Heat Transfer in Droplet-Laden Turbulent Channel Flow with Phase Transition in the Presence of a Thin Film of Water

A. Bukhvostova, J.G.M. Kuerten and Bernard J. Geurts

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 droplets modulate the flow. In this contribution we focus on droplet-laden turbulent channel flow with phase transition generalizing earlier work by [1, 2] and introducing gravity in the wall-normal direction which acts both on the flow and on the droplets. Gravity leads to a mean motion of droplets towards the bottom wall where they accumulate and form a film of water.

We introduce a thin film of water at the bottom wall and account for droplets which fall into the film. 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. The total mass of water is kept constant by continuously adding droplets at the top wall.

We investigate the case for the flow conditions considered in [1] using 1 million droplets initially distributed randomly 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. The computational setting is similar to a simple heat exchanger widely used in industry. The better understanding of heat transfer enhancement for liquids and gases made it possible to incorporate different types of heat exchangers into gas

A. Bukhvostova (✉) · J.G.M. Kuerten (✉) · B. J. Geurts
Faculty EEMCS, University of Twente, Enschede, The Netherlands
e-mail: a.bukhvostova@utwente.nl

J.G.M. Kuerten
Department of Mechanical Engineering, Eindhoven University of Technology, Eindhoven, The Netherlands
e-mail: j.g.m.kuerten@tue.nl

B. J. Geurts
e-mail: b.j.geurts@utwente.nl

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turbines to improve their efficiency [3]. In our situation the heat exchange between the channel walls at a given temperature difference between the walls is an important property to study.

2 Mathematical Model

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. The computational 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 $y = -H$. 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 $T_t < T_b$.

We consider the carrier phase to be a Newtonian fluid, whose behavior is described by the continuity equation, Navier-Stokes equation, energy conservation equation and vapor mass conservation equation. Droplets are described in a Lagrangian manner by a set of ordinary differential equations for the position, mass, velocity and temperature of each droplet. All details of the model can be found in [1]. The presence of gravity leads to some small changes in the equations of motion for the two phases and to an additional contribution to the energy from the potential energy. Two-way coupling between the two phases is implemented via momentum, energy and mass source terms in the governing equations of the carrier phase by requiring conservation of mass, momentum, energy and water mass [1].

2.1 Simplified Model for the Film

Formally, the thin film at the bottom channel wall requires the solution of a partial differential equation for its temperature as a function of time and the spatial coordinates. Along with the film temperature T_f we also consider the film energy per unit area E_s since for the carrier gas we solve the system of equations for the conservative variables and for the film we also choose a conservative variable.

The film is assumed to be sufficiently thin so that derivatives of its temperature parallel to the film are small compared to derivatives in the wall-normal direction such that they can be neglected. At the same time when droplets merge with the film, they bring locally diffusive and convective fluxes in the periodic directions parallel to the walls, which can not be neglected. The film is assumed not to move, consequently, the convective flux is not taken into account. These assumptions and simplifications permit to write the change in the film energy per unit area as:

$$\frac{\partial E_s}{\partial t}(x, z) = q_2 - q_1 + s_2 - s_1 \tag{1}$$

where q_1 and q_2 represent the fluxes in the wall-normal direction at the bottom wall $y = -H$ and at the film interface $y = -H + h$, respectively. The terms q_1 and q_2 reflect the thermal conduction. The thickness of the film can change because of two reasons: (1) the film evaporates or water vapor condenses on the film and (2) droplets fall and merge with the film because of gravity. These two contributions compose the source term s_2 at the interface of the film with the carrier gas.

In order to maintain a constant film thickness we extract or add water at the bottom of the film. This defines the source term s_1 in (1).

In order to maintain on average a constant mass of water in the channel we distribute new droplets at the top wall according to the following procedure. The diameter of the inserted droplets is taken equal to the initial diameter d_0 and the corresponding mass of one droplet is denoted by m_0. Each stage of a time step we determine the mass of droplets that should be inserted to keep the total mass of water in the system constant. This mass will in general not correspond to an integer number of droplets of mass m_0. Therefore, we insert the nearest integer just below this value and keep the remainder for the next stage. In this way, on average the total mass of water is kept constant. The droplets are inserted at random locations at the top wall at the temperature of the top wall T_t. The stream- and spanwise velocity components of these droplets are equal to zero and the wall-normal component is equal to the terminal velocity of the droplet.

