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Physical modelling of slag-metal dispersion

G. AKDOGAN and R.H. ERIC
School of Process and Materials Engineering, University of the Witwatersrand, South Africa

A physical modelling study has been carried out to simulate the slag-metal dispersion induced by a high-strength bottom gas injection. Water and kerosene were utilized to simulate metal and slag respectively. A water model of CLU (Creusot-Loire Uddeholm) vessel was used with three different nozzle orientations, namely, off-centre, triangular off-centre and centre. The gas flow rates changed from 0.00599m^3/sec to 0.01081m^3/sec. Height of heavy and light phases was kept fixed at 0.23 m and 0.02 m respectively. The dispersed phase holdup was determined at various axial and radial distances, gas flow rates, and tuyere configurations.

The observations revealed that at a fixed gas injection rate, as the vertical distance increased in the centerline, straight off-centre orientation resulted in greater dispersed phase holdup values than those of the centre configuration and the triangular off-centre orientation. The dispersed phase holdup was found to increase with gas injection rate and decreased with axial distance. The variation of the dispersed phase holdup with the dimensionless axial distance and the gas injection rate was correlated by using the Modified Froude Number. The experimental values of the dispersed phase holdup were found to be in good agreement with the correlated values obtained from the modelling equations. The findings of the present study may be utilized in the ferroalloy refining vessels in terms of designing tuyere locations for optimum processing conditions.

Introduction

Dispersion of one liquid in another immiscible liquid is of significant importance in metallurgical processes. This emulsification process generates a large interfacial area between slag and molten metal resulting in rapid chemical reaction and mass transfer between the two phases encountered in BOF and Q-BOP processes. Other examples include direct iron ore smelting and in-bath smelting of iron ore in direct steelmaking.

The emulsification process caused by gas bubbles rising through a slag/metal interface was studied using oil/water analogues by a number of researchers. Oeters and Wei[1] studied emulsification of slag droplets into molten metal in bottom stirred ladle models with 30Nl/min gas injection rates and with about 10% slag volume. They reported that the number of slag droplets increased with an increase in gas flow rate. Lin and Guthrie[2], Lee and Sohn[3], and Zaidi and Sohn[4] investigated emulsion behaviour in various slag/metal systems by using cold models. In an attempt to simulate bottom blown in-bath smelting processes, Lin and Guthrie[2] observed that the dispersion of metal phase into slag phase was more significant than the inverse emulsion. Lee and Sohn[3], on the other hand, carried out liquid-liquid emulsion experiments by bottom gas injection using water at gas flow rates from 60 to 300 Nl/min. The height ratio of simulated slag to metal ranged from 0.45 to around 2. They reported that the dispersed phase holdup increased with gas velocity and decreased with axial and radial distances.

From the literature it is clear that the previous investigations focused on liquid-liquid emulsions for low gas flow rates and low slag volumes. The objective of the present study was to investigate the dispersion behaviour encountered in high strength bottom blown processes, namely, CLU reactor, where the volume ratio of slag to metal is low. For this purpose, a 1/7 water model of CLU converter utilized in ferroalloy refining was used in order to characterize the dispersed phase holdup in high strength bottom blown reactors for various injection rates and tuyere arrangements.

Experimental technique

The experimental set-up comprised a cylindrical clear PVC tank, which is one-seventh model of a CLU converter tapered from 0.5 m in diameter at the top to 0.35 m in diameter at the bottom. For simulation purposes, water and kerosene were used as metal and slag phases respectively. Air was purged into the bath through three nozzles placed at the bottom of the tank. Three different tuyere configurations orientations namely; Off-centre (straight), Centre, and Off-centre triangular configurations were used to observe the influence of tuyere pattern on dispersed phase holdup (Figure 1).

After filling the tank water and kerosene in to the desired heights, tests were carried out by purging air into the reactor. Water and kerosene levels were 0.23 m and 0.02 m respectively. The simulated slag volume was around 6.7%. During experiments the air flow rates varied from 0.00599 m^3/s to 0.01081 m^3/s. The axial and radial position from where the samples were taken was recorded together with the gas flow rate and the heights of water and kerosene before gas injection. After a half hour injection period, which was sufficient for steady state operation, 30 ml samples were collected from various axial and radial points by using a volumetric pipette. Samples were taken from the left-axis of the tank where the tuyeres are situated and the right-axis (side opposite to the side of the tuyeres).

