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气流床煤气化炉内流动、混合与反应过程的研究进展

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Review for research of flow, mixing and reaction process in entrained flow coal gasifier

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摘要 气流床气化过程涉及高温高压下湍流多相流动与复杂化学反应过程的相互作用,涵盖喷嘴雾化与弥散、复杂多相射流流动、炉内湍流混合、复杂气化反应、火焰结构及温度分布等诸多方面,是世界各国研究的热点.对近年来世界各国在气流床气化过程研究上取得的进展进行了综述,包括喷嘴雾化与颗粒弥散机理与雾化过程的影响因素、撞击流驻点偏移规律和撞击面振荡规律、撞击火焰结构与炉内三维温度场、典型煤种气化反应特性与石油焦气化特性以及气流床气化过程模拟.对气流床气化过程未来的研究重点进行了展望.

关键词: 气流床气化 流动过程 混合过程 气化反应特性 气化炉模拟

Abstract: Entrained flow gasification process involves turbulent multiphase flow and the interaction of complex chemical reaction process at high temperature and pressure, covering the nozzle atomization and dispersion, complex multiphase jet flows, turbulent mixing, complex gasification reaction, flame structure and its temperature distribution and many other aspects. It is a very important research focus. In this paper, the research progress of entrained flow gasification process, which had been made in recent years, were reviewed, including the atomization mechanism of coal-water-slurry nozzle, the particle dispersion mechanism of pulverized coal nozzle, the rule of stagnation point offset of opposed impinging stream, oscillation of the impingement plane, the pattern of opposed impinging flame structure and its three-dimensional temperature field, the gasification characteristics of the typical coal and petroleum coke, and the simulation for entrained flow gasifier. It is also discussed about the research priorities of entrained flow gasification process in future.

Key words: entrained flow gasification flow pattern mixing process gasification characteristics simulation of gasifier

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[1] 王辅臣. 大规模高效气流床煤气化技术基础研究进展[J]. 中国基础科学, 2008, 3: 4-13. (WANG Fu-chen. Progress on the large-scale and high-efficiency entrained flow coal gasification technology[J]. China Basic Science, 3: 4-13.)

[2] 王辅臣, 于广锁, 龚欣, 刘海峰, 王亦飞, 梁钦锋. 大型煤气化技术的研究与发展[J]. 化工进展, 2009, 28(2): 173-180. (WANG Fu-chen, YU Guang-suo, GONG Xin, LIU Hai-feng, WANG Yi-fei, LIANG Qin-feng. Research and development of large-scale coal gasification technology[J]. Chemical Industry and Engineering Process, 2009, 28(2):173-180.)

[3] 于遵宏, 王辅臣. 煤炭气化技术[M]. 北京: 化学工业出版社, 2010. (YU Zun-hong, WANG Fu-chen. Coal gasification technology[M]. Beijing: Chemical Industry Press, 2010.)

[4] 章明川, 吕勇, 王峻晔, 范浩杰, 李德贵, 陈启峰. Y型喷嘴内部气液两相流动及液膜雾化的数学模型[J]. 燃烧科学与技术, 2000, 6(3): 205-209. (ZHANG Ming-chuan, LV Yong, WANG Jun-ye, FAN Hao-jie, LI De-gui, CHEN Qi-feng. Mathematical modeling on the gas-liquid two phase flow in the Y-jet nozzle and its atomization process[J]. Journal of Combustion Science and Technology, 2000, 6(3): 205-209.)

[5] EGGERS J, VILLERMAUX E. Physics of liquid jets[J]. Rep Prog Phys, 2008, 71(3): 036601.

[6] GOROKHOVSKI M, HERRMANN M. Modeling primary atomization[J]. Annu Rev Fluid Mech, 2008, 40: 343-366.

[7] DUMOUCHEL C. On the experimental investigation on primary atomization of liquid streams[J]. Exp Fluids, 2008, 45: 371-422.

[8] GUILDENBECHER D R, L ° PEZ-RIVERA C, SOJKA P E. Secondary atomization[J]. Exp Fluids, 2009, 6: 371-402.

[9] JIANG X, SIAMAS G A, JAGUS K, KARAYIANNIS T G. Physical modelling and advanced simulations of gas-liquid two-phase jet flows in atomization and sprays[J]. Prog Energy Combust Sci, 2010, 36(2): 131-167.

[10] BENJAMIN M A, JENSEN R J, ARIENTI M. Review of atomization: Current knowledge and future requirements for propulsion combustors [J]. Atom Sprays, 2010, 20(6): 485-512.

[11] THEOFANOUS T G. Aerobreakup of Newtonian and viscoelastic liquids[J]. Annu Rev Fluid Mech, 2011, 43(1): 661-690.

[12] ZHOU W X, ZHAO T J, WU T, YU Z H. Application of fractal geometry to atomization process[J]. Chem Eng J, 2000, 78(2/3): 193-197.

