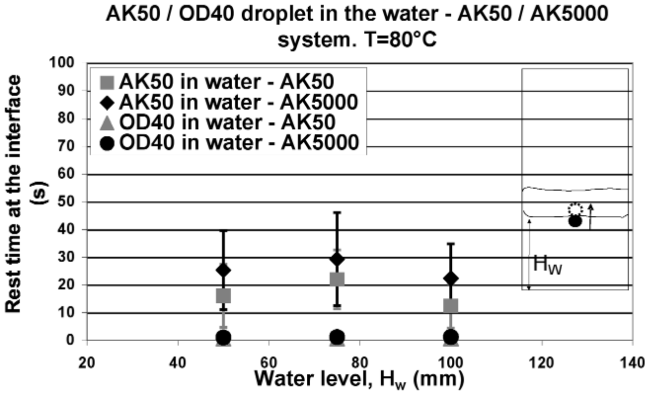

Figure 8. Rest time at 80°C

Figure 9 shows the rest time as a function of the drop size. The shortest rest time, 5.6 seconds was observed in the case of the droplet with the diameter 4.6 mm in the water-AK50 system. The longest rest time, 23.5 seconds was found with the droplet of 4.6 mm in diameter in the water-AK5000 system.

Figures 10–11 present the results of the rest time when a flow parallel to the interface was applied. The flow was introduced by gas injection and asymmetrical heating of the vessel. In Figure 10, the rest time in the case of asymmetrical heating is compared with the result of the symmetrical (from the results with different drop sizes) heating. The rest time of asymmetrical heating is about 5 seconds lower than that with symmetrical heating.

The rest times obtained in the experiments with gas injection are presented in Figure 11. Nitrogen gas was employed. The flow rate was varied in the range of 3.6–10.8 l_N/min. The results from the symmetrical heating experiments are also included in the same figure for comparison. The rest time first increases and then decreases with the increase of the gas flow. At the gas flows 7.2 and 10.8 l_N/min, the rest times are at the same level as that in the experiments without injection of gas, around 10–15 seconds.

Dissolution

It was found that a droplet would spread out changing its shape from a sphere into a lens while it entered the oil phase. It took a certain length of period before the droplet was completely dissolved in the oil. The complete dissolution is distinguished by the vanishing of the boundary of the diffused droplet indicated by the Sudan Red colour. In the present work, the dissolution time is defined as the time required for the complete dissolution after the droplet just enters the oil phase and starts changing its shape.

In the dissolution study, only the droplets with a diameter of 3.4 mm were employed. Directly after the separation, the droplets deformed into a shape of a lens with a diameter of 6 mm. Figure 12 illustrates a typical example of the deformed droplet just after it enters the oil.

Table III presents the dissolution times for the droplets in the different water-oil systems. The AK50 droplets dissolved in different ways depending on the water-oil

