CHARACTERIZATION OF DYNAMICS OF UNARY AND BINARY GAS-SOLID FLOWS IN A CYLINDRICAL FLUIDIZED BED: ELECTRICAL CAPACITANCE TOMOGRAPHY MEASUREMENTS AND CFD SIMULATIONS

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by

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Certificate

This is to certify that the thesis entitled **"Characterization of Dynamics of Unary and Binary Gas-Solid Flows in a Cylindrical Fluidized Bed: Electrical Capacitance Tomography Measurements and CFD Simulations"** being submitted by **Mr. Brajesh Kumar Singh** to the **Indian Institute of Technology Delhi, New 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 thesis focuses on the study of space-/time-resolved phase volume fraction distribution of unary and binary gas-solid flows in a cylindrical fluidized bed. The thesis particularly deliberates on the characterization of time-/space-resolved phase distribution in unary and binary gas-solids flow and also segregation through measurements using the Electrical Capacitance Tomography (ECT), and through CFD simulations using two-/multi-fluid Eulerian models.

The ability of two-fluid Eulerian model to predict the instantaneous phase distribution was studied. The measured time-averaged phase distributions, bubble chord length distributions and bubbling frequency are compared with the corresponding predictions obtained from two-fluid Eulerian simulations for unary gas-solid flows. The results showed that the predicted time-averaged solid volume fraction distribution differed marginally and was in a satisfactory agreement with the corresponding measurements. However, the bubbling frequency and bubble chord length distribution predicted using different drag models, in particular, the formation of large bubbles/slugs, were considerably different. A modified drag model is proposed that led to a reduction in the regions in the bed in which higher drag force was applied, allowed the formation of larger bubbles/slugs and led to an improvement in the predicted bubbling behavior. It was also found that the use of different drag models, in turn, also affects the total solid viscosity and therefore the bubbling behavior.

The posterior analysis showed that among solid-phase kinematic, collisional, and frictional viscosities, the influence of frictional viscosity on the bubbling behavior was found to be more dominant. Also, the magnitude of frictional viscosity often goes up to more than 1000 times of the collisional and kinetic viscosity in the fluid domain. An increase in the frictional viscosity leads to compaction of the solid phase and increase in the formation of

large bubbles/slugs, those were observed experimentally. The predicted bubbling frequency and bubble chord length distribution were in a quantitative agreement with those measured using the ECT for different gas velocities and particle sizes.

Further, the ECT technique was applied to measure the segregation time for binary gas-solids flow in a cylindrical fluidized bed. The measurements of segregation and fluidization of binary mixtures were investigated using the ECT and high-speed imaging. It was shown that ECT can be used to detect the regions of complete segregation in a cylindrical fluidized beds. In particular, the binary gas-solids flows in systems with large D/d_p ratio, which are otherwise difficult to characterize using high-speed imaging. Under the fluidization conditions, the bubbling behavior of the mixtures was governed by the smaller-sized particles in spite of having an equal percentage by weight of the particles in the mixture. For the fluidization of binary mixtures, a relation between the measured variance of solid volume fraction fluctuations and the corresponding flow structures was studied. It was also found that different bubbling behaviors can produce the same time-averaged solid volume fraction profiles. As a consequence, different phase distributions can lead to different heat and mass transport rates depending on the local interfacial area, despite having the same time-averaged phase hold-up distribution.

Further, efforts are made to predict the segregation time using the Eulerian multi-fluid model. It was seen that due to higher gas-particle drag force magnitude, the larger particles were carried away from bottom to the top of the bed resulting into less extent of segregation and higher segregation time in comparison to the corresponding experiments. The collisional contribution in the particle-particle drag model, led to increase in the segregation time, and therefore it was neglected and frictional coefficient of 0.5 was used which improved the agreement with the measured segregation time. In fluidized bed conditions for binary mixtures, the predicted distribution was in a qualitative agreement. The reason for quantitative difference was due to ad-hoc values of different parameters used in particle-particle drag models for collision and friction interactions between the solids.

The present thesis helps to understand the characteristics of instantaneous phase distribution and segregation in gas-solids fluidization. It also helps in accessing the ability of Eulerian multi-fluid CFD models to predict the dynamics of instantaneous phase distribution (in terms of bubble size distribution and bubbling frequency) and segregation in gas-solids fluidization.

