EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF DISPERSED GAS-LIQUID FLOW AND MIXING IN A SCALED-DOWN COLD FLOW MODEL OF BASIC OXYGEN FURNACE

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by

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Certificate

This is to certify that the thesis entitled "**Experimental and Numerical Investigations of Dispersed Gas-Liquid Flow and Mixing in a Scaled-down Cold Flow Model of Basic Oxygen Furnace"** being submitted by **Mr. Abdul Quiyoom** 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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Abdul Quiyoom

Abstract

The present thesis focuses on the characterization of dynamics of dispersed gas-liquid flow and liquid-phase mixing generated by multiple meandering bubble plumes in a scaled-down cold flow model of Basic Oxygen Furnace (BOF) through measurements and CFD simulations. The role of complex interactions among meandering bubble plumes in the primary (in r-direction) and secondary (in θ-direction) flow, that governs the local mixing inside the vessel BOF vessel, was quantified. Cold flow experiments were performed to measure the instantaneous and time-averaged gas volume fraction, and local mixing time at different gas mass flow rates using in-house developed voidage and conductivity probes, respectively. 3D transient Euler-Lagrange (EL) simulations of dispersed gas-liquid flow were performed under cold flow conditions. The predicted instantaneous and time-averaged gas volume fraction and local as well as spatially-averaged mixing time were found in a satisfactory agreement with the measurements. The effect of oscillatory behavior of multiple bubble plumes on the dynamics of gas-liquid flow and mixing was studied. In the case of uniform flow scheme (conventional flow scheme used in industry), the liquid-phase flow field was found to be asymmetric and it led to asymmetric mixing inside the vessel. In this case, the local mixing time varied considerably from one location to the other location in the vessel.

3D/transient Euler-Lagrange (EL) without/with Volume-of-Fluid (VOF) simulations of dispersed gas-liquid flow were performed to investigate the effect of the free gas-liquid interface on the dynamics of gas-liquid flow and mixing at different H/D ratios. For lower H/D ratios, EL simulations performed with no-slip and free-slip boundary conditions led to oscillatory plume behaviour and higher liquid velocity regions which in turn led to lesser mixing time. In contrast, EL+VOF simulations led to reduced meandering motion of bubble

plumes and lower liquid velocities resulting in higher mixing times. Interestingly, the mixing time predicted using the EL+VOF approach was found to be in a good agreement with the measurements

The effect of PCD (pitch-to circle-diameter ratio), which provide the flow variation in the radial direction, on dynamics of gas-liquid flow and mixing was studied. It was found that the flow was symmetric when eight bottom tuyeres were placed at PCD of 0.5 and it led to efficient mixing than that the configurations in which tuyeres were placed at the PCD of 0.7 and 0.59. The contributions of different mixing mechanism and the role of primary and secondary flow in determining the dynamics of gas-liquid flow and local mixing were studied. The modified bottom tuyere arrangements (referred as STAR-configurations) that create the flow variation in r-direction (primary flow) and also in θ-direction (secondary flow) were proposed. The flow rate variation along the radial and circumferential direction in an alternating arrangement generated re-circulatory cells in the circumferential direction (in addition to the re-circulatory cells in the radial direction) and this led to fast mixing inside the vessel. The mixing time was found to be reduced by 40-45 % than that of the conventional flow scheme. The experimentally verified computational model and the proposed STAR-type configuration will be useful to improve mixing efficiency, hence steel quality in BOF vessels.

सार

वर्तमान थीसिस फैलाने वाले गैस-तरल प्रवाह के मापने और सीएफडी सिमुलेशन के माध्यम से बेसिक ऑक्सीजन फर्नेस (बीओएफ) के स्केल किए गए ठंडे प्रवाह मॉडल में कई घूमने वाले बबल प्लूम्स द्वारा उत्पन्न तरल चरण मिश्रण की गतिशीलता की विशेषता पर केंद्रित है। प्राथमिक (r-दिशा में) और द्वितीयक (θ- दिशा में) प्रवाह में घूमने वाले बबल प्लुम बीच जटिल इंटरैक्शन की भूमिका, जो बीओएफ वेसेल के अंदर स्थानीय मिश्रण को नियंत्रित करती है, को प्रमाणित किया गया था। तत्काल और समय-औसत गैस वॉल्यूम अंश और स्थानीय मिश्रण समय को मापने के लिए इन-हाउस विकसित प्रोब्स का उपयोग किया गया है। यूलर-लग्रेंज (ईएल) अप्रोच का प्रयोग फैलाने वाले गैस-तरल के ठंडे प्रवाह का 3 डी क्षणिक सिमुलेशन के लिए किया गया था। अनुमानित तात्कालिक और समय-औसत गैस वॉल्यूम अंश और स्थानीय के साथ-साथ स्थानिक रूप से औसत मिश्रण समय माप के सात संतोषजनक पाए गए थे। गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर बबल प्लुम के असंतुलित व्यवहार का प्रभाव अध्ययन किया गया था। डिफ़ाल्ट प्रवाह योजना (उद्योग में उपयोग की जाने वाली पारंपरिक प्रवाह योजना) के मामले में, तरल चरण प्रवाह क्षेत्र असममित पाया गया था और इससे वेसेल के अंदर विषम मिश्रण होता है। इस मामले में, स्थानीय मिश्रण समय एक स्थान से दूसरे स्थान पर काफी भिन्न था।

गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर मुक्त गैस-तरल इंटरफेस के प्रभाव की जांच के लिए फैले हुए गैस-तरल प्रवाह को वॉल्यूम-ऑफ-फ्लुइड (वीओएफ) + यूलर-लैग्रेज (ईएल) सिम्युलेशन और यूलर-लैग्रेज (ईएल) के साथ विभिन्न एच / डी अनुपात में किया गया । निचले एच / डी अनुपात के लिए, ईएल सिमुलेशन ने नो-स्लिप और फ्री-स्लिप सीमा परिस्थितियों के साथ प्रदर्शन किया, जिससे ऑसीलेटररी बबल प्लूम्स व्यवहार, उच्च तरल वेग वाले क्षेत्रों का कारण बन गया जो बदले में कम मिश्रण समय का कारण बना। इसके विपरीत, ईएल + वीओएफ सिमुलेशन ने बबल प्लूम्स और कम तरल वेगों की घूमने वाली गति को कम कर दिया जिसके परिणामस्वरूप मिश्रण समय बढ़ गया। दिलचस्प बात यह

है कि ईएल + वीओएफ दृष्टिकोण का उपयोग करके अनुमानित मिश्रण समय माप के साथ एक अच्छे समझौते में पाया गया था

पीसीडी (पिच-टू सर्कल-व्यास अनुपात) का प्रभाव, जो रेडियल दिशा में प्रवाह भिन्नता प्रदान करता है का गैस-तरल प्रवाह और मिश्रण की गतिशीलता पर अध्ययन किया गया था। यह पाया गया कि प्रवाह सममित था जब आठ गॅस ईंलेट 0.5 के पीसीडी पर रखे गए थे और इससे कॉन्फ़िगरेशन में उनीफ़ोर्म मिश्रण हुआ, 0.7 और 0.59 के पीसीडी की तुलना में। गैस-तरल प्रवाह और स्थानीय मिश्रण की गतिशीलता को निर्धारित करने में विभिन्न मिश्रण तंत्र और प्राथमिक और माध्यमिक प्रवाह की भूमिका का अध्ययन किया गया। संशोधित टायर व्यवस्था (स्टार-कॉन्फ़िगरेशन के रूप में संदर्भित) जो आर-दिशा (प्राथमिक प्रवाह) में प्रवाह भिन्नता और θ-दिशा (माध्यमिक प्रवाह) में भी प्रवाह भिन्नता का प्रस्ताव दिया गया था। इस वैकल्पिक व्यवस्था में रेडियल और परिधीय दिशा के साथ प्रवाह दर भिन्नता परिधीय दिशा में पुन: परिसंचरण उत्पन्न होता है (रेडियल दिशा में पुन: परिसंचरण के अतिरिक्त) और इससे वेसेल के अंदर तेजी से मिश्रण होता है। परंपरागत प्रवाह योजना की तुलना में मिश्रण समय 40-45% कम पाया गया। प्रयोगात्मक सत्यापित कम्प्यूटेशनल मॉडल और प्रस्तावित स्टार-प्रकार कॉन्फ़िगरेशन मिश्रण दक्षता में सुधार के लिए उपयोगी होगा।

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Nomenclature

C_1, C_2, C_m	turbulent model parameters, -
C_D	drag force coefficient, -
C_L	lift force coefficient, -
C_{VM}	virtual mass coefficient, -
d_B	bubble diameter, m
$E\ddot{o}$	Eotvos number,-
F'	Modified Froude number,-
$\overline{F}_G, \overline{F}_D, \overline{F}_L, \overline{F}_{VM}, \overline{F}_P$	gravitational force, drag force, lifts force, virtual mass force and pressure force, respectively, $kg/m^2 \cdot s^2$
$\overline{F}$	surface tension force, $kg/m^2.s^2$
g	gravitational acceleration, m/s^2
H	liquid height in the vessel, m
M	interphase momentum exchange term, $kg/m^3 \cdot s$
P	pressure, Pa
R_{e_B}	bubble Reynolds number,
U	means velocity, m/s
x, y, z	spatial coordinates (along width, depth and height, respectively) , m

Greek Symbols

α	volume fraction,-
θ	azimuthal direction,-
ε	energy dissipation rate, m^2/s^3
κ	energy dissipation rate, m^2/s^2
μ	viscosity, Pa.s
μ_{eff}	effective viscosity, Pa.s
$\bar{\bar{\tau}}$	viscous stress tensor
ν_t	kinematic turbulent viscosity, m^2/s
σ	surface tension, N/m
ρ	density, kg/m^3

Subscripts and superscripts

k	surface curvature
G	gas
L	liquid
lam,t, eff	laminar, turbulent, effective

Acronyms list

BOF	basic oxygen furnace
CFD	computational fluid dynamics
EL	Euler–Lagrange
EE	Euler–Euler
VOF	volume of fluid