Effect of Fluid Physical Properties on the Emulsification

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Slag entrainment during metallurgical processes is a common source of macro inclusions, existing in a final product. This is the main reason why emulsification of slag should be controlled during the steel making processes. The onset for emulsification during the metallurgical processes is a function of practice specific issues and properties of used melts. The objective of this research was to study the effect of fluid physical properties on the emulsification. The research was made with a water model, using oil simulating slag and water simulating metal. Critical fluid flow velocity needed for emulsification and diameter of entrained droplets were measured. Role of fluid physical properties, affecting critical fluid flow velocity and diameter of entrained droplet were studied with varying density difference, oil viscosity and interfacial tension. Thickness of oil layer was also varied. Use of dimensionless numbers were also studied as a criterion for droplet formation. The results of this research proved, that the increase in density difference, oil viscosity, interfacial tension and oil layer thickness increase the fluid flow velocity needed for emulsification. Entrained oil droplet diameter increased with increasing oil viscosity, interfacial tension and oil layer thickness. On the other hand, oil droplet diameter decreased with increasing density difference. Research proved also, that dimensionless numbers can be used as a criterion for emulsification but dimensionless numbers usually suffers from lack of necessary variables. Studied dimensionless numbers were also compared to the real ladle system.

KEY WORDS: emulsification; slag entrainment; droplet formation; slag entrapment; physical model.

1. Introduction

Emulsification of slag is very common phenomenon that occurs during treatments of liquid steel and slag in different units of the steel making processes. It can cause problems like occurrence of macro inclusions originating from ladle, tundish or the mold of continuous caster. On the other hand, intensive emulsification of slag into the steel can accelerate chemical reactions for example in desulphurisation because of the increased surface area between slag and metal.

Numerous studies concerning on the emulsification are available in the literature typically made by cold models. Harman and Cramb have defined relation for the critical velocity of denser phase for the occurrence of emulsification. Iguchi et al. have also developed empirical relation for the entrainment of slag into the steel based on the cold model study simulating the ladle environment. In the addition of physical properties of phases, it also takes into account dimensions of the ladle and gas injection rate. The entrainment of lighter phase in the continuous caster has been studied by Iguchi et al. The research proved that the kinematic viscosity of lighter phase effects clearly on the critical velocity needed for entrainment.

The effect of fluid physical properties on mass transfer during emulsification have been studied by Wei and Oeters and Oeters et al. According to their experiments and mathematical model, the amount of formed droplets depend on the flow of kinetic energy to the thin slag layer accelerated by momentum transfer from metal to slag. They studied drop generation mechanism by injecting water through cyclohexane layer to create cyclohexane droplets to the water bath. Generated droplet size and the number of formed droplets per time unit was studied by varying fluid flow rates. Oeters et al. pointed out the effects of construction of gas injection system (nozzle position and vessel size) on the intensity of emulsification and mass transfer. Furthermore, Xiao et al. have studied entrainment phenomena by the water model and the mathematical one. They also defined criterion on the emulsification in ladle environment based on the modified Weber number.

Although the effects of physical properties as well as geometrical or constructional parameters on the emulsification have been studied, phenomenon has not been clearly explained or understood. In this paper the effects of the most important physical properties (oil viscosity, density difference and interfacial tension between the phases) and thickness of the lighter phase on the emulsification was studied by water model with constant fluid flow angle between the lighter and denser phase. Critical velocity for slag entrainment and diameter of formed droplets were measured. Furthermore, the emulsification phenomenon was evaluated by dimensionless numbers. Calculated dimensionless numbers were also compared to the real ladle system.
2. Model Apparatus and Test Procedure

The aim of the study was to define the effects of the most important physical properties (oil viscosity, density difference and interfacial tension) and thickness of the lighter phase on the emulsification of lighter phase. Model box (0.51 m, 0.148 m and 0.10 m) is made of acryl plastic. The total height of the used oil–H<sub>2</sub>O–NaCl-solution is set to be 0.087 m. Temperature of the model fluids is controlled to be 25°C with heat bath. Flow rate of the H<sub>2</sub>O–NaCl-solution during the experiments is controlled by centrifugal pump and rotameter. Three plates were used to control fluid flows and to standardise the angle between the flow of H<sub>2</sub>O–NaCl-solution and oil layer. This is needed when the thickness of the oil layer is increased without changing the emulsification mechanism. Constant fluid flow angle also made the velocity measurement of H<sub>2</sub>O–NaCl-solution easier and directed the flow of solution more accurately to the oil layer. Schematic picture of model box is presented in the Fig. 1.