सार

थीसिस अंतरिक्ष के अध्ययन पर केंद्रित है - एक बेलनाकार द्रवीकृत बिस्तर में एकता और बाइनरी गैस-ठोस प्रवाह के अंतरिक्ष-समय-निर्धारित चरण मात्रा अंश वितरण। थीसिस विशेष रूप से असमान और द्विआधारी गैस-ठोस प्रवाह में समय अंतरिक्ष-समाधान चरण वितरण के विचलन पर विचार-विमर्श करता है और विद्युत संधारित्र टोमोग्राफी (ईसीटी) का उपयोग करके माप के माध्यम से अलगाव, और दो- / बहु-द्रव यूलरियन का उपयोग करके सीएफडी सिमुलेशन के माध्यम से करता है। मॉडल।
तात्कालिक चरण वितरण की भविष्यवाणी करने के लिए दो-द्रव यूलरियन मॉडल की क्षमता का अध्ययन किया गया था। मापा समय-औसत चरण वितरण, बुलबुला कॉर्ड लंबाई वितरण और बुदबुदाहट आवृत्ति की तुलना गैस-ठोस प्रवाह के लिए दो-द्रव यूलर सिमुलेशन से प्राप्त संगत भविष्यवाणियों के साथ की जाती है। परिणामों से पता चलता है कि अनुमानित समय-औसत ठोस मात्रा अंश वितरण भिन्न रूप से भिन्न था और इसी माप के साथ एक संतोषजनक समझौते में था। हालांकि, बुदबुदाहट आवृत्ति और बबल कॉर्ड लंबाई वितरण ने अलग-अलग ड्रैग मॉडल का उपयोग करके भविष्यवाणी की, विशेष रूप से, बड़े बुलबुले / स्लग के गठन, काफी भिन्न थे। एक संशोधित ड्रैग मॉडल प्रस्तावित किया गया है जिससे बेड में उन क्षेत्रों में कमी आई है जिसमें उच्च ड्रैग फोर्स लागू किया गया था, जिससे बड़े बुलबुले / स्लग के गठन की अनुमति मिली और पूर्वानुमानित बुदबुदाहट व्यवहार में सुधार हुआ। यह भी पाया गया कि अलग-अलग ड्रैग मॉडल का उपयोग, बदले में, कुल ठोस चिपचिपाहट और इसलिए बुदबुदाने वाले व्यवहार को भी प्रभावित करता है।

पीछे के विश्लेषण से पता चला है कि ठोस-चरण कीनेमेटीक्स, कोलाइज़ल और घर्षण चिपचिपाहट के बीच, बुदबुदाती हुई व्यवहार पर घर्षण चिपचिपाहट का प्रभाव अधिक प्रभावी पाया गया। इसके अलावा, घर्षण चिपचिपाहट की भयावहता अक्सर द्रव क्षेत्र में टकराव और गतिज चिपचिपाहट के 1000 से अधिक बार तक जाती है। घर्षण चिपचिपाहट में वृद्धि से ठोस चरण का संघनन होता है और बड़े बुलबुले / स्लग के निर्माण में वृद्धि होती है, जिन्हें प्रायोगिक तौर पर देखा गया था। पूर्वानुमानित बुदबुदाहट आवृत्ति और बबल कॉर्ड लंबाई वितरण विभिन्न गैस वेगों और कण आकारों के लिए ईसीटी का उपयोग करके मापा गया उन लोगों के साथ एक मात्रात्मक समझौते में थे।

इसके अलावा, बेलनाकार द्रवित बिस्तर में द्विआधारी गैस-ठोस प्रवाह के लिए अलगाव समय को मापने के लिए ईसीटी तकनीक लागू की गई थी। ईसीटी और उच्च गति इमेजिंग का उपयोग करके द्विआधारी मिश्रण के अलगाव और द्रवीकरण के माप की जांच की गई। यह दिखाया गया

कि ईसीटी का उपयोग एक बेलनाकार द्रवीकृत बेड में पूर्ण अलगाव के क्षेत्रों का पता लगाने के लिए किया जा सकता है। विशेष रूप से, बाइनरी गैस-सोलिड्स बड़े डी / डीपी अनुपात वाले सिस्टम में बहते हैं, जो उच्च गति इमेजिंग का उपयोग करके चिह्नित करना मुश्किल है। विखंडन की स्थिति के तहत, मिश्रण के बबलिंग व्यवहार को मिश्रण में कणों के वजन के बराबर प्रतिशत होने के बावजूद छोटे आकार के कणों द्वारा नियंत्रित किया गया था। बाइनरी मिश्रण के द्रवीकरण के लिए, ठोस मात्रा अंश में उतार-चढ़ाव और संबंधित प्रवाह संरचनाओं के मापा विचरण के बीच एक संबंध का अध्ययन किया गया था। यह भी पाया गया कि विभिन्न बुदबुदाहट व्यवहार एक ही समय-औसत ठोस मात्रा अंश प्रोफाइल का उत्पादन कर सकते हैं। एक परिणाम के रूप में, अलग-अलग चरण के वितरण में एक ही समय-औसत चरण होल्ड-अप वितरण होने के बावजूद, स्थानीय इंटरफेशियल क्षेत्र के आधार पर विभिन्न गर्मी और बड़े पैमाने पर परिवहन दरों का कारण बन सकता है।

