International Journal of Heat and Mass Transfer 93 (2016) 778–787

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Heat transfer enhancement in a gas–solid suspension flow by applying electric field

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ARTICLE INFO

Article history:
Received 27 May 2015
Received in revised form 22 September 2015
Accepted 22 September 2015
Available online 12 November 2015

Keywords:
Gas–solid suspension flow
Heat transfer enhancement
Electric field
Hollow glass beads

ABSTRACT

Enhancing convective heat transfer is important for improving performance of heat exchangers. We studied the enhancement of heat transfer in a gas–solid suspension flow wherein the solid particle motions were controlled using an electric field. In the experiments, hollow glass particles suspended in air flowed vertically upward in a channel confined by parallel-plate electrodes, one of which served as a heat transfer surface. Particle trajectories, temperature profiles in the airflow, and heat transfer rates were measured. A theoretical study was also performed by considering the particle equations of motion, electric charge transfer at the walls, and heat exchange between particles and the gas phase using the particle source in cell model. As the results, we found that Coulomb forces acting on particles caused alternating one-sided motion in the flow direction through contact charging on the wall electrodes. Thus, particles repeatedly collided with both channel walls. Hence, heat transfer was enhanced, primarily due to heat transport by particles across thermal boundary layer at the heated wall. The simulation results of heat transfer rates were compared with the experimental results, and show quantitatively good agreement. On the basis of the results, the optimum particle diameter for enhancing heat transfer was determined by imposing the condition that the thermal relaxation time of a particle is equal to the contact-charging time of the particle on the wall.

1. Introduction

In recent years, a great deal of research effort has been directed toward developing high-performance thermal systems for more efficient utilization of thermal energy. Improving the performance of heat exchangers is a primary issue that could be attained by enhancing heat transfer and reducing pump power. Techniques for heat transfer enhancement can largely be classified into three methods: passive, active, and combined [1]. Though external power and additional devices are required for active methods, they have become common because they have high controllability of heat transfer. Among various active methods, enhancement technique utilizing an electric field can be a promising method because of its several advantages such as quick response to heat transfer control, low consumption of electric power, low levels of vibration and noise, and simplified implementation [2,3]. Basic strategies for enhancing convective heat transfer can be divided into four categories: (1) leading edge effects, (2) thinning of boundary layers and/or thermal resistance layers due to changes in primary flow structures, (3) local displacement of fluid layers near wall surfaces due to incoming fluid, and (4) additive effects [4]. In this study, we focus on additive effects and examine heat transfer enhancement by applying an electric field to a gas–solid suspension flow in which the motion of solid particles is controlled by Coulomb forces. Specifically, we intend to augment particle effects, such as conveying heat by particles in the thermal boundary layer, by producing more active collisions between particles and heat transfer surfaces.

In previous studies, electrohydrodynamic (EHD) effects in a gas–solid suspension flow were examined for an internal flow. Min and Chao [5] demonstrated the feasibility of improving heat transfer by applying an alternating electric field. In the experiments, the gas–solid suspension consisted of 30-μm glass beads and air, which flowed vertically downward in a rectangular channel. By applying an electric field with 10 kV peak to peak potential at a frequency of 7.7 Hz, heat transfer was increased by a factor of 2 under a loading ratio of 2 and a Reynolds number of 2920. The high enhancement effect was obtained at low frequency because the residence time of particles in the thermal boundary layer was long. Through semi-empirical analyses, the authors suggested that heat

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.09.063
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Nomenclature

C_D	drag coefficient
C_P	specific heat, J/(kg K)
d_e	hydraulic diameter, m
d_p	particle diameter, m
e	coefficient of restitution
G	number of trajectories used in calculations
H	plate spacing in test section, m
k	thermal conductivity, W/(m K)
m_p	mass of a particle, kg
Nu	Nusselt number
N^*	number flow rate of particles for a given trajectory, 1/s
q	electric charge on a particle, C
q_H	heat flux, W/m^2
q_w	heat flux on wall surface, W/m^2
Re	Reynolds number = $U_m d_e/\nu$
Re_p	particle Reynolds number = $u_r d_p/\nu$
T	air temperature, K
T_p	particle temperature, K
T_m	mixed mean temperature = $T_{in} + q_w x/(\rho_f C_p U_m H)$, K
T_{in}	air temperature at inlet of test section, K
t	time, s
U_m	mean velocity of airflow, m/s
u	air velocity in x-direction, m/s
u_p	particle velocity in x-direction, m/s
u_r	relative particle velocity = $\sqrt{(u-u_p)^2+(v-v_p)^2}$, m/s
V_0	applied voltage between wall electrodes, V
v	air velocity in y-direction, m/s
v_p	particle velocity in y-direction, m/s
x	longitudinal coordinate, m
y	vertical coordinate from wall surface, m
α	heat transfer coefficient, W/(m^2 K)
Γ	loading ratio as the ratio of mass flow rate of solid particle to that of fluid
$\Delta t_{contact}$	electric contact charging time, s
ε	electric permittivity of particle, F/m
ε_0	electric permittivity of free space, F/m
ε_r	emissivity
η	absorption efficiency of particle
ν	kinetic viscosity, m^2/s
ρ	density, kg/m^3
σ_c	electric conductivity of particle, 1/(Ω m)
σ_B	Stefan–Boltzmann constant, W/(m^2 K^4)
τ_c	relaxation time-constant of electric charge = ε/σ_c, s
τ_H	thermal relaxation time-constant = $\rho_p C_p d_p{}^2/(12k_f)$, s