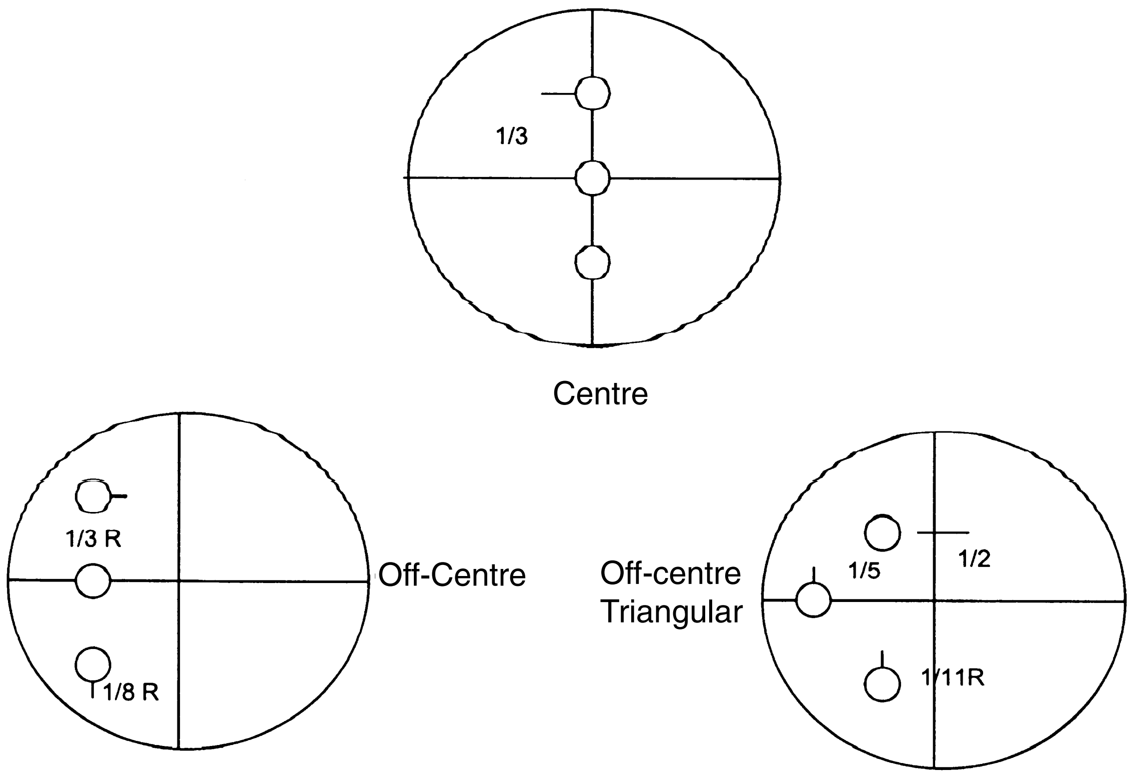

Figure 1. Tuyere configurations used in the present study

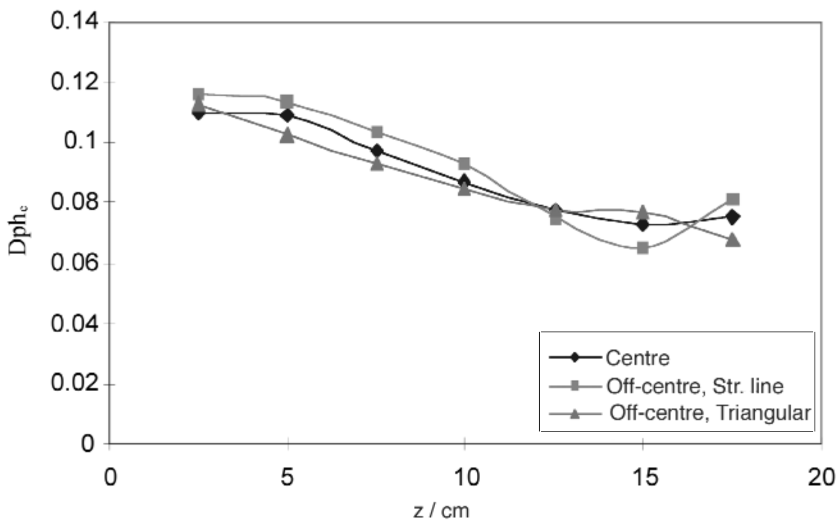

Figure 2. Axial variation of the dispersed phase holdup for different configuration at 0.00599 m3/s

The two phases in the collected samples were allowed to separate for half an hour after which the volumes of the water and kerosene were read. This was repeated ten times for one sampling location and the mean value was taken as the dispersed phase holdup. It was observed that the standard deviation was around 0.0176.

