HYDRODYNAMICS OF FLUIDIZED BED GASIFIERS

SANGRAM ROY

DEPARTMENT OF CHEMICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2020

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by

SANGRAM ROY

Department of Chemical Engineering

Submitted

in fulfilment of the requirements of the degree of Doctor of Philosophy

to the

INDIAN INSTITUTE OF TECHNOLOGY DELHI

OCTOBER 2020

CERTIFICATE

This is to certify that the thesis entitled '**Hydrodynamics of Fluidized Bed Gasifier**' submitted by **Mr. Sangram Roy** to the Indian Institute of Technology-Delhi for the award of the degree of **Doctor of Philosophy (Ph.D.)** is a bona fide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted to any other institute or university for the award of any degree or diploma.

Date:

IIT Delhi

Professor Shantanu Roy
Institute Chair Professor
Department of Chemical Engineering
Indian Institute of Technology Delhi
Hauz Khas, New 110016, India

ACKNOWLEDGMENTS

The journey as a graduate student is a unique pursuit of intellectual excellence. Although the Chapters enshrined in this thesis attempts to capture a fraction of this journey feebly, it would be a gross injustice if all those whose contributions were pivotal for its culmination are not acknowledged.

At the outset, I would like to express my sincere gratitude to Prof. Shantanu Roy for his guidance. I have been singularly fortunate to have benefited from his scholarly direction in possibly as many ways as one could have imagined – thesis examiner, course instructor, and lastly, but not the least, as my doctoral supervisor. Prof. Roy's carefully crafted and captivating lectures in graduate-level courses on Chemical Reaction Engineering and Industrial Multiphase Reactors laid a strong foundation on which I could pursue my doctoral research. Apart from being a teacher par excellence, I appreciate his meticulous supervisory of the projects. I also thank him for establishing a unique state-of-the-art experimental and computational facility here at Multiphase Reaction Engineering Laboratory (MREL), without which none of the work in this thesis would have been possible. On most occasions, the discussions with him were thought-provoking and had always opened multiple avenues. His stress on weaving coherent stories with in-depth analysis of observations without losing sight of the actual problem has left an indelible influence on my personality. I cherish working with him and hope to gain from his support in the future as well.

At MREL, it is always ensured that irrespective of the project that one works for dissertation, everyone benefits from a plethora of exposure required to lead a successful professional career later. At this juncture, I am thankful to Dr. Harish J. Pant (Scientist-H, Isotope Application and Radiation Division, Bhabha Atomic Research Centre, Mumbai) for the opportunity of working with him. It was a very fruitful experience with him while performing radiotracing experiments and its analysis in a hot fluidized bed gasifier. I thoroughly enjoyed his professionalism, which was instrumental in the timely and successful execution of experiments under a very demanding condition. I also place my sincere thanks to his entire group – Dr. V.K. Sharma, Dr. Sunil Goswami, Dr. Jayashree Biswal, who assisted me in innumerable ways during my visit to BARC. The experiments would have been very difficult but for the able support by Jitendra Samantaray, and S. Patil.

I sincerely acknowledge all the assistance extended during my visit to the Research and Technology Innovation Centre (RTIC) of Thermax Limited, Pune. I am especially thankful to Dr. Ramakrishna R Sonde and his group – Dr. Devkumar F Gupta, Mr. Kiran Chauhan, and Mr. Chaitanya Mitra for sharing their invaluable experience in the operation of a hot coal fluidized bed gasifier.

A large part of the work reported in this thesis was possible due to generous financial and logistical contributions from industrial partners. I acknowledge Bharat Heavy Electricals Limited (BHEL) Research and Development Centre at Hyderabad for their funding initially. A significant portion of the work reported in this thesis supported by contributions from the Department of Science and Technology (DST) sponsored project on developing indigenous technology for conversion of Indian Coal to Methanol. BRIT, BARC Mumbai deserves sincere thanks for providing the radiotracers required for executing RPT experiments. I am also appreciative of the Ministry of Human Resource Department (MHRD), Government of India, for providing scholarship during my stay.

I convey my sincere appreciation to the members of my Students Research Committee (SRC): Prof. Ratan Mohan (Chairman), Prof. M.R.Ravi (External Member, Department of Mechanical

Engineering), and Dr. Jyoti Phirani (Departmental Member) for their scrupulous review of my progress.