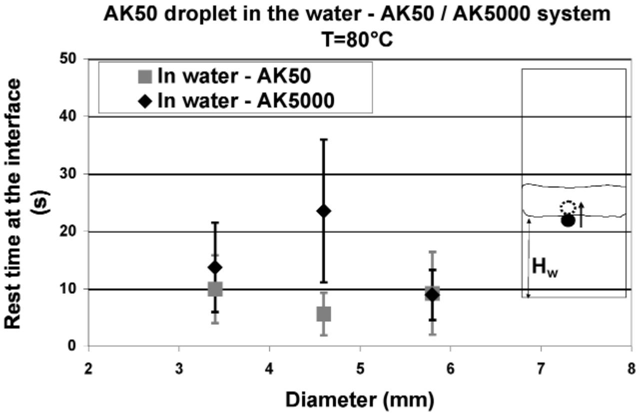

Figure 9. Drop size

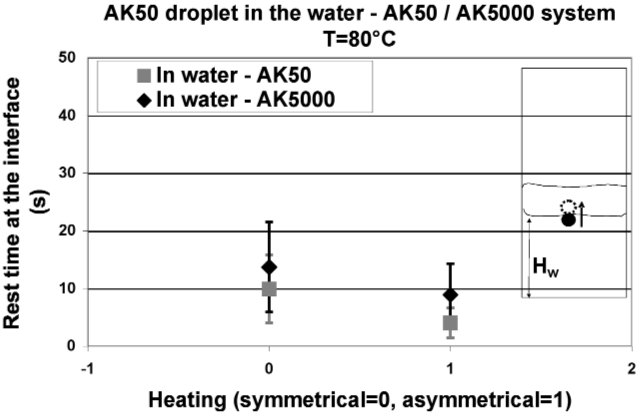

Figure 10. Asymmetrical heating

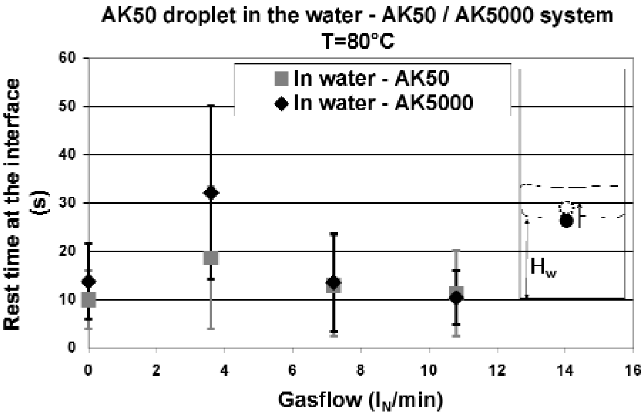

Figure 11. Nitrogen injection

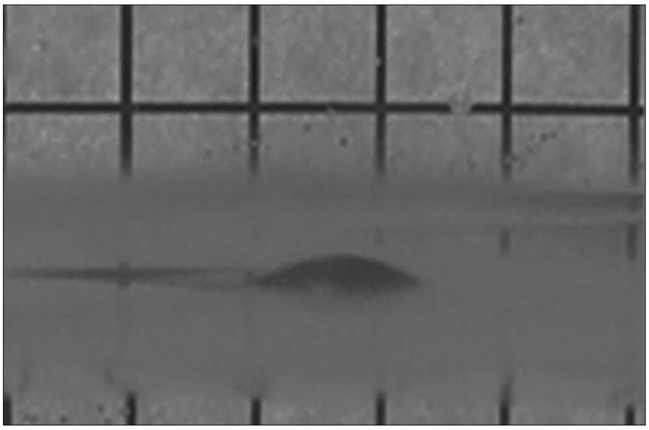

Figure 12. Directly after the separation

Table III
Dissolution time of the droplets in the oil phase

Droplet / oil phase	Dissolution time		
	20°C	50°C	80°C
AK50 / AK50	~45 minutes	6–8 minutes	3.5 minutes
AK50 / AK5000	~2 hours	30 minutes	15–20 minutes
OD40 / AK50	3 seconds	3 seconds	2 seconds
OD40 / AK5000	2.5 minutes	75–90 seconds	50–60 seconds

system. During the dissolution, the droplet changed its shape spreading to different diameters in the oil phase at the interface. In some cases, it started to soar in the oil phase. At higher temperatures, 50 and 80°C, in the water-AK50 system, the droplet was found to stretch out in a column-like shape, after it had passed the interface. This situation is shown in Figure 13. Similar phenomenon was observed in the water-AK5000 system at 80°C.

When the OD40 droplet crossed the interface, it spread out very fast, resulting in a wave at the interface. The wave was observed to stretch out towards the walls of the vessel leading to local convection. As shown in Table III, the dissolution times for the AK50 droplets are much longer than the time for the OD40 droplets.

Discussion

Terminal velocity

In the experiments without any heating, the droplets had a straight trajectory towards the interface, because the water bath was stagnant. The motion of a droplet in a liquid phase is controlled by forces. Once the gravitational force (buoyancy), the frictional force and the inertial force equilibrate, the particles move at a constant velocity known as the terminal velocity[6]. As mentioned in the result section, the droplets reached their terminal velocity soon after a few millimetres transportation through the water phase.