Results and discussion

The variation of dispersed slag phase holdup (ratio of volume of dispersed oil phase to total volume of emulsion) versus axial (vertical) distance (z) from the original position of the interface along the centre of the bath according to various gas injection rates is shown in Figures 2 and 3 for Centre and Off-centre and Off-centre triangular configurations.

Axial distribution of the dispersed-phase holdup

As can be seen from Figures 2 and 3 an increase in gas injection rate increases the centerline dispersed slag phase holdup (Dphc) at any axial distance. These results are also in line with the findings of Lee and Sohn[3], Zaidi and Sohn[4], and Lin and Guthrie[2] where the investigators observed that the dispersed phase holdup increased with gas injection rate respectively. Figures 2 and 3 also depicted that at a fixed gas injection rate, the dispersed phase holdup at centreline of the bath decreased with an increase in the axial distance

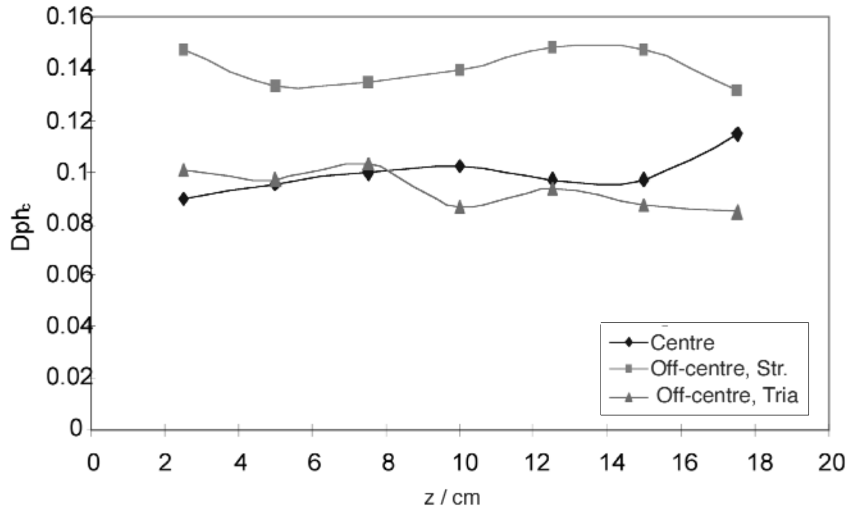

Figure 3. Axial variation of the dispersed phase holdup for different configuration at 0.01081 m^3/s

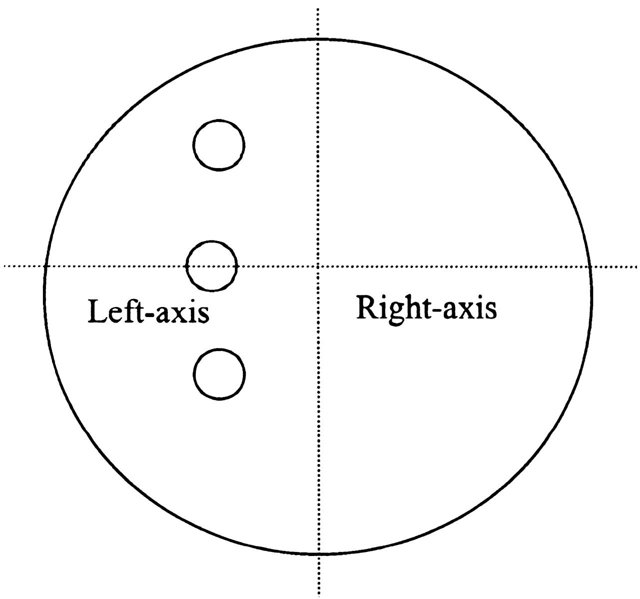

Figure 4. Top view of left and right axes

from the original interface which was also observed by Lee and Sohn[5]. They explained this phenomenon with the decrease in kinetic energy of the dispersed phase because of collision and viscous friction as the axial distance increased.