Three different oils and H<sub>2</sub>O–NaCl-solutions with multiple NaCl concentrations were used in the experiments. Furthermore, commercial soap was used in two experiments to change interfacial tension between the water and oil with minor change of other physical properties. Experiments were made with three (0.005 m, 0.010 m and 0.015 m) thicknesses of lighter phase (oil). Studied emulsification phenomena were observed by video camera (Sony HDV 1080i) during the test. In the individual test, the fluid flow of H<sub>2</sub>O–NaCl-solution was increased as far as the oil droplets are formed and entrainment of oil droplets into the H<sub>2</sub>O–NaCl-solution was continuous, which is the definition of critical velocity in this research. Figure 2(a) describes the situation before the test and Fig. 2(b) critical velocity situation e.g. when the entrainment of the oil droplets is continuous.

Measured physical properties (densities, viscosities, surface tensions and interfacial tensions) of model fluids are presented in the Table 1 and Table 2. Densities and viscosities of H<sub>2</sub>O–NaCl-solutions are taken from the literature. Viscosities of oils were measured by Haake VT550 viscosimeter and surface tensions as well as interfacial tensions for oils and H<sub>2</sub>O–NaCl-solutions by CAHN DCA-312 tensiometer based on the Du Noüy’ ring method. Critical velocity of H<sub>2</sub>O–NaCl-solution in narrow gap

![Fig. 1. Schematic description of model apparatus.](image1)

![Fig. 2. (a) Situation of oil–water solution system before experiment and (b) during the experiments when critical velocity was achieved and oil droplets are formed.](image2)

![Table 1. Physical properties of oils and H<sub>2</sub>O–NaCl-solutions at T=25°C.](table1)

| Oil          | Density [kg/m³] | Viscosity [mPas] | Interfacial Tension [mN/m] |
|--------------|-----------------|------------------|----------------------------|
| Rapeseed     | 903             | 61.34            | 35.84                      |
| Mobil 1 0W40 Motor oil | 848   | 96.02            | 31.86                      |
| Mobil Super S 10W40 Motor oil | 867 | 149.8            | 33.32                      |
| Pure water   | 997             | 0.88             | 71.97                      |
| Water-0.2% NaCl-solution | 1071 | 1.07            | 74.38                      |
| Water-0.5% NaCl-solution | 1169 | 1.56        | 77.35                      |

![Table 2. Measured interfacial tensions between the oils and H<sub>2</sub>O–NaCl-solutions at T=25°C.](table2)
(0.005–0.01 m) between the oil and plate was determined by utilising plastic balls (ρ = 950 kg/m³ with diameter 2–3 mm). Plastic ball moved together with the H₂O–NaCl-solution through the gap and velocity of plastic balls was defined from subsequent video frames by measuring the transferred distance in the certain time (Fig. 3). Nature of fluid flow in the gap was determined by Reynolds number (Re) presented in Eq. (1). Values of Reynolds number varied between (640 < Re < 1 860) depending on the physical properties and fluid flow velocity of denser phase. Thus, fluid flow in the gap is assumed to be laminar.

\[ \text{Re} = \frac{v \cdot \rho_m \cdot H}{\mu} \] ..........................(1)

where \( v \) is critical velocity of denser phase (m/s), \( \rho_m \) is density of heavier phase (kg/m³), \( H \) is hydraulic radius (m) presented in Eq. (2) and \( \mu \) is viscosity of lighter phase (Pa·s).

\[ H = \frac{S}{Z} = \frac{\text{cross section (m²)}}{\text{circumference (m)}} \] ..........................(2)

3. Results of Experiments

Measured critical velocities of oil–H₂O–NaCl-systems with three different thicknesses of the oil layers are presented in the Table 3.

Diameters of formed oil droplets were defined from the video frames. Determination of droplet size was made for as many droplets as possible (10–20 droplets depending on the experiment). Average values of measured diameters of droplets are collected in the Table 4.