इसके अलावा, यूलरियन बहु-द्रव मॉडल का उपयोग करके अलगाव के समय की भविष्यवाणी करने का प्रयास किया जाता है। यह देखा गया कि उच्च गैस-कण ड्रैग फोर्स परिमाण के कारण, बड़े कणों को बेड के ऊपर से नीचे तक ले जाया गया था, जिसके परिणामस्वरूप संबंधित प्रयोगों की तुलना में अलगाव और कम अलगाव समय था। कण-कण ड्रैग मॉडल में समवर्ती योगदान, अलगाव के समय में वृद्धि का कारण बना, और इसलिए इसे उपेक्षित किया गया और 0.5 के घर्षण गुणांक का उपयोग किया गया, जिसने मापा पृथक्करण समय के साथ समझौते में सुधार किया। बाइनरी मिश्रण के लिए द्रवित बिस्तर की स्थिति में, अनुमानित वितरण एक गुणात्मक समझौते में था। मात्रात्मक अंतर का कारण ठोस पदार्थों के बीच टकराव और घर्षण इंटरैक्शन के लिए कण-कण ड्रैग मॉडल में उपयोग किए जाने वाले विभिन्न मापदंडों के तदर्थ मूल्यों के कारण था।

वर्तमान थीसिस गैस-ठोस तरल पदार्थ में तात्कालिक चरण वितरण और अलगाव की विशेषताओं को समझने में मदद करता है। यह तात्कालिक चरण वितरण (बुलबुला आकार वितरण और बुदबुदाहट आवृत्ति के संदर्भ में) और गैस-ठोस द्रव के अलगाव में अलगाव की गतिशीलता की भविष्यवाणी करने के लिए यूलियन मल्टी-द्रव सीएफडी मॉडल की क्षमता तक पहुंचने में भी मदद करता है।

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Nomenclature

C_D	drag coefficient, -
C_{fr}	friction coefficient, -
D_b	fluidized bed (internal) diameter, cm
d_s	solid particle diameter, μm
d_h	horizontal bubble chord length, cm
d_v	vertical bubble chord, s
e_{ss}	particle-particle restitution co–efficient, -
g	gravitational acceleration, m/s^2
$g_{0,ss}$	radial distribution function, -
H_b	bed height, cm
H_d	heterogeneity index, -
H_s	static bed height, cm
I_{2D}	second invariant of the strain rate tensor, 1/s^2
I	identity tensor, -
K_{gs}	gas-solid interphase momentum exchange coefficient, kg/(m^3·s)
K_{ss}, K_{ij}	solid-solid interphase momentum exchange coefficient, kg/(m^3·s)
l_i	chord length, cm
l_{32}	Sauter mean chord length, cm
p_s	solid pressure, Pa
$P_{s,f}$	solid frictional pressure, Pa
Re_s	particles Reynolds number, -
t	flow time, s
U	velocity, m/s
U_G	superficial gas velocity, m/s

Greek Letters

α	instantaneous phase volume fraction, -
α_i	gas volume fraction value for dividing criteria in the switch function, -
α_{st}	total solids volume fraction, -
$\bar{\alpha}_s$	time-averaged solid volume fraction, -

$\alpha_{s,max}$	maximum solid packing limit, -
$\alpha_{s,f,min}$	critical solid volume fraction, -
μ	viscosity, Pa·s
ρ	density, kg/m^3
$\bar{\bar{\tau}}$	shear stress, N/m^2
ε	relative permittivity, -
β	interphase momentum exchange coefficient, kg/(m^{3}s)
φ	specularity co–efficient, -
λ_s	solid bulk viscosity, Pa.s
$\kappa_{\theta,s}$	granular diffusion co-efficient, kg/(m.s)
$\gamma_{\theta,s}$	granular dissipation, W/m^3
Θ	granular temperature, m^2/s^2
ϕ	switch function, -
θ	angle of internal friction, degree

Subscripts

col	collisional
fr	friction
g	gas
kin	kinetic
m	mixture
mf	minimum fluidization
r	relative
s	solid phase
sf	solid phase friction

Acronyms

CFD	Computational Fluid Dynamics
ECT	Electrical Capacitance Tomography
ILBP	Iterative Linear Back Projection
KTGF	Kinetic Theory of Granular Flow
TFM	Two-Fluid Model