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Simulation of heat transfer enhancement by longitudinal vortex generators in dimple heat exchangers

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ABSTRACT

A three-dimensional DDF-MRT-LBE (double distribution function multi-relaxation-time lattice Boltzmann equation) is presented to study the flow and heat transfer in dimple heat exchangers. Results are obtained for periodically fully-developed laminar flow in parallel-plate channels with spherical dimples symmetrically opposing onto both walls. Both the heat transfer and flow resistance are discussed. Furthermore, to enhance the heat transfer with low pressure penalty, a small crescent-shape protrusion was added as a LVG (longitudinal vortex generator). And a grooved LVG was developed to reduce the drop loss caused by the crescent-shape protrusion. The streamline contours, isotherms, Nusselt numbers and friction coefficients at various Reynolds numbers are presented. The results show that the thermal performance of the LVG cases is higher than that of the dimple cases with similar flow characteristics. Moreover, from the viewpoint of energy saving, LVG cases perform better than the dimple cases.

1. Introduction

The air-side heat transfer enhancement is essential to the performance improvement of compact heat exchangers. Typically, air-side part can share 80% of the total thermal resistance to heat transfer [1]. Accordingly, sophisticated techniques, such as fins [2–5] are commonly found to enhance air-side heat transfer either by extending the area in contact with fluid or by increasing mixing. However, they also increase the pressure loss. Thus, optimizing the thermal performance of a heat exchanger involves a compromise between enhancing heat transfer rate and maintaining the concomitant rise of pressure drop [6–9]. Dimples, like the special cavities on a golf ball, have recently attracted much interest for the capacity of heat transfer enhancement with low pressure drop penalty [10,11]. Heat transfer in these heat exchangers is enhanced as they behave as a vortex generator to reduce thermal resistance with interruption of the hydrodynamic and thermal boundary layers.

Many investigators have studied the flow and heat transfer characteristics in dimpled channels. Afanasyev et al. [12] studied the performance of aligned dimples and reported that the heat transfer could increase 30–40% with a negligible pressure drop. Moon et al. [13] observed that both the heat transfer enhancement and pressure drop loss have no detectable effect of channel height within the studied relative channel heights ($0.37 \leq H/d \leq 1.49$). Mahmood et al. [14] reported that the heat transfer enhancement achieved highest on the downstream surface of the dimple and lowest on the upstream surface. Burgress et al. [15] found that the heat transfer enhancement increases with the dimple depth. And when the dimple depth (δ/D) is smaller than 0.2, the pressure drop loss is negligible but the pressure drop loss increases as the depth is larger than 0.2. Bi et al. [16] presented a detailed analysis of the local heat transfer characteristics in mini-channels. They concluded that the dimple surface shows higher performance compared with cylindrical groove surface and low fins. Although abundant studies have been carried out in this field of research, the information on laminar flow and heat transfer is relatively limited.

Attempts to design a compact heat exchanger, especially a very small but efficient heat exchanger, have to be limited by the fact that the flow is mostly in laminar regime, in which the flow is quite different from that in turbulent regime. Elyyan et al. [17] studied the effect of shallow dimples and suggested that the heat transfer enhancement is not observed in laminar flow while the heat transfer is enhanced in turbulent flow. Lan et al. [18] studied the water flow and heat transfer in micro-channels with dimples and protrusions with the Reynolds number ranging from 100 to 900. The results show that dimples with protrusions on the opposite wall perform better than the conventional dimple channel. According to their research, dimples generally cause smaller pressure drop penalty than other devices, such as protrusions and pin-fins, but also result in smaller heat transfer enhancement especially in laminar flow regime.

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The LB (lattice Boltzmann) method is a promising alternative numerical technique for its inherent advantages over other conventional CFD (computational fluid dynamics) methods [19,20], especially in incorporating of microscopic interactions, treatment of complex boundaries [21], computer programming and parallelism of algorithm. Tang et al. [22] used a thermal LB method with a separate internal energy distribution function to predict the forced convection heat transfer between two parallel plates. They [23] thereafter proposed a scheme to treat the heat flux boundary condition to improve the consistency with the finite volume method and analytical solution. Moussaoui et al. [24] studied the forced convection in a plane channel with an inclined square cylinder based on the combination of the MRT (multiple-relaxation-time) equation for hydrodynamics and the finite difference method for temperature. Benim et al. [25] investigated the incompressible laminar flow and heat transfer in channel with a built-in triangular prism. They showed that the LBE (lattice Boltzmann equation) is of similar accuracy to the CFD method and has a distinct advantage in computing time in such a way that the cell Courant number is 0.2.