Fluid particles moving in a continuous media exhibit internal circulation which affects the external flow and their shape[1]. For small particles, the shape is still spherical but the internal circulation creates a mobile interface, which in turn affects the velocity. The internal circulation depends on the viscosity ratio, $\kappa = \mu_P/\mu$. For high value of κ can the internal circulation be neglected and the droplet can be approximated as a rigid sphere. For slag droplets in melted steel will the viscosity ratio be 20. Therefore, a slag droplet can be approximated as a solid particle with a relatively small error in the terminal velocity. In order to examine whether this argument is reasonable and to examine the applicability of the velocity equation to the rising droplets, the velocities of the droplets were evaluated using the following equation[6], 'intermediate law', valid for $0.5 < Re_D < 10^3$

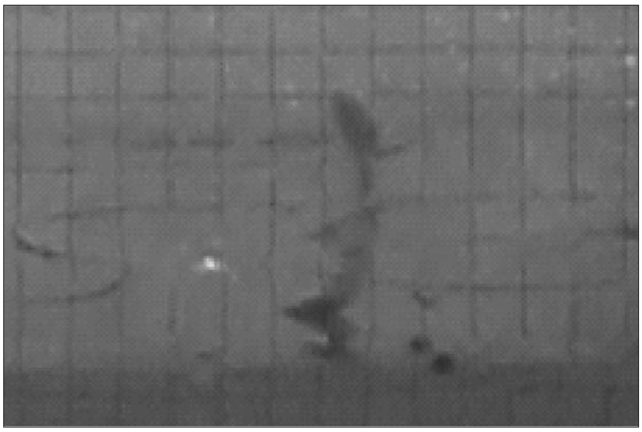

Figure 13. Some seconds after separation through the interface

$$C_D = \frac{12}{\mathrm{Re}_D^{1/2}} \Rightarrow V_{term} = \left[\frac{(\rho_L - \rho_P)\cdot g}{9\cdot\mu^{1/2}\cdot\rho_L^{1/2}}\right]^{2/3}\cdot d_p \qquad [1]$$

The calculated velocities for the AK50 droplets are compared with the experimental data in Figure 14. The experimental velocities differ from the calculated values 22.6% in maximal. Similar calculations were made for the OD40 droplets. The maximum deviation from the theoretical values was 14.9 %.

The above discussion indicates that even in a stagnant liquid bath, the use of Equation [1] would give a considerable error. In a tundish, liquid steel is expected to flow in different directions. This is particularly true in the area close to the region, wherein steel is teemed into the tundish. Any model prediction for the floatation of liquid inclusions in a tundish on the basis of Equation [1] should be used with precaution.

As shown in Figure 3, the terminal velocities are relatively equal to each other at the different water levels at low temperatures. On the other hand, the terminal velocity appears to show an increasing trend at 80°C, when the

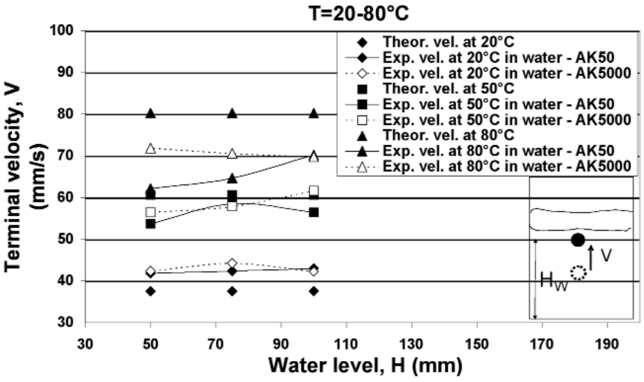

Figure 14. Theoretical and experimental velocities for AK50

water level is increased. This could be explained by the plausible convection introduced by the slightly uneven heating.

