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Investigation of bed-to-wall heat transfer characteristics in a rolling circulating fluidized bed

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ABSTRACT

In order to enhance the heat recovery properties of the circulating fluidized bed (CFB) which is proposed to be a potential choice for the waste heat recovery system in a ship to solve the corrosion problem, effect of the rolling motion induced by the ship on the bed-to-wall heat transfer characteristics has been investigated. Improved cluster-based models (ICBM), in which the potential dynamic feature change of clusters induced by the rolling motion is considered, have been proposed for the prediction of the heat transfer coefficient in the rolling CFB. The predicted heat transfer coefficients by ICBM were compared with the predicted results of cluster renewal model (CRM) which is applied commonly to the CFB at upright attitude, and evaluated by the measurement results in the heat transfer experiment. As results, the predicted heat transfer coefficient by CRM agrees well with the experimental results in the CFB at upright attitude. However, in the case that the rolling motion is applied, the heat transfer coefficient is extremely under-estimated by CRM. Meanwhile, the predicted heat transfer coefficient by ICBM I, which takes into account the disappearance of the gas layer next to the wall and the increase of the particle volume fraction in clusters due to the rolling motion, is in good accord with the measured heat transfer coefficient in the heat transfer experiments. The dynamic feature changes of the cluster are proposed to be the primary factors for the heat transfer augmentation in the rolling CFB.

1. Introduction

Recently, the emission reductions of nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon dioxide (CO_2) from ships have become issues in the International Maritime Organization (IMO), because the emission controls from ships are getting more stringent than ever [1,2]. This trend of environmental protection requires the shipping industries to improve the propulsion efficiency of ships. The current efficiencies of large diesel engines which are commonly used as prime movers in ships are only 50%. Therefore, the waste heat recovery system of the engine exhaust gases becomes a solution to enhance the efficiency of the diesel engines. However, marine diesel engines usually use heavy fuel oils that include high sulfur quantity unlike regular diesel engines. During the combustion process of the fuel oils, sulfur oxide is produced in the exhaust gases. These gaseous sulfur species cause corrosion problems by sulfuric acid formation to constrain the enhancement of heat recovery properties of the ordinary waste heat recovery system such as exhaust gas economizers (EGE) in diesel ships [3].

Circulating fluidized bed (CFB) is a popular device that provides excellent heat transfer and chemical reaction property due to its ability to promote high contact ratio between gases and particles [4,5]. During the contact between exhaust gases and desulfurization particle in CFB, the gaseous sulfur species in the gas phase are removed by desulfurization reaction. Simultaneously, particles transport the heat of the exhaust gases to the heat exchanger. Therefore, CFB is proposed to be a potential choice for the waste heat recovery system in a ship in order to solve the corrosion problems and to enhance the heat recovery properties [6]. However, the application of the CFB to the ship is still very limited due to the unclear influences of the rolling motion induced by the ship on the heat transfer characteristics. Therefore, it is necessary to clarify the heat transfer characteristics in a rolling CFB.

The interaction between the particles and the wall of the CFB is an important factor for the heat transfer from the particle bed to the wall of the CFB. A number of mechanical models were proposed to explain the heat transfer mechanism of fluidized beds. One of the common approaches is single particle model which considers the heat transfer process at the particle level. The primary concern of this model is to treat the first layer of particles adjacent to the wall [7,8]. A similar approach called continuous film model assumes that the wall of the CFB is always covered by a homogeneous film of gas and particles, and the dispersed phase moving upward in the center does not come into contact with the wall [9,10]. However, the lack of detailed information on the individual particle motion and the existence of discrete particle clusters rather than continuous particle film near the wall hinder any promotion

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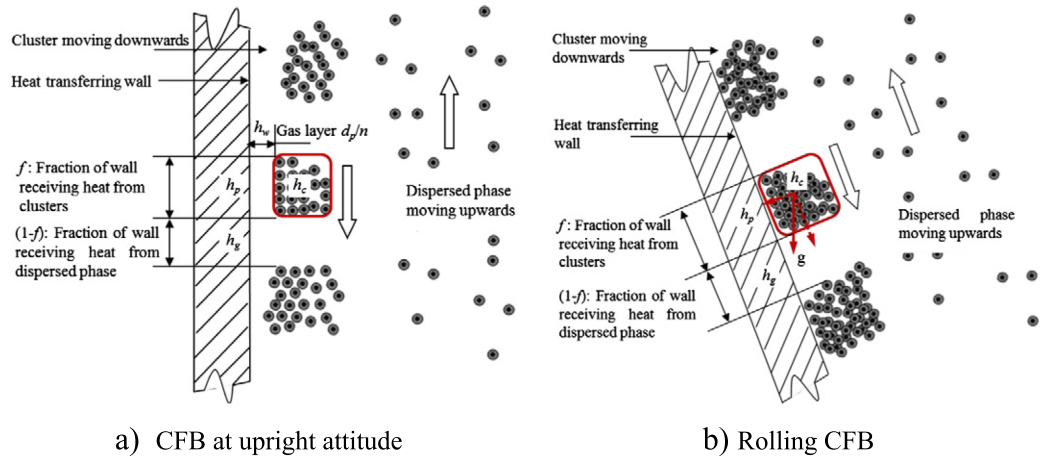

Fig. 1. Heat transfer mechanism in the CFB at different attitudes.

of these models [11,12]. Under these circumstances, the cluster renewal model (CRM) which considers the discrete clusters instead of a continuous film of particles becomes a novel alternative approach for the evaluation of heat transfer coefficient of the CFB. In the cluster renewal model, the heat transfer coefficient is highly dependent on the dynamic feature of clusters [13]. Results of our previous study already indicate that the rolling motion of the CFB causes potential dynamic feature changes of clusters [14,15]. Therefore, improvement of the cluster renewal model is necessary for the prediction of the heat transfer coefficient in the rolling CFB.