4. Discussion

Effects of the physical properties (density difference, interfacial tension, lighter phase viscosity and oil layer thickness) on the occurrence of emulsification, sizes of formed droplets and the use of dimensionless numbers are discussed separately.

4.1. Viscosity

According to the experiments (Fig. 4 and Fig. 5), critical velocity as well as average size of formed droplets are increased when viscosity of lighter phase is increased. It should be noted that when oil viscosity was increased, the density difference and interfacial tension between the phases also changed. Increase in oil viscosity slightly increased average droplet diameter and the size distribution of droplets was also enlarged (Fig. 5). Higher force i.e.

| Table 3. Measured critical velocities of H₂O–NaCl-solutions in the studied tests. |
|-----------------------------------------------|
| Oil layer thickness | 0.005m | 0.010m | 0.015m |
| Water 1 - Oil 1     | 0.285  | 0.286  | 0.324  |
| Water 2 - Oil 1     | 0.294  | 0.291  | 0.3    |
| Water 3 - Oil 1     | 0.288  | 0.358  | 0.358  |
| Water 1 - Oil 2     | 0.355  | 0.326  | 0.342  |
| Water 2 - Oil 2     | 0.358  | 0.377  | 0.369  |
| Water 3 - Oil 2     | 0.336  | 0.375  | 0.408  |
| Water 1 - Oil 3     | 0.361  | 0.375  | 0.444  |
| Water 2 - Oil 3     | 0.358  | 0.381  | 0.431  |
| Water 3 - Oil 3     | 0.366  | 0.392  | 0.439  |
| Soap 1 - Oil 1      | 0.222  |        |        |
| Soap 2 - Oil 1      | 0.203  |        |        |

| Table 4. Average values of measured diameters of the droplets. |
|-------------------------------------------------------------|
| Oil layer thickness | 0.005m | 0.010m | 0.015m |
| Water 1 - Oil 1     | 6.750  | 8.143  | 8.222  |
| Water 2 - Oil 1     | 6.625  | 7.000  | 7.667  |
| Water 3 - Oil 1     | 6.571  | 5.667  | 5.571  |
| Water 1 - Oil 2     | 6.571  | 9.167  | 7.286  |
| Water 2 - Oil 2     | 7.000  | 6.444  | 5.778  |
| Water 3 - Oil 2     | 5.900  | 6.273  | 5.375  |
| Water 1 - Oil 3     | 7.500  | 8.786  | 8.500  |
| Water 2 - Oil 3     | 7.250  | 8.333  | 7.333  |
| Water 3 - Oil 3     | 6.333  | 6.875  | 7.800  |
| Soap 1 - Oil 1      | 3.909  |        |        |
| Soap 2 - Oil 1      | 2.000  |        |        |

Fig. 4. Effect of oil viscosity on the critical velocity in studied system.

Fig. 5. Effect of oil viscosity on the formed droplet size in studied system.
higher velocity of H₂O–NaCl-solution flow is needed to move oil layer and to generate droplets when oil viscosity was increased. Thus, the shear force is stronger and bigger oil droplets are emulsified. Although the effect of viscosity on the critical velocity is analogous with Harman and Cramb, the increase of needed critical velocity is remarkable higher when viscosity change is at the same level with this study. On the other hand the size of formed droplets did not increase as much as in Harman and Cramb’s study. In Harman and Cramb’s study the highest value of used oil viscosity was twice as high than in this study.

4.2. Interfacial Tension

It can be seen from the Fig. 6 that the critical velocity was increased clearly with the increased interfacial tension. Average size of generated droplets as well as size distribution were also enlarged with increased interfacial tension (Fig. 7). Interfacial tension can be assumed to be the force, which is formed based on the energy of disorder at the interface. The disorder of the molecules at the interface binds the energy because those molecules are under the stress state. Stress state caused by the disorder of the interface forms more stiff surface and higher critical velocity is needed to break that surface. Effects of interfacial tension to the entrainment velocity and droplet size were stronger than in Harman and Cramb’s study.