Irrespective of the temperature, the terminal velocity of the OD40 droplets are always lower than the AK50 droplets under the same experimental conditions. As indicated by Equation [1], a higher density of the droplet would lead to a lower terminal velocity. The lower density of the AK50 oil compared with OD40 is believed to be the main reason for the higher terminal velocities for the droplets of this oil. The present results show that good knowledge of the slag density is essential for any meaningful model for the separation of liquid inclusions introduced by slag entrainment.

Rest time

It is seen in Figures 6–11 the rest times of the droplets of AK50 at the water-AK50 interface are considerably long. According to the supplier, the addition of the traces of Sudan Red colour into the AK50 would not change the physical properties of this oil appreciably. Hence, the AK50 droplet would practically have the same physical properties of the AK50 bulk above the water phase. It is very interesting to notice that the AK50 droplets do not enter the bulk of the AK50 oil immediately. The droplets stay at the interface for a certain length of time before separation. As can be seen in the Figures, the rest time varies. Since the interfacial tension between an AK50 droplet and the AK50 bulk is zero, the most logical explanation for the resistance stopping AK50 droplet entering its bulk phase would be a thin water film surrounding the droplet. Since the droplet, water bulk and AK50 bulk are all liquid and are able to deform easily to adjust force balance, the AK50 droplet would be able to stay at the interface until the rupture of the water film. The rupture of the water film would depend on all the forces acting on it. An in-depth analysis regarding this aspect would require the data for the interfacial tension and even the effect of the addition of Sudan Red colour on the same. The study is very important to gain an insight into the separation of the liquid inclusions introduced by entrainment during teeming. Similar as the AK50 droplets entering the AK50 bulk, the entrained slag droplets have almost the same composition of the top slag. A reliable theoretical analysis would be able to throw some light on whether a metal film would form around the slag droplet and delay the entering of the slag droplets into the top slag. This analysis is currently planned in the present research group.

Figure 15 shows how the rest time of the AK50 droplet varies with the water level and temperature. The rest time is generally somewhat longer when AK5000 is used as the simulated slag phase except in the experiments without heating. This exception could be due to either the experimental uncertainties or the fact that in contrast with the other experiments, the droplets do not move along the interface. Even the interfacial energy variation with temperature could be one of the reasons. Detail study is required to obtain a conclusive answer.

A further examination of Figures 6–11 indicates that in most cases, the rest times in the water-AK5000 systems appears to be longer. The viscosity of the AK5000 oil is about 100 times higher than that of AK50 oil. A higher viscosity would provide higher resistance to the droplet entering the oil phase, resulting in longer rest time. On the other hand, the higher viscosity would also damp the lateral movement of the droplet along the interface, leading to easier stabilization and shorter rest time. The two opposite effects would reach compromise. In most cases, the resistance to the droplet entering the oil phase predominates. This explains why the rest times in the water-AK5000 systems are longer in most cases.

Figures 7 and 8 indicate that the rest time does not show an appreciable dependence on temperature. This is in accordance with the effect of the viscosity of the top slag on the rest time. It can be seen in Table II that the temperature has a strong effect on viscosities but not on the other properties of both AK50 and AK5000.

Figures 6–8 show evidently that the OD40 droplets have much shorter rest time than the AK50 droplets. A possible explanation for the shorter rest time would be the lower energy required to break the water film surrounding the droplet. Unfortunately, no interfacial tension data is available for the water-OD40 system. However, as seen in Tables II, the surface tension of OD40 is considerably higher than the AK oils. It is reasonable to expect that its interfacial value also differs from the AK oils. Further investigation is needed to clarify the reason for the shorter rest time of OD40 droplet. The difference in the rest time between AK50 oil and OD40 oil demonstrates that the separation of liquid inclusions would meet very different resistance when different inclusions are involved. A model without considering the compositions of the inclusions and the top slag would be very misleading and should not be applied.

