MIXING IN A BASIC OXYGEN FURNACE (BOF) UNDER COMBINED BLOWING CONDITIONS: COLD-FLOW MEASUREMENTS AND DEVELOPMENT OF CFD MODEL

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Mixing in a Basic Oxygen Furnace (BOF) under Combined Blowing Conditions: Cold-flow Measurements and Development of CFD Model

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Certificate

This is to certify that the thesis entitled “Mixing **in a Basic Oxygen Furnace (BOF) under Combined Blowing Conditions: Cold-Flow Measurements and Development of CFD Model”** being submitted by **Mr. Sayantan Biswas** to the **Indian Institute of Technology, Delhi** for the award of the degree of **Doctor of Philosophy** is a bonafide record of original research work carried out by him under my supervision in conformity with rules and regulations of the institute. The results contained in this thesis have not been submitted, in part or in full, to any other University or Institute for the award of any Degree or Diploma.

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Abstract

The Basic Oxygen Furnace (BOF) is widely used to produce high-quality steel from pig iron as a part of the primary steel refining process. In this present work, we have simulated the dynamics of dispersed gas-liquid flow in a 6:1 scaled-down BOF vessel under cold-flow conditions using two two-fluid Euler-Euler method. The effect of interphase coupling forces (drag and non-drag forces) on the behaviour of multiple interacting bubble plumes are systematically investigated and a reasonable agreement is found with the corresponding measurements.

The experimentally- validated computational model is extended to the Eulerian multi-fluid approach to incorporate the slag layer. The implementation of three-phase interphase coupling forces in the Eulerian framework is analysed in detail. Cold flow measurements are performed to measure the 'open-eye' formation and the measurements are compared with the corresponding simulations for different mass flow rates and heights of the slag layer. The mixing time predicted by two-fluid Euler-Euler model (without slag layer) is compared with corresponding measurements and a good agreement is found for different mass flow rates. Further, the effect of the slag layer, its height, and physical properties (density and viscosity) on the liquid-phase hydrodynamics and mixing behaviour is numerically investigated. The spatial distribution of the slag layer and liquid-phase hydrodynamics is found to be significantly influenced by mass flow rate, height of the slag layer, and its density.

The bottom-blowing BOF model is integrated with a top-blowing lance consist of 4 converging-diverging nozzles to simulate dispersed gas-liquid flow under combined blowing conditions using two fluid Euler-Euler method. The cavity/ crater formation created by multiple impinging jets is compared with theoretical corelation. A reasonable agreement is found for wide different top blowing mass flow rate and lance height. Further, the effect of top-blowing

flow rates, and lance height on the liquid-phase hydrodynamics and mixing behaviour is investigated. We found liquid-phase mixing is found to be delayed as compared to bottom blowing in spite of the additional energy provided by the top blowing.

In a separate work, the rise of a bubble plume through two immiscible liquids is simulated using the Discrete Particle-Volume of Fluid (DPM-VOF) approach in a rectangular column. The relative contributions of different forces (inertial, gravitational, viscous, and interfacial tension) that govern the oil-water interface topology are investigated by varying the liquid properties systematically (density, viscosity, and interfacial tension) and operating conditions (thickness of oil layer, flow rate, and bubble size). We identified four different interface topologies and a regime map is proposed to characterize the interplay of governing forces using modified Froude (Fr^*) and Capillary Number (Ca).

The results presented in this thesis will help to understand the liquid-phase hydrodynamics and mixing behviour generated by meandering multiple bubble plumes in presence of slag layer and in a scaled-down BOF vessel under bottom and combined blowing conditions. In addition, role of forces that govern liquid-liquid interface distribution when a bubble plume is rising through two immiscible liquid layer. The refining reactions kinetics and heat transfer can be integrated with the present computational model which will allow to simulate the commercial BOF vessel at actual conditions to improve its performance.