4.3. Density Difference

According to the results, increase in density difference between the phases caused non-linear increase to the critical velocity as can be seen in Fig. 8. Figure 9 shows that average diameter of generated oil droplets decreases linearly with higher density difference in the studied system. Effect of density difference can be explained by buoyancy force. With higher density difference stronger buoyancy force is affecting on the oil droplets and increase in critical velocity is needed to overcome the strengthened buoyancy force. Formed droplets are also smaller because the higher buoyancy force prevents the entrainment of larger droplets. In Harman and Cramb’s study increase of density difference caused linear increase in critical velocity and non-linear decrease in droplet size which is different comparing to this study. Effect on density difference is also stronger in this study than Harman and Cramb’s.

4.4. Thickness of Oil Layer

Effect of the oil layer thickness to the entrainment velocity and average droplet size is presented on the Fig. 10 and Fig. 11. According to the experiments, critical velocity is increased substantially only with thickest oil layer. The in-
crease of layer thickness increased droplet size in the beginning but increasing oil layer thickness further had no effect to the droplet size. Size distribution of generated droplets extended remarkably with thicker oil layer. Effect of layer thickness to the critical velocity was not analogous with other studies (Harman and Cramb). According to the Harman and Cramb, the increase of thickness decreases the entrainment velocity for the certain level and then further increase in oil layer thickness has no effect on the entrainment velocity. On the other hand, in the present work thickness of the oil layer has not effect on the droplet size with 0.010 m and 0.015 m thicknesses which agrees with the results of Harman and Cramb.

The reason for the differences between this study and Harman and Cramb’s study is the constant fluid flow angle in the present study. The effect of constant and non-constant fluid flow angle to the fluid flow path is presented in Fig. 12. It can be seen that with non constant fluid flow angle, downward flow increases with increasing oil layer thickness. Downward fluid flow rips oil more easily from the layer which causes decrease in critical velocity needed for emulsification. With constant fluid flow angle pushing fluid flow component needs to increase in order to rip droplet from oil layer. Thus, more fluctuating oil layer with increasing oil layer thickness isn’t good enough explanation for decreasing critical velocity which is presented in previous study.

Percentage significance of the physical properties on the emulsification in the studied parameter range is evaluated in the Table 5 and Table 6. Table 5 shows that the effect of oil viscosity, density difference between the phases and interfacial tension has equal significance on the critical velocity. According to the experiments, interfacial tension has the biggest significance on the droplet size (Table 6). Furthermore, effect of density difference is higher than oil viscosity and thickness of oil layer. It should be noted that the values presented in the table are related only studied variation range of physical properties.

4.5. Evaluation with Dimensionless Numbers

Studied systems were evaluated by dimensionless numbers. Xiao et al. have presented modified Weber number (We_mod) as a criterion for occurrence of emulsification. According to their study, emulsification occurs when modified Weber number is higher than 12.3 calculated by Eq. (3).

\[
\text{We}_{\text{mod}} = \frac{v^2 \cdot \rho_s}{(\sigma \cdot g \cdot \Delta \rho)^{0.5}} \quad \text{(3)}
\]

where \(\sigma\) is interfacial tension between the phases (N/m), \(g\) is gravitational constant (m/s\(^2\)), \(\rho_s\) is density of lighter phase (kg/m\(^3\)) and \(\Delta \rho\) is density difference between the phases (kg/m\(^3\)).

Using the Eq. (3) modified Weber number has been calculated for this system. According to the evaluation, there are no differences between the thicknesses of the oil layer (Fig. 13). Figure 13 shows that values of modified Weber number in all studied cases is higher that emulsification criterion made by Xiao et al. predicts. If fluid flow velocity of H\(_2\)O–NaCl-solution is lowered, in data points where viscosity of lighter phase is high, there is no emulsification but still the values of modified Weber number are over, the criterion. This indicates that modified Weber number is insufficient criterion for emulsification because of the lack of the viscosity of lighter phase.

When the effect of viscous force are compared to the interfacial forces, Capillary number (Ca) can be used. Formula of Capillary number (Ca) is presented in Eq. (4).

\[
\text{Ca} = \frac{v \cdot \mu}{\sigma} \quad \text{(4)}
\]
where $\mu$ is viscosity of lighter phase (Pa·s)

**Figure 14** demonstrates correlation between the Capillary number and critical velocity. In Fig. 14 all oil layers are separated with own correlation curve. With the narrow oil layer the correlation is good but when oil layer thickness, viscosity and density difference have high values (circled points) correlation becomes bad. Circled measurement points are from the tests of Oil3–Water3 systems with three tested layer thicknesses. It can be concluded that Capillary number alone is not good enough criterion for emulsification due to the lack of density difference. Raise in density difference creates large increase in critical velocity alongside with high viscosity and thick oil layer which reduces the correlation.