It can be expected that at smaller travelling distances, the inclusions do not reach their terminal velocities and therefore impact the interface with a lower impact energy. On the other hand, the droplets reached their terminal velocities at all the water levels in the present work. In Figure 6–8, it can be seen that the variation of rest time with the height of the water bath has no clear trend, indicating thereby that the travelling distance does not affect the rest time.

Chevrier[1] has also studied the rest time for gas bubbles (diameter of the gas bubbles were in the interval 3–6 mm) in water-oil systems. He reports that the rest time increases with the size of the bubble. The present experimental results obtained with different droplet sizes do not follow the same trend. The variation of the rest time with droplet size appears to be within the scatter of the experimental data, as indicated by Figure 9.

The asymmetrical heating gave a shorter rest time compared to the symmetrical heating. Asymmetrical

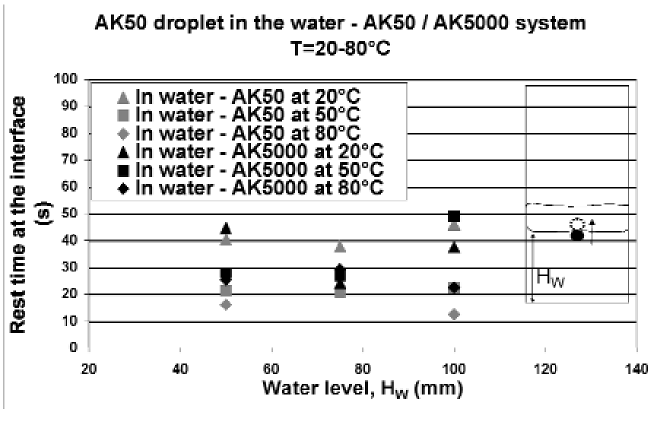

Figure 15. Rest time for the AK50 droplet in the two water-oil systems

heating was performed to investigate how a flow at the interface could affect the rest time. On the other hand, asymmetrical heating did not lead to substantial movement of the droplets at the interface. Figure 10 indicates that the asymmetrical heating results in shorter rest time. The reason for this phenomenon is not clear. A possible explanation could be the uneven temperature distribution at the interface, which helped the rupture of the water film.

Gas injection of nitrogen gave a flow at the interface and the flow is higher in the water-AK50 system than in water-AK5000 system due to the lower viscosity of AK50. The slag viscosity dampens the surface oscillations in the high viscosity oil. Figure 11 shows that at the lowest gas flow rate, the rest time became longer compared to the experiments without gas injection. The flow at the interface could have hindered the stabilization and therefore led to longer rest time. At higher gas flow rate, the rest times appear to be at the same level as that without gas stirring. It should be mentioned that the experiments with high gas injection rate involved higher experimental uncertainties. The droplets were observed to be entrained into the gas jet causing difficulties in determining the rest time. Also at the lowest gas flow rate for the droplets in the water-AK5000 system it was difficult to determine the rest time for all the measurements.

If the inclusions do not separate fast at the interface, they might be brought back to the metal phase by the flow. The pileup of the inclusions at the interface might even be able to hinder further separation. Hence, a short rest time is desired with respect to the separation of inclusions. The present results show that even when the droplets have the same composition of the top liquid, the rest time can still be very long. In some cases, the rest time is more than one minute. In the existing models, the criterion for the separation of an inclusion is the arrival of the inclusion at the interface. The present work suggests that a detailed description of the separation process taking into account the interfacial energy aspect is a precondition for any meaningful modelling approach.

Dissolution

As mentioned in the result section, the dissolution took longer time when AK5000 was used as the simulated slag phase. This observation could well be explained by the high viscosity value of the AK5000 oil. Table II indicates that the viscosity of the AK5000 is about 100 times higher than AK50. A higher viscosity would provide higher resistance to the mass transfer of the component. It was also noticed that the higher the temperature the lower was the dissolution time. Again, this could be attributed to the viscosity variation of the oil with temperature. Table II shows that the viscosities of both AK50 and AK5000 depend greatly on the temperature.