सारांश:

बेसिक ऑक्सीजन फर्नेस (BOF) का व्यापक रूप से उपयोग कच्चा लोहे से उच्च गुणवत्ता वाला इस्पात बनाने के लिए प्राथमिक स्टील शोधन प्रक्रिया के एक भाग के रूप में किया जाता है। इस वर्तमान कार्य में, हमने ठंडे प्रवाह (cold-flow) की स्थिति में 6:1 स्केल-डाउन BOF पात्र में गैस-तरल प्रवाह की गतिशीलता का अनुकरण, दो-द्रव (Euler-Euler) विधि द्वारा किया है। इंटरफेज कपलिंग बलों (ड्रैग और गैर-ड्रैग बलों) का प्रभाव बहु-बबल प्लूम के व्यवहार पर व्यवस्थित रूप से अध्ययन किया गया और इसके परिणामों की तुलनात्मक मापनों से अच्छी संगति पाई गई।

प्रायोगिक रूप से मान्यीकृत इस गणनात्मक मॉडल को स्लैग परत को शामिल करने के लिए यूलरियन मल्टी-फ्लुइड दृष्टिकोण तक विस्तारित किया गया है। यूलरियन रूपरेखा में तीन-चरण इंटरफेज कपलिंग बलों के कार्यान्वयन का विस्तार से विश्लेषण किया गया है। "ओपन-आई" बनने की प्रक्रिया को मापने के लिए ठंडे प्रवाह के प्रयोग किए गए और अलग-अलग मास फ्लो दरों तथा स्लैग परत की ऊँचाई के लिए प्राप्त मापनों की संबंधित सिमुलेशन के साथ तुलना की गई। बिना स्लैग परत वाले दो-द्रव यूलर-यूलर मॉडल द्वारा पूर्वानुमानित मिक्सिंग समय की तुलना मापनों से की गई और विभिन्न फ्लो दरों के लिए अच्छी संगति देखी गई। इसके अतिरिक्त, स्लैग परत, उसकी ऊँचाई, और उसकी भौतिक गुणों (घनत्व और श्यानता) के प्रभाव का तरल-चरण गतिशीलता और मिश्रण व्यवहार पर संख्यात्मक रूप से अध्ययन किया गया। यह पाया गया कि स्लैग परत की स्थानिक संरचना और तरल की गतिशीलता को मास फ्लो दर, स्लैग परत की ऊँचाई, और घनत्व द्वारा महत्वपूर्ण रूप से प्रभावित किया जाता है।

बॉटम ब्लोइंग BOF मॉडल को चार संकुचन-विस्तारण नोजल वाली टॉप ब्लोइंग लांस के साथ जोड़ा गया है, ताकि सम्मिलित ब्लोइंग स्थितियों में दो-द्रव यूलर-यूलर विधि का उपयोग करते हुए गैस-तरल प्रवाह का अनुकरण किया जा सके। बहु-प्रभावी जेट्स द्वारा निर्मित गुफा/क्रेटर संरचना की तुलना सैद्धांतिक संबंधों से की गई और विभिन्न टॉप ब्लोइंग फ्लो दरों तथा लांस की ऊँचाई के लिए अच्छी संगति प्राप्त हुई।

आगे, टॉप ब्लोइंग फ्लो दरों और लांस ऊँचाई के तरल-चरण गतिशीलता और मिश्रण व्यवहार पर प्रभाव का अध्ययन किया गया। यह पाया गया कि टॉप ब्लोइंग के अतिरिक्त ऊर्जा के बावजूद, बॉटम ब्लोइंग की तुलना में तरल-चरण मिक्सिंग में विलंब होता है।

एक अन्य स्वतंत्र अध्ययन में, दो अमिश्रणीय तरल परतों के माध्यम से बबल प्लूम के उठने की प्रक्रिया का अनुकरण एक आयताकार स्तंभ में डिस्क्रीट पार्टिकल-वॉल्यूम ऑफ फ्लुइड (DPM-VOF) विधि से किया गया है। इस अध्ययन में तेल-पानी इंटरफेस की आकृति विज्ञान को नियंत्रित करने वाली विभिन्न बलों (जड़त्वीय, गुरुत्वीय, श्यान, और अंतरफलक तन्यता) के सापेक्ष योगदान का विश्लेषण किया गया है, जिसमें तरल गुणों (घनत्व, श्यानता और अंतरफलक तन्यता) और परिचालन स्थितियों (तेल परत की मोटाई, प्रवाह दर, और बबल का आकार) को व्यवस्थित रूप से परिवर्तित किया गया है। हमने चार विभिन्न इंटरफेस आकृतियों की पहचान की और एक रेजीम मैप प्रस्तावित किया है जो नियंत्रक बलों की अंत:क्रिया को संशोधित फ्रौड संख्या (Fr*) और कैपिलरी संख्या (Ca) के माध्यम से दर्शाता है।