System can also be evaluated with Weber number (We) presented in Eq. (5), which is used for droplet formation when inertial and interfacial forces are compared.

$$We = \frac{\nu^2 \cdot 1.2 \cdot D}{\sigma} \tag{5}$$

where $D$ is average diameter of entrained droplet (m).

**Figure 15** shows Weber number as a function of critical velocity. Because Weber number includes only the critical velocity, interfacial tension and slag density as physical parameters, the correlation decreases when critical velocity is

Table 5. Scaled effects of the studied parameters on the critical velocity.

| Parameter                  | Oil layer thickness [m] | 0.005 | 0.010 | 0.015 | Change% | Scaled change% |
|----------------------------|-------------------------|-------|-------|-------|---------|---------------|
|                            | Critical velocity [m/s] | 0.29  | 0.29  | 0.32  | 13.44   | 6.72          |

| Parameter                  | Oil viscosity [mPas]    | 61.34 | 96.02 | 149.80| 144.21 | 100           |
|----------------------------|-------------------------|-------|-------|-------|---------|---------------|
|                            | Critical velocity [m/s] | 0.29  | 0.33  | 0.36  | 26.45   | 18.34         |

| Parameter                  | Density difference [kg/m³] | 94.00 | 168.00| 266.00| 182.98 | 100           |
|----------------------------|-----------------------------|-------|-------|-------|---------|---------------|
|                            | Critical velocity [m/s]     | 0.28  | 0.30  | 0.36  | 26.19   | 14.31         |

| Parameter                  | Interfacial tension [mN/m] | 3.85  | 4.56  | 13.04 | 228.70 | 100           |
|----------------------------|-----------------------------|-------|-------|-------|---------|---------------|
|                            | Critical velocity [m/s]     | 0.20  | 0.22  | 0.28  | 40.48   | 16.96         |

Table 6. Scaled effects of the studied parameters on the average droplet size.

| Parameter                  | Oil layer thickness [m] | 0.005 | 0.010 | 0.015 | Change% | Scaled change% |
|----------------------------|-------------------------|-------|-------|-------|---------|---------------|
|                            | Average droplet diameter [mm] | 6.75  | 8.18  | 8.19  | 21.31   | 10.66         |

| Parameter                  | Oil viscosity [mPas]    | 61.34 | 96.02 | 149.80| 144.21 | 100           |
|----------------------------|-------------------------|-------|-------|-------|---------|---------------|
|                            | Average droplet diameter [mm] | 7.15  | 6.78  | 7.50  | 4.80    | 3.32          |

| Parameter                  | Density difference [kg/m³] | 94.00 | 168.00| 266.00| 182.98 | 100           |
|----------------------------|-----------------------------|-------|-------|-------|---------|---------------|
|                            | Average droplet diameter [mm] | 8.12  | 7.05  | 5.64  | 43.90   | 23.99         |

| Parameter                  | Interfacial tension [mN/m] | 3.85  | 4.56  | 13.04 | 228.70 | 100           |
|----------------------------|-----------------------------|-------|-------|-------|---------|---------------|
|                            | Average droplet diameter [mm] | 3.10  | 3.91  | 6.75  | 117.66  | 49.29         |
increased and significance of viscosity and thickness of oil layer is increased. Circled measurement points are from the tests of Oil3–Water3 systems with three tested oil layer thicknesses. From circled points same kind of effect can be seen as when using Capillary number. When oil viscosity, oil layer thickness and density difference are at high values a new emulsification mechanism occurs which raises critical velocity. New mechanism could consist on cumulative effect of oil viscosity, oil layer thickness and density difference.

From studied numbers one can say that new overall criterion is needed if occurrence of emulsification is described with dimensionless number. New criterion should consist all the most important variables described in this paper. Dimensionless number which includes all the necessary variables should also describe cumulative effect of variables which caused poor correlation.

