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Heat transfer in droplet-laden turbulent channel flow with phase transition in the presence of a thin film of water

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ABSTRACT

We present results of a numerical study of turbulent droplet-laden channel flow with phase transition. Previous studies of the same system did not take into account the presence of gravity. Here, we do so introducing a thin film of water at the bottom wall and permitting droplets to fall into and merge with it. We treat the carrier phase with the Eulerian approach. Each droplet is considered separately in the Lagrangian formulation, adopting the point–particle approximation. We maintain the film thickness constant by draining water from the bottom wall to compensate for (a) the droplets that fall onto the film and (b) evaporation/condensation. We also maintain on average the total mass of water in the channel by inserting new droplets at the top wall to compensate for the water that has been drained from the bottom wall. We analyze the behavior of the statistically averaged gas and droplet quantities focusing on the heat exchange between the two phases. We increase (a) the initial droplet diameter keeping the same initial droplet volume fraction and (b) the initial number of droplets in the channel keeping their diameter the same. In both parameter studies we find that droplets grow less than in the reference case. In case (a) this is explained by the larger velocity with which they travel to the bottom wall and in case (b) by the lower rate of condensation of vapor due to the presence of neighboring droplets.

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1. Introduction

In the field of multiphase systems droplet-laden channel flow presents a challenging topic not only because of how turbulent flow influences the mass and heat transfer properties of droplets but also how, in turn, droplets modulate the flow. In particular, the two-way coupling influences the heat transfer which is relevant both in nature and in industrial applications. Important examples are cloud formation and particle dispersion in atmosphere and oceans along with combustion in engines and heat transfer in power stations (Barigou et al., 1998).

Several studies dedicated to multiphase flows with a large number of dispersed droplets have been conducted. The first investigation was done by Mashayek (1998). He applied an Euler–Lagrange approach to describe two phases which were coupled by transfer of momentum, mass and energy. Later, a study of the mixing layer with embedded evaporating droplets was conducted by Miller and Bellan (1998). The presence of evaporating droplets in a turbulent planar jet was investigated by Masi et al. (2010). We focus on a new setting of a wall-bounded turbulent flow in which droplets not only evaporate, like in the studies cited above, but also where condensational growth due to the interaction with the vapor phase is also important. We focus on the enhancement of the heat transfer between the channel walls. The motivation for this setting comes from the previous work of Kuerten et al. (2011), where it was shown that the presence of particles increases the Nusselt number by more than a factor of two. In this study we add several new features into the system among which phase transition is one.

In this contribution we generalize earlier work by Bukhvostova et al. (2014a), Russo et al. (2014a) and Bukhvostova et al. (2014b) and introduce gravity in the wall-normal direction which acts both on the flow and the droplets. Gravity leads to a mean motion of droplets towards the bottom wall where they accumulate and form a film of water. Initially we introduce a thin film of water at the bottom wall and account for droplets which fall into the film by adding new droplets at the top wall. In this paper we keep the film height constant by draining water from the film at the bottom wall and keep the surface of the film stationary.

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First, we investigate the reference case for the flow conditions considered in Bukhvostova et al. (2014a) using 1 million droplets initially distributed in the channel. We consider statistically averaged heat and mass transfer properties of the droplets and gas, obtained by averaging over all droplets present in the channel and over the periodic directions, respectively. To illustrate the included mechanisms better we also follow the trajectory of a single droplet, inserted at the top wall, and examine its motion and evolving properties. In real applications of systems with a large number of dispersed droplets, important parameters are the droplet size and the number of droplets. This motivates us to perform two additional sets of simulations. In the first we increase the initial droplet diameter keeping their initial volume fraction constant. In the second set of simulations, we increase the number of droplets up to 2 million keeping their initial diameter the same as in the reference case. We report and analyze differences in the results confronting them with the results of the reference case.

The computational setting is similar to a simple heat exchange widely used in industry (Abdul Karim et al., 2012). The better understanding of heat transfer enhancement for liquids and gases made it possible to incorporate different types of heat exchangers into gas turbines to improve their efficiency (Donald et al., 2010). In our situation the heat exchange between the channel walls at given temperature difference between the walls is an important property to study.

The structure of the paper is as follows. In Section 2 the mathematical model for the two phases and for the film is given along with the details on the numerical method. In Section 3 we describe the initial conditions of the simulations. In Section 4 the results of the reference case and of the two sets of simulations are presented. Finally, we collect concluding remarks in Section 5.

2. Models and methods

This section is divided into four sections. Section 2.1 is dedicated to the mathematical model for the droplets and gas which is identical to the model which was adopted in Bukhvostova et al. (2014a). In Section 2.2 we describe the model for the film of water. Section 2.3 is dedicated to the spatial discretization which is used in this study and finally, in Section 2.4 we give details on the time integration.

