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The effect of gradual changes in wind speed or heat load on natural ventilation in a thermally massive building

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ABSTRACT

We examine the transitions in flow regime which can occur in naturally ventilated thermally massive buildings subject to changes in the wind and buoyancy forcing. For a range of heat loads there are both wind-dominated and buoyancy-dominated flow regimes. However, outside this range, only the steady state wind-dominated or buoyancy-dominated flow can develop. As a result of this non-linearity, and the different timescales for the evolution of the air and of the thermal mass, the transient evolution of the system caused by changes in either the heat load or the wind forcing can be complex. We develop a simplified model to identify the influence of the thermal mass on transitions in flow regime caused by changes in heat load or wind forcing. We show that the interior air responds rapidly to changes in the forcing, and as a result, the thermal mass can then act as a slowly evolving heat source or heat sink. In some situations this can lead to temporary buffering of the interior temperature, followed by a second, rapid transition in the interior temperature and ventilation regime as the system adjusts to the new steady state.

1. Introduction

The presence of material with high heat capacity within the insulated envelope of a building can be very effective in buffering the interior temperature from variations in the exterior temperature. Several theoretical models have examined the effect of thermal mass in attenuating the diurnal variations of the exterior temperature, within a ventilated enclosed space [11]. Approximate expressions have been derived for both the attenuation and the phase lag as a function of the ventilation rate, the rate of heat exchange between the thermal mass and the air, and the mass of material within the space [12,4]. In their analysis Yam et al assumed that there was a fixed ventilation rate, while Holford and Woods [4] modelled the interaction between buoyancy-dominated ventilation and thermal mass over a diurnal cycle. In many buildings, this phase lag is of comparable timescale to the timescale of the diurnal forcing of either the heat load or the wind.

However, natural ventilation flows are often influenced by both wind and buoyancy forcing, leading to a non-linear convecting system. This can lead to a buoyancy-dominated and a wind-dominated flow regime under the same forcing [2,3,5-7,9]. Yuan and Glicksman [13] showed that an instantaneous change in the heat load or wind forcing can lead to transitions between the wind-dominated and buoyancy-dominated flow regimes. They also identified that if the forcing returned to the original value after a relatively short time, then the flow returns to the original regime, whereas for longer lived fluctuations in the forcing, the flow may undergo an irreversible transition in regime. In their modelling, it was assumed that the thermal mass was in equilibrium with the interior air, and so the timescale for evolution of the net thermal mass of the building determined whether any transitions occurred.

Lishman and Woods [10] considered the transient adjustment of the ventilation flow in a lightweight building which results from more gradual changes in the heating load or the wind speed. Firstly they established that if the flow is wind-dominated, then an increase in the heat load can cause a transition to the buoyancy-dominated flow regime, but with a decrease in the heat load, the flow always remains in the wind-dominated regime. In contrast, they showed that if the flow is initially buoyancy-dominated, then with either a decrease or increase in the heat load, the flow remains in the buoyancy-dominated regime. Secondly, they showed that if the flow is buoyancy-dominated, then with a sufficiently rapid increase in the wind speed, there may be a transition to the wind-dominated regime, whereas with a more gradual increase in the wind speed, the flow remains in the buoyancy-dominated regime. This transition is therefore distinguished by its dependence on the rate of change of the wind forcing. Finally, they also showed that if the building is in the wind-dominated regime, and the wind forcing decreases sufficiently, then there will be a transition to the buoyancy-dominated regime. (Also, if the building is in the buoyancy

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controlled regime, and the wind forcing decreases, then they showed that the flow regime remains in the buoyancy controlled regime.)

In practice, many low energy buildings which deploy natural ventilation also tend to incorporate large amounts of thermal mass. It is therefore of interest to understand the effect of slow-response thermal mass on the non-linear transitions in the air flow which result from relatively rapid changes in the heat load or wind forcing. This forms the topic of the present paper.