[13] 周炜星, 吴韬, 赵铁均, 于遵宏. 喷雾射流中粒度, 时间和速度信号的双重自仿射性[J]. 化工学报, 2000, 51(5): 654-659. (Zhou Wei-xing, Wu Tao, Zhao Tie-jun, Yu Zun-hong. Dyadic self-affinity of diameter, transmit time and velocity signals of droplets in air blast spray[J]. Journal of Chemical Industry and Engineering (China), 2000, 51(5): 654-659.)

[14] ZHOU W X, YU Z H. Multifractality of drop breakup in the air-blast nozzle atomization process[J]. Phys Rev E, 2001, 63: 016302.

[15] ZHOU, W X, LIU, H F , YU Z H . Anomalous features arising from random multifractals[J]. Fractals, 2001, 9(3): 317-328.

[16] 龚欣, 刘海峰, 李伟锋, 陈谋志, 秦军, 于广锁, 王辅臣, 于遵宏. 气流式雾化过程的有限随机分裂模型[J]. 化工学报, 2005, 56(5): 786-790. (GONG Xin, LIU Hai-feng, LI Wei-feng, CHEN Mou-zhi, QIN Jun, YU Guang-suo, WANG Fu-chen, YU Zun-hong. Finite stochastic breakup model of air-blast atomization process[J]. Journal of Chemical Industry and Engineering (China), 2005, 56(5): 786-790.)

[17] 刘海峰, 李伟锋, 陈谋志, 秦军, 许建良, 曹显奎, 于遵宏. 大液气质量流量比双通道气流式喷嘴雾化滴径[J]. 化工学报, 2005, 56(8): 1462-1466. (LIU Hai-feng, LI Wei-feng, CHEN Mou-zhi, QIN Jun, XU Jian-liang, CAO Xian-kui, YU Zun-hong. Droplet size of two-fluid airblast atomizer with large water/air mass flux ratio. Journal of Chemical Industry and Engineering (China), 2005, 56(8): 1462-1466.)

[18] LIU H F, GONG X, LI W F, WANG F C, YU Z H. Prediction of droplet size distribution in sprays of prefilming air-blast atomizers[J]. Chem Eng Sci, 2006, 61(6): 1741-1747.

[19] JIANG D J, LIU H F, LI W F, XU J L, WANG F C, GONG X. Modeling atomization of a round water jet by a high-speed annular air jet based on the self-similarity of droplet breakup[J]. Chemical Engineering Research and Design, 2012, 90(2): 185-192.

[20] 田秀山, 赵辉, 许建良, 李伟锋, 刘海峰. 气-液同轴射流的LES-VOF模拟[J]. 燃烧科学与技术, 2012, 18(5): 461-466. (TIAN Xiu-shan, ZHAO Hui, XU Jian-liang, LI Wei-feng, LIU Hai-feng. LES-VOF simulation of 3D coaxial gas-liquid jet[J]. Journal of Combustion Science and Technology, 2012, 18(5): 461-466.)

[21] 曹显奎, 许建良, 李伟锋, 刘海峰, 于遵宏. 同轴双通道气流式雾化喷嘴初次雾化过程[J]. 化工学报, 2006, 57(11): 2591-2596. (CAO Xian-kui, XU Jian-liang, LI Wei-feng, LIU Hai-feng, YU Zun-hong. Primary atomization of coaxial two-channel air-blast atomizer[J]. Journal of Chemical Industry and Engineering (China), 2006, 57(11): 2591-2596.)

[22] 曹显奎, 孙志刚, 许建良, 李伟锋, 刘海峰, 于遵宏. 液体射流在同向气流中的破裂[J]. 化学工程, 2007, 35(5): 29-31. (CAO Xian-kui, SUN Zhi-gang, XU Jian-liang, LI Wei-feng, LIU Hai-feng, YU Zun-hong. Breakup of a liquid jet in co-flowing air streams[J]. Chemical Engineering (China), 2007, 35(5): 29-31.)

[23] 栗涛, 许建良, 李伟锋, 刘海峰. 同轴双通道喷嘴雾化滴径沿轴向分布特性[J]. 化工学报, 2009, 60(4): 886-891. (LI Tao, XU Jian-liang, LI Wei-feng, LIU Hai-feng. Characteristics of droplet size distribution downstream of coaxial twin-fluid atomizer[J]. Journal of Chemical Industry and Engineering (China), 2009, 60(4): 886-891.)

[24] 陈谋志, 秦军, 李伟锋, 刘海峰, 于遵宏. 三通道喷嘴雾化过程噪声性能的实验研究[J]. 振动与冲击, 2005, 24(6): 88-90. (CHEN Mou-zhi, QIN Jun, LI Wei-feng, LIU Hai-feng, YU Zun-hong. Experimental study on noise characteristics of three channels nozzle in the process of atomization[J]. Journal of Vibration and Shock, 2005, 24(6): 88-90.)

[25] ZHAO H, LIU H F, LI W F, XU J L. Morphological classification of low viscosity drop bag breakup in a continuous air jet stream[J]. Phys Fluids, 2010, 22: 114103.