The results also showed that dispersed slag phase holdup (simulated slag dispersed in simulated metal) at the center of the model bath for off-centre straight configuration resulted in relatively higher dispersed slag phase hold up values than those of centre and off-centre triangular arrangements. These results may be attributed to be one of the reasons behind significantly reduced mixing times and improved mass transfer rates encountered when off-centre straight tuyere orientation was utilized as discussed in the previous studies[5–6] on the physical modelling of the high strength bottom blown processes.

Radial distribution of the dispersed-phase holdup

The radial distribution of the dispersed slag phase holdup on the left-axis at 0.00599 m^3/s is shown in Figures 5 and 6 at different axial distances. At axial positions close to the surface (Figure 5) radial distribution did not vary significantly for off-centre straight configuration. Centre configuration displayed lower distribution values compared to the other arrangements nearer to the wall side region. Nearer to the tuyere region (Figure 6) the dispersed slag phase holdup for Off-centre straight arrangement increased dramatically with the radial distance as the wall of the tank is approached. At 15cm axial distance on the Left axis where the off-centre nozzles situated, Off-centre triangular configuration showed better dispersion than that of Centre orientation. In Figure 7 it can be seen that at an increased gas flow rate Centre arrangement slag phase dispersion values were higher in the centre of the tank and were decreased towards the wall region.

Also on the right-axis similar trends were observed which are highlighted in Figures 8 and 9. Nearer to the surface, the dispersed slag phase holdup decreased with the radial distance and eventually increased as the wall of the tank was approached for centre and off-centre triangular configurations whereas off-centre straight arrangement resulted in straight line distribution. One expects that the holdup should decrease with the radial distance because the liquid velocity would be slower away from the nozzle region. Contrary to that, the radial distribution of the dispersed slag phase holdup values were found to be very similar to those found on the left-axis for all tuyere arrangements.

Figure 10 illustrates the effect of tuyere configuration on the measured dispersed slag phase holdup values along the centreline according to dimensionless axial distance (z/H_w) from the original interface. At a fixed gas injection rate, off-centre straight configuration was found to be more effective in dispersing the simulated slag (oil) phase in the metal phase (water) which might well be used to explain reasons for improved mixing times and mass transfer rates[5–6].

Figure 11 compares the dispersed slag phase distribution between off-centre straight and centre configuration along the left-right axes. The figure clearly demonstrates better dispersion of the slag phase in the simulated metal phase when off-centre straight configuration was used.

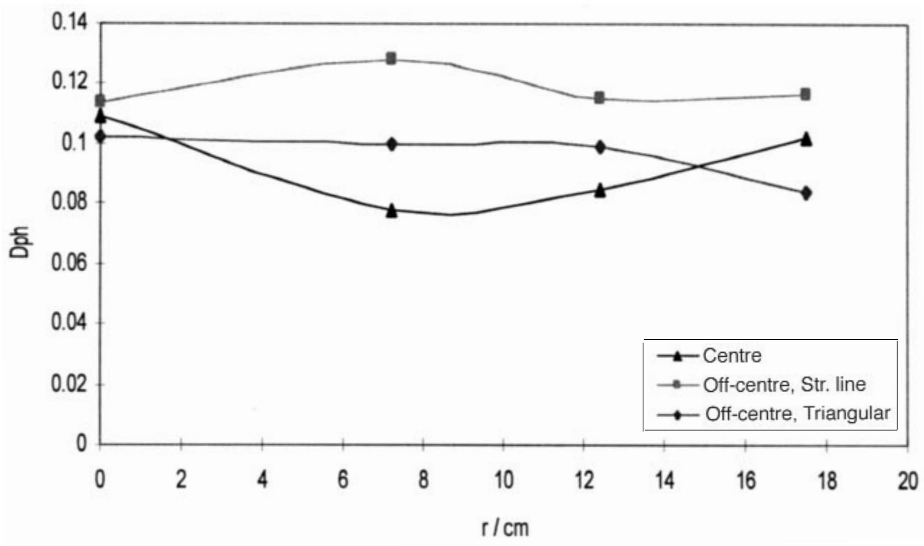

Figure 5. Effect of tuyere configuration on the radial variation of the Dph on the left-axis of the tank (0.00599 m³/s and z = 5 cm)

