Unveiling Rayleigh–Bénard Convection: Exploring Surface Modifications

Direct numerical simulations of Rayleigh–Bénard convection with surface modifications

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In Short

- Investigates the RB convection for different surface conditions such as phobic, philic and compared with neutral surface.
- Direct numerical simulations will be performed with a characteristic based Off-Lattice Boltzmann method solver.
- Investigate the scaling laws and effect of aspect ratio in Rayleigh-Bénard convection for different surface conditions.

Motivation: Studying and understanding Rayleigh-Bénard convection can contribute to optimizing the efficiency and design of various energy systems, including geothermal energy extraction and solar thermal systems, resulting in energy savings and improved performance [1]. Energy-related applications can be significantly influenced by surface coatings. For instance, in solar panels, coatings can enhance light absorption and reduce reflection, thereby increasing the efficiency of solar energy conversion. Similarly, coatings can be applied in heat exchangers or boilers to reduce fouling or corrosion, improving overall performance and equipment longevity. These techniques change the surface energy properties by changing the contact angle through various surface coatings and patterns. The influence of surfaces on a dispersed phase, a multiphase, and pool boiling has been extensively studied through experiments and simulations in the literature. However, the effect of surfaces on single-phase natural convection has not been explored much. It is limited to two-dimensional flow at lower Rayleigh numbers [2] and experimental studies [3] only. Three-dimensional simulations needed to be performed for quantitative and qualitative analysis of the flow and thermal behavior for the different surfaces thoroughly.

This study combines Rayleigh-Bénard convection and surface coatings to explore heat transfer enhancement. Enhancing heat transfer is a desired objective in multiple applications such as heat exchangers, power generation systems, and thermal management of electronic devices. By improving heat transfer efficiency, it is possible to minimize energy losses and create more sustainable and efficient energy systems. Three-dimensional simulations are proposed in this work to investigate the flow and heat transfer behavior in turbulent single-phase Rayleigh-Bénard convection with surface modifications. Now the surface in the Rayleigh–Bénard convection can be studied for different surface conditions, such as phobic, philic surfaces, and compared with the neutral surface. This study aims to answer some important questions such as follows: i) In Rayleigh–Bénard convection flow, how do phobic and philic surfaces behave in comparison to neutral surfaces? ii) How do surface properties affect the boundary layer, rate of heat transfer, and turbulence phenomena? iii) Is it possible to increase heat transfer rates from surfaces? iv) How does the modification of the surface impact the scaling laws in Rayleigh-Bénard convection?

In the future, the research will be extended to encompass multiphase flows and complex geometries, with potential applications in energy storage systems, fuel cell cooling, carbon capture and storage, renewable energy applications, and power plants. Additionally, the development of the lattice Boltzmann method is also considered for these applications.

Numerical Methods: A characteristic-based Off-Lattice Boltzmann method (OLBM) in a finite-difference framework is used for the simulations. LBM is based on the discretization of the Boltzmann equation [4]. LBM is, hence, a kinetic-theory-based method that describes the evolution of particle distribution functions in phase space rather than transported Eulerian flow variables. The LBM approach is particularly suited to describe complex fluids or geometries and provides many advantages, including an easy implementation of boundary conditions and good efficiency on massively parallel machines. The current solver is second-order accurate, and detailed implementation can be found in articles [5].

Goals: The objective of this research study is to investigate the influence of surface modifications on flow and heat transfer characteristics in turbulent Rayleigh–Bénard convection. The study aims to conduct direct numerical simulations using the Off-Lattice Boltzmann method, focusing specifically on different surface phenomena. The objectives of the current proposal are listed as below:

- Investigate the impact of surface modifications on turbulence and heat transfer rates. The study aims to explore how different surface conditions and modifications affect the convection patterns and enhance heat transfer in various engineering applications.

- Focus on improving the heat transfer rate in Rayleigh–Bénard convection, considering its significance in enhancing performance and efficiency in diverse applications. The objective is to identify strategies and surface modifications that can lead to higher heat transfer rates.
- Address the influence of different surfaces on the flow and thermal characteristics in Rayleigh–Bénard convection. The study will investigate how the presence of various surfaces affects the turbulence and boundary layers in Rayleigh–Bénard convection.
- Investigate the scaling laws and effect of aspect ratio in Rayleigh-Bénard convection for different surface conditions.

Case Setup and Preliminary Results: Figure. 1 shows a schematic diagram of the Rayleigh–Bénard cell investigated. The top wall is cooled and maintained at the low temperature T_c, while the bottom wall is heated and kept at a higher temperature T_h. Distinct boundary conditions will be implemented on horizontal walls based on the surface type. Initially, simulations will focus on a cubic box cavity, with the subsequent examination of periodic boxes featuring larger aspect ratios.

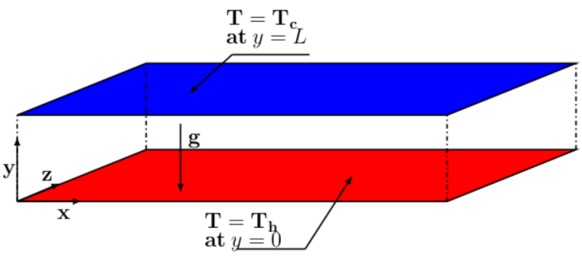

Figure 1: *Schematic diagram of the domain.*

Figures. 2 and 3 show contours of instantaneous isotherms and streamlines on the mid-spanwise plane at Rayleigh number of $Ra = 6.3 \times 10^5$ and Prandtl number of $Pr = 0.71$ for the neutral surface. The temperature contours exhibit elongated and irregularly shaped structures corresponding to rising and descending thermal plumes. The instantaneous isotherms appear complex without any discernible pattern. The instantaneous streamlines appear chaotic and are colored based on the non-dimensional velocity magnitude. The presence of large-scale circulation and vortices is visually confirmed by the eddying streamline contours.

Through this proposed study, a deeper understanding of the behavior and performance of

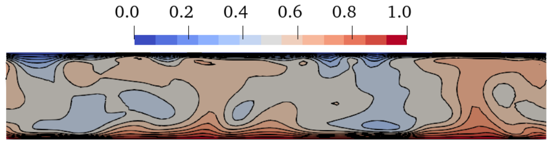

Figure 2: *Contours of the instantaneous temperature.*

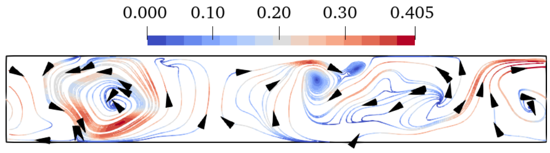

Figure 3: *streamlines of the instantaneous velocity field.*

Rayleigh–Bénard convection, particularly with respect to surface modifications, will be achieved. The simulations will be carried out at turbulent Rayleigh numbers of $Ra = 10^6, 10^7$, and 10^8, allowing for a comprehensive analysis of the effects of surface modifications. The research aims to bridge the existing gap in understanding by utilizing OLBM and three-dimensional simulations to provide insights into the relationship between surface characteristics and single-phase natural convection.

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https://www.b-tu.de/fg-stroemungsmodellierung/

More Information

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DFG Subject Area

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