[26] ZHAO H, LIU H F, XU J. L, LI W F. Experimental study of drop size distribution in the bag breakup regime[J]. Ind Eng Chem Res, 2011, 50(16): 9767-9773.

[27] ZHAO H, LIU H F, CAO X K, LI W F, XU J L. Breakup characteristics of liquid drops in bag regime by a continuous and uniform air jet flow[J]. Int J Multiph Flow, 2011, 37(5): 530-534.

[28] ZHAO H, LIU H F, XU J. L, LI W F, LIN K F. Temporal properties of secondary drop breakup in the bag-stamen breakup regime[J]. Phys

Fluids, 2013, 25(5): 054102.

[29] CAO X K, SUN Z G, LI W F, LIU H F, YU Z H. A new breakup regime of liquid drops identified in a continuous and uniform air jet flow[J]. Phy Fluids, 2007, 19(5): 057103.

[30] 李巧红，刘海峰，李伟锋，于遵宏. 最大熵原理预测气流式喷嘴雾化液滴粒径分布[J]. 华东理工大学学报：自然科学版，2009, 35(1): 25-29. (LI Qiao-hong, LIU Hai-feng, LI Wei-feng, YU Zun-hong. Prediction of droplet size distribution in spray of air-blast nozzle using maximum entropy principle[J]. Journal of East China University of Science and Technology (Natural Science Edition), 2009, 35(1): 25-29.)

[31] 王少云，杨永喆，李伟锋，刘海峰，龚欣，于遵宏. 三通道空气气流式喷嘴的雾化性能[J]. 华东理工大学学报：自然科学版，2003, 29(6): 595-598. (WANG Shao-yun, YANG Yong-zhe, LI Wei-feng, LIU Hai-feng, GONG Xin, YU Zun-hong. Atomization property of airblast three-channel nozzle [J]. Journal of East China University of Science and Technology (Natural Science Edition), 2003, 29(6): 595-598.)

[32] 侯妍冰，田秀山，赵辉，李伟锋，许建良，刘海峰. 黏弹性对液体初次雾化特性的影响[J]. 化工学报，2013, 64(5): 1601-1606. (HOU Yan-bing, TIAN Xiu-shan, ZHAO Hui, LI Wei-feng, XU Jian-liang, LIU Hai-feng. Influence of viscoelasticity on liquid primary atomization[J]. Journal of Chemical Industry and Engineering (China), 2013, 64(5): 1601-1606.)

[33] 秦军，陈谋志，李伟锋，刘海峰，于遵宏. 双通道气流式喷嘴加压雾化的实验研究[J]. 燃烧科学与技术，2005, 11(4): 384-387. (QIN Jun, CHEN Mou-zhi, LI Wei-feng, LIU Hai-feng, YU Zun-hong. Experimental study on twin-fluid air-blast nozzle atomization under high ambient pressures[J]. Journal of Combustion Science and Technology, 2005, 11(4): 384-387.)

[34] 侯丽英，王辅臣，于建国，龚欣，沈才大，于遵宏. 渣油气化双通道喷嘴的雾化性能[J]. 高校化学工程学报，1995, 9(1): 18-23. (HOU Li-ying, WANG Fu-chen, YU Jian-guo, GONG Xin, SHEN Cai-da, YU Zun-hong. Performance of twin-fluid residual oil atomizer[J]. Journal of Chemical Engineering of Chinese Universities, 1995, 9(1): 18-23.)

[35] 王少云，陈谋志，秦军，刘海峰，龚欣，于广锁，王辅臣，于遵宏. 三通道气流式喷嘴内粘性流体雾化过程[J]. 化学工程，2005, 33(5): 26-29. (WANG Shao-yun, CHEN Mou-zhi, QIN Jun, LIU Hai-feng, GONG Xin, YU Guang-suo, WANG Fu-chen, YU Zun-hong. Atomization process of viscous fluid via airblast three-channel nozzle[J]. Chemical Engineering (China), 2005, 33(5): 26-29.)

[36] 蒋德军，赵辉，刘海峰，王辅臣，于遵宏. 黏性流体的二次雾化特性[J]. 石油学报(石油加工)，2011, 27(4): 575-582. (JIANG De-jun, ZHAO Hui, LIU Hai-feng, WANG Fu-chen, YU Zun-hong. Experimental characteristics of viscous fluid secondary breakup[J]. Acta Petrolei Sinica (Petroleum Processing Section), 2011, 27(4): 575-582.)

[37] 程维，赵辉，孟沁玮，李伟锋，许建良，刘海峰. 水煤浆气流雾化的初次破裂特性[J]. 化工学报，2011, 62(1): 25-31. (CHENG Wei, ZHAO Hui, MENG Qin-wei, LI Wei-feng, XU Jian-liang, LIU Haifeng. Primary breakup characteristics of air-blast atomization of coal-water slurry[J]. Journal of Chemical Industry and Engineering (China), 2011, 62(1): 25-31.)

