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Inert-droplet and combustion effects on turbulence in a diluted diffusion flame

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ABSTRACT

The inert-droplet and combustion effects on turbulence in a diluted diffusion flame are investigated using direct numerical simulation (DNS) through parametric study. The computational configuration is a temporally-developing reacting mixing layer laden with close to 17×10^6 inert evaporating droplets. The gas phase is described in the Eulerian frame while the discrete droplet phase is traced in the Lagrangian frame, with strong two-way coupling between the two phases through mass, momentum, and energy exchange. In the two-way coupling, distributing droplet source terms onto the Eulerian grids is a key procedure. Different distribution methods are compared to examine its impact on the statistics, including correlations between droplet source term and gas phase flow variables. The physical parameter considered is the characteristic droplet evaporation time, which is varied with the latent heat of vapourisation and plays a crucial role in both dynamic and evaporation effects of droplets on the turbulent reacting flow. To detail the analysis, the transport equation for the turbulence kinetic energy (TKE) is employed, in which the droplet contributions are categorised into three terms. The direct droplet and combustion effects on the TKE and their effects on the turbulence production and dissipation rate, pressure-dilatation are then scrutinised and compared to analyse the interactions among turbulence, combustion, and inert droplets in the multi-phase reacting flow.

1. Introduction

Turbulent multi-phase combustion remains an important and unresolved subject in combustion science as one of the most challenging fundamental and practical problems. First, energy conversion is usually related to the transfer of chemical energy to sensible energy via combustion in a turbulent flow, which is often further complicated by a dispersed phase such as solid fuel particles or liquid fuel spray droplets. For instance, liquid fuel injection is one of the most common procedures in non-premixed combustion systems such as internal combustion engines and aircraft gas turbine combustors for road and air transportation. Another important practical application is pulverised-coal combustion in coal-fired power stations.

Another type of turbulent multi-phase reacting flow is non-premixed gas combustion diluted with or suppressed by inert evaporating droplets. It appears in a multiplicity of industrial and residential applications such as the water-misting, dilution or injection technique [1–3] and combustion suppression using water sprays/mists [4–6], and is thus practically important and scientifically interesting. Compared to the concentrated interest in solid- and liquid-fuel-based combustion, publications on turbulent multi-phase combustion of this kind are relatively few, despite its crucial role in the water-injection technique and fire safety engineering. Due to the distinct role played by the inert droplets, the combustion physics is completely different from that in spray combustion with entirely new classes of phenomena. Therefore, to properly model the multi-phase reacting flow, we must improve the scientific understanding on the complex multilateral unsteady, nonlinear interactions among turbulence, combustion, and droplets.

Over the past several decades, study using high-fidelity numerical techniques on the interaction between combustion and turbulence [7] has been active for both premixed [8–10] and non-premixed [11–13] flames. The turbulent burning velocity [14] is a typical and important research topic in studying the complex interactions of turbulence and premixed combustion. The relationship between turbulent scalar flux and local dilatation in premixed flames were investigated in [15] using two-dimensional DNS databases involving a multi-step chemical mechanism. In [16], zone conditional averaging [17] was applied to the DNS database of a turbulent premixed flame to understand the mechanism of flame-generated turbulence. The effects of Lewis

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number, i.e., differential diffusion rates of heat and mass, on turbulence kinetic energy transport in premixed flames were investigated using DNS database in [18]. For non-premixed combustion, the effect of combustion-released heat on turbulence has been scrutinised based on budget analysis of the transport equation of turbulence kinetic energy using DNS in temporally-developing mixing layer [19,20], spatially-developing mixing layer [21], and homogeneous shear turbulence [22].

In parallel to the research on interaction between combustion and turbulence, interaction between solid particles, liquid droplets and turbulent flow has also received considerable research interest due to the ubiquitous phenomenon of gas-solid and gas-liquid two-phase turbulent flow in engineering combustion devices and applications. The current state of the research on turbulent dispersed multi-phase flow was recently reviewed in [23], with mechanisms of turbulence modulation due to particles as one of the main themes.

The preferential concentration [24–26] of particles is a key feature of particle distribution in turbulent flow and determined by the ratio of the inertia between the two phases, which is quantified by the Stokes number *St*. For the $St \sim 1$ particles, the preferential concentration is most manifest, i.e., particles accumulating in high-strain-rate regions and avoiding high-vorticity regions. In liquid-droplet-laden turbulent flows, the preferential concentration has important implication on droplet evaporation and turbulent scalar mixing. As shown in [27], the preferential segregation of droplets in homogeneous isotropic turbulence is important for the evolution of global variables such as the mean mixture fraction $\overline{Z}$ and mixture fraction fluctuations Z', which are the key parameters of non-premixed combustion models. In a DNS study of reacting droplets interacting homogeneous shear turbulence [28], the reaction rate is found higher in high-strain-rate regions due to the preferential concentration of fuel droplets in those regions.