Working at MREL has been an experience of a lifetime. I owe sincere gratefulness to several past and present members. Special thanks to – Akarsha, Deepali, Loveleen, Meenakshi, Tejas, Ashutosh, Indranil, Thameed, and Misti. They have been very kind in providing valuable technical suggestions and grooming my presentation skills. But for the frequent stimulating discussions on a host of issues with Ashutosh and Thameed, a fair share of my maturity would have been incomplete. I owe a lot to Meenakshi, who would unfailingly strive to any extent to assist me. I am thankful to her for all the elderly affection and care showered on me. Brahm Prakash owes special thanks for his expertise in the fabrication and upkeep of experimental facilities. I am thankful to Girish and Naresh for all their help in documentation. Aman, Manoj, Aashna, Halima, Shilpi, Aditya, Kuldeep – to all of them, special thanks for presenting a conducive environment in the lab that was very helpful during the later stages of my stay.

I express my profound gratitude to my parents and brother, who have been very supportive throughout this entire journey. I am incredibly thankful to my parents for all their blessing and to bear my long absence away from home. No words can adequately express and justify the painful sacrifices they underwent happily.

Sangram Roy
New Delhi

ABSTRACT

Fluidized bed reactors are increasingly being employed in various solid processing and energy industries. With the widening of the scope and complexity of applications, the gamut of solids handled has increased manifold. One of the principal fields of its deployment relates to its utility as coal gasifiers. Even though industrial coal processing in fluidized bed has been in know-how for nearly a century now, fundamental knowledge concerning flow hydrodynamics has largely impeded its operation and scale up to being mostly empirical. Thus the primary motivation of the present thesis is to investigate the underlying hydrodynamics of fluidized beds affecting coal gasifiers.

The first part of the study is focussed on deciphering velocity fields in a binary fluidized bed (0.1 mm ID) of standard bed materials. Non-invasive Radioactive Particle Tracking (RPT) was employed to measure the solids velocity of a bed with a mixture of glass beads of sizes 0.5 and 2 mm. The coarser fraction for the present study was varied from 10-40%. Distinct features of solids flow were observed with varying bed composition. The mean velocity of finer flotsam (0.5 mm particles) fractions were found to achieve higher velocity, which is reduced upon increasing the jetsam fraction (2 mm) due to variation in bed voidage.

The second part of the thesis deals for the first time the determination of velocity fields in a fluidized bed of coal-ash mixtures. Suitable tracers were designed and deployed to determine the solids flow path of a typical particle through RPT. Experiments were conducted in a cylindrical bed of 0.1 m in ID with two inventory compositions, namely, 70% Coal + 30% Bottom Ash (Composition I) and 20% Coal + 80% Bottom Ash (Composition II). Comparative analysis of RPT measurements yielded overall bed behavior, which was quantified in terms of time-averaged mean velocity, solids flux, RMS velocity, and kinetic energy per unit volume of the coal – bottom ash

mixture. The mean axial velocity and solids flux profile indicated the influence of strong slugs on the solids flow patterns. Further, a three-dimensional transient CFD model was set up to predict the time-averaged profiles of coal and ash concentrations. Further, the distributions were compared against solids holdup (coal and ash) characteristics measured using γ-ray densitometry, with a single collimated source. Similarly, a comparison of measured solids velocity profiles is also reported between the CFD-predicted and those measured by RPT.

The last part of the study dwells on Residence Time Distribution (RTD) measurements and its analysis. The experiments were conducted by pulse radiotracer (Au-198) injection in a ‘hot’ industrial fluidized bed coal gasifier. The data obtained was treated and analyzed employing a network model based on a cascade of perfectly mixed tanks in series. Based on the non-ideality of flow, three flow Schemes 1, 2, and 3 were proposed whose RTD function was deduced in the Laplace domain. These RTD functions were numerically transformed into the time domain and were compared with that measured using radiotracing. It was noted that Scheme 3, which was based on the backflow of solids in the bed could satisfactorily predict the actual RTD function. Besides, the parameters of the model provided insights into the actual solids flow pattern in the gasifier. Furthermore, the model demonstrated its adaptability in analyzing RTD of similar studies reported earlier for both single as well as pulse injection of the tracer.

