

## Lattice Boltzmann Study of Flow and Temperature Structures of Non-Isothermal Laminar Impinging Streams

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**Abstract.** Previous works on impinging streams mainly focused on the structures of flow field, but paid less attention to the structures of temperature field, which are very important in practical applications. In this paper, the influences of the Reynolds number ( $Re$ ) and Prandtl number ( $Pr$ ) on the structures of flow and temperature fields of non-isothermal laminar impinging streams are both studied numerically with the lattice Boltzmann method, and two cases with and without buoyancy effect are considered. Numerical results show that the structures are quite different in these cases. Moreover, in the case with buoyancy effect, some new deflection and periodic structures are found, and their independence on the outlet boundary condition is also verified. These findings may help to understand the flow and temperature structures of non-isothermal impinging streams further.

**AMS subject classifications:** 76E99

**Key words:** Impinging streams, lattice Boltzmann method, flow structure, temperature structure.

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## 1 Introduction

Impinging streams (IS) have been used in many industrial applications such as mixing [1,2], absorption [3], liquid-liquid extraction [4] and drying [5], etc. A detailed discussion of IS reactors can be found in [6,7]. Therefore, understanding the flow and temperature structures of such streams is very important for choosing the appropriate operation conditions of processing equipment.

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Related studies in the past have shown that the impinging streams are susceptible to instabilities which will lead to asymmetric and deflecting flows. Rolon et al. [10] investigated isothermal impinging streams of air experimentally and observed two different asymmetric stable flows even under the same momentum condition. Denshchikov et al. [8, 9] studied isothermal planar impinging streams of water with experiments and found that each stream was deflected in the opposite direction from the other, and they periodically switched directions.

Motivated by the above findings that show a rich dynamic behavior in impinging streams system, Pawlowski et al. [11] carried out a numerical study of the structure and stability of isothermal laminar impinging streams in planar and cylindrical geometries. For the planar configuration, four flow regimes were found, which are single steady state (symmetric) regime, multiple steady states (asymmetric) regime, deflecting jet regime and vortex shedding regime, respectively. By employing a bifurcation and linearized stability analysis based on the continuity and Navier-Stokes equations, two kinds of bifurcations, i.e., pitchfork bifurcation and Hopf bifurcation, were found. When pitchfork bifurcation and Hopf bifurcation occur, the flow field changes from symmetric regime to asymmetric regime and from asymmetric regime to deflecting jet or vortex shedding regime. Additionally, they also investigated the critical Reynolds number, beyond which the pitchfork or Hopf bifurcation occurs, for different geometry configuration parameters.

In addition to the study of isothermal laminar impinging streams, Hasan et al. [12] performed a numerical investigation of two-dimensional interaction of non-isothermal laminar impinging streams with different fluids (same phase, miscible) in the mixed convection regime. Two kinds of buoyancy, the thermal and the intrinsic buoyancy (owing to the inherently different densities of the two fluids), were considered through the Boussinesq approximation, and two configurations, aiding buoyancy forces and opposing buoyancy forces, were used. For both configurations, some numerical simulations have been conducted under different combinations of  $Ri_T$  and  $Ri_C$ , which are two important dimensionless numbers in reflecting significance of thermal and intrinsic buoyancy force. The numerical results show that three flow modes, which are symmetric steady flow, asymmetric steady flow and the periodic unsteady flow, may appear depending upon the flow configuration and the effects of the buoyancy forces.

From the survey of available literature, it can be found that above studies were mainly focused on the structures of flow field, but less attention was paid to the structures of temperature field, which are very important in practical applications. To fill this gap, the structures of temperature field with and without buoyancy effect are studied under different  $Re$  and  $Pr$ , and the relationships between the structures of flow field and the structures of temperature field are also discussed.

In this work, we will study the non-isothermal laminar impinging streams numerically. Among various numerical methods, lattice Boltzmann method (LBM) is a relatively new one and has attracted interest of researchers in a variety of fields [13–15]. Compared to traditional computational fluid dynamics methods, LBM has many advantages, espe-