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Direct numerical simulation of a particle-laden mixing layer with a chemical reaction

Takenobu Michioka [a,*], Ryoichi Kurose [b,1], Kouichi Sada [a], Hisao Makino [b]

[a] *Environmental Science Research Laboratory, Central Research Institute of Electric Power Industry (CRIEPI), Chiba 270-1194, Japan*

[b] *Energy Engineering Research Laboratory, Central Research Institute of Electric Power Industry (CRIEPI), Yokosuka, Kanagawa 240-0196, Japan*

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Abstract

A direct numerical simulation (DNS) is applied to a particle-laden turbulent mixing layer with a chemical reaction, and the effects of particles on turbulence and chemical species' diffusion and reaction in both zero and finite gravity cases are investigated. Unreactive particles, whose response time, τ_P, is smaller than the Kolmogorov time scale, τ_K [$\tau_P/\tau_K = O(10^{-1})$], are uniformly injected into the high-speed side of the mixing layer. Two reactive chemical species are separately introduced through different sides. The results show that although laden particles generally depress turbulent intensities, they begin to enhance turbulent intensities downstream as the particle size decreases provided that the inlet particle volume fraction is fixed. This is because that the small particles with small particle response time easily accumulate at the circumference of coherent vortices and act to suppress the growth of primitive small-scale coherent vortices upstream but enhance that of relatively developing large-scale ones downstream. Also, since the small-scale turbulence, which promotes the chemical reaction, is suppressed by the laden particles in the entire region, chemical product decreases overall. Furthermore, the presence of finite gravity on the particles acts to depress the turbulent intensities, but its effects on chemical species' diffusion and reaction are quite small.

* Corresponding author. Tel.: +81 4 7182 1181; fax: +81 4 7183 2966.
E-mail address: michioka@crieipi.denken.or.jp (T. Michioka).
[1] Present address: Center for Turbulence Research, Stanford University, Stanford, CA 94305-3035, USA.

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1. Introduction

Particle-laden turbulent flows with chemical reactions are encountered in atmospheric environment and in a number of engineering applications such as energy conversion and propulsive devices using solid or liquid fuels. It is therefore of great importance to understand the effects of the laden particles on turbulence and chemical species' diffusion and reaction in turbulent reacting flows.

With the advantage of powerful supercomputers, numerical simulations such as direct numerical simulation (DNS) and large-eddy simulation (LES), have become a viable tool for investigating particle-laden turbulent flows with chemical reactions (Mashayek, 2000; Glaze and Frankel, 2000; Kurose and Makino, 2003). For simulating the particle-laden turbulent flows with these methods, the particle–particle interactions and turbulent modulation by particles are significant. However, in most practical particle-laden turbulent flows, the volume fraction of the dispersed particle is small, so that particle–particle interactions are often negligible. On the other hand, the particle mass volume fraction often becomes large owing to a large density ratio of solid particle to air, so that the modulation of turbulence by particles cannot be neglected and two-way coupled simulation including momentum exchange between them must be implemented (Elghobashi, 1991, 1994).

Squires and Eaton (1990), Elghobashi and Truesdell (1993), Boivin et al. (1998) and Sundaram and Collins (1999) performed the two-way coupled DNS of isotropic turbulence with solid particles, whose response time, τ_P, is larger than the Kolmogorov time scale, τ_K, and found that the particles with $\tau_P \geqslant \tau_K$ reduce the turbulent kinetic energy (turbulent intensities). Yamamoto et al. (2001) performed two-way coupled LES of the turbulent gas–particle flow in a vertical channel, and showed that the particles with $\tau_P \geqslant \tau_K$ decrease the turbulent intensities. On the other hand, Druzhinin (2001) performed the two-way coupled DNS of isotropic turbulence under the condition of $\tau_P < \tau_K$, and showed that the particles enhance the kinetic energy (turbulent intensities), which is in contrast to the reduction of turbulent intensities by particles with $\tau_P \geqslant \tau_K$. A similar result was also obtained by Ahmed and Elghobashi (2000) for two-way coupled DNS of turbulent homogeneous shear flows with dispersed particles. Thus, it is known that in the homogeneous flows, the laden particles with $\tau_P \geqslant \tau_K$ and $\tau_P < \tau_K$ tend to depress and enhance the turbulent intensities, respectively.

However, the above previous studies were performed only for fully developed homogeneous turbulent flows, and the number of studies for inhomogeneous turbulent flows such as a spatially developed mixing layer and a jet, in which the physical mechanisms of turbulent modulation may change with the streamwise distance, is small. Yuu et al. (1996) performed two-way coupled DNS of a turbulent jet, and showed that the particles with $\tau_P \geqslant \tau_K$ decrease the turbulent intensities. Yang et al. (1990) and Dimas and Kiger (1998) investigated the stability of two-way coupled mixing layers with uniformly distributed particles by linear stability analysis under the condition of $\tau_P \geqslant \tau_K$, and showed that the presence of the particles enhances the stability of the flows and decreases the amplification rate of perturbations in the flow. However, the influence of particles with