2.1. Mathematical model for the carrier and dispersed phases

We consider a water–air system in a channel, bounded by two parallel horizontal plates. In particular, a two-phase system, consisting of a carrier phase of dry air and water vapor and a dispersed phase of liquid water droplets next to a continuous water film will be investigated. The mixture of air and water vapor will be referred to as the carrier gas or gas and the liquid droplets as the dispersed phase. We use an Eulerian approach for the gas and track every droplet individually in a Lagrangian manner. In addition, we treat the carrier gas as compressible. In Fig. 1 a sketch of the flow domain is presented. The domain has a size of $x_l = 4\pi H$ in the streamwise direction, which is denoted by x, and $z_l = 2\pi H$ in the spanwise direction, z, where H is half the channel height. In addition, y is the coordinate in the wall-normal direction. The top wall of the channel is located at $y = H$ and the bottom wall at $y = -H$. We use periodic boundary conditions in the stream- and spanwise directions because there is no dependence of the results on these directions (Pope, 2000) and the same approach was used in the early work by Kim et al. (1987). A thin film of water of a fixed thickness h is maintained at the bottom wall, such that $h \ll H$. The temperatures at the top and bottom walls of the channel are denoted by T_t and T_b, respectively, and kept fixed such that $T_t < T_b$. In addition, no-slip conditions are applied to the carrier phase at the upper wall and at the film surface. In this study we consider a simplified problem where the film surface does not move and is kept perfectly flat.

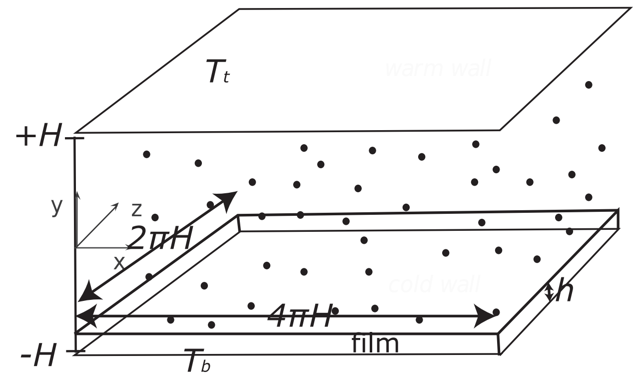

Fig. 1. Sketch of channel geometry, bounded by two horizontal planes, with water droplets and film of fixed height h. The size of the computational domain in the periodic stream- and spanwise directions is equal to $4\pi H$ and $2\pi H$, respectively, where H is half the channel height. The temperature at the bottom and top wall is kept constant, equal to T_b and T_t, respectively.

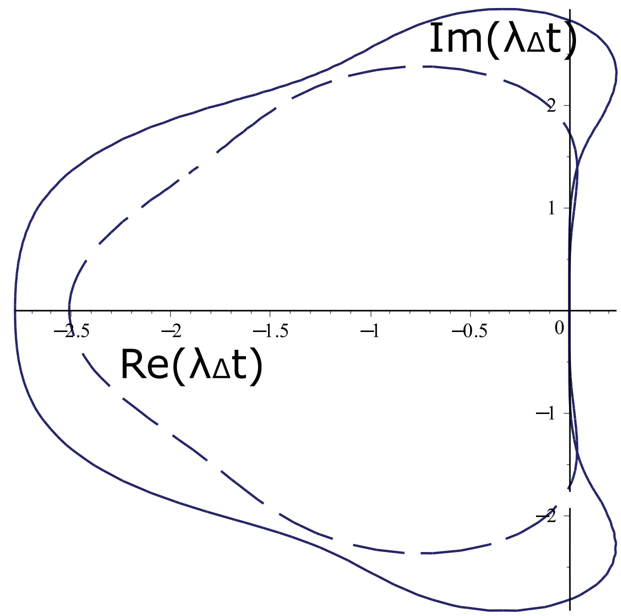

Fig. 2. The outer bound of the stability region for solid: RK4 dashed: RK3. The figure shows the region in which the amplification factor of the scheme is smaller than 1.

We first present the system of ordinary differential equations for the droplets which are described in a Lagrangian manner by the equations for the change of the position, mass, velocity and temperature of each droplet. The dispersed phase of the system consists of small water droplets, which, when sufficiently small, can be assumed to be spherical as surface tension will be dominant and drives droplets to this shape. Droplets are in addition assumed to be smaller than the local turbulence scales, which motivates the point–particle approach. In the current study the droplet volume fraction is chosen to fluctuate around 10^{-4} and therefore we consider two-way coupling according to the classification proposed by Elghobashi (1994).

In the Lagrangian method for the droplets adopted here a system of ordinary differential equations for each droplet is obtained following the model used in Miller and Bellan (1998) and Masi et al. (2010). The location of a droplet is governed by the kinematic

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