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Cheng Chen

Investigations on Mesoscale Structure in Gas–Solid Fluidization and Heterogeneous Drag Model

Doctoral Thesis accepted by
Tsinghua University, Beijing, China

Springer

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ISSN 2190-5053 ISSN 2190-5061 (electronic)
Springer Theses
ISBN 978-3-662-48371-8 ISBN 978-3-662-48373-2 (eBook)
DOI 10.1007/978-3-662-48373-2

Library of Congress Control Number: 2015948764

Springer Heidelberg New York Dordrecht London

Printed on acid-free paper

Springer-Verlag GmbH Berlin Heidelberg is part of Springer Science+Business Media
(www.springer.com)

Parts of this thesis have been published in the following articles:

Cheng Chen, Fei Li, Haiying Qi. Modeling of the flue gas desulfurization in a CFB riser using the Eulerian approach with heterogeneous drag coefficient. *Chemical Engineering Science*, 2012, 69: 659–668. (SCI accession No.: 000298325800060, *Impact Factor*: 2.386, EI accession No.: 20115114630129)
Cheng Chen, Joachim Werther, Stefan Heinrich, Haiying Qi, Ernst-Ulrich Hartge. CPFD simulation of circulating fluidized bed risers. Powder Technology, 2013, 235: 238–247. (SCI accession No.: 000316039400028, Impact Factor: 2.024)
Cheng Chen, Fei Li, Haiying Qi. An improved EMMS-based drag model for gas–solid flow in CFB risers with a novel sub-model for clusters. 8th International Conference on Multiphase Flow, Jeju, Korea, 2013. (International Conference)
Cheng Chen, Haiying Qi. Modeling of cluster and its application in EMMS drag model for heterogeneous gas–solid flows. 11th International Conference on Fluidized Bed Technology, CFB-11, Beijing, China, 2014. (International Conference)
Cheng Chen, Haiying Qi. Development and validation of cluster and EMMS drag model. CIESC Journal, 2014, 65(6): 2003–2012. (In Chinese)
Cheng Chen, Feng Xu, Zhulin Yuan, Haiying Qi. Study on influence of bubble-breaking structure upon the gas bubble properties in the scrubbing chamber. Thermo Power Plant, 2010, 40(7): 42–47. (In Chinese)
Qunte Dai, Cheng Chen, Haiying Qi. Developing Heterogeneous Drag Model for Fluidization Process and Its Generalization. Journal of Engineering Thermophysics, 2015, 4(36): 1–6. (In Chinese)
Qunte Dai, Cheng Chen, Haiying Qi. A Generalized Drag Law for Heterogeneous Gas–solid Flows in Fluidized Beds. Powder Technology. (Accepted)

Supervisor's Foreword

The modeling of drag between gas and solid phase has always been a challenging issue in Eulerian simulation of heterogeneous fluidization processes for a long time.

It is generally known that existing drag models such as Wen-Yu and Ergun do not apply to above processes because of their hypothesis of a homogeneous flow. The key of the modeling is whether a drag model can account for effects of the mesoscale structure, namely clusters that characterize the heterogeneous flow state. It has been proved in recent years that the theory of Energy Minimization Multi-scale (EMMS) is effective for developing heterogeneous drag models. However, this theory still needs further improvement in hypothesis, description of the mesoscale structure, definite conditions of conservative equations, and generalization of drag models.

Dr. Cheng Chen devoted herself in last 5 years to drag modeling based on the EMMS and made a series of significant progress. She focused on analysis of flow heterogeneity and found a common feature—the "single peak" profile—in many relationships, including cluster size d_{cl}, cluster density $\varepsilon_{\mathrm{sc}}$, and local gas–solid slip velocity via local particle volume fraction ε_{s}, as well as overall slip velocity via superficial velocity of circulating fluidized bed. She indicated that cluster size tends to single particle diameter at the dense extreme and clarified the difference between cluster size defined by the EMMS theory and measured in experiments. Compared with the size, cluster density is the major factor that causes qualitative change of drag. In addition, she established a relationship between the local heterogeneity and operation parameters of fluidized bed reactors.

According to the above research, she developed a new drag model named QC-EMMS and verified its prediction ability, accuracy, and universality by simulations and comparison with experiments.

