Experimental Study on Condensation Heat Transfer Characteristics of Fine-Particle-Laden Gas Mixtures in Vertical Channels (Postprint)

Authors: Guan Chengyi, Jia Li

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Abstract

Using nitrogen, water vapor, and lignite coal powder to simulate lignite flue gas mixtures, an experimental investigation was conducted on the condensation heat transfer characteristics of gas mixtures containing fine particles in a vertical channel under parameter ranges of water vapor mass fraction of 30%}, lignite coal powder particle size less than 70um}, particle concentration of 0. 13-1. 37 g/m3}, and mixture Reynolds number of 24331, analyzing the effects of fine particle concentration and particle size on the condensation heat transfer characteristics of the gas mixture. The results demonstrate that particles move within the condensate film along with the condensate flow, and the heat transfer ultimately reaches a steady state; as the particle size and concentration in the gas mixture increase, the sensible heat transfer intensity of the gas mixture decreases.

Full Text

Experimental Investigation on Condensation Heat Transfer Characteristics of Gas-Steam Mixtures with Fine Particles in a Vertical Channel

GUAN Cheng-Yi[1,2], **JIA Li**[1,2*]
[1] Institute of Thermal Engineering, School of Mechanical, Electronic, and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
[2] Beijing Key Laboratory of Flow and Heat Transfer of Phase Changing in Micro and Small Scale, Beijing 100044, China

Abstract: This study experimentally investigates the condensation heat transfer characteristics of gas mixtures containing fine particles in a vertical channel. Using nitrogen, water vapor, and lignite coal powder to simulate lignite flue gas mixtures, experiments were conducted under the following conditions: water vapor mass fraction of 30%, lignite coal powder particle size less than 70 m, particle concentration of 0.13–1.37 g/m^3, and mixture Reynolds number of 24,331. The effects of fine particle concentration and particle size on the condensation heat transfer characteristics were analyzed. Results demonstrate that particles move within the condensate film along with the condensate flow, and the heat transfer eventually reaches a steady state. As both the particle size and concentration in the gas mixture increase, the sensible heat transfer intensity of the mixture decreases.

Keywords: lignite coal; condensation heat transfer; fine particle

1. Introduction

China possesses abundant lignite resources, primarily concentrated in water-scarce regions. Lignite flue gas exhibits high waste heat content and substantial moisture levels, making the clean and efficient recovery of energy and water from lignite pulverization mixtures and flue gas a focal point of research [1]. Both lignite pulverization mixtures and flue gas contain certain concentrations of fine coal particles. Investigating the influence of these fine particles on energy and water recovery is therefore of significant importance.

Numerous studies have examined condensation heat transfer characteristics of gas mixtures containing non-condensable gases in vertical tubes [2-7]. Lee and Kim [8] experimentally compared condensation heat transfer coefficients in channels for gas mixtures with non-condensable gases versus pure steam, revealing that the presence of non-condensable gases substantially affects the condensation heat transfer coefficient. Jia Li and Lu Guoli [9] investigated condensation heat transfer characteristics of gas mixtures with water vapor mass fractions of 8%–28% in vertical tubes, finding that at Reynolds numbers of 3,000–7,000, lower wall temperatures resulted in thicker liquid films and greater condensate quantities, with film thickness increasing as Reynolds number increased. Qi Wei et al. [10] experimentally studied factors influencing condensation heat transfer with large quantities of non-condensable gases, concluding that increased cooling water pipe wall temperature inhibited latent heat transfer.

Published literature on particle effects on condensation heat transfer remains limited [10]-[12]. Gao Xiang [13] proposed a heat transfer enhancement model in which particles disrupt the boundary layer during wall collisions, calculating how wind speed, particle concentration, and particle size affect boundary layer disturbance and heat transfer. Zhang Yi [14] employed numerical modeling to study particle effects on boundary layer disturbance and tube wall erosion in vertical tubes, concluding that within a certain particle size range, increased particle diameter reduced disturbance effects while shear stress remained nearly unchanged.

This research focuses on condensation heat transfer characteristics of gas mixtures containing fine particles in vertical channels, specifically exploring the effects of particle concentration and particle size on condensation heat transfer.

2. Experimental System and Methods

The experimental study utilized nitrogen, water vapor, and lignite coal powder to prepare simulated lignite pulverization mixtures and flue gas. Coal powder concentration and particle size were controlled systematically. The experimental system is illustrated in [Figure 1: see original paper].