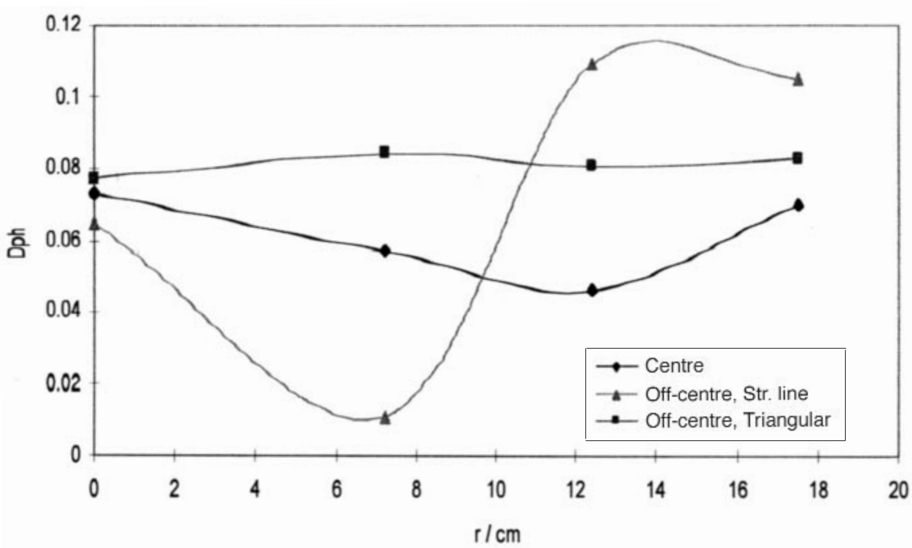

Figure 6. Effect of tuyere configuration on the radial variation of the Dph on the left-axis of the tank (0.00599 m³/s and z =15 cm)

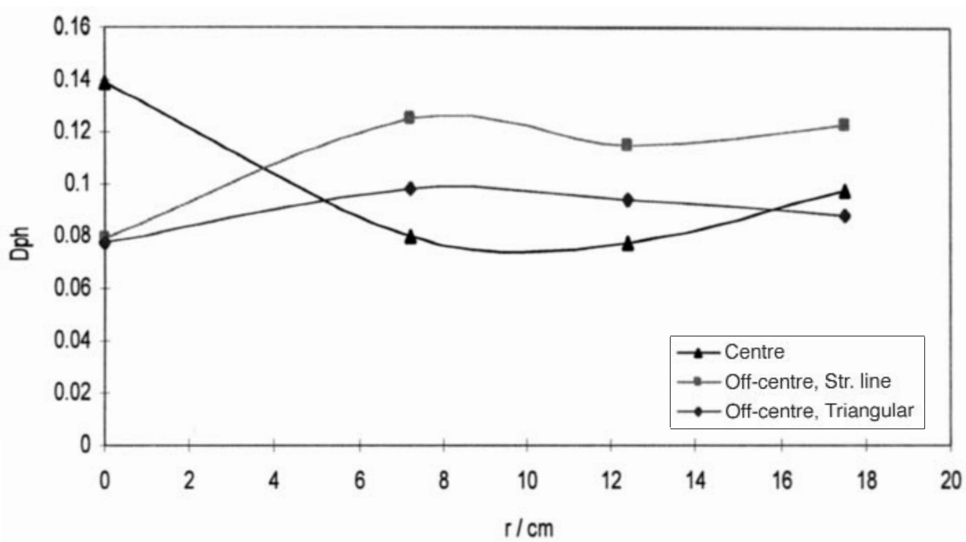

Figure 7. Effect of tuyere configuration on the radial variation of the Dph on the left-axis of the tank (0.00849 m³/s and z =15 cm)