Moreover, in order to evaluate the dynamic feature changes of clusters induced by the rolling motion, a powerful measurement technique is indispensable. Particle Imaging Velocimetry (PIV) is a non-intrusive optical measurement technique to obtain the instantaneous fluid velocity fields of continuous fluids [16]. Recently, PIV has also been successfully applied to the measurement of the velocity distribution in circulating fluidized beds [17], because the improvements in flow-visualization equipment have facilitated the measurement of the velocity of cluster near the wall. Shi [18] determined the boundary of particle clusters by the gray level threshold method and investigated the cluster properties in a circulating fluidized bed riser by PIV. Kashyap et al. [19] used PIV to obtain laminar and turbulent properties near the wall in the developing region in the riser part of the circulating gas–solid fluidized bed, and the instantaneous velocities of the particle were also measured simultaneously in the axial and radial directions.

In the present work, in order to clarify the bed-to-wall heat transfer characteristics in the rolling CFB, the dynamic feature change of clusters induced by the rolling motion and its potential effect on the bed-to-wall heat transfer are discussed. On this basis, improved cluster-based models (ICBM) for the rolling CFB are proposed. PIV is used to validate the dynamic feature changes of clusters induced by the rolling motion, and then the heat transfer coefficient of the rolling CFB is calculated based on the measured dynamic parameters of clusters obtained from PIV in the cold mode experiments. The heat transfer experiments were also carried out to evaluate the prediction results of CRM and ICBM.

Table 1
Formula of CRM and ICBM.

	Basic formulas
CRM	$h_p = \left(\sqrt{\frac{\pi t}{4k_c c_c \rho_c}} + \frac{d_p}{nk_g}\right)^{-1}, \ \alpha_c = 1.23\alpha_p^{0.54}.$
ICBM I	$h_p = \left(\sqrt{\frac{\pi t}{4k_c c_c \rho_c}}\right)^{-1}, \ \alpha_c = \alpha_{mf}.$
ICBM II	$h_p = \left(\sqrt{\frac{\pi t}{4k_c c_c \rho_c}} + \frac{d_p}{nk_g}\right)^{-1}, \ \alpha_c = \alpha_{mf}.$
ICBM III	$h_p = \left(\sqrt{\frac{\pi t}{4k_c c_c \rho_c}}\right)^{-1}, \ \alpha_c = 1.23\alpha_p^{0.54}.$

2. Mechanical model of heat transfer

In this work, the radiant heat transfer contribution to the waste heat recovery system in ships is omitted due to the relatively low temperature. Fig. 1 (a) shows the basic heat transfer mechanism in the CFB at upright attitude. As shown in Fig. 1, the heat transferring wall is covered either by gas or clusters, so that the wall is presumed to receive heat from gas and clusters in parallel. Therefore, the overall heat transfer from the bed to the wall is modeled as the sum of particle convective transfer due to the clusters moving downward and gas convective transfer due to the gas–particle dispersed phase moving upward. The overall heat transfer coefficient, combining the contributions of clusters and the dispersed phase is modeled as:

$$h = (1-f)h_g + fh_p \tag{1}$$

where $(1-f)$ is the fraction of the wall receiving heat from the dispersed phase, f is the fraction of the wall receiving heat from clusters, h_g is the heat transfer coefficient from the dispersed phase to the wall and h_p is the heat transfer coefficient from the clusters to the wall.

As shown in Fig. 1 (a) and (b), the fractional wall, which is not covered by the clusters, receives heat from the gas–particle dispersed phase moving upward. The convection heat transfer from this dilute dispersed phase to the wall is estimated by the modified equation of dust-laden gas flow as [20,21]

$$h_g = \frac{k_g c_p}{d_p c_g}\left(\frac{\rho_{dis}}{\rho_p}\right)^{0.3}\left(\frac{V_t^{\,2}}{g d_p}\right)^{0.21} P_{r,g} \tag{2}$$

where k_g is the thermal conductivity of the gas, c_g and c_p are the specific heat of the gas and particles, respectively, d_p is the particle diameter, ρ_p is the density of the gas and particle respectively, ρ_{dis} is the density of the gas–particle dispersed phase, V_t is the terminal velocity of a particle and $P_{r,g}$ is the Prandtl number of the gas phase. The density of the gas–particle dispersed phase ρ_{dis} is given by

$$\rho_{dis} = \rho_g(1-Y) + \rho_p Y \tag{3}$$

where Y is the particle volumetric fraction in the gas–particle dispersed phase. The value of Y is recommended as 0.00001 [22]. The terminal velocity of particle V_t is calculated by [23,24]

$$V_t = 1.2 d_p\left(\frac{\rho_p^2}{\mu_g}\right)^{\frac{1}{3}} \tag{4}$$

where μ_g is the gas viscosity.