[38] ZHAO H, LIU H F, XU J L, LI W F. CHENG W. Breakup and atomization of a round coal water slurry jet by an annular air jet[J]. Chem Eng Sci, 2012, 78: 63-74.

[39] ZHAO H, LIU H F, XU J L, LI W F. Secondary breakup of coal water slurry drops[J]. Phys Fluids, 2011, 23(11): 113101.

[40] 李伟锋，刘海峰，曹显奎，王辅臣，于遵宏. 液体射流直径对大液气质量比双通道气流式喷嘴雾化性能的影响[J]. 华东理工大学学报：自然科学版，2006, 32(5): 572-575. (LI Wei-feng, LIU Hai-feng, CAO Xian-kui, WANG Fu-chen, YU Zun-hong. Effect of liquid jet diameter on performance of two-fluid airblast atomizer under large water/air mass flux ratio[J]. Journal of East China University of Science and Technology (Natural Science Edition), 2006, 32(5): 572-575.)

[41] LIU H F, LI W F, GONG X, CAO X K, XU J L, CHEN X L, WANG Y F, YU G S, WANG F C, YU Z H. Effect of liquid jet diameter on performance of coaxial two-fluid airblast atomizers[J]. Chem Eng Process, 2006, 45(4): 240-245.

[42] NORMAN C. Challenges for future research in atomization and spray technology: Arthur lefebvre memorial lecture[J]. Atom Sprays, 2006, 16(7): 727-736.

[43] CROWE C T, GORE R A, TROUTT T R. Particle dispersion by coherent structures in free shear flows[J]. Part Sci Technol, 1985, 3(3/4): 149-158.

[44] CROWE C T, CHUNG J N, TROUTT T R. Particle mixing in free shear flows[J]. Prog Energy Combust Sci, 1988, 14(3): 171-194.

[45] ANDERSON S L, LONGMIRE E K. Particle motion in the stagnation zone of an impinging air jet[J]. J Fluid Mech, 1995, 299: 333-366.

[46] LONGMIRE E K, EATON J K. Structure of a particle-laden round jet[J]. J Fluid Mech, 1992, 236: 217-257.

[47] SAKAKIBARA J, WICKER R B, EATON J K. Measurements of the particle-fluid velocity correlation and the extra dissipation in a round jet [J]. Int J Multiph Flow, 1996, 22(5): 863-881.

[48] CERECEDO L M, AISA L, BALLESTER J. Experimental study on a non-dilute two-phase coflowing jet: Dynamics of particles in the near flow field[J]. Int J Multiph Flow, 2009, 35(5): 468-483.

[49] SBRIZZAI F, VERZICCO R, PIDRIA M F, SOLDATI A. Mechanisms for selective radial dispersion of microparticles in the transitional region of a confined turbulent round jet[J]. Int J Multiph Flow, 2004, 30(11): 1389-1417.

[50] MODARRESS D, TAN H, ELGHOBASHI S. Two-component LDA measurement in a two-phase turbulent jet[J]. AIAA Journal, 1984, 22(5): 624-630.

[51] FLECKHAUS D, HISHIDA K, MAEDA M. Effect of laden solid particles on the turbulent flow structure of a round free jet[J]. Exp Fluids, 1987, 5(5): 323-333.

[52] MOSTAFA A A, MONGIA H C, MCDONELL V G, SAMUELSEN G S. An experimental and numerical study of particle-laden coaxial jet flows [J]. Int J Heat Fluid Flow, 1990, 11(2): 90-97.

[53] FAN J, ZHAO H, JIN J. Two-phase velocity measurements in particle-laden coaxial jets[J]. Chem Eng J Biochem Eng J, 1996, 63(1): 11-17.

[54] GORE R A, CROWE C T. Modulation of turbulence by a dispersed phase[J]. J Fluids Eng-T ASME, 1991, 113(2): 304-307.

[55] MERGHENI M A, SAUTET J C, GODARD G, BEN TICHA H, BEN NASRALLAH S. Experimental investigation of turbulence modulation in particle-laden coaxial jets by Phase Doppler Anemometry[J]. Exp Therm Fluid Sci, 2009, 33(3): 517-526.

[56] BALACHANDAR S, EATON J K. Turbulent dispersed multiphase flow[J]. Annu Rev Fluid Mech, 2010, 42(1): 111-133.

[57] BARLOW R S, MORRISON C Q. Two-phase velocity measurements in dense particle-laden jets[J]. Exp Fluids, 1990, 9(1/2): 93-104.

[58] FAN J R, SUN P, CEN K F. Numerical study of a dense gas-solid jet flow[J]. Energy, 1998, 23(10): 823-833.

[59] FAN J R, JIN J, ZHANG X Y, CEN K F. A numerical model for dense particle-laden jets[J]. Powder Technol, 2001, 115(3): 256-264.

[60] WARDJIMAN C, LEE A, SHEEHAN M, RHODES M. Shape of a particle curtain falling in stagnant air[J]. Powder Technol, 2009, 192(3): 384-388.