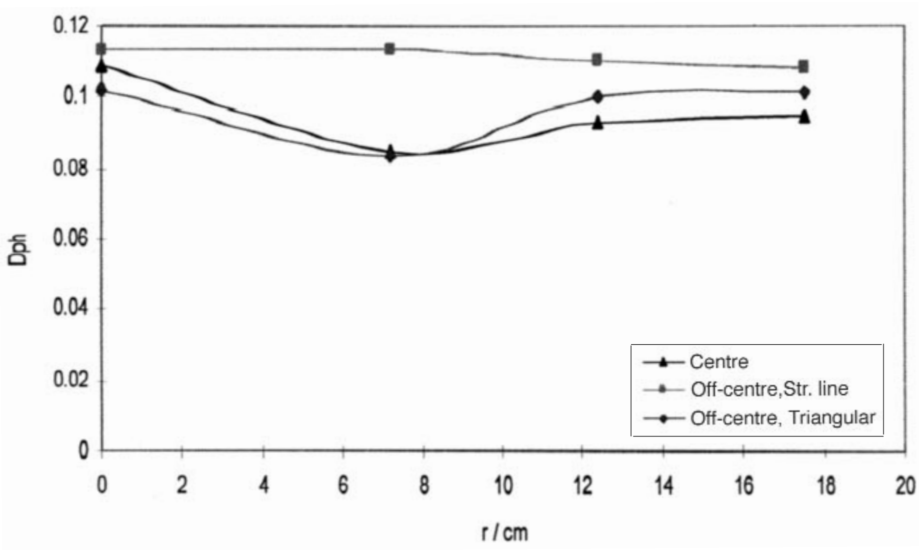

Figure 8. Effect of tuyere configuration on the radial variation of the Dph on the right-axis of the tank (0.00599 m3/s and z = 5 cm)

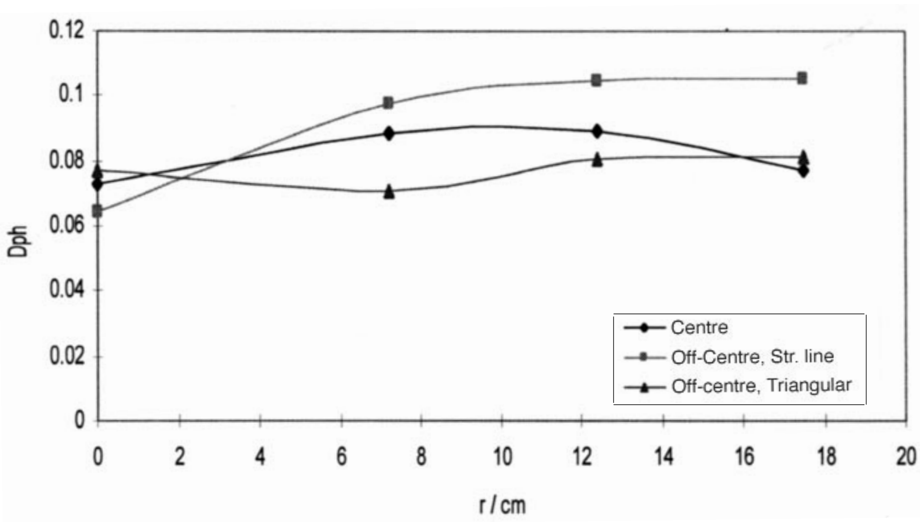

Figure 9. Effect of tuyere configuration on the radial variation of the Dph on the right-axis of the tank (0.00599 m³/s and z =15 cm)

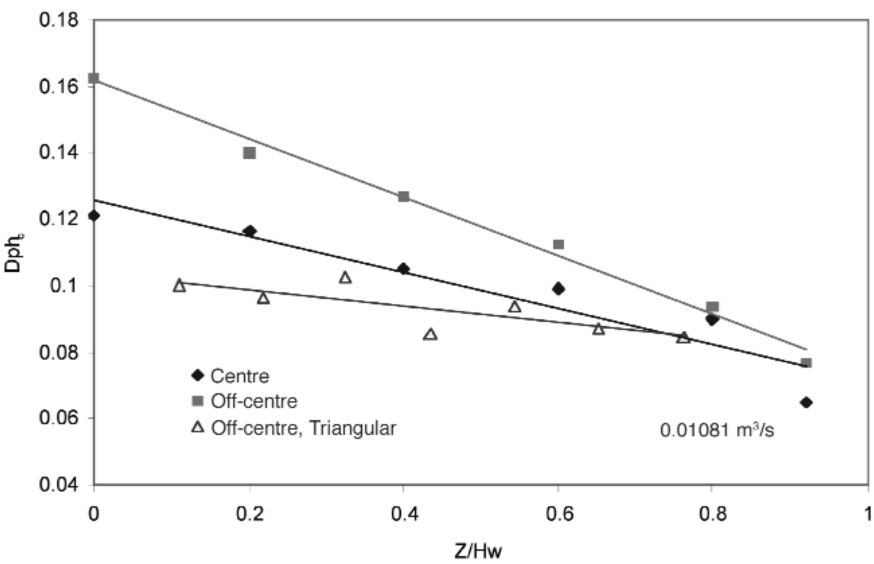

Figure 10. Effect of tuyere configuration on the dispersed phase holdup along the centreline