[Figure 1: see original paper] Schematic of experimental apparatus

The experimental system comprises a gas mixture preparation system, cooling water system, test section, and data acquisition system. The gas mixture preparation process involves nitrogen supplied from cylinder tanks, with flow rate controlled through needle valves coordinated with flow meters. Coal powder feed rate is regulated by adjusting the vibration frequency of a vibrating powder feeder. Water vapor flow rate is controlled by varying the input voltage to a steam generator to achieve the desired heating power. The nitrogen and steam are thoroughly mixed to form the test gas mixture, which is then delivered to the test section. The test section employs a three-plate aluminum structure, with the middle plate forming hollow flow regions for the gas mixture and cooling water. The side plates compress the assembly to form enclosed channels, with glass viewing windows installed to observe flow and condensation phenomena within the channel. The gas flow channel dimensions are 10 mm $\times$ 10 mm $\times$ 300 mm. Both the test section and gas preparation system are wrapped with insulation material to minimize heat exchange with the ambient environment. The test section is shown in [Figure 2: see original paper].

[Figure 2: see original paper] Schematic of test section

Thermometers are installed at the cooling water inlet and outlet. Cooling water is supplied from a tank, heated by a constant-temperature water bath to achieve precise temperature control and monitoring at the inlet and outlet. The gas mixture flows downward through the channel, condensing on the condensing wall surface. Condensate flows down the wall and passes through a filter screen to separate condensate liquid, vapor, and fine particles. The condensate quantity is collected and weighed using an electronic balance. Six temperature measurement points are uniformly arranged on the condensing wall surface at 60 mm intervals from top to bottom. Two temperature measurement points and pressure measurement points are installed at the gas mixture inlet and outlet. Temperatures are measured using thermocouples connected via compensation wires to a data acquisition system. The thermocouple voltage signals are processed through acquisition boards into a computer for data storage and analysis.

2.1 Effect of Particle Size on Condensation Heat Transfer Characteristics

The variation of condensing wall temperature over time is shown in [Figure 3: see original paper]. The experimental conditions were: water vapor mass fraction of 30%, particle concentration of 5 g/m^3, mixture Reynolds number of 24,331, gas mixture inlet temperature of 98°C, gas mixture inlet pressure of 101,330 Pa, cooling water inlet temperature of 30°C, and cooling water flow rate of 8.16 g/s.

[Figure 3: see original paper] Condensing wall temperature changes with time

The temperature at the middle measurement point of the test section gradually increased during the first 100 seconds of the experiment before reaching a stable state. The condensate film flowed downward, adsorbing and carrying fine particles along with it. No sustained particle deposition occurred on the condensing wall surface, and the particle deposition fouling resistance reached a constant value.

As shown in [Figure 4: see original paper], the condensation heat transfer coefficient of gas mixtures containing particles of different sizes decreases as particle size increases. [Figure 5: see original paper] indicates that at a particle concentration of 0.44 g/m^3, the latent heat release remains essentially constant while sensible heat release decreases with increasing particle size. Particle motion within the gas mixture channel is primarily governed by inertial forces. As particle size increases, the particles' ability to follow the gas film motion weakens. This reduces the probability of particles being adsorbed by the fluctuating liquid film near the gas-liquid interface. Additionally, the presence of particles increasingly hinders gas film fluctuations, resulting in reduced sensible heat transfer. Steam in the mainstream gas diffuses through the non-condensable gas layer via diffusion. Since gas film fluctuations have minimal influence on water vapor molecular diffusion and weak effects on the vapor partial pressure difference across the gas film, increasing particle size in the gas mixture does not alter the latent heat release.

[Figure 4: see original paper] Nu changes with particle size

[Figure 5: see original paper] Heat flux changes with particle size

[Figure 6: see original paper] Condensing wall temperature changes with time under different particle concentration

2.2 Effect of Particle Concentration on Condensation Heat Transfer Characteristics

The experimental conditions for [Figure 6: see original paper] were: water vapor mass fraction of 30%, particle size of 0–3 m, mixture Reynolds number of 24,331, gas mixture inlet temperature of 98°C, gas mixture inlet pressure of 101,330 Pa, cooling water inlet temperature of 30°C, and cooling water flow rate of

8.16 g/s. At the beginning of the experiment, the temperature at the middle measurement point gradually increased with time, reaching stability after 100 seconds. Within the condensate film, condensate flowed downward, adsorbing and carrying fine particles. The heat transfer resistance remained constant, indicating that substantial particle deposition did not occur on the condensing wall surface.

The heat transfer coefficient decreases as particle concentration increases, as shown in [Figure 7: see original paper], indicating that the thermal resistance on the gas mixture side increases with particle concentration. When the particle size is 0–3 m, the change in heat transfer is primarily caused by decreasing sensible heat release with increasing particle concentration, as demonstrated in [Figure 8: see original paper]. At the gas-liquid interface, liquid film fluctuations adsorb fine particles into the liquid film under the action of longitudinal shear forces in the gas film thermal resistance layer. Increasing particle concentration in the gas mixture increases the quantity of adsorbed particles in the liquid film, thereby increasing liquid film thermal resistance. Meanwhile, the quantity of particles remaining in the gas film resistance layer increases with inlet particle concentration, reducing gas-phase thermal resistance. The combined effect increases the overall conductive thermal resistance on the gas mixture side without altering the driving potential for steam mass transfer.