[61] LIU Z, COOPER P, WYPYCH P W. Experimental investigation of air entrainment in free-falling particle plumes[J]. Part Sci Technol, 2007, 25(4): 357-373.

[62] ANSART R, RYCK A D, DODDS J A. Dust emission in powder handling: Free falling particle plume characterisation[J]. Chem Eng J, 2009, 152(2/3): 415-420.

[63] ANSART R, RYCK A D, DODDS J A, ROUDET M, FABRE D, CHARRU F. Dust emission by powder handling: Comparison between numerical analysis and experimental results[J]. Powder Technol, 2009, 190(1/2): 274-281.

[64] 周华辉，许建良，李伟锋，刘海峰. 稠密气固两相同轴射流颗粒弥散特性[J]. 化工学报，2009, 60(2): 332-337. (ZHOU Hua-hui, XU Jian-liang, LI Wei-feng, LIU Hai-feng. Particle dispersion characteristics of dense gas-solids two-phase coaxial jets[J]. Journal of Chemical Industry and Engineering (China), 2009, 60(2): 332-337.)

[65] LIU H, CAO W, XU J, LI W, SUN Z. Dispersion mode of granular jet in a coaxial air jet[J]. Powder Technol, 2012, 217: 566-573.

[66] LIU H, CAO W, XU J, LI W, GUO X, SUN Z. Characterization of the granular jet in a coaxial gas stream[J]. Powder Technol, 2012, 225: 206-213.

[67] LU H, LIU H F, LI W F, XU J L. Bubble formation in an annular granular jet dispersed by a central air round jet[J]. AIChE J, 2013, 59(6): 1882-1893.

[68] LU H, LIU H, LI W, XU J. Factors influencing the characterization of bubbles produced by coaxial gas-particle jet flow[J]. Fuel, 2013, 108: 723-730.

[69] 吕慧，李伟锋，许建良，刘海峰. 稠密气固两相旋转射流在气源扰动作用下的流动特征[J]. 化工学报，2012, 63(2): 393-400. (LV Hui, LI Wei-feng, XU Jian-liang, LIU Hai-feng. Characteristics of particle flow in dense gas-particles swirling jet with disturbance of air source [J]. CIESC Journal, 2012, 63(2): 393-400.)

[70] 刘海峰，刘辉，龚欣，王辅臣，于遵宏. 大喷嘴间距对置撞击流径向速度分布[J]. 华东理工大学学报(自然科学版)，2000, 26(2): 168-172. (LIU Hai-feng, LIU Hui, GONG Xin, WANG Fu-chen, YU Zun-hong. Radial velocity of wide spaced impinging streams[J]. Journal of East China University of Science and Technology (Natural Science Edition), 2000, 26(2): 168-172.)

[71] 李伟锋，孙志刚，刘海峰，王辅臣. 两喷嘴对置撞击流径向射流流动特征[J]. 化工学报，2009, 60(10): 2453-2459. (LI Wei-feng, SUN Zhi-gang, LIU Hai-feng, WANG Fu-chen. Flow characteristics of radial jet from two opposed jets[J]. CIESC Journal, 2009, 60(10): 2453-2459.)

[72] 孙志刚，李伟锋，刘海峰. 小喷嘴间距撞击流径向射流的速度分布[J]. 燃烧科学与技术，2010, 16(2): 165-169. (SUN Zhi-gang, LI Wei-feng, LIU Hai-feng. Radial jet velocity distribution of two closely opposed Jets[J]. Journal of Combustion Science and Technology, 2010, 16(2): 165-169.)

[73] SUN Z G, LI W F, LIU H F. Study on the radial jet velocity distribution of two closely spaced opposed jets[J]. Int J Heat Fluid Flow, 2009, 30(6): 1106-1113.

[74] 李伟锋，孙志刚，刘海峰，王辅臣，于遵宏. 小间距两喷嘴对置撞击流场的数值模拟与实验研究[J]. 化工学报，2007, 58(6): 1385-1390. (LI Wei-feng, SUN Zhi-gang, LIU Hai-feng, WANG Fu-chen, YU Zun-hong. Numerical simulation and experimental study on flow field of two closely spaced opposed jets[J]. Journal of Chemical Industry and Engineering (China), 2007, 58(6):1385-1390.)

[75] 李伟锋，孙志刚，刘海峰，王辅臣，于遵宏. 两喷嘴对置撞击流驻点偏移规律的实验研究[J]. 化工学报，2008, 59(1): 46-52. (LI Wei-feng, SUN Zhi-gang, LIU Hai-feng, WANG Fu-chen, YU Zun-hong. Stagnation point offset of two opposed jets[J]. Journal of Chemical Industry and Engineering (China), 2008, 59(1): 46-52.)