इस शोध में प्रस्तुत परिणाम तरल-चरण गतिशीलता और मिश्रण व्यवहार को समझने में सहायक होंगे, विशेषकर स्लैग परत की उपस्थिति में और स्केल-डाउन BOF पात्र में बहती बहु-बबल प्लूम की स्थिति में, बॉटम और सम्मिलित ब्लोइंग स्थितियों में। इसके अतिरिक्त, यह भी स्पष्ट होता है कि जब बबल प्लूम दो अमिश्रणीय तरल परतों के माध्यम से उठता है, तो तरल-तरल इंटरफेस वितरण को नियंत्रित करने वाले बलों की भूमिका क्या होती है। वर्तमान गणनात्मक मॉडल में परिशोधन अभिक्रियाओं की गति और ऊष्मा स्थानांतरण को भी जोड़ा जा सकता है, जिससे वास्तविक परिस्थितियों में वाणिज्यिक BOF पात्र का अनुकरण कर उसकी कार्यक्षमता को बेहतर बनाया जा सकेगा।

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Nomenclature

H	Liquid bath height, m
g	Gravitational acceleration, m/s^2
Re_b	Bubble Reynold's number, -
$E\ddot{o}$	Eotvos number, -
Ca	Capillary number
Fr^*	Modified Froud number, -
m_G	Gas mass flowrate, kg/s
$\vec{M}$	Interphase momentum exchange force, N/ m^3
P	Pressure, N/m^2
$\vec{U}$	Mean velocity, m/s
$\vec{F}_D$	Drag force, N/m^3
C_D	Drag coefficient, -
$\vec{F}_L$	Lift force, N/m^3
C_L	Lift coefficient, -
$\vec{F}_{TD}$	Turbulent dispersion force, N/m^3
C_{TD}	Turbulent dispersion coefficient, -
K_{cd}	Momentum exchange coefficient, kg/m^3 s
h_O	Oil layer thickness, mm
C_A	Tracer mass fraction,-
D	Diffusivity, m^2/s
X, Y, Z	Spatial coordinates (along the width, height, and depth respectively), m
h_c	Depth of cavity, m
H_l	Lance height, m
$\bar{V}_W$	Instantaneous water-phase velocity magnitude, m/s
$\bar{V}_{W,Y}$	Instantaneous water-phase vertical velocity, m/s
$\bar{V}_{W,\theta}$	Instantaneous water-phase circumferential velocity, m/s
$\langle\bar{V}_W\rangle$	Time-averaged water phase velocity magnitude, m/s
$\langle\bar{V}_{W,Y}\rangle$	Time-averaged water phase vertical velocity, m/s
$\langle\bar{\alpha}_{G,\theta}\rangle$	Time- and- θ-averaged gas volume fraction, -

Greek letters

α	Volume fraction, -
μ	Viscosity, Pa-s
ρ	Density, kg/m^3
k	Turbulent kinetic energy, m^2/s^2
ε	Turbulent kinetic energy dissipation rate, m^2/s^3
$\bar{\bar{\tau}}$	Shear stress, N/m^2
σ	Surface tension coefficient, N/m

Subscripts

A	Actual
M	Model
i	i th phase
G	Air/ gas
O	Oil/ slag
W	Water
lam	Laminar
eff	Effective
t	Turbulent
T	Top blowing
B	Bottom blowing
c	Continuous
d	Dispersed

Acronyms

BOF	Basic Oxygen Furnace
E-E	Euler-Euler
CFD	Computational Fluid Dynamics
VOF	Volume of fluid
DPM	Discrete Particle Method
PBM	Population Balance Method
PCD	Pitch to circle diameter ratio
RANS	Reynolds Averaged Navier-Stoke equation
TKE	Turbulent kinetic energy