Lecture 38 Modeling of steelmaking processes

Contents

Key words: Physical modeling, water modeling, tundish metallurgic

Introduction

With the globalization, steel market has become competitive both with respect to quality and cost of steel. Steel industry is required to produce quality steel at a reasonable cost so that it remains competitive with the world market. For this purpose constant and continuous efforts are required to introduce either new steelmaking technology or to improve the process technologies in the existing steel processing vessels like converter, ladle, continuous casting tundish and mold. In order to meet these objectives, a sustainable research and development activities must be carried out in the plant to address the quality issues in the steel product and then to introduce changes in the steel processing line, that is product- process integration approach. One of the research tools is to design the model of the actual process (here after we call proto type) so that specific studies can be made. The results of these studies can then be implemented for the desired objectives. A model of the process can either be physical or mathematical. The present lecture deals with some issue related to design of physical models of steelmaking processes.

Physical model

In physical modeling, the model reactor and experiments are designed based on the similarity criteria between the prototype and model. Both, model and prototype, must be similar geometrically, dynamically, chemically and thermally.

Two systems are said to be geometrically similar when for every point in the model, there exists a corresponding point in the prototype. This can be achieved by maintaining a constant ratio between the linear dimensions of the systems. This is called scale factor λ.

$$\lambda = \frac{D_m}{D_p} = \frac{L_m}{L_p} \qquad (1)$$

The above relation suggests that two systems following the geometrical similarly should have the same aspect ratio of the vessel . The value of scale factor indicates how big or small model would be. For example, a scale factor of 0.2 means that diameter of the model cylindrical vessel is 1/5 of the diameter of the actual vessel, if the actual vessel is cylindrical in shape. For a rectangular vessel all the linear dimensions of the model vessel are 1/5 of the actual ones.

Dynamic similarity requires that the corresponding forces acting at corresponding time and location must bear the same ratio between the model and the prototype. In steelmaking the inertial, viscous and surface tension forces are of relevance. The ratio between inertial and viscous force is called Reynold's number

$$\mathrm{Re} = \frac{\text{inertial force}}{\text{viscous force}} = \frac{\rho\ \mathrm{uL}}{\mu} = \frac{\mathrm{uL}}{\gamma} \qquad (2)$$

Where u is velocity, L is characteristic linear dimension and γ is kinematic viscosity. Reynold's number characterize the type of flow, that is whether laminar or turbulent.

The ratio between inertia and gravity force is Froude number (Fr)

$$(\mathrm{Fr}) = \frac{\mathrm{u}^2}{\mathrm{gL}}$$

Modified Froude number Fr^1 is more relevant than simple Froude number

$$\mathrm{Fr}^1 = \frac{\rho_g \mathrm{u}^2}{(\rho_l - \rho_g)\mathrm{gL}} = \frac{\text{aerodynamic force}}{\text{gravitational force}} \qquad (3)$$

ρ_g is the density of gas and ρ_l is density of liquid. Froude number determines the importance of aerodynamics force and gravitational force when gas jet either impinges the bath or submerged into the bath. Froude number similarity is very important to model the chemically active or inert gas injection in steelmaking processes.

Weber number (We) is the ratio of aerodynamic to surface tension force

$$\mathrm{We} = \frac{\rho \mathrm{u}^2 \mathrm{L}}{\sigma} \qquad (4)$$

σ is surface tension of liquid. The dynamic similarity requires

$$\mathrm{Re_m} = \mathrm{Re_p} \qquad (5)$$

$$\mathrm{Fr_m} = \mathrm{Fr_p} \text{ or } \mathrm{Fr^1_m} = \mathrm{Fr^1_p} \quad \text{and} \qquad (6)$$

$$\mathrm{We_m} = \mathrm{We_p} \qquad (7)$$

The similarity in Reynold's number requires that,

$$\frac{\mathrm{u_{om}}}{\mathrm{u_{op}}} = \frac{\gamma_m}{\gamma_p} \times \frac{1}{\lambda} \qquad (8)$$

The subscript m denotes model and p denotes prototype. The similarity in Froude number requires that.

$$\frac{\mathrm{u_{om}}}{\mathrm{u_{op}}} = \lambda^{0.5} \qquad (9)$$

And Weber number requires that,

$$\frac{u_{om}}{u_{op}} = \frac{\rho_p}{\rho_m} \frac{\sigma_m}{\sigma_p} \lambda^{0.5} \tag{10}$$

Weber number is relevant when droplet formation occurs in the actual system.