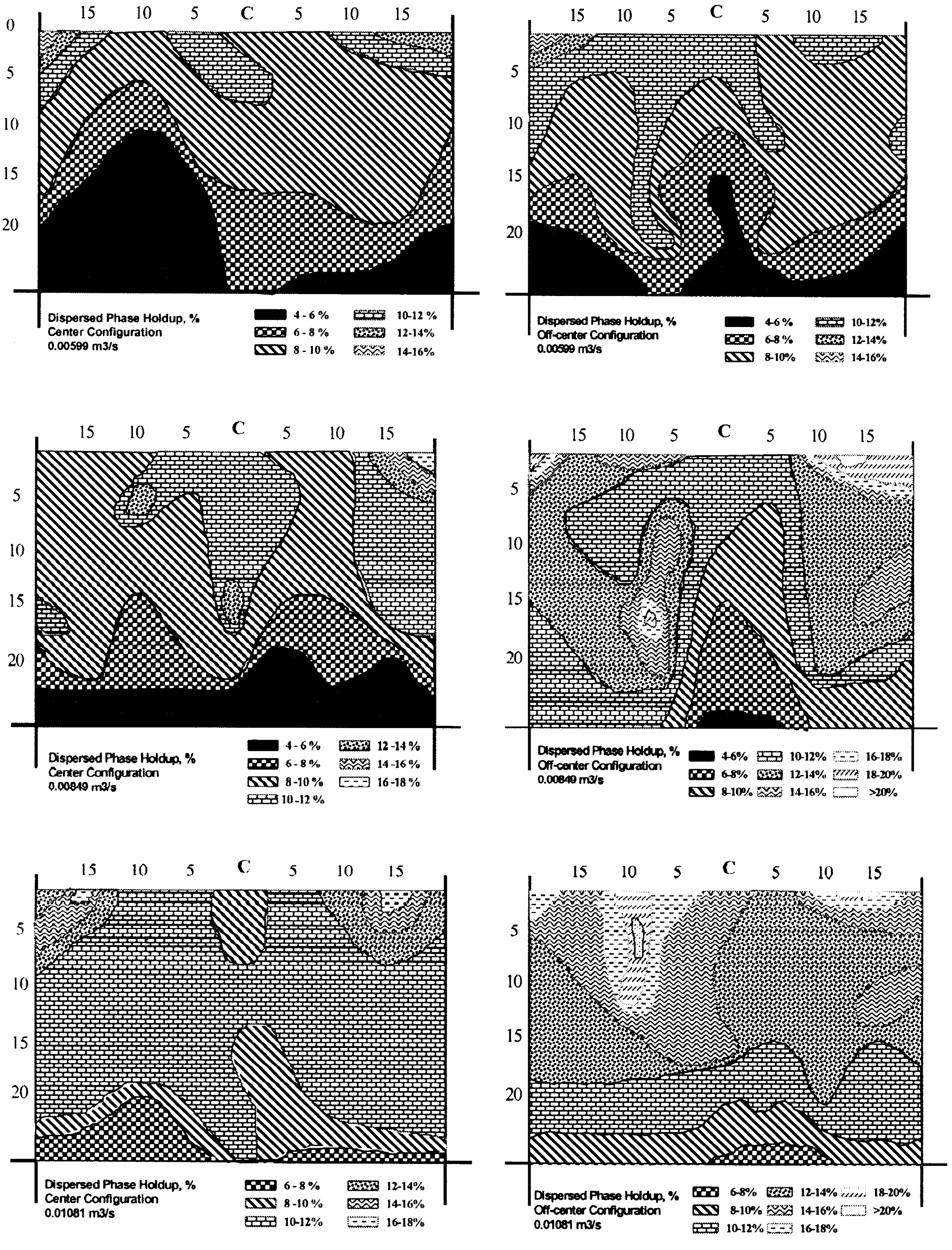

Figure 11. Comparison of dispersed slag phase holdup between off-centre straight and centre configuration along the left-right axis

