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Characteristics of complex interaction between two oppositely-moving laminar buoyant-plumes within slender vertical-channels

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ABSTRACT

The article presents laminar plumes, cellular structures and spatial-waviness in free convective flow within a vertical channel under anti-symmetric heating, and the subtle flow-features during the transition to anti-asymmetry. We perform numerical simulations for a wide range of cross-sectional Grashof numbers ($262.4 \leq Gr_b \leq 33025$), channel aspect ratio ($0.0375 \leq \psi \leq 0.1255$) and isothermal boundary conditions (anti-asymmetric heating to anti-symmetric heating). The chosen working fluid is air; hence the Prandtl number (Pr) is fixed at 0.715. Certain modified parameters are defined for the present study, such as the channel Grashof number (Gr) and symmetry ratio (ε_C), to govern the working condition of the channel. The physics of the interaction between oppositely moving wall plumes is studied thoroughly, and the highly sensitive, spatially-oscillatory nature of the flow near the plume interface is shown with the help of velocity and temperature contours. Analytical expressions for the primary velocity and temperature have been derived for the wall plumes for the developed region. Also, the crucial role of the secondary velocity field on the heat and mass transfer across the plume interface and convection cell formation is highlighted, which fails to find much attention in the available literature. Motivated by the flow-features, a novel vorticity-mapping is performed, and the entire flow domain is divided into two regimes, viz. a highly rotational core region and a unidirectional near-wall region, which are separated and illustrated using limiting streamlines. The rotational, stagnant core region seems to expand as Gr increases, resulting in a drop in pumping performance. The Gr is varied by changing both the ψ as well as the hot wall temperature Θ_H. The relative effects of these methods on the channel pumping, and thermal performance are studied and an optimum method of Gr variation is proposed for the channel. Finally, the effect of the degree of opposing buoyancy forces is studied by varying the cold wall temperature to attain thermal boundary conditions ranging from anti-asymmetry to anti-symmetry. As the opposing buoyancy increases, the heat transfer becomes more convection dominant near the colder wall and less convection dominant near the hotter wall. Also, the pumping performance seems to be affected adversely, as ε_C is increased. A peculiar change in the channel performance is also highlighted during the transition to anti-symmetric heating conditions near ε_C=0.9.

1. Introduction

Understanding the physics behind free convection in vertical channels has attracted quite significant interest in recent years. Improved computational and experimental capabilities, along with the influence of free convection in the development of alternate energy systems has resulted in a good deal of interest in understanding free convection, most notable areas of application-interests being photovoltaic systems and energy-efficient, passive cooling. When the fluid is heated up above the ambient, its density decreases, and it tends to rise due to upward buoyancy force. Taking a step further, if it is cooled below the ambient, an opposite buoyancy acts on it, and a downward flow is induced. Precisely, buoyancy is the motive force for free convective flows within enclosures and channels. Opposing buoyancy forces yield the possibilities of two separate and oppositely moving plumes inside a vertical-channel, with complex interacting regions between the two plumes. The flow characteristics within the channel are highly sensitive to the imposed thermal conditions on the channel-walls. Walls can be heated or cooled symmetrically, asymmetrically, anti-symmetrically or anti-asymmetrically, resulting in different pairs of buoyancy forces, the defining parameter being, R_T $\left(\equiv \frac{T_C - T_a}{T_H - T_a}\right)$, where T_H is the temperature of the heated wall, T_C is the tem-

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