Design of a physical model for fluid flow in steel melt

In steelmaking, fluid flow in steel melt controls mixing and mass transfer reactions in converter and ladle. Fluid flow in the tundish of a continuous caster is also important to evaluate the performance of the tundish with reference to its ability to distribute molten steel in all molds at constant superheand to remove inclusions during the process of continuous casting. Experiment in full scale size of the steelmaking vessel with molten steel is very difficult and pose practical difficulties. Suitably designed models are very helpful to conduct large number of experiments to arrive at optimum results. These optimum results can be verified in the prototype selectively.

i. Selection of model vessel

The prototype vessels in steelmaking are converter, ladle and tundish. Converters and ladles are more or less cylindrical in shape. Whereas tundish is a rectangular with side walls inclined. Model vessel is designed by geometric similarity. A scale factor =1 represents full scale model. Full scale models may become difficult to handle since the dimensions involved would be large.

We select scale factor $\lambda = 0.2$for the purpose of illustration. If the industrial ladle has a diameter of 4m, model vessel diameter would be 80cm, while the aspect ratio (bath height/bath diameter) for both vessels will be same. The aspect ratio of industrial ladle is 0.9. Therefore model bath height is 72cm. similarly we can design model converter and model tundish by selecting a suitable scale factor.

ii. Selection of model steel melt phase

In order to compare the results of two geometrically similar systems it is essential that transport mechanisms should be similar in both the systems. For example if flow is turbulent in the prototype then turbulent flow should also prevail in model liquid. Density and viscosity of the fluid are the two important fluid properties that govern fluid flow behavior. Density represents inertia of fluid against an applied force and viscosity is internal friction of fluid. The ratio of density to viscosity, that is

$$\gamma = \frac{\mu}{\rho} \tag{11}$$

is called kinematic viscosity of fluid. Kinematic viscosity represents the diffusion of momentum flux into the liquid and governs the fluid flow behavior. Though absolute value of viscosity and density of steel melt may differ from the model liquid, similarity in kinematic viscosity in both the fluids ensures similar fluid flow behavior. In this connection water is the fluid whose kinematic viscosity is $10^{-6}\ \mathrm{m}^2/\mathrm{s}$ which is very close to that of molten steel melt. Thus water can be selected as model liquid. In fact water model has been very widely used to investigate the behavior of steel melt. Some references are given at the end of the lecture.

iii) Selection for model slag phase

It is in fact very difficult to find a low temperature model slag which is similar to actual slag. Density of slag in prototype is around 0.4 times that of molten steel. Slag floats on steel.

Transitory and permanent contact of slag phase with molten steel are the principle refining mechanisms. In transitory contact, the refining occurs by rising molten slag droplets. Due to large difference in the density of molten slag and steel, transitory contact mode is difficult to model. Permanent contact mode can be modeled. Several organic oils like paraffin, mineral oil can be used as a model slag to study the physics of slag/ metal interface.

iv) Selection of model velocity of gas

In steelmaking processes, gas is used to stirr the molten phases

Dynamic similarity must be observed between model and prototype, that

$(\mathrm{Re})_\mathrm{m} = (\mathrm{Re})_\mathrm{p}$

$(\mathrm{Fr})_\mathrm{m} = (\mathrm{Fr})_\mathrm{m}$ and

$(\mathrm{We})_\mathrm{m} = (\mathrm{We})_\mathrm{p}$

Substituting the quantitative value of the dimensionless numbers, we get.

$$\left.\begin{aligned} \left(\frac{\rho u L}{\mu}\right)_\mathrm{m} &= \left(\frac{\rho u L}{\mu}\right)_\mathrm{p} \\ \left(\frac{u^2}{gL}\right)_\mathrm{m} &= \left(\frac{u^2}{gL}\right)_\mathrm{p} \\ \left(\frac{\rho u^2 L}{\sigma}\right)_\mathrm{m} &= \left(\frac{\rho u^2 L}{\sigma}\right)_\mathrm{p} \end{aligned}\right\} \qquad 12)$$

From equations 12 we get for Reynold's number similarity

$$\frac{u_m}{u_p} = \frac{\gamma_m}{\gamma_p} \times \frac{1}{\lambda} \qquad (13)$$

For Froude number similarity

$$\frac{u_m}{u_p} = \left(\frac{\sigma_m}{\sigma_p}\right)^{0.5} \qquad (14)$$

For Weber number similarity

$$\frac{u_m}{u_p} = \left(\frac{\rho_p}{\rho_m}\right)^{0.5} \left(\frac{\sigma_m}{\sigma_p}\right)^{0.5} \lambda^{-0.5} \qquad (15)$$

The Weber number similarity can be neglected since the inertial forces in the prototype are very large as compared to surface tension forces.

Froude and Reynold's number similarity can be obtained in a aqueous model only when $\lambda = 1$. This lecture highlights some of the important aspects of physical modeling of steelmaking processes. In the past several years physical modeling or more precisely water modeling has become a very important tool to investigate the physical effects in steelmaking caused by either impinging or submerged gas jets. The references are given at the end of the lecture 39.