Overall, her work gives us valuable information and methods to deal with drag issue and enlightens us that one should pay major attention to physical judgment and understanding of mesoscale effects in fluidization process. I believe this work will be helpful in simulating large-scale fluidization systems.

Beijing
July 2015

Prof. Haiying Qi

Acknowledgments

I want to express my hearty gratitude to my dear teacher Prof. Qi Haiying for his instructions and for his keen insight, persistence in science research, high responsibility, and care toward students. His rigorous scholarship and impartial character have greatly inspired me and will benefit my whole life.

I'm also thankful to Prof. Joachim Werther for his kind instructions and support during the 6-month cooperative research at Technical University of Hamburg.

Thanks to Prof. You Changfu and Dr. Li Fei for their extensive instructions and support for my project.

Thank you all my partners in the project including Wang Jinsheng, Luan Chao, Zhu Junzong, Zhang Wei, Wang Haiming, and Xi Yingtao for their communication on learning and their care and support in everyday life. I was so lucky to have a chance of spending five unforgettable years with you and I wish you a brilliant future.

Thank you my classmates and best friends during my doctoral career Mei Zhequn, Wang Zhongnan, Li Xinzi, Huang Keman, and Gong Yuanyuan for adding color to my doctorate studies and I wish our friendship will last forever.

Thank you my husband Zhong Xiaobo for loving me and growing up together with me, for your constant understanding, tolerance, encouragement, and love. We have had hardships accompanying each other and I hope we will continue to treasure our time together.

Thank you my dear daughter Zhong Chenxi for coming to me during my doctoral dissertation. Your appearance has shown me how beautiful and valuable life is and given me great courage and confidence. I wish you will grow up healthily and happily.

Thank you my father Chen Chunshan and my mother Yin Zifeng for their selfless contribution to the family and unconditional support and encouragement to me. I wish you good health and happiness.

This project is funded by the National Natural Science Foundation of China (NO. 91334111), hereby I express my thanks.

Contents

Nomenclature

a_c, a_f	Internal particle acceleration in dense, dilute phase (m/s^2)
a, b, c	Coefficients in drag expressions (–)
Ar	Archimedes number, $Ar = \frac{\rho_g(\rho_p-\rho_g)d_p^3 g}{\mu_g^2}$ (–)
C_1, C_2, C_3	Empirical coefficients (–)
C_{D0}	Single-particle drag coefficient (–)
C_D	Multi-particle drag coefficient (–)
d_{cl}	Cluster size (m)
d_p	Particle size (m)
$d_p{}^*$	Dimensionless particle size, $d_p^* = Ar^{1/3} = \left(\frac{\rho_g(\rho_p-\rho_g)d_p^3 g}{\mu_g^2}\right)^{1/3}$ (–)
D	Diameter of fluidized bed riser (m)
d_v	Bubble diameter (m)
e_s	Particle elastic collision coefficient (–)
f	Volumetric fraction of particle dense phase (–)
f_c	Heterogeneity correction factor in O-S model (–)
F_c, F_f, F_i	Single-particle drag in dense phase, dilute phase, and interaction phase (N)
F_D	Grid-average drag force (N)
g	Gravity acceleration (m/s^2)
G_s	Particle circulating mass flux (kg/m^{2}s)
h	Fluidized bed height (m)
H_0	Initial particle accumulation height in fluidized bed (m)
H_d	Heterogeneous drag correction factor (–)
I_{inv}	Particle inventory in fluidized bed (kg)
n	Empirical coefficient (–)
n_c, n_f, n_i	Numerical density of particles in dense phase, dilute phase and interaction phase (1/m^3)
n_p	Number of single particles in computational parcel (–)
N_p	Number of computational parcels in grid (–)
N_{st}	Suspended transport energy (J/kg)

