Stability and transition in the near-field of pure planar plumes

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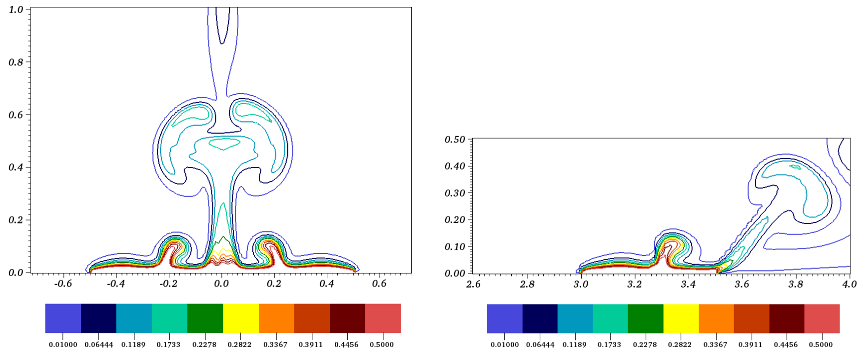
Abstract: The near-field of a buoyant plume exhibits puffing behaviour characterised by the periodic formation of vortical structures (puffs). In this study, a plume is generated from a finite-width fixed temperature planar source. The periodic formation of puffs is seen to be associated with an instability in the thermal boundary layer that forms on the heated source region away from the plume axis. The instability produces a bulge in the thermal boundary layer, that is further investigated by modelling the boundary layer flow in the vicinity of the plume source by use of a channel flow with a heated floor section.

Keywords: Natural Convection, Direct Numerical Simulation

1 Introduction

The near-field behaviour of a buoyant plume in the transitional regime is characterised by the periodic formation of vortical structures (puffing). Such behaviour has been observed for forced axisymmetric plumes [2, 3], for forced planar plumes [1, 5] and for a pure thermal axisymmetric plume [4]. In the pure plume case of Plourde et al. [4] the puffing appears to be associated with an instability of the lapping flow on the bottom boundary, forming a thermal plumelet (bulge) that eventually merges with and surrounds the central ascending column. Similar near-field plume behaviour has been observed for a pure planar plume in the present study.

We will focus on this near-field plume instability, namely the bulge forming in the thermal boundary layer away from the plume axis and the associated puffing behaviour. The formation of the bulge and its dependence on the lapping flow velocity along the bottom boundary is further investigated by modelling the boundary layer flow in the vicinity of the plume source by a channel flow with a heated floor section, providing an additional control parameter. Three dimensional direct numerical simulations are used to obtain the near-field planar plume flow and the channel flow with Prandtl number of 7.0 and Reynolds numbers in the range $200 \leq \mathrm{Re} \leq 1000$. The three-dimensional effect has been found to be small in this flow. Control parameters for the plume are the Reynolds and Prandtl numbers. The Reynolds number is defined as $\mathrm{Re} = U^* L^* / \nu^*$, where $U^* = \sqrt{g^* \beta^* (T_s^* - T_\infty^*) L^*}$, with L^* the source width, ν^* the kinematic viscosity, g^* the gravitational acceleration, β^* the thermal expansion coefficient, T_s^* and T_∞^* are the source and ambient temperatures, respectively. In the case of the channel flow with a heated floor section, in addition to the above two parameters, the inlet velocity (u_{in}) is controlled to vary a Froude



(a) Plume

(b) Channel flow with $\mathrm{Fr} = 0.04$

Figure 1: Temperature contours for the plume and the channel flow with a heated floor section, both with $\mathrm{Re} = 1000$.

number, that is defined as $\mathrm{Fr} = U^*_{\delta^*_T}/U^*$, where $U^*_{\delta^*_T}$ is the average horizontal velocity in the thermal boundary layer, of thickness δ^*_T.

2 Results

Figure 1a shows the plume with $\mathrm{Re} = 1000$, showing the instability bulges in the lapping flow on either side of the plume axis, as well as the puffing in the plume flow. Figure 1b shows the channel flow with heated floor section, also at $\mathrm{Re} = 1000$ with $\mathrm{Fr} = 0.04$, with the instability bulge also apparent. The critical Re for the formation of bulges and puffing in the plume flow is in the range $300 < \mathrm{Re} < 400$, while for the channel flow the critical Re is in the range $400 < \mathrm{Re} < 500$ and the critical Fr in the range $0.045 < \mathrm{Fr} < 0.05$, with the bulge observed above the critical Re and below the critical Fr. The puffing frequency in the plume is found to correlate with the oscillation in the thermal boundary layer, which implies a convective-type instability. Further the oscillation frequency in the thermal boundary layer for the plume is found to scale with $\mathrm{Re}^{1/2}$, and for the channel flow with $\mathrm{Re}^{1/2}$ and Fr.

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