Chemical Engineering Science 170 (2017) 777–789

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Effect of differential flow schemes on gas-liquid flow and liquid phase mixing in a Basic Oxygen Furnace

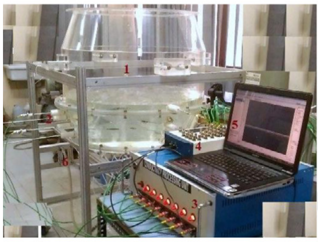
Abdul Quiyoom [a], Ravi Golani [b], Vikas Singh [b], Vivek V. Buwa [a,*]

[a] *Department of Chemical Engineering, Indian Institute of Technology Delhi, New Delhi 110016, India*
[b] *R & D Division, Tata Steel Limited, Jamshedpur 831001, India*

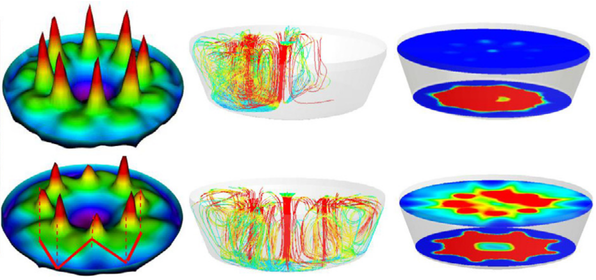
## HIGHLIGHTS

- 3D transient Euler-Lagrange simulations of dispersed gas-liquid flow and liquid phase mixing in a scaled-down BOF vessel.
- Dynamics of gas-liquid flow generated by different flow schemes characterized.
- Simultaneous measurements of mixing time at multiple locations.
- Satisfactory prediction of mixing time generated by different flow schemes.
- Differential θ-direction led to significant improvement in mixing performance.

## GRAPHICAL ABSTRACT



Scaled-down cold flow model of BOF vessel



Simulated instantaneous vertical liquid velocity, pathlines and instantaneous tracer mass fraction distribution for uniform (top) and W-differential (bottom) flow schemes

## ARTICLE INFO

*Article history:*
Received 31 August 2016
Received in revised form 14 December 2016
Accepted 2 March 2017
Available online 6 March 2017

*Keywords:*
Computational Fluid Dynamics
Basic Oxygen Furnace
Euler-Lagrange Simulation
Gas-Liquid Flow
Mixing
Differential Flow
Dynamics

## ABSTRACT

At present, for about 70% steel production worldwide, a Basic Oxygen Furnace (BOF) is used to reduce impurities like C, Mn, P, S, Si, etc. present in liquid metal. In order to improve the mixing efficiency and therefore the quality of steel, bottom blowing plays a prominent role and is affected by several parameters i.e. gas flow rate, flow schemes, the number of bottom tuyeres used and their locations. In the present study, 3D transient Euler–Lagrange (EL) simulations of dispersed gas–liquid flow were performed in a 6:1 scaled–down cold flow model of BOF steel converter to predict the gas-liquid flow and mixing time for different bottom blowing schemes. The predictions of mixing time were verified using mixing time measurements performed using in-house developed miniaturized conductivity probes. Effect of various differential flow schemes on dynamics of gas-liquid flow and mixing time was investigated. The predicted spatially–averaged mixing times were found to be in a good agreement with the measurements, for various differential flow schemes considered in the present work. Among these schemes, W– and V–differential flow schemes, that provide variation of gas flow rate in θ–direction led to the best mixing. The mixing time for these schemes was found to be reduced by 25–30% than that of conventional uniform flow scheme. The dynamic differential scheme in which the inlet flow was changed with time, required additional time to attain a new flow field corresponding to the changed inlet flow condition and therefore required a longer mixing time. The experimentally verified computational model and the results presented in the present work will be useful to improve mixing in commercial BOF vessels.

---

* Corresponding author.
*E-mail address:* vvbuwa@iitd.ac.in (V.V. Buwa).

http://dx.doi.org/10.1016/j.ces.2017.03.010
0009-2509/

## 1. Introduction

At present, for about 70% worldwide steel production, a Basic Oxygen Furnace (BOF) is used to reduce impurities like C, Mn, P, S, Si, etc. present in liquid metal. In the BOF steelmaking process, a supersonic jet of high purity oxygen is blown from the top (known as "top blowing") into the metal bath. The top blowing provides oxygen for the oxidation of impurities present in the metal bath by the addition of fluxes (lime, fluorspar, dolomite, etc.). The intensity of mixing in the metal bath provided by top blowing is insufficient (Ajmani and Chatterjee, 2005; Emi, 2015) and therefore, in most of the steel making processes, mixing is also assisted by injection of inert gases from the bottom (known as "bottom blowing") to provide efficient mixing inside the vessel. This leads to an improved homogeneity, slag–metal interaction, heat and mass transfer rate and reaction kinetics within the metal bath (Ajmani and Chatterjee, 1996; Choudhary and Ajmani, 2006; Luomala et al., 2004; Singh et al., 2007, 2009; Zhong et al., 2006). The bottom blowing is affected by several parameters i.e. gas flow rate, flow schemes, number of bottom tuyeres and their locations, etc. Therefore, in order to optimize the bottom tuyere configurations in terms of improved mixing performance, it is important to simulate the gas–liquid flow and liquid phase mixing in a BOF vessel accurately to understand the dynamic characteristics of gas–liquid flow and the reasons/mechanisms of mixing generated by different bottom tuyere configurations or schemes.