The AK50 droplets had much higher dissolution times than the OD40 droplets. When AK50 is used to simulate the top slag, the AK50 droplets would have the same physical and chemical properties as the bulk. As the AK50 bulk was not stirred, the mass transfer process would proceed mostly by diffusion. In the case of the AK50 droplet-AK50 bulk system, it is almost only a self-diffusion process, as no chemical potential gradient is involved. It should be pointed out that the 'dissolution' was distinguished by the vanishing of the red colour. The vanishing time of the colour observed in the AK50 droplet-AK50 bulk system could even more likely be due to the diffusion of the traces of Sudan Red added to the droplets. While the 'dissolution' times for this system are listed in Table III, they should be regarded as reference values and should be used with precaution. Even in the case of AK50 droplet-AK5000 bulk system, the chemical potential gradient is expected to be very small because of the similarity of the two kinds of oils. The OD40 oil has a very different chemical composition in comparison with the AK50 and AK5000. The potential difference, acting as the driving force would speed up the mass transfer process and consequently the dissolution.

A slow dissolution process would build up high concentration of the dissolved component at the interface in the top slag. The high concentration, in turn, would hinder further separation of the inclusions. When the liquid at the interface is saturated, it will stop the separation of the inclusion completely. For example, in the case of high viscous top slag, the dissolution of Al_2O_3 produced by reoxidation would be slow. The slow dissolution would result in the saturation of Al_2O_3 of the slag at the interface. As a result, alumina pileup is expected. The piled up alumina particles would possibly be carried away by the flow and enter the melt again as a source of inclusions.

The experimental work has only been performed in water models at low temperatures. It should be pointed out that the properties of the water, oil phase and the droplets differ from the liquid steel, slag and inclusions in steelmaking. Even the droplets were much bigger than the inclusions. The foremost difference between the cold model and the tundish is the difference in density and interfacial tension. Preliminary experiments have revealed that the interfacial tensions between the AK50 and water as well as OD40 and water are both lower than 30 ($mN.m^{-1}.K^{-1}$). On the other hand, the interfacial tension between the slag droplet and steel is usually above 1000 ($mN.m^{-1}.K^{-1}$). Hence, the buoyancy force imposed on the slag drop as well as the energy associated with the rupture of the film surrounding a droplet while it is crossing the boundary between the bulk liquid and top liquid would be considerably different in the two systems. Well-designed experiments at high temperatures are needed to clarify the effect of these differences on the separation of the droplets from the bulk phase. However, it has been observed by the present authors[7] that inclusions pile up at the slag-metal interface. This piling-up indicates that the rest time of the inclusions at the slag-metal interface is considerably long, which is quite similar to the present observation. Despite of the differences in the physical properties in the model and real tundish systems, the present work could still provide some important information, especially with respect to the separation of the inclusions entrained into the tundish during teeming.

Summary

Cold model experiments have been carried out to study the floatation of droplets and the rest times of the same at the metal-slag interface. Water has been used to simulate the steel bath, while AK50 and AK5000 oils have been used to simulate the top slag. Liquid inclusions have been simulated using either AK50 oil or OD40 oil.

The experimentally obtained terminal velocities have been compared with the values predicted using 'intermediate law'. The experimental velocities of AK50 and OD40 have been found to differ from the calculated values as much as 22.6% and 14.9%, respectively, indicating thereby that any model prediction for the floatation of liquid inclusions in a tundish based on this equation should be used with precaution.

The rest times of the AK50 droplets at the interface have been found to be considerably long, even more than 1 minute in some cases. A water film formed around the droplet was expected to be the main reason. The rupture of this film was believed to be the precondition for the entering of the droplets into the oil phase. The viscosity of the oil phase was observed to have a certain effect on the rest time. The OD40 droplets have much shorter rest time than the AK50 droplets, probably because of the lower energy required to break the water film surrounding the droplet. The results have indicated that any useful model to predict inclusion separation at the metal-slag interface must take the interfacial effects into consideration.

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