[Figure 7: see original paper] Nu changes with particle concentration

[Figure 8: see original paper] Heat flux changes with particle concentration

3. Conclusions

Through experimental investigation of condensation heat transfer of gas mixtures containing fine particles in a vertical channel under various particle concentrations and sizes, the following main conclusions are drawn:

1. Under conditions of 30% water vapor mass fraction, lignite coal powder particle size less than 70 m, particle concentration of 0.13–1.37 g/m^3, mixture Reynolds number of 24,331, and cooling water inlet temperature of 30°C, particles move within the condensate film along with condensate flow, and the heat transfer eventually reaches a steady state.

2. Increasing coal powder particle size weakens the particles' following characteristics with the gas-phase film and enhances their hindrance to gas film fluctuations, resulting in reduced sensible heat transfer.

3. Increasing particle concentration in the gas mixture alters both the gas film and liquid film thermal resistances, leading to reduced sensible heat transfer, though the magnitude of change is not significant.

References

[1] Mao Y F, Guo X K, Xiao F, et al. Efficient Lignite-fired Power Generation

Technology Based on Open Pulverizing Systems with Flue Gas Drying Fan Mill and Recovery of Heat and Water From Pulverizing Exhaust[J], Proceeding of the CEED,2013,33(5):13-20.

[2] Tong Z.M., Xu B, Li S.J, et al. Experimental Study of Condensation of Multicomponent Vapors inside Vertical Tubes[J]. Journal of University of Shanghai for Science and Techonology, 2005, 27(2):120-123.

[3] Zhang J X. Vapor Diffusion Flow and Condensation Heat Transfer with High Partial Pressure Non Condensation Gases in Tubes[D]. University of Science and Technology in Beijing, Doctor, 2011.

[4] Jia L, Sun J D Li X P. ，The Research on Condensing Heat Transfer of Wet Flue Gas[J]. Journal of Beijing Institute of Civil Engineering and Architecture. 2011,17(2):15-19.

[5] Rao V D, Krihna V M, Sharma K V, et al. Convective Condensation of Vapor the Presence of a Non-condensable Gas of High Concentration in Laminar Flow in a Vertical Pipe[J]. International Journal of Heat and Mass Transfer, 2008, 51(25-26):1-12.

[6] Zhu A M, Wang S C, Wang Z, Liu Q L. Mathematical Simulation of Steam Condensation with High Fractional Noncondensable Gas in the Dewvaporation Desalination Process[J]. Desalination, 2009, 243(1-3):145-158.

[7] Oh S, Shripad T R, Experimental and Theoretical Investigation of Film Condensation with Noncondensable Gas[J]. International Journal of Heat and Mass Transfer, 2006, 49(15-16):2523-2534.

[8] Lee K Y, Kim M H. Experimental and Empirical Study of Steam Condensation Heat Transfer with a Non Condensable Gas in a Small-diameter Vertical Tube[J]. Nuclear Engineering and Design, 2008, 238(1):207-216.

[9] Jia L, Lu G L. The Research on Condensation of Vapor of Wet Flue Gas and SO2 Absorption in Vertical Tube [J]. Journal of Engineering Thermophysics, 2003, 24(6):

[10] Bi H T, Ellis N, Abba I A, et al. A State of Theart Review of Gas–solid Turbulent Fluidization[J]. Chemical Engineering Science, 2000, 55(21): 4789-4825.

[11] Shi M Y, Han Z H, Sun F Z, et al. Experimental Study on Anti-abrasion and Anti-ash-deposition Property of Spirally Finned Tubes[J]. Journal of Power Engineering, 2006, 26(1): 146-148.

[12] Ping L, Wang P. Non-liner Characteristics Study on Wear In-line Bundle by Fly-ash with Different Diameters[J]. Journal of Taiyuan University of Technology, 2011, 42(4): 420-423.

[13] Gao X, Luo Zhongyang, Zhou jinsong, et al. Mechanics of Enhancement of Convenctive Heat Transfer Due to Particle Impact in Gas-solid Two-phase Flow[J]. Journal of Chemical Industry and Engineering,1998,49(3):294-302.

[14] Zhang Y, Zhou W, Sun Z Q, et al. Numerical Simulation of Scouring Erosion Characteristics for Gas-solid Two-phase Flow in Pipes[J]. Metal Materials and Metallurgy Engineering,2011,39(1):11-15.

Note: Figure translations are in progress. See original paper for figures.