The film temperature T_f enters into the proposed model, for example, into the conductive fluxes q_1 and q_2. That is why we also need to determine the film temperature. Since the film height is very small compared to the height of the channel, instead of discretizing the film, we approximate the film temperature by a second-order polynomial in the wall-normal coordinate, closely following [4]. The coefficients in this polynomial are found from the boundary condition at the bottom channel wall, continuity of flux at the film interface and the relation between the film temperature and its known energy per unit area.

3 Numerical Details and Initial Condition

The spatial discretization of the equations in the gas is based on a finite volume method which follows the approach in [1]. The geometry is divided into rectangular cells. A uniform grid is used in the two periodic directions. In the wall-normal direction a non-uniform grid is applied which is finer near the walls in order to resolve the boundary layers. We apply the same non-uniform grid in the wall-normal direction as in [1] but the height of the first cell is smaller since it starts from the film interface $y = -H + h$. The film thickness is taken equal to 1/3 of the height of the first cell. The variables are stored in the centers of the cells. We use 128 cells in each direction.

We use the time integration procedure proposed by [5]. It is a hybrid implicit-explicit time iteration method. For the nonlinear terms each stage is analogous to forward Euler or second-order Adams-Bashforth but with different coefficients while for the linear part the method is similar to the Crank-Nicolson scheme but again with different coefficients. The coefficients are derived from the condition of highest possible order of the algorithm. In the present work we only use the explicit part of the algorithm and this guarantees the third-order accuracy of the scheme.

We start the simulations from turbulent velocity, density and temperature fields obtained from a simulation without droplets and with adiabatic boundary conditions at the walls [1]. This simulation was performed until a statistically steady state was reached. In the present study we keep the wall temperatures constant. We keep the temperature difference between the walls equal to 3K choosing $T_b = 293.15$K and $T_t = 290.15$K. This temperature difference is the same as in the steady state in the reference case in [1]. The reference scales of the system define the non-dimensional parameters, such as the Reynolds number based on the bulk velocity $\mathrm{Re_b}$, the Mach number Ma, the Prandtl number Pr and the Schmidt number Sc, along with the thermodynamic parameters of the simulations. We choose the same reference scales as in the reference case in [1]. Initially, we take the film temperature uniform and equal everywhere to T_b.

We randomly distribute droplets over the volume of the channel. We define a reference case in which the initial number of droplets is equal to 1,000,000 and the initial diameter d_0 is 3.09×10^{-3} in non-dimensional units.

4 Results

We focus on the heat and mass transfer results of the gas and droplets. We consider the evolution of mean quantities which are averaged over the periodic directions. The averaging is denoted by brackets, $\langle \cdot \rangle$. All quantities are presented in dimensional units. In all figures where results at different times are shown, the arrow denotes the direction of time.

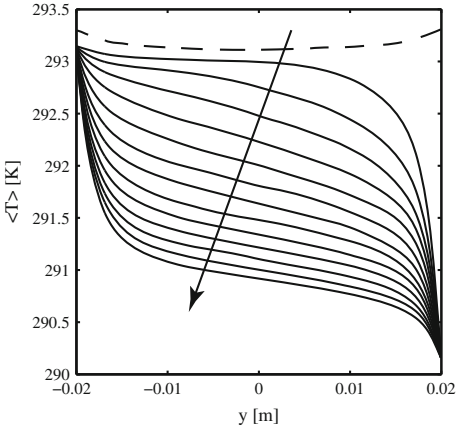

Fig. 1 Mean gas temperature as a function of the wall-normal coordinate plotted every 0.2 s in the interval [0 s, 3 s]. The dashed line corresponds to $t = 0$