The supersonic oxygen jet emanating from the top lance causes splashing, splitting and foaming of the slag phase that makes the overall process highly exothermic and complex. Therefore, the simulations of the complete process (with the top blowing) become extremely challenging and also it is very difficult to perform the actual measurements because of very high temperature (~1600 °C) inside the vessel. Since most of the mixing in the metal bath is achieved by bottom blowing and the kinematic viscosity the water is same as molten steel (Ajmani and Chatterjee, 1996; Krishnakumar et al., 1999), cold flow (water model) experiments, performed without top blowing, have been used successfully to optimize bottom tuyere configurations and different flow schemes (Ballal and Ghosh, 1981; Choudhary and Ajmani, 2006; Luomala et al., 2004; Singh et al., 2007, 2009).

Over the years, several experimental investigations (Ajmani and Chatterjee, 1996; Choudhary and Ajmani, 2006; Krishnakumar et al., 1999; Lai et al., 2008; Singh and Ghosh, 1990; Singh et al., 2007, 2009; Zhong et al., 2006) on the optimization of bottom tuyere configurations have been carried out to enhance the mixing inside the metal bath. Singh and Ghosh (1990) performed cold flow experiments in a 40:1 scaled–down model of 230 t LD converter. They studied the effect of number of bottom tuyeres and gas flow rate on mixing time and showed the mixing time to decrease with increase in the number of tuyeres. However, due to experimental limitations, their study was limited to a maximum 4 tuyeres only. Choudhary and Ajmani (2006) performed cold flow experiments in a 6:1 scaled–down model of BOF vessel to optimize the bottom tuyere configurations. Among the various bottom tuyere configurations, they showed that the configuration consisting of 8 tuyeres in symmetric non-equiangular position was found to give the best mixing in the vessel. An improvement of about 40% in the mixing was observed in comparison to a configuration with six bottom tuyeres. Later, Lai et al. (2008) carried out water–model experiments in a 8.5:1 scaled–down model to study the influence of symmetric and asymmetric bottom tuyere configurations on mixing in a combined blown converter. They showed that the bath stirring could be improved by using asymmetric bottom tuyere arrangement in the case of combined blowing converter. However, Ballal and Ghosh (1981) suggested to avoid the asymmetric tuyere arrangement, due to more wearing of refractories than that of symmetric tuyere arrangements.

Based on the previous studies, it was realized that with increase in number of bottom tuyeres from a single concentric bottom tuyere to as high as eight number of bottom tuyeres, the mixing efficiency in the metal bath was found to increase. However, due to the limitation of operating conditions in actual plant and to avoid the mechanical wear of bottom refractories, further increment in the number of bottom tuyeres was unfavorable. Therefore, within the limitation of maximum number of bottom tuyeres (i.e., 8), Singh et al. (2009) investigated the effect of differential flow schemes on mixing in 6:1 scaled–down cold flow model of the BOF vessel and reported a reduction in the mixing time. However, the effect of different flow schemes on dynamics of gas–liquid flow and reasons for the reduction in mixing time were not analyzed.

Over the years, a few experimental (Luomala et al., 2004; Martín et al., 2005; Wuppermann et al., 2012) and numerical (Odenthal et al., 2010; Wu et al., 2015) studies have been performed to investigate the dynamics of gas–liquid flow and mixing in BOF vessels. Martín et al. (2005) performed the mixing experiments in a steel converter using colorimetric methods and showed regions with varying extent of mixing arising due to dynamics and locally recirculatory liquid flow in the converter. Based on visual observations, they concluded that local mixing plays a major role in the overall mixing efficiency in the converter. Wuppermann et al. (2012) performed PIV experiments to understand the flow field inside the BOF vessel qualitatively. They showed that flow pattern with randomly distributed vortices governed the mixing in the vessel. Odenthal et al. (2010) performed the CFD studies of combined blown BOF converter to simulate the behavior of gas plumes and their interactions with the bulk liquid flow to describe the flow pattern and mixing in the process vessel. They used DPM + VOF model to predict the oscillation and splashing of slag caused by top blowing. However, due to the limitation of the VOF method, the complex behavior of foaming and splitting of the slag phase was predicted only qualitatively. Also, experimental validation and detailed quantitative analysis of dynamics of the gas–liquid flow was not studied. Recently, Wu et al. (2015) performed simulations of BOF vessel (by considering a quarter of the converter) to optimize the bottom configuration and showed that eight bottom tuyeres placed at PCR of 0.55 provided the best mixing in the converter. However, their study was limited to simulation of a single bubble plume.

The present state of the art shows that in most of the investigations, performed for the BOF vessel with bottom blowing, optimization of bottom tuyeres configuration was analyzed in term of mixing time. The dynamics of gas–liquid flow generated by multiple meandering bubble plumes and the effect of different differential flow schemes for bottom gas injection on the dynamics of gas–liquid flow are not reported in the open literature. Further, in most of the studies reported in the literature, simulations of gas–liquid flow and mixing in BOF vessels were performed for a small section (often a quarter of the vessel) that consisted of only one bubble plume with the assumption of symmetric flow and mixing in the vessel. The objective of the present work is to simulate the gas–liquid flow and mixing in a BOF vessel under cold flow conditions and to investigate the effect of differential flow schemes on liquid phase velocity distribution, dynamics and eventually on liquid phase mixing and to verify the predictions using mixing time measurements.

## 2. Experimental set-up

A 6:1 scaled–down BOF vessel made of Plexi–glass was used to carry out cold flow experiments. The schematic of the experimen-