[76] 许建良，李伟锋，曹显奎，代正华，刘海峰，王辅臣，龚欣，于遵宏. 不对称撞击流的实验研究与数值模拟[J]. 化工学报，2006, 57(2): 288-291. (XU Jian-liang, LI Wei-feng, CAO Xian-kui, DAI Zheng-hua, LIU Hai-feng, WANG Fu-chen, GONG Xin, YU Zun-hong. Experimental research and numerical simulation of asymmetric impinging streams[J]. Journal of Chemical Industry and Engineering (China), 2006, 57(2): 288-291.)

[77] 孙志刚，李伟锋，刘海峰. 大间距两不对称喷嘴对置撞击流驻点偏移规律[J]. 高校化学工程学报，2009, 23(6): 990-994. (SUN Zhi-gang, LI Wei-feng, LIU Hai-feng. Stagnation point offset of two asymmetric nozzle opposed jets with large nozzle separation distance[J]. Journal of Chemical Engineering of Chinese Universities, 2009, 23(6): 990-994.)

[78] LI W, SUN Z, LIU H, WANG F, YU Z. Experimental and numerical study on stagnation point offset of turbulent opposed jets[J]. Chem Eng J, 2008, 138(1/3): 283-294.

[79] LI W F, YAO T L, WANG F C. Study on factors influencing stagnation point offset of turbulent opposed jets[J]. AIChE J, 2010, 56(10): 2513-2522.

[80] SUN Z G, LI W F, LIU H F. Stagnation point offset of two opposed jets[J]. Ind Eng Chem Res, 2010, 49(12): 5877-5883.

[81] 孙志刚，李伟锋，刘海峰,于遵宏. 平面撞击流振荡特性[J]. 化工学报，2009, 60(2): 338-344. (SUN Zhi-gang, LI Wei-feng, LIU Hai-feng, YU Zun-hong. Oscillation characteristics of two planar opposed jets[J] Journal of Chemical Industry and Engineering (China), 2009, 60(2): 338-344.)

[82] LI W F, YAO T L, LIU H F, WANG F C. Experimental investigation of flow regimes of axisymmetric and planar opposed jets[J]. AIChE J, 2011, 57(6): 1434-1445.

[83] LI W F, HUANG G F, TU G Y, LIU H G, WANG F C. Experimental study of planar opposed jets with acoustic excitation[J]. Phys Fluids, 2013, 25: 014108.

[84] 屠功毅，李伟锋，黄国峰，王辅臣. 平面撞击流偏斜振荡的实验研究与大涡模拟[J]. 物理学报，2013, 62(8): 084704. (TU Gong-yi, LI Wei-feng, HUANG Guo-feng, WANG Fu-chen. Large-eddy simulation and experimental study of deflecting oscillation of planar opposed jets[J]. Acta Physica Sinica, 2013, 62(8): 084704.)

[85] BAUKAL C E, GEBHART B. A review of flame impingement heat transfer part 1: Experimental conditions[J]. Combust Sci Technol, 1995, 104(4/6): 339-357.

[86] BAUKAL C E, GEBHART B. A review of flame impingement heat transfer part 2: measurements[J]. Combust Sci Technol, 1995, 104(4/6): 359-385.

[87] CHANDER S, RAY A, Flame impingement heat transfer: A review[J]. Energy Conv Manag, 2005, 46(18/19): 2803-2837.

[88] FOAT T, YAP K P, ZHANG Y, The visualization and mapping of turbulent premixed impinging flames[J]. Combust Flame, 2001, 125(1/2): 839-851.

[89] HOU S S, KO Y C. Effects of heating height on flame appearance, temperature field and efficiency of an impinging laminar jet flame used in domestic gas stoves[J]. Energy Conv Manag, 2004, 45(9/10): 1583-1595.

[90] HOU S S, KO Y C. Influence of oblique angle and heating height on flame structure, temperature field and efficiency of an impinging laminar jet flame[J]. Energy Conv Manag, 2005, 46(6): 941-958.

[91] KITAJIMA A, UEDA T, MATSUO A, MIZOMOTO M. A comprehensive examination of the structure and extinction of turbulent non-premixed flame formed in a counterflow[J]. Combus Flame, 2000, 121(1/2): 301-311.

[92] SU A, LIU Y C. Investigation of impinging diffusion flames with inert gas[J]. Int J Heat Mass Trans, 2002, 45(15): 3251-3257.

[93] MILSON A, CHIGIER N A. Studies of methane and methane-air flames impinging on a cold plate[J]. Combust Flame, 1973, 21(3): 295-305.

[94] KOSTIUK L W, BRAY K N C, CHEW T C. Premixed turbulent combustion in counterflowing streams[J]. Combust Sci Technol, 1989, 64 (4/6): 233-241.

[95] Z HAZAOV, Y GOLDMAN, Y M TIMNAT. Opposed-flow combustion of pulverized coal[J]. Combust Flame, 1985, 61(2): 119-130.

[96] GUO Q H, YU G S, YAN Z Y, LIANG Q F, NIU M R, YU Z H. Properties of impinging flames in entrained-flow gasifier with opposed multi-burner. International Technology & Innovation Conference, 2006, 2006.11.