4.6. Comparison of Dimensionless Numbers between Ladle and Water Model

Properties of three different kinds of slags and melts are gathered from Slag atlas11) and research done by Jimbo et al.12) Properties of melts in temperature between 1 460–1 530°C are shown in Table 7. Velocities of liquid steel at top horizontal flow in a 60 t gas stirred ladle are gathered from studies done by Hsiao et al.13) According to the study made by Hsiao et al. the near-surface steel flow velocities in the 60 t ladle varied between 0–0.45 m/s depending of the distance from the plume center.13)

Modified Weber number and Capillary number for all the measuring points in water model and for three different slags and steels in 60 t ladle are plotted in Fig. 16 and Fig. 17. Interfacial tensions in Table 7 are from equilibrium situations when slag and melt are in steady state. Therefore Fig. 16 and Fig. 17 include also non-equilibrium situation of used melts when interfacial tension is low (0.05 N/m). From Fig. 16 it can be seen that in real ladle modified Weber number is over the criterion when horizontal flow is considerably high. It should be also noted that surface velocities measured by Hsiao et al.13) are done without top slag layer. It can be assumed that horizontal velocities in real ladle system should be slower because of the slowing effect of the slag layer. Considering the non-equilibrium situation in real ladle it can be seen from Fig. 16 that values of modified Weber number are near the measuring points in water model when modified Weber number is higher than 12.3.

For Capillary number only Slag1–Steel1 and Slag3–Steel3 were plotted to the Fig. 17 because of the high Capillary number values of Slag2–Steel2. Figure 17 shows that calculated Capillary numbers for water model are at the same level with real ladle system even when viscosity is considerably high (3.5 Pa·s). However when interfacial tension is low at non-equilibrium situation, Capillary numbers of Slag3–Steel3 system with slag viscosity of 3.5 Pa·s differs much from Capillary numbers of water model.

5. Conclusions

The experiments showed that critical fluid flow velocity of H2O–NaCl-solution for emulsification is depended most on oil viscosity, density difference and interfacial tension. When oil viscosity, density difference or interfacial tension is increased the critical velocity is also increased. Interfacial tension and density difference affected most to the average droplet diameter. Increase in interfacial tension or

| Weight-% | Al2O3 | CaO | SiO2 | C | Density [kg/m³] | Viscosity [Pas] | Interfacial tension [N/m] |
|--------|------|-----|------|---|----------------|---------------|------------------------|
| Slag1  | 26   | 39  | 36   | 0 | 2800           | 0.7           |                       |
| Slag2  | 26   | 16  | 38   | 0 | 2450           | 60            |                       |
| Slag3  | 26   | 27  | 47   | 0 | 2500           | 5.5           |                       |
| Steel1 | 0.3  |     | 1100 | 0.3| 7100           |               |                       |
| Steel2 | 4.6  |     | 6850 |   |                |               |                       |
| Steel3 | 2.6  |     | 6950 |   |                |               |                       |

Table 7. Properties of three different kinds of melts in temperature range of 1 460–1 530°C (Slag Atlas,11) Jimbo et al.12))
density difference produced smaller oil droplets. Oil viscosity and oil layer thickness had minor effect on the average droplet diameter but droplet size distribution increased with increasing oil viscosity and oil layer thickness.

Modified Weber number showed to be a good criterion for droplet formation from the oil layer. However modified Weber number do not include oil viscosity which makes it insufficient criterion for slag entrainment. Effect of slag viscosity was approached by Capillary number which contains all the other variables except density and oil layer thickness. It was noted that with high density difference, oil viscosity and oil layer thickness, Capillary number becomes an insufficient criterion. Weber number as a criterion was also studied but the lack of variables such as oil viscosity and oil layer thickness were also noted. Creating a new criterion which contains all the most important variables can be a challenging process. The possible change of emulsification mechanism which occurs from cumulative effect of variables may cause the finding such a criterion impossible.

When values of modified Weber number and Capillary number were compared to the values of real ladle system it was noted that values of modified Weber number were at the same level in real ladle and water model when interfacial tension was low. Capillary numbers of real ladle system were also at same level with water model when viscosity of slag was fairly high. This indicates that water model system can be useful at describing the system with real melts in non-equilibrium situation even though geometrical aspects are not nearly same.

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