सार

द्रवित बिस्तर रिएक्टर विभिन्न ठोस प्रसंस्करण और ऊर्जा उद्योगों में तेजी से कार्यरत हैं। अनुप्रयोगों के दायरे और जटिलता के विस्तार के साथ, संभाले गए ठोस पदार्थों का सरगम कई गुना बढ़ गया है। इसकी तैनाती के प्रमुख क्षेत्रों में से एक कोयला गैसीफायर के रूप में इसकी उपयोगिता से संबंधित है। भले ही द्रवित बिस्तर में औद्योगिक कोयले का प्रसंस्करण लगभग एक सदी से हो रहा है, लेकिन प्रवाह हाइड्रोडायनामिक्स के बारे में मौलिक ज्ञान ने मोटे तौर पर इसके संचालन को बाधित कर दिया है और ज्यादातर अनुभवजन्य होने का पैमाना है। इस प्रकार वर्तमान थीसिस की प्राथमिक प्रेरणा कोयला गैसीफायर को प्रभावित करने वाले द्रवित बेड के अंतर्निहित हाइड्रोडायनामिक्स की जांच करना है।

अध्ययन का पहला हिस्सा मानक बिस्तर सामग्री के एक बाइनरी द्रवीकृत बिस्तर (0.1 मिमी आईडी) में वेग के क्षेत्र पर डिकॉकिंग है। गैर-आक्रामक रेडियोधर्मी कण ट्रैकिंग (RPT) को आकार के ग्लास मोतियों के मिश्रण 0.5 और 2 मिमी के साथ बिस्तर के ठोस वेग को मापने के लिए नियोजित किया गया था। वर्तमान अध्ययन के लिए मोटे अंश 10-40% से भिन्न थे। अलग बिस्तर संरचना के साथ ठोस प्रवाह की विशिष्ट विशेषताएं देखी गईं। मध्यम वेग (0.5 मिमी कण) अंशों के मध्य वेग को उच्च वेग प्राप्त करने के लिए पाया गया था, जो कि बेड वेपरेज में भिन्नता के कारण जेट्सम अंश (2 मिमी) को बढ़ाने पर कम होता है।

थीसिस का दूसरा हिस्सा पहली बार कोयले की राख मिश्रण के द्रवित बिस्तर में वेग क्षेत्रों का निर्धारण करता है। आरपीटी के माध्यम से एक विशिष्ट कण के ठोस प्रवाह पथ को निर्धारित करने के लिए उपयुक्त ट्रेसर डिजाइन और तैनात किए गए थे। प्रयोगों को दो इन्वेंट्री रचनाओं के साथ आईडी में 0.1 मीटर के एक बेलनाकार बिस्तर में आयोजित किया गया था, अर्थात्, 70% कोयला + 30% बॉटम ऐश (रचना I) और 20% कोयला + 80% बॉटम ऐश (रचना II)। RPT मापों के तुलनात्मक विश्लेषण से कुल मिलाकर बिस्तर का व्यवहार हुआ, जो कि समय-औसतन औसत वेग, ठोस प्रवाह, RMS वेग और कोयले की ऊर्जा इकाई प्रति कोयले की मात्रा के बराबर मात्रा में मिलाया गया था। माध्य अक्षीय वेग और ठोस प्रवाह प्रोफ़ाइल ने ठोस प्रवाह पैटर्न पर मजबूत स्लग के प्रभाव को इंगित किया। इसके अलावा, एक त्रि-आयामी क्षणिक सीएफडी मॉडल की स्थापना कोयला और राख सांद्रता के समय-औसत प्रोफाइल की भविष्यवाणी करने के लिए की गई थी। इसके अलावा, वितरण की तुलना एकल ठोस स्रोत के

साथ सॉलिड होल्डअप (कोयला और राख) विशेषताओं के साथ की गई, जिसका उपयोग वितरक डेंसिटोमेट्री से किया जाता है। इसी प्रकार, सीएफडी-पूर्वानुमानित और आरपीटी द्वारा मापे गए के बीच मापा ठोस वेग प्रोफाइल की तुलना भी रिपोर्ट की जाती है।