Overall correlation of the dispersed-phase holdup

The variation of the dispersed slag phase holdup according to operating conditions was correlated by using modified Froude Number (Nfr). The overall distribution of the dispersed slag phase holdup can be approximated by the following equation:

$$\phi(z,r) = \phi_{centreline}\left[1-\left(\frac{r}{H_w}\right)^2\right]^a + \sin\left[b\left(\frac{r}{H_w}\right)\right] \qquad [1]$$

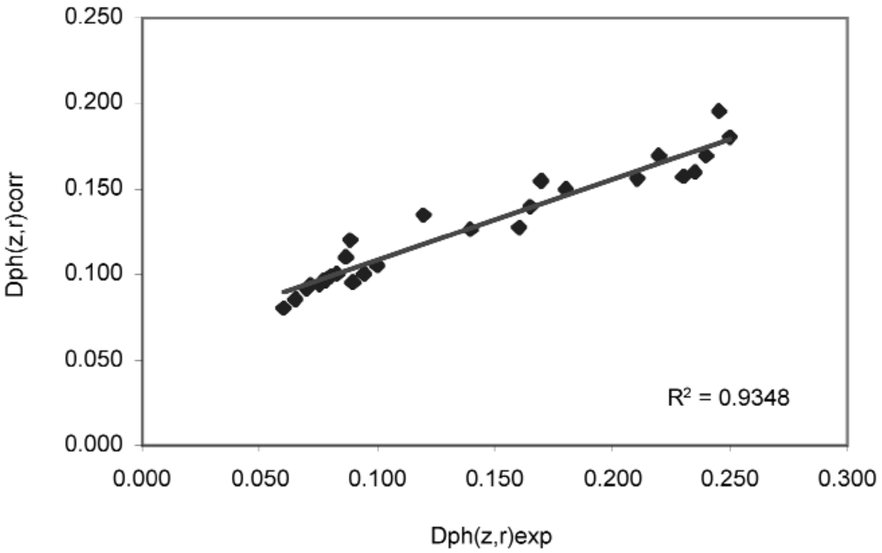

Figure 12. Comparison between the experimental and calculated values of the dispersed phase holdup

where:

$$\phi_{centreline} = 0.22\left[(Nfr)^{0.12}\left(\frac{H_o}{H_w}\right)^{0.74}\left[1-\left(\frac{z}{H_w}\right)^{2}\right]^{0.483}\right]^{1.02} \quad [2]$$

$$a = 0.00062\left[\left(\frac{z}{H_w}\right)^{0.9264}(Nfr)^{0.3278}\left(\frac{H_o}{H_w}\right)^{-1.8219}\right]^{0.7262} \quad [3]$$

$$b = 0.17\left(\frac{z}{H_w}\right)^{0.3523} \quad [4]$$

Equation [1] was used to represent the dispersed slag phase holdup for off-centre configuration at axial positions including the radial variations. The relationship between the experimental dispersed phase holdup values and those calculated using Equations [1] is illustrated in Figure 12. The standard deviation and standard error between the two values were 0.092 of about 0.0189, respectively, which indicates a satisfactory agreement between the experimental dispersed phase holdup values and the values calculated by using Equation [1]. R-squared value for the equation of correlation was 0.93.

Conclusions

A water model study has been carried out to determine the dispersed slag phase holdup for CLU process with different tuyere configurations and gas injection rates. The experimental results revealed that the dispersed phase holdup along the centreline of the model bath increased with the gas injection rate. The off-centre straight configuration displayed better dispersion results as compared to the centre and off-centre triangular configuration. The dispersed phase holdup decreased with the axial distance from the original interface. The variation of the dispersed phase holdup with radial distance from the center was found to vary according to tuyere configuration at a particular gas injection rate. The variation of the dispersed phase holdup for off-centre configuration with the dimensionless axial distance, radial variation and the gas injection rate was correlated by using the modified Froude number. The experimental values of the dispersed phase holdup were found to be in good agreement with the calculated values obtained from the correlation equations. The physical and mathematical model of the dispersed slag phase holdup developed in this work might provide a useful basis to describe the slag dispersion in actual industrial CLU processes.

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