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Propagation of Perturbations in a Vertical Air Flow Channel with Uniformly and Symmetrically Heated Sidewalls

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1. INTRODUCTION

A fundamental flow structure in natural convection systems is the thermal boundary layer (TBL) that develops adjacent to heated surfaces. Investigating the instability and transition of the TBL is crucial for understanding the boundary-layer flow behaviour and associated thermal performance. Extensive studies have examined the stability properties of TBLs [1]. However, most investigations have focused on TBLs adjacent to isothermally heated surfaces [2], while little attention has been given to TBLs subjected to uniform heating, particularly under confined conditions. The present study addresses this gap by investigating the propagation of perturbations in TBLs adjacent to uniformly heated channel walls.

2. APPROACH

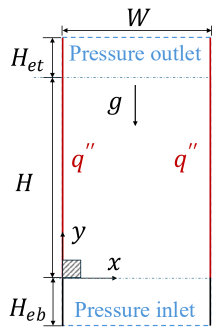


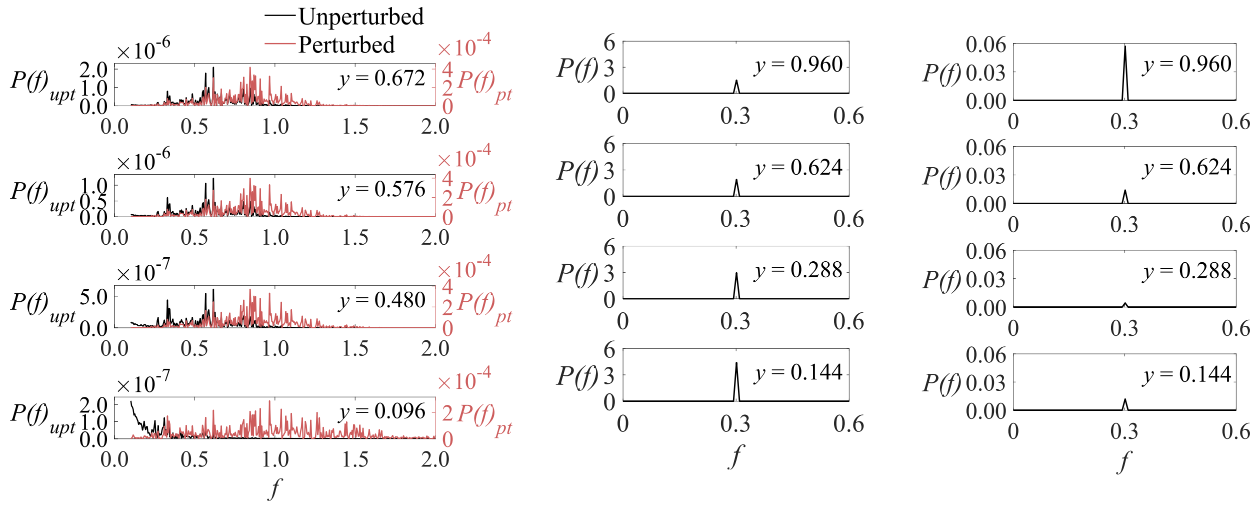
Figure 1. Model geometry

A two-dimensional (2-D) numerical model with Boussinesq approximation is adopted to investigate perturbation propagation in TBLs. The model geometry and boundary conditions are displayed in **Figure 1**. The channel walls are symmetrically heated by a constant heat flux q''. The computational domain is extended at both the top and bottom ends by $H_{et} = 0.2H$ (heated) and $H_{eb} = 0.24H$ (adiabatic), respectively. The convective flow in the channel is characterised by the Rayleigh number for isoflux heating [3]. In this study, $Ra = 4.8\times10^{10}$ and the Prandtl number $Pr = 0.74$. The confinement is characterised by a confinement ratio $\Lambda = \delta_T/W$, where δ_T is the calculated thickness of the TBL adjacent to a uniformly heated and unconfined vertical plate at the same Rayleigh number. A range of confinement ratios (Λ = 5%~50%) are considered, and a source term is added to the energy equation to introduce perturbations to one TBL near the leading edge (the shaded region in **Figure 1**). The spectral behaviour of temperature fluctuations at different locations in the TBL is examined.