अध्ययन का अंतिम भाग रेसिडेंस टाइम डिस्ट्रीब्यूशन (आरटीडी) माप और उसके विश्लेषण पर रहता है। प्रयोग गर्म 'औद्योगिक द्रवयुक्त बिस्तर कोयला गैसीफायर में पल्स रेडियोट्रैसर (Au-198) इंजेक्शन द्वारा किए गए थे। प्राप्त आंकड़ों का इलाज किया गया और श्रृंखला में पूरी तरह से मिश्रित टैंकों के कैस्केड के आधार पर एक नेटवर्क मॉडल को नियोजित करने का विश्लेषण किया गया। प्रवाह की गैर-आदर्शता के आधार पर, तीन प्रवाह योजनाएं 1, 2, और 3 प्रस्तावित की गईं जिनका आरटीडी फ़ंक्शन लाप्लास डोमेन में घटाया गया था। ये आरटीडी फ़ंक्शन संख्यात्मक रूप से टाइम डोमेन में बदल दिए गए थे और उनकी तुलना रेडियोट्रैसिंग के उपयोग से की गई थी। यह नोट किया गया था कि योजना 3, जो बिस्तर में ठोस पदार्थों के बैकफ़्लो पर आधारित थी, वास्तविक आरटीडी फ़ंक्शन का संतोषजनक रूप से अनुमान लगा सकती है। इसके अलावा, मॉडल के मापदंडों ने गैसीफायर में वास्तविक ठोस प्रवाह पैटर्न में अंतर्दृष्टि प्रदान की है। इसके अलावा, मॉडल ने दोनों के लिए पहले से बताए गए समान अध्ययन के आरटीडी के विश्लेषण के साथ-साथ ट्रेसर के पल्स इंजेक्शन का भी प्रदर्शन किया।

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NOTATIONS

l_d^k	Penetration depth of the *k*th photon in detector crystal
r	Radial coordinate, m
n_i	Fractional tracer visit
u_{mf}	Minimum fluidization velocity in transition bed,ms^{-1}
u	Normalized superficial velocity, [-]
u_g	Superficial air velocity,ms^{-1}
z	Axial coordinate, m
G_s	Axial mass flux, kg/m^2-s
v_i	Instantaneous solid velocity, ms^{-1}
$\overline{v_i}$	Time-averaged solid velocity, ms^{-1}
v_i'	Fluctuating solid velocity, ms^{-1}
d	Distance traversed in gas-solid medium, m
e	Restitution coefficient,-
g	Gravitational constant, ms^{-2}
A	Source strength (Bq)
C_j , C_j^M	Calculated and measured count for the detector j using Monte Carlo model for detector j
H, H_w, H_n	Expanded Bed height, m
J	Interphase energy exchange
k	Granular Conductivity, kg, $m^{-1}s^{-1}$

P	Pressure, Nm^{-2}
t	Time, s

Greek Letters

α	Fraction of recycle stream in Schemes 1,2 &3, [-]
β	Momentum exchange coefficient and Fraction of volume of bottom bed, top bed, recycle and freeboard in Schemes 1,2 &3, [-]
χ^2	Error in **Eq. 3.4**
δ	Fraction of backflow in Scheme 3, [-]
ε	Phase holdup,-
γ	Collision dissipation of kinetic energy and Fraction of bypass stream in Schemes 2 &3, [-]
μ_d and μ_m	Linear attenuation coefficients of the detector and intervening medium between source and detector
μ	Viscosity, $kgm^{-1}s^{-1}$
ν	Number of photons emitted per disintegration (radioactive source property)
ϕ	Fraction of total energy spectrum captured by the detector
ξ	Error in **Eq. 3.3**
ρ	Density,kgm^{-3}
Ω^k	Solid angle fraction of the *k*th photon
$\overline{\overline{\tau}}$	Stress, Nm^{-2}

Θ	Granular temperature, m^2s^{-2}

Subscripts

a	Ash
c	Coal
f	air
i	Phase
s,j	Solid phase
d	diameter, µm or mm
C	Concentration, [SI]
D	Dispersion [m^2/s]
E	RTD Function, [1/s] or [1/min]
G_s	Solid Flux, [kg/m^2-s]
M	Number of times a tracer/fluid element undergoes recirculation in Schemes 1,2 and 3
N	Total data
u_g	Superficial gas velocity [m/s]
s	Complex Laplace domain
t	time, s or min
B	Bottom Bed
T	Top Bed
F	Freeboard
R	Recycle
p	Particle
1-3	Schemes 1, 2 and 3

Abbreviations

ADM	Axial Dispersion Model
AR	Aspect Ratio
MC	Monte Carlo
MC-RGA	Monte Carlo Real Coded Genetic Algorithm
RANS	Reynolds Averaged Navier Stokes
RMS	Root Mean Square
RPT	Radioactive Particle Tracking
RTD	Residence Time Distribution