Due to its capability of resolving the large-scale motion of the turbulence, the LES methodology for engineering multi-phase flows has been under active development with the rapid advance of computational techniques. LES of swirling particle-laden flows in a coaxial-jet combustor was performed in [29], where the filtered incompressible Navier–Stokes equations were solved and efficient particle-tracking scheme was developed on unstructured grids for the complex engineering configuration. In [30], the probabilistic approach [31] was developed for the dispersed phase. It is based on the transport equation for the spatially filtered joint probability density function of a set of macroscopic particle variables. The approach was extended in [32] to incorporate a stochastic subgrid model of particle breakup to simulate spray atomisation using LES.

Compared to the research on the bilateral turbulence–combustion and turbulence–particles/droplets interactions, publications on the multilateral turbulence–combustion–particles/droplets interactions are relatively few. In [28], evaporation and combustion of fuel droplets dispersed in a compressible oxidiser gas were investigated using DNS in homogeneous shear turbulence. The particle effects on turbulence and diffusion of reactive species were studied using DNS in a spatially-developing particle-laden turbulent mixing layer with an isothermal chemical reaction in [33]. DNS was used for fundamental studies of the ignition of two-dimensional temporally-developing fuel spray jets with detailed chemical mechanism incorporated in [34]. LES of spray–turbulence–flame interactions in a lean direct-injection combustor was performed in [35]. A spray breakup model was employed to eliminate the need to specify the inflow conditions of the liquid phase, i.e., droplet sizes and velocities. In [36], ignition and the subsequent turbulent edge spray flame propagation in fuel-droplet-laden turbulent mixing layers were studied using DNS.

As can be seen, the complex interactions among the hydrodynamic turbulence, combustion and a dispersed phase are further compounded by new physical phenomena if a liquid phase is engaged. Among others, evaporation is another key phenomenon which must be prudently considered to fully account for the interactions between the two phases. In addition to all the physical effects (preferential concentration and turbulence modulation) of solid particles due to the interphase aerodynamic drag, which leads to momentum exchange between the phases and governs particle effects on the turbulent flow, evaporation also causes both mass and thermal energy exchange between the gas and liquid phases. For a non-premixed gaseous flame diluted with inert droplets, mass addition by the third scalar-inert evaporated vapour, which is neither the fuel gas nor the oxidiser gas, leads to the breakdown of mass conservation in the control system of the gas phase. Therefore the conventional mixture fraction cannot be directly applied and a new mixture fraction has been proposed for the system of non-premixed gas combustion diluted with inert droplets [37]. Compared to the heat transfer due to temperature difference between solid particles and the carrier phase, the heat exchange to provide the latent heat of vapourisation for droplet evaporation could be significant. Meanwhile evaporation causes the decrease of droplet size and droplets vanish when evaporation completes, which will alter droplet distribution in and thus droplet dynamic effects on the flow. Combustion-released heat has been known as an important mechanism of combustion effect on turbulence [20–22]. Dispersed in the reacting flow, droplets absorb combustion-released heat to drive evaporation. Therefore the combustion effects on turbulence will be affected by droplet evaporation.

Similar to the particle dynamic response time τ_{d} which is a characteristic time scale designating how rapidly particles respond to flow dynamics, droplet evaporation can be characterised by the droplet life time or characteristic evaporation time τ_{v}, which can significantly affect the droplet effects, due to both droplet dynamics and evaporation, on turbulence and consequently the turbulence–combustion–droplets interactions. The topic of the effects induced by droplet evaporation on the turbulence–combustion–droplets interactions has not been sufficiently investigated and will be the main objective of the present study.

Specifically, the objective of this paper is to investigate the inert-droplet effects, including droplet evaporation and momentum exchange with the carrier phase via the interphase drag, and combustion effects on flow turbulence. A temporal turbulent reacting mixing layer initially laden with close to 17×10^6 inert droplets is simulated, with the characteristic evaporation time scale τ_{v} as the key parameter in the parametric study. The transport equation of the turbulence kinetic energy is employed to detail the analysis, in which the droplet effects have been classified in three terms, i.e., the power due to the interphase drag, the power due to an "evaporating drag", and an additional production rate due to evaporation. By integrating the TKE transport equation across the mixing layer, the redistributive terms which transport, but do not produce or dissipate, TKE within the flow disappear, and the droplet and combustion effects on the TKE and their effects on the turbulence production and dissipation rate, pressure-dilatation are then scrutinised and compared to analyse the interactions among turbulence, combustion and inert evaporating droplets in the multi-phase reacting flow.

To achieve the objective, DNS has been used to numerically solve the turbulent flow field. Due to the manifest rapid advances of computational power and numerical algorithms over the past two decades, a wealth of information, for example high-order correlations between fluctuating quantities, can now be obtained via high-fidelity numerical simulations and is otherwise unavailable [38]. In particular, DNS has become a powerful tool to explore