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Steady flows in a naturally-ventilated enclosure containing both a distributed and a localised source of buoyancy

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ABSTRACT

We consider the flows and stratification established in a naturally-ventilated enclosure containing both localised and distributed sources of buoyancy. In this study, both the localised and distributed sources originate from the same horizontal plane, with both adding buoyancy to the enclosure, i.e. representing a point source of heat and a horizontally distributed source of heat at the base of a room. An important parameter controlling the transient and steady states of the enclosure is the ratio of the source buoyancy fluxes $\psi = \frac{B_D}{B_L}$, with B_D and B_L the source buoyancy flux of the distributed and localised source, respectively. We examine the role of entrainment between the layers, due to turbulent mixing, and construct a mathematical model to predict the stratification within the room for a range of ψ. We also show that for large ψ and opening areas the two-layer nature of the flow breaks down and there is a short circuit that allows the incoming air to escape through the upper opening without interacting with the full volume of the space. The validity of this model and its break down as predicted by a critical Richardson number are verified against small-scale experiments and the consequences for real-world buildings are discussed.

1. Introduction

Natural ventilation harnesses the natural conditions of an environment to drive a ventilation flow (i.e. the flow between an indoor enclosure and the exterior ambient) and establish a thermal stratification within the enclosure. On the other hand, mechanical ventilation uses energy directly to impose a desired ventilation flow rate and thermal stratification. Mechanical ventilation has the advantage that buildings can be designed with little constraint on how the building will perform thermally. For example, buildings with large glazed facades can be air conditioned to give comfortable interior conditions. Unfortunately, heating, ventilation and air conditioning (HVAC) uses significant amounts of energy and produces greenhouse gas (GHG) emissions. Mechanical ventilation accounts for approximately half of the built environment energy consumption, which itself accounts for $20-40\%$ of total energy consumption in the developed world [25]. Given the urgent need to reduced energy consumption and GHG emissions, it is desirable to use naturally-ventilated buildings where possible. However, as a naturally-ventilated building relies solely on the natural conditions of the environment, smart design of such buildings is required to guarantee thermally comfortable, well-ventilated buildings. The adequate design of naturally-ventilated buildings relies on an understanding of the underlying fluid mechanics that control the flow and stratification within the enclosure [20]. This makes mathematical models powerful tools in the design of naturally-ventilated buildings.

There has been a great deal of work in this area, especially in the last three decades, with much of the understanding coming from small-scale experimental studies in conjunction with the development of theoretical models starting with the work of Linden et al. [21]. Linden et al. [21] conducted a series of small-scale experimental models to verify a mathematical model that predicted the steady-state ventilation flow rate and thermal stratification within an enclosure containing a single, or multiple non-interacting localised sources of buoyancy (heat). Localised sources are good models for the flow produced by people, equipment or lighting. Localised sources generate turbulent plumes that transport buoyancy throughout the space and can be solely parameterised, in the idealised case of a point source, by a buoyancy flux B_L. For a source with a heat flux W_L, B_L can be determined from

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$$B_L = \frac{g\gamma W_L}{\rho C_p}, \quad (1)$$

where g is gravitational acceleration, γ is the thermal expansion coefficient, ρ is the density and C_p is the specific heat at constant pressure.

Further work has investigated other fundamental natural-ventilation flows including: the transients of naturally-ventilated enclosures containing localised [17] or distributed sources, e.g. representing a sun patch on the floor [6]; wind-driven or wind-assisted natural ventilation (e.g. Refs. [16] and [4]); flows within complex enclosures, e.g. atria [10]; the role of thermal mass within the enclosure [11]; and the role of radiative heating (e.g. Refs. [19] and [22]). However, to date the interaction between localised and distributed sources in naturally-ventilated enclosures remains unstudied. Distributed sources are very common, such as a floor being heated from a space below or a patch of floor heated by solar gains through a window. Furthermore, due to the prevalence of both types of buoyancy source in a building, the interaction of the flow generated by them and the subsequent effect on the ventilation and stratification within a building needs to be understood and modelled. Moreover, reduced mathematical models of such flows are needed to assist the design of naturally-ventilated buildings due to the computational cost of computational fluid dynamics (CFD).

