Numerical Simulation of Unsteady Convective Flow and Heat Transfer under Transient Boundary Condition using Lattice Boltzmann Method: Application to Geothermal System

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論 文 名　：　Numerical Simulation of Unsteady Convective Flow and Heat Transfer under Transient Boundary Condition using Lattice Boltzmann Method: Application to Geothermal System（格子ボルツマン法を用いた非定常境界条件における非定常対流熱伝達現象の数値シミュレーション研究：地熱システムへの応用）

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論　文　内　容　の　要　旨

Development of environmental-friendly natural energies has raised interest within the international research community due to their potential to prevent global warming by reduction of carbon dioxide (CO_2) emissions. Geothermal energy, amongst them, is acknowledged as the most promising underground natural resource. However, porous and fracture water flows in underground reserves include unclear factors. To increase efficiency in acquisition of geothermal heat, a better understanding of heat transfer processes occurring within geothermal reservoirs is necessary. This could be achieved by the development of a suitable numerical simulation methodology representative of the geothermal phenomena.

The direction of simulation studies on underground natural water flows related to the geothermal system has shifted to account for the importance of disclosing the fundamental physics behind the phenomena. Accordingly, the corresponding heat and mass transfer pertinent to the geothermal system may be regarded as a special mode of Rayleigh-Bènard convection flow with time-varying heat flux contribution from the hot underground rock formation. Such conditions trigger the emergence of unsteady convective fluid and thermal motions within the porous formation of the geothermal system. Undoubtedly, understanding such complex thermo-hydrodynamics system possesses considerable challenges.

The Lattice Boltzmann Method (LBM) has emerged as a powerful computational fluid dynamics (CFD) technique not only for handling typical industrial fluid-thermal problems, but also in uncovering the foundational aspects pertinent to the thermo-hydrodynamics of the geothermal system. As such, LBM can be a promising tool to assess the heat and mass transport problems at hand, due to its uniqueness compared to the traditional CFD methods in sense that LBM solves the representative Boltzmann expression of the flowing substances rather than directly handling the constitutive hydrodynamics equations in their operations. Modeling a flow problem using LBM has several advantages including a clear algorithm, straightforward treatment of boundary conditions, and innate feasibility for parallel computing architecture.

This study therefore aims to simulate the unsteady Rayleigh-Bénard convective fluid flow and heat transfer in a cavity domain with a time-varying temperature condition using the discrete numerical scheme (modified LBM scheme) that has been presented by considering second-order accurate in space and time coordinates to follow complex and fast heat and mass transfer phenomena.

The thesis consists of six chapters laid out as follows:

Chapter 1 presents the background and primary objectives of the present study followed by a comprehensive literature. The chapter finalizes by posing the structure of the current treatise.

Chapter 2 explains the formulation of fundamental theory of the lattice Boltzmann method (LBM) with emphasis on the establishment of the modified LBM scheme that is second-order accurate in spatial and temporal coordinates. The discussion was commenced by delivering the core concept of LBM, which is based on statistical mechanics. Thereupon, the perspective of LBM in respect of the flowing materials was elucidated. The stress was given to the uniqueness of LBM amongst other CFD methods. Subsequently, the Chapman-Enskog analysis was introduced as the vital element in LBM framework. The concept of discrete lattice velocity arrangement was presented, alongside associated procedures for assigning initial and boundary conditions in LBM. The prescribed LBM scheme was preliminarily applied for conducting natural convection simulation in a differentially-heated cavity with opposing hot and cold vertical walls to confirm the capacity and validity of the present LBM scheme.

Chapter 3 demonstrates the applicability of present LBM scheme in simulating natural convection and heat transfer phenomena during the unsteady period of the flow. As far as modeling the flow problem using LBM is concerned, two analytical schemes, that are (a) discrete lattice Boltzmann scheme and (b) the discrete forcing scheme, are routinely applied to the numerical simulation model. Based on the availability of diverse expressions relates to the aforementioned two schemes, the contemporary issue regarding proper selection of LBM scheme was examined in detail. Later on, the computational performance of disparate LBM scheme was tested upon two distinct physical configurations, namely the natural convection in a cavity with temperature difference on internal boundary surfaces and the Rayleigh-Bènard convection with aspect ratio equal to unity. The superior capacity of the modified LBM scheme considering to the standard first-order counterpart was discernible from the numerical results of both physical model.

Chapter 4 investigates the unsteady Rayleigh-Bènard convection with transient boundary conditions in a rectangular cavity of aspect ratio two. Herein, the transient boundary was invoked by assigning a time-periodic condition for the hot wall at the bottom side of the cavity. Meanwhile, the opposing horizontal wall at the top was kept at constant cold temperature. By appointing the vertical boundaries to be perfectly insulated, the flow domain was a simplification of a closed-thermodynamic system with unsteady heat flux from the bottom ambient. Using the modified LBM scheme by considering second-order accurate, principal focus was bestowed upon disclosing the impact of amplitude and frequency of the hot oscillating wall upon the convective fluid flow and heat transfer characteristics for different Rayleigh number conditions.

Chapter 5 extends the analysis to the effect of distinct aspect ratios upon the convective flow and heat transfer characteristics of the system under investigation. Finally, the currently unresolved problem regarding heat and mass transfer behavior of Rayleigh-Bènard system under the influence of high-oscillation frequency of the hot wall was investigated in detail. It was therefore concluded that the modified LBM simulation methodology is capable in simulating diverse conditions of the unsteady Rayleigh-Bénard convection system, including the extreme cases of high-frequency oscillation of the hot wall.

Chapter 6 poses some concluding remarks of the present study. As final annotation, a few plausible directions for future works were provided therein, as well.