Subscripts

f	gas (air) phase
p	particle phase
$\bar{}$	mean value

conveyed by particles from a heated wall to the fluid plays an important role for enhancing heat transfer. For the EHD effect of electrically conductive particles, Bologa et al. [6] first discussed the EHD effects of steel particles of 75-μm diameter or bronze particles of 141-μm diameter flowing in a concentric annular passage. The results showed increases in heat transfer coefficients due to the EHD effect of up to a factor of 2 or 3 at the Reynolds number of 3000. Because of the increased ability for contact charging on electrode surfaces, electrically conductive particles are more suitable for long heat transfer surfaces than dielectric particles. They also indicated that the electric field increased the cross-section-averaged concentration and velocity of particles, and it induced turbulization of a laminar sublayer on the heating surface. Studies of the effects of glass particles of 49-μm diameter in a turbulent pipe flow were performed by Yoshida et al. [7]. The maximum enhancement factor was approximately 1.4 when the Reynolds number was 5200 and the loading ratio was 0.6. The enhancement factor of the heat transfer coefficient and pressure loss increased as the applied voltage and loading ratio were increased and the Reynolds number was decreased. They estimated that interactions between particles and the gas phase was an important factor for enhancing turbulent heat transfer. These studies indicate that EHD effects can enhance heat transfer in gas–solid suspension flows. However, particle effects in EHD fields are too complicated to explicitly explain the mechanism of heat transfer enhancement. For pursuing heat transfer enhancement in EHD fields, studies should be conducted to clarify the following: dynamical behavior of particles including collisions with wall surfaces, electric charge transfer between particles and walls, and mechanisms of heat transfer enhancement relevant to operating parameters and the electrical and thermal properties of the particles.

Therefore, we have undertaken theoretical and experimental studies to clarify the fundamental characteristics of gas–solid suspension flows in EHD fields. A vertically oriented channel was selected not only as a typical geometry for heat exchangers but also as a convenience for simplifying the behavior of particles colliding with walls. Hollow glass beads were tested as low-density particles whose electric-charge relaxation times are comparatively long. First, particle trajectories were visualized, and the time for contact charging of particles on the wall surface was obtained. Next, characteristics of heat transfer were examined as functions of operating parameters. On the basis of the results, a simplified EHD model for convective heat transfer is proposed that considers contact charging on the wall and heat exchange between the particles and the gas phase. Finally, optimum sizes of particles for enhancing heat transfer are addressed in relation to thermal relaxation times and the strength of the applied electric field.

2. Experimental apparatus and method

2.1. Experimental apparatus

Fig. 1 shows a schematic of the experimental apparatus used in this work. The experiments were performed in a loop system for a dispersed solid component and an open system for air. A rectangular channel measuring 10 mm in height, 1805 mm in length, and 100 mm in spanwise width was set vertically. The channel contained a starting section of 1030 mm in length and a test section of 775 mm in length. The starting section was fabricated from polymethyl methacrylate (PMMA) plates. Solid particles were supplied to the airflow in the starting section using a vibrating feeder (Tuji Science Instruments, VSS-50). The particles were positively and electrostatically precharged using an ionic shower caused by corona discharge at the outlet of the starting section. The corona discharge was generated by a high-voltage supply (Matsusada Precision Inc., HER-10R6) and a nickel-wire electrode of 0.2-mm diameter placed spanwise in the channel. Thus, a gas–solid suspension flow entered the upper test section. The test section comprised a heated plate and an adiabatic plate electrode. High voltage was applied between these plates using a high-voltage supply (Treak Japan Incorporated, model 662), and a uniform electric field was