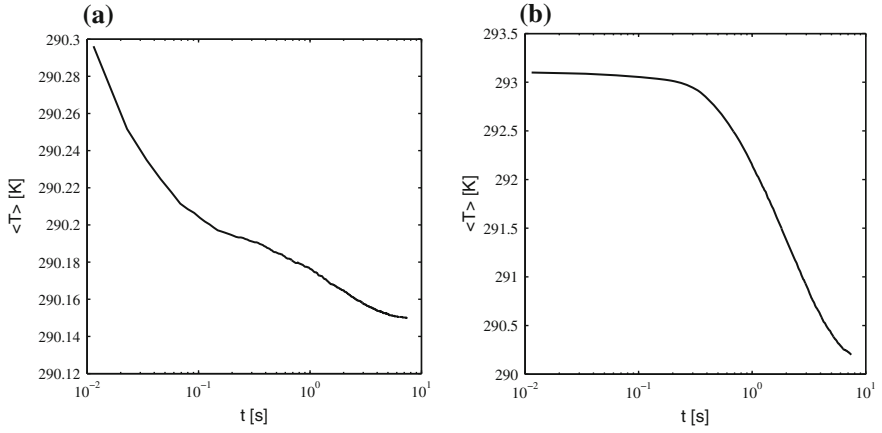

Fig. 2 History of mean gas temperature **a** near the *top* wall and **b** in the *center* of the channel

In Fig. 1 we show the development in time of the mean gas temperature as a function of the wall-normal coordinate. We start from a statistically steady turbulent solution with adiabatic boundary conditions and at $t = 0$ suddenly impose fixed temperatures at both walls, in which the temperature at the top wall is lower than at the bottom wall. This causes the development and propagation of a thermal front from the colder top wall of the channel to the warmer bottom wall. We consider separately the history of the mean gas temperature near the top wall and in the center of the channel, Fig. 2. This figure shows that indeed the temperature near the top wall starts decreasing almost immediately, while it takes some time before the temperature in the center of the channel decreases. The mean gas temperature near the top wall

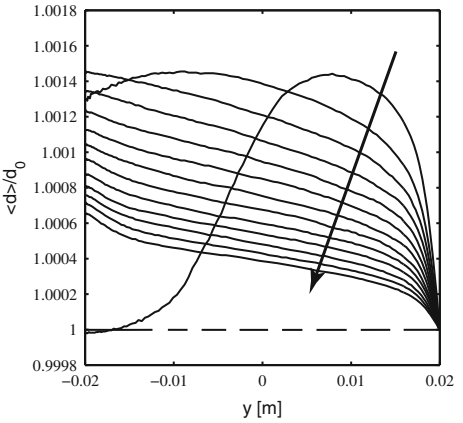

Fig. 3 Mean droplet diameter as a function of the wall-normal coordinate plotted every 0.2 s in the interval [0 s, 3 s]. The *dashed line* indicates the result at $t = 0$

initially decreases significantly because of the imposed lower temperature at the top wall, Fig. 2a, which leads to oversaturation of the gas.

As characteristic for the droplet behavior we consider the evolution of the mean droplet diameter normalized by the initial diameter as a function of the wall-normal coordinate in Fig. 3. A noticeable feature is the presence of a hump in this profile which moves and eventually disappears. It appears because of the intensive initial condensation of water vapor onto the droplet surface which is the result of two mechanisms: first, the positive difference between the gas temperature at the droplet location and the droplet temperature and second, the high relative humidity. Droplets fall towards the bottom wall under the action of gravity and the hump moves with them. The hump disappears in time since the mean droplet growth rate decreases later in time because of the decreasing over-saturation.

5 Conclusions

In this contribution we presented results on a study of turbulent droplet-laden channel flow with phase transition in the presence of gravity in the wall-normal direction and a thin film of water at the bottom wall. We maintain a constant film thickness by draining water from the bottom wall to compensate for (a) the droplets that fall onto the film and (b) evaporation/condensation at the film surface. 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 averaged gas and droplet quantities focusing on the heat and mass transfer properties of the system.

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