p_g	Gas pressure (Pa)
p_s	Particle pressure (Pa)
$\Delta p/\Delta h$	Pressure drop per unit bed height (Pa/m)
Re	Local gas–solid slip Reynolds Number, $Re = \frac{\rho_g d_p}{\mu_g}\left(u_g - u_s\right)$ (–)
Re^*	Overall gas–solid slip Reynolds number, $Re^* = \frac{\rho_g d_p}{\mu_g}\left(U_g - \frac{\varepsilon_g}{1-\varepsilon_g}\cdot\frac{G_s}{\rho_p}\right)$ (–)
Re_t	Terminal velocity Reynolds number, $Re_t = \frac{\rho_g d_p}{\mu_g} U_t$ (–)
Δt	Time step (s)
U^*	Dimensionless gas velocity, $U^* = \frac{\rho_g d_p}{\mu_g}\left(U_g - \frac{\varepsilon_g}{1-\varepsilon_g}\cdot\frac{G_s}{\rho_p}\right)/Ar^{1/3}$ (–)
U_c	Gas velocity in dense phase (m/s)
U_f	Gas velocity in dilute phase (m/s)
U_{FD}	Critical gas velocity between fast and transport fluidization (m/s)
u_g	Grid-average gas velocity (m/s)
U_g	Cross-sectional average gas velocity (empty-bed gas velocity) (m/s)
U_{mf}	Minimum fluidization gas velocity (m/s)
u_p	Computational parcel velocity (m/s)
U_p	Cross-sectional average particle velocity (m/s)
U_{pc}	Particle velocity in dense phase (m/s)
U_{pf}	Particle velocity in dilute phase (m/s)
U_{PT}	Critical gas velocity between dilute and dense pneumatic transport (m/s)
u_s	Grid-average particle velocity (m/s)
u_{slip}	Local gas–solid slip velocity in grid, $u_{slip} = u_g - u_s$ (m/s)
U_{slip}	Overall gas–solid slip velocity, $U_{slip} = U_g - U_p$ (m/s)
U_t	Single-particle terminal velocity (m/s)
$U_{t,cl}$	Cluster terminal velocity (m/s)
U_{TF}	Critical gas velocity between turbulent and fast fluidization (m/s)
V_m	Grid volume (m^3)
V_p	Particle volume (m^3)
V_r	The ratio of gas–solid slip velocity to terminal velocity in O-S model (–)
x_p	Position coordinate of computational parcel (–)

Greek Character

β	Drag function for heterogeneous flows (Ns/m^4)
β_0	Drag function for uniform flows (Ns/m^4)
ε_g	Gas volume fraction (Voidage) (–)
ε_{max}	Max voidage where clusters exist, $\varepsilon_{max} = 0.9997$ (–)
ε_{mf}	Minimum fluidization voidage (–)
ε_s	Local time-averaged volume fraction of particle (local solids concentration) (–)

$\varepsilon_{s,av}$	Cross-sectional averaged volume fraction of particle (Cross-sectional averaged solids concentration) (–)
$\varepsilon_{s,cr}$	Critical solids concentration, $\varepsilon_{s,cr} = \varepsilon_s + n \cdot \sigma_s$ (–)
$\varepsilon_{s,in}$	Solids concentration at fluidized bed return inlet (–)
ε_{sc}	Solids concentration in clusters (Cluster density) (–)
ε_{sf}	Solids concentration in dilute phase (–)
ε_{smf}	Solids concentration for minimum fluidization (–)
σ_s	Standard deviation of solids concentration fluctuation (–)
φ	Particle-wall specular reflection coefficient (–)
Φ	Local heterogeneous index (–)
Ψ	The overall system heterogeneous index (–)
γ	Local heterogeneity defined by solids concentration fluctuation (–)
μ_g	Gas kinematic viscosity coefficient (Pa s)
ρ_{cl}	Cluster density, $\rho_{cl} = \varepsilon_{sc} \cdot \rho_p + (1 - \varepsilon_{sc}) \cdot \rho_g$ (kg/m^3)
ρ_g	Gas density (kg/m^3)
ρ_p	Particle density (kg/m^3)
τ_g, τ_s	Gas/solid phase stress tensor (–)

Subscript

c, cl	Particle dense phase (cluster)
f	Particle dilute phase
g	Gas
i	Interaction phase
p, s	Particle/Solid

Abbreviation

DNS	Direct numerical simulation
EMMS	Energy minimization multi-scale
MP-PIC	Multiphase particle-in-cell
UDF	User defined function