3. RESULTS

First, random perturbations are introduced to the TBL. The present numerical results show that in the perturbed TBL, a narrow frequency band appears in the entire TBL (due to the so-called frequency filtering effect of the TBL [1]) except for the region near the leading edge. In contrast, no meaningful frequencies appear in the unperturbed TBL at low confinement ratios ($\Lambda \leq 10\%$). However, at higher confinement ratios ($\Lambda \geq 15\%$), distinct frequency bands can be observed in the downstream region of the unperturbed TBL (**Figure 2**a). In a very narrow channel (Λ = 50%), temperature fluctuations are detected throughout both the unperturbed and perturbed TBLs, with a distinct frequency band centred around $f = 0.3$ appears from approximately mid-channel height. For brevity, the results are not presented here. These observations suggest that perturbations may have been transmitted from the perturbed TBL to the unperturbed TBL through their interactions and subsequently propagate from downstream towards upstream in the unperturbed TBL.

To confirm the above observations, a single-mode perturbation experiment is conducted at Λ = 50%. In this experiment, the added source term is given as $S = A_s \sin(2\pi f_{pt} t)$, where A_s is the perturbation amplitude, and $f_{pt} = 0.3$ is the perturbation frequency. Only one TBL is perturbed. **Figure 2**b and **2**c show that both TBLs respond to the perturbation at f_{pt}, confirming that the perturbations are indeed transmitted between the two TBLs.



(a) (b) (c)

Figure 1. Power spectra of fluctuating temperatures at various streamwise locations in TBLs. Monitoring points are located at Δx = 0.0018 off the channel walls. (a) Spectra under random perturbations for Λ = 15%. (b) and (c) Spectra under single-mode perturbation for Λ = 50% of (b) the perturbed TBL, and (c) the unperturbed TBL.

To ascertain if downstream perturbations can propagate upstream, we calculate a modified Froude number at various confinement ratios, $Fr_m = \frac{u}{\sqrt{g'L}}$, where $g' = g\frac{\rho-\rho_0}{\rho} = g\alpha\Delta T = g\alpha\frac{q_w''W/2}{k}$ is a reduced gravity under uniform heating. The spatially and temporally averaged inlet velocity $\bar{u}_{in}$ is applied as the characteristic velocity u, and the hydraulic radius of the channel ($L = W/2$) is adopted as the characteristic length L in this study [4]. Table 1 shows the calculated Fr_m values at different confinement ratios. It can be seen in the table that $Fr_m < 1$ for $\Lambda \leq 30\%$, which supports the downstream-to-upstream propagations of disturbances at relatively low confinement ratios. It is also seen that Fr_m increases monotonically with Λ and exceeds 1 at Λ = 50%, implying that the convective flow velocity is greater than the propagation speed of disturbances in a very narrow channel. In this case, the perturbation frequency detected at upstream of the unperturbed TBL (**Figure 2**c) may be due to a direct interaction of the two TBLs.

Table 1. The Froude numbers of DHC cases across five Λ at Ra = 4.8×10^{10}.

Confinement ratio	**Λ = 5%**	**Λ = 10%**	**Λ = 15%**	**Λ = 30%**	**Λ = 50%**
Fr	0.019	0.058	0.118	0.458	1.167

It is worth noting that the definition of the modified Froude number involves subjective choices of characteristic length and velocity scales. Despite the calculated Fr_m provides useful insights into the possible mechanism for perturbation propagation in the TBL, the underlying physics remains unresolved. Further investigations are required to elucidate the governing flow mechanism.

4. CONCLUSIONS

The propagation of perturbations in the TBLs of a uniformly heated vertical channel is numerically investigated. Perturbations are observed to transmit between the two TBLs when $\Lambda \geq$ 15% and are likely to propagate from downstream towards upstream at low to moderate confinement ratios.

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