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Scaling Analysis and Direct Simulation of Unsteady Natural Convection Boundary Layers on an Evenly Heated Plate with Time-Dependent Heating Flux

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It is of fundamental significance and application importance to fully understand the flow behavior of the unsteady natural convection boundary layers on a vertical plate heated by a time-dependent heat flux. Such an understanding is currently lacking. In this paper, a scaling analysis using a simple three-region structure was conducted for the unsteady natural convection boundary layer of a homogeneous Newtonian fluid with Pr>1 adjacent to a vertical plate evenly heated with a time-varying sinusoidal oscillating heat flux. A series of scalings were developed for the thermal boundary thickness, the plate temperature, the viscous boundary thicknesses, and the maximum vertical velocity within the boundary layer, which are the major parameters representing the flow behavior, in terms of the governing parameters of the flow, i.e., the Rayleigh number Ra, the Prandtl number Pr, and the dimensionless natural frequency fn of the time-varying sinusoidal oscillating heat flux, at both the start-up stage and the steady state. These scalings were validated by comparison to ten full direct numerical solutions of the governing equations with Ra, Pr, and fn in the ranges 106≤Ra≤109, 3≤Pr≤100, and 0.01≤fn≤0.1, and were shown to provide an accurate description of the flow at both the start-up stage and the steady state, except for high Pr runs in which a further, although weak, Pr dependence is present, which cannot be accurately predicted by the current scaling analysis using the simple three-region structure, attributed to the non-boundary-layer nature of the velocity field with high Pr fluids.

Keywords: Scaling, Natural convection boundary layer, Scaling analysis, Direct numerical simulation, Unsteady flow, Time-dependent heat flux