[97] 郭庆华，梁钦锋，于遵宏，于广锁. 气化炉内撞击区气体浓度与火焰形状分析[J]. 热能动力工程，2008, 23(5): 512-515. (GUO Qing-hua, LIANG Qin-feng, YU Zun-hong, YU Guang-suo. Gas Concentration and Flame Shape Analysis of the Impinging Zone in a Gasification Furnace[J]. Journal of Engineering for Thermal Energy and Power, 2008, 23(5): 512-515.)

[98] 郭庆华. 多喷嘴对置式气流床气化过程与火焰撞击特性的研究. 上海：华东理工大学，2009. (GUO Qing-hua. Research on opposed multi-burners entrained-flow gasifier process and the flame impinging characteristics. Shanghai: East China University of Science and Technology, 2009.)

[99] 颜卓勇，梁钦锋，郭庆华，于广锁，于遵宏. 撞击流气流床气化炉内火焰截面温度场研究[J]. 中国电机工程学报，2008, 28(32): 24-28. (YAN Zhuo-yong, LiANG Qin-feng, GUO Qing-hua, YU Guang-suo, YU Zun-hong. Research on the Reconstruction of flame section temperature distribution in an entrained-flow gasifier[J]. Proceedings of The Chinese Society for Electrical Engineering, 2008, 28(32): 24-28.)

[100] 颜卓勇，郭庆华，周志杰，梁钦锋，于广锁. 撞击流气化炉内火焰二维温度场分布的测量[J]. 动力工程，2007, 27(3): 353-356. (YAN Zhuo-yong, GUO Qing-hua, ZHOU Zhi-jie, LIANG Qin-feng, YU Guang-suo. Measurement of 2-dimensional temperature distribution in gasification flame' of entrained-flow gasifiers[J].Journal of Power Engineering, 2007, 27(3): 353-356.)

[101] 颜卓勇. 多喷嘴对置式气化炉内火焰特征及温度分布的研究. 上海：华东理工大学，2009. (YAN Zhuo-yong. Research on opposed multi-burners entrained-flow gasifier flame characteristics and temperature distribution. Shanghai: East China University of Science and Technology, 2009.)

[102] GONG Y, GUO Q H, LIANG Q F, ZHOU Z J, YU G S. Three-dimensional temperature distribution of impinging flames in an opposed multiburner gasifier[J]. Ind Eng Chem Res, 2012, 51(22): 7828-7837.

[103] GONG Y, GUO Q H, ZHANG J, FAN P X, LIANG Q F, YU G S. Impinging flame characteristics in an opposed multiburner gasifier. Ind Eng Chem Res, 2013, 52(8): 3007-3018.

[104] 龚岩，张婷，郭庆华，梁钦锋，于广锁. 多喷嘴对置式气化炉撞击火焰三维温度场[J]. 燃烧科学与技术，2012, 18(2): 149-155. (GONG Yan, ZHANG Ting, GUO Qing-hua, LIANG Qin-feng, YU Guang-suo. 3D temperature distribution of impinging flames in an opposed multi-burner gasifier. Journal of Combustion Science and Technology, 2012, 18(2): 149-155.)

[105] 龚岩. 多喷嘴对置式气化炉内火焰可视化研究. 上海: 华东理工大学, 2013. (GONG Yan. Research on opposed multi-burners entrained-flow gasifier flame visualization. Shanghai: East China University of Science and Technology, 2013.)

[106] 高晋生. 高温高压下不同煤种气化反应特性的研究. 国家973计划项目课题结题验收报告(2004CB217704), 2009. (GAO Jin-sheng. Research on gasification reactivity of different coals under high temperature and high pressure. Acceptance report for national 973 plan project (2004CB217704), 2009.)

[107] WU S Y, GU J, ZHANG X, YOU Y Q, GAO J S. Variation of carbon crystalline structures and CO_2 gasification reactivity of Shenfu coal chars at elevated temperatures[J]. Energy Fuels, 2008, 22(1): 199-206.

[108] GU J, WU S Y, WU Y Q, LI Y, GAO J S. Differences in gasification behaviors and related properties between entrained gasifier fly ash and coal char[J]. Energy Fuels, 2008, 22(6): 4029-4033.

[109] GU J, WU S, ZHANG X, WU Y, GAO J. CO_2-gasification reactivity of different carbonaceous material at elevated temperatures[J]. Energy Sources Part A, 2009, 31: 232-243.

[110] WU Y, HUANG S, WU S, GAO J. Investigations on CS_2-solube fractions and gasification reactivity of liquid-phase carbonization cokes [J]. Energy Fuels, 2010, 24(10): 5596-5601.

[111] WU Y, WU S, HUANG S, GAO J. Physicochemical properties and structural evolutions of gas-phase carbonization chars at high Temperatures[J]. Fuel Process Technol, 2010, 91(11): 1662-1669.

[112] 吴幼青. 不同热解过程产物炭的理化性质及石油焦催化气化反应特性研究. 上海: 华东理工大学, 2010: 22-62. (WU You-qing. Studies on physico-chemical properties of resultant carbons from different pyrolysis processes and catalytic gasification reaction characteristics of petroleum coke. Shanghai: East China University of Science and Technology, 2010: 22-62.)