The purpose of this paper is to use the MRT-LB method to simulate incompressible forced convection in parallel-plate dimpled channels. The combination of the DDF-LBE (double distribution function lattice Boltzmann equation) with an improved boundary treatment to curved boundaries is applied for both three-dimensional flow and temperature fields. Implementations of the boundary conditions with the DDF-MRT-LBE (double distribution function multi-relaxation-time lattice Boltzmann equation) method will also be validated by test. Besides, for further application, small crescent-shape protrusions are arranged on the rim of the dimple as a LVG (longitudinal vortex generator) to enhance thermal performance with small pressure drop loss. The computation is based on GPU (graphics processing unit) computing with CUDA (compute unified device architecture), which can reach a large scale parallel computing economically and efficiently.

2. Physical model and numerical methodology

2.1. Problem statement

In various pressure-driven flow systems, identical unit cells are generally arranged in an aligned or staggered array that is periodic in one or two directions. A fluid reaches a fully developed flow state after passing through specific rows of unit cells. Hence, it is desirable to take one unit cell into consideration to minimize the computational cost. And for the same purpose, the symmetric boundary is applied on the upper computational domain in this paper. The configurations of a dimple surface and a crescent-shape protrusion on the downstream rim of the dimple are shown in Fig. 1 (a) and (b), respectively. As shown in Fig. 1, the computational domain consists of a channel of longitudinal length L (AB), transversal width W (AD) and vertical height H (AE), with a dimple of δ in depth imprinted on the center of the plate. In the present study, L and W are actually the longitudinal and transversal dimple pitch, respectively. All the dimensions are normalized with the diameter of the dimple, D, as the reference length. Details of the parameters are shown in Table 1.

To enhance the heat transfer with low pressure penalty, two types of crescent-shape LVGs (see Fig. 1 (b)) were added in the flow system with one grooved and the other not. The height of the protrusion h is 0.175, and the groove width is 0.15. The fluid was driven into the computational region by pressure, with the inlet and outlet periodic velocity and temperature. No-slip boundary condition and uniform wall temperature are applied on the lower wall surface.

2.2. Numerical method

2.2.1. MRT-LBE (Multiple-relaxation-time lattice Boltzmann equation) for flow fluid

The flow is assumed to be incompressible and without viscous heat dissipation. Instead of solving the Navier–Stokes equations

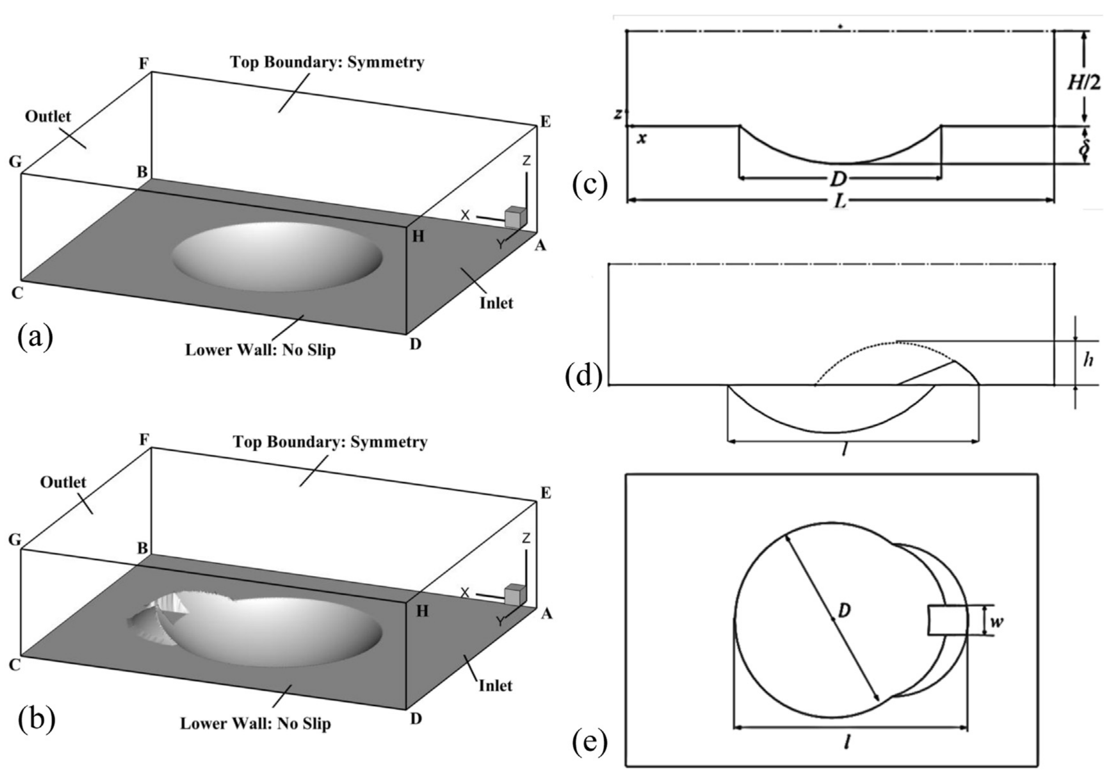

Fig. 1. Computational domains and dimensions. (a) and (c) a conventional dimple surface; (b), (d) and (e) a grooved crescent-shape protrusion added surface.