Wells et al. [26] examined the competition between a localised and distributed source of buoyancy in an *unventilated* enclosure. They considered the case of two buoyancy sources located in the bottom boundary, with both providing a positive flux of buoyancy into the space, i.e. in a building both sources would be heating the space. In such a scenario, they found that the enclosure could either be completely stratified, completely mixed, or have both a stratified and mixed region depending on the ratio of the buoyancy fluxes $\psi = \frac{B_D}{B_L}$, where B_D is the buoyancy flux from the distributed source and B_L is the buoyancy flux of the localised source. For $0 < \psi < 1$ the classic filling box mechanism stratified the upper region of the enclosure and the distributed source was only able to mix the lower region. However, if $\psi > 1$ the convective motion from the distributed source was too strong compared to the stratification formed by the filling box flow, and the fluid in the enclosure became, to a good approximation, well mixed.

For the ventilated case, Hunt et al. [14] conducted some preliminary experiments in the set-up we seek to model here. As in the unventilated case, the dynamics depends on the ratio of buoyancy fluxes ψ. There are two limiting cases: when $\psi = \infty$ the space becomes well mixed, driven by a distributed source of buoyancy alone, whereas in the opposite limit, $\psi = 0$, the space becomes stratified with a two-layer stratification [21]. Empirically, a critical value ψ_c corresponding to the transition between these possible states was found: for $\psi < \psi_c$ the space can maintain a stratification, and for $\psi > \psi_c$ the space becomes well mixed. The experiments of Hunt et al. [14] suggested $\psi_c \simeq 6$ which was found to be independent of the effective opening area

$$A^* = \frac{2c_b c_t a_b a_t}{\sqrt{2\left(c_b^2 a_b^2 + c_t^2 a_t^2\right)}}, \quad (2)$$

where a_t and a_b are the area of the upper and lower openings, respectively and c_t, c_b are coefficients accounting for dissipation and the contraction of the flow through the sharp upper and lower openings [20].

Similar steady states, stratified and well mixed, are also found when the ventilation flow rate is imposed, as is the case of a mechanically ventilated space. Chenvidyakarn and Woods [1] constructed a steady-state model for such a system and validated their theory with small-scale experiments. They found that the stratification within the room was set by the ratio of the buoyancy fluxes ψ and also the imposed ventilation rate. For small ψ or low ventilation rates there was a two-layer stratification within the space but for large ψ or high ventilation rates the space became approximately well mixed, as if driven by a distributed heat source alone with buoyancy flux $B_D + B_L$.

In this paper we extend these studies by examining the steady states of a naturally-ventilated enclosure with both a distributed and a localised heat source originating from the bottom boundary of the enclosure, where the ventilation flow rate is dependent on the effective opening area A^*.

The theoretical model is discussed in §2. Experiments are described §3 and compared with the theoretical model in §4. The breakdown of the simplified model is discussed in §5. An application of the theory is detailed in §6. Finally, conclusions are given in §7.

2. Problem description

We consider the steady states of buoyancy-driven flow in a ventilated enclosure containing both a localised and distributed source of buoyancy originating from the lower boundary. The enclosure is a rectangular box with height H, cross-sectional area S and vertical openings at the top and bottom of the side walls, of areas a_t and a_b, respectively. The openings connect the enclosure to an exterior ambient environment of constant density ρ_a. The localised source has a constant buoyancy flux B_L and is located on the lower boundary along with the horizontally distributed source, covering the full extent of the boundary, that has a constant and spatially uniform buoyancy flux B_D.

First we consider the flows and stratification of an enclosure containing only a localised source of buoyancy. The flow from the localised source will rise through the enclosure as a buoyant plume, increasing in volume flux while losing buoyancy due to entrainment of ambient fluid. The plume spreads radially when it reaches the upper boundary of the enclosure and forms a horizontal front between the buoyant and ambient fluid that descends through the enclosure. It has been previously shown that, for an initially unstratified ambient and plume with constant buoyancy flux B_L, the enclosure will reach a steady state with a stable two-layer stratification consisting of two layers with uniform, but different, temperatures and with depths that are independent of B_L [21].

On the other hand, when a ventilated enclosure contains only a distributed source of constant buoyancy flux B_D at high Rayleigh number the convection is turbulent and, to a first approximation, a well-mixed steady state is reached [7]. The steady-state buoyancy of the enclosure can be calculated by determining the ventilation flow rate and balancing the buoyancy flux into and out of the enclosure. The flow rate out of the enclosure, when in a well-mixed steady state, is given by

$$Q_v = A^* \sqrt{g'_m H}, \quad (3)$$

where $g'_m = g\frac{\rho_m - \rho_a}{\rho_a}$ is the reduced gravity of the fluid in the well-mixed enclosure, a measure of how buoyant the fluid is, with ρ_m the density of the well-mixed space. Therefore, the buoyancy flux (the flux of g') out of the space is given by $g'_m Q_v$. Balancing this buoyancy flux out with the buoyancy flux supplied by the distributed source B_D yields