[113] 胡启静, 周志杰, 刘鑫, 于广锁. 氯化铁对高硫石油焦-CO_2气化的催化作用[J]. 石油学报(石油加工), 2012, 28(3): 463-469. (HU Qi-jing, ZHOU Zhi-jie, LIU Xin, YU Guang-suo. Catalytic activity of ferric chloride for high-sulfur petroleum coke-carbon dioxide gasification[J]. Acta Petroleum Sinica (Petroleum Processing Section) (Chinese), 2012, 28(3): 463-469.)

[114] ZHOU Z J, HU Q J, LIU X, YU G S, WANG F C. Effect of iron species and calcium hydroxide on high-sulfur petroleum coke CO_2 gasification[J]. Energy Fuels, 2012, 26(3): 1489-1495.

[115] ZHAN X L, ZHOU Z J, WANG F C. Catalytic effect of black liquor on the gasification reactivity of petroleum coke[J]. Appl Energy, 2010, 87(5): 1710-1715.

[116] ZOU J H, YANG B L, GONG K F, WU S Y, ZHOU Z J, WANG F C. Effect of mechanochemical treatment on petroleum coke-CO_2 gasification[J]. Fuel, 2008, 87(6): 622-627.

[117] LIU X, ZHOU Z J, ZHANG B S, CHEN L, WANG F C. Effect of microwave treatment on structural changes and gasification reactivity of petroleum coke[J]. Ind Eng Chem Res, 2011, 50(15): 9063-9068.

[118] WATANABE H, OTAKA M. Numerical simulation of coal gasification in entrained flow coal gasifier[J]. Fuel, 2006, 85(12/13): 1935-1943.

[119] 吴玉新, 张建胜, 王明敏, 岳光溪, 吕俊复. 简化PDF模型对Texaco气化炉的三维数值模拟[J]. 化工学报, 2007, 58(9): 2369-2374. (WU Yu-xin, ZHANG Jian-sheng, WANG Ming-min, YUE Guang-xi, LV Jun-fu. 3D numerical simulation of Texaco gasifier using assumed PDF model[J]. Journal of Chemical Industry and Engineering (China), 2007, 58(9): 2369-2374.)

[120] SLEZAK A, KUHLMAN J M, SHADLE L J, SPENIK J, SHI S. CFD simulation of entrained-flow coal gasification: Coal particle density/sizefraction effects[J]. Powder Technol, 2010, 203(1): 98-108.

[121] 许建良. 气流床气化炉内多相湍流反应流动的实验研究和数值模拟. 上海: 华东理工大学, 2008. (XU Jian-liang. Experimental research and numerical simulation of the multiphase turbulent reaction flow in entrained-flow gasifiers . Shanghai: East China University of Science and Technology, 2013.)

[122] SUN Z, DAI Z, ZHOU Z, GUO Q, YU G. Numerical simulation of industrial opposed multiburner coal-water slurry entrained flow gasifier[J]. Ind Eng Chem Res, 2012, 51(6): 2560-2569.

[123] SUN Z, DAI Z, ZHOU Z, XU J, YU G. Comparative study of gasification performance between bituminous coal and petroleum coke in the industrial opposed multiburner entrained flow gasifier[J]. Energy Fuels, 26(11): 6792-6802.

[124] LI C, DAI Z, LI W, XU J, WANG F. 3D numerical study of particle flow behavior in the impinging zone of an opposed multi-burner gasifier [J]. Powder Technol, 2012, 225: 118-123.

[125] DU M, ZHAO C, ZHOU B, GUO H, HAO Y. A modified DSMC method for simulating gas-particle two-phase impinging streams[J]. Chem Eng Sci, 2011, 66(20): 4922-4931.

[126] NI J, ZHOU Z, YU G, LIANG Q, WANG F. Molten slag flow and phase transformation behaviors in a slagging entrained-flow coal gasifier [J]. Ind Eng Chem Res, 2010, 49(23): 12302-12310.

[127] GAZZANI M, MANOLINI G, MACCHI E, GHONIEM A F. Reduced order modeling of the Shell-Prenflo entrained flow gasifier[J]. Fuel, 2012, 104: 822-837.

[128] LI C, DAI Z, SUN Z, WANG F. Modeling of an opposed multiburner gasifier with a reduced-order model[J]. Ind Eng Chem Res, 2013, 52 (16): 5825-5834.

[1] 占旺兵, 梁钦锋, 董志, 刘海峰, 于广锁. 水冷壁气流床气化炉灰渣结构分析[J]. 燃料化学学报, 2010, 38(01): 6-11.

[2] 陈忠, 袁帅, 梁钦锋, 龚凯峰, 王辅臣, 于遵宏. 煤的模型化合物混合燃料气流床气化中N的迁移研究[J]. 燃料化学学报, 2008, 36(05): 513-518.