A key to gain insight into this problem lies in recognition of the timescales which control different processes. There is the timescale over which the forcing evolves, t_f, the timescale for the air to ventilate from the building, and hence readjust to a change in the forcing, t_a, and the timescale over which the thermal mass responds to a change in the air temperature, t_m. In buildings with substantial thermal mass, $t_m \gg t_a$ and so we expect the air temperature to adjust to a change in forcing relatively rapidly. Over a longer timescale, the thermal mass will then evolve. Changes in the heat load, or the passage of weather fronts typically occur over times$t_f \sim t_a \ll t_m$, so that the transition time for the air flow is comparable to the forcing. As a result we expect that after a relatively fast adjustment of the air flow in response to a change in the forcing, the thermal mass then effectively provides a heat load or heat sink which controls the subsequent adjustment to steady state as the thermal mass itself evolves in temperature.

In this paper, we focus on the effect of relatively rapid changes in forcing compared to the timescale of evolution of the thermal mass, $t_f \sim t_a \ll t_m$. We first analyse the effect of a gradual change in the heat load examining how the wind-dominated and buoyancy-dominated flow regimes may evolve. We then examine the effect of a gradual variation in the wind forcing and derive a criterion which determines whether a transition in regime can occur.

In Section 2, we introduce a theoretical model for the coupled ventilation flow and thermal mass. We then present and test models for the transient response to changes in heat load (Section 3) and changes in the wind forcing (Section 4), exploring the control of the timescale of these changes on the evolution of the flow. We consider the impact of our results on real buildings in Section 5 and draw some conclusions.

In contrast to the relatively rapid changes in forcing considered in this paper, $t_f \ll t_m$, with slower changes to the forcing such that $t_f \geq t_m$, the thermal mass is able to adjust on a timescale comparable to the change in forcing. In that case, the air and thermal mass evolve together, and the dynamics of such changes are comparable to the analysis presented by Lishman and Woods [10].

2. Theoretical model of heat and mass transfer

We consider a building model similar to that shown in Fig. 1, with two openings of area A, one at a high level on the left face of the building, and one at a low level on the right face of the building. In the model, the wind blows from the left, leading to a pressure drop across the building, Δp_w. We assume there is a distributed heat source on the base of the building, which leads to a well-mixed interior. There is also a distributed thermal mass, which exchanges heat with the interior air. Our model focuses on the convective heat transfer between the thermal mass and the air using a bulk model of the thermal mass (cf [4]). Convective heat transfer between the thermal mass and the interior air is typically described by a heat transfer coefficient which depends on a variety of factors, including surface orientation and air properties [1]. Here we consider an idealised problem, and assume the heat transfer coefficient has constant value f which is representative of the overall heat transfer rate, and typically around 2.5 W m^{-2} K^{-1} (cf [4]). The heat exchange between the thermal mass and the interior air is therefore given by

$$P_{tm} = Sf(\Delta T_m - \Delta T) \tag{1}$$

where S is the surface area of the thermal mass, ΔT is the temperature difference between the interior fluid and the exterior fluid and ΔT_m is the temperature difference between the thermal mass and the exterior fluid. The heat balance equation for the air then takes the form

$$\rho C_p V \frac{d\Delta T}{dt} = Q - \rho C_p A^* \Delta T \sqrt{\frac{|\Delta p_w - \beta g h \Delta T|}{\rho}} + Sf(\Delta T_m - \Delta T) \tag{2}$$

The first term on the right hand side denotes the heating, while the second term denotes the heat transfer associated with the ventilation flow (cf [9]). The final term is the heat exchange with the thermal mass. In the equation, ρ is the fluid density, C_p is the specific heat capacity of the fluid, β is the thermal expansion coefficient of the fluid, V is the volume of air in the building, h is the height between openings, and A^* is an effective window area including losses [2]. Also, g is acceleration due to gravity, Q is the heat load, Δp_w is the pressure difference between the openings associated with the wind, and ΔT is the temperature difference between the interior and exterior.

The flow direction is determined by the term inside the square root: if the wind pressure Δp_w is greater than the buoyancy pressure $\beta g h \Delta T$ then the flow will be wind-dominated; otherwise, it is buoyancy-dominated. Neglecting the effects of any radiative heat fluxes, then the temperature of the thermal mass primarily evolves owing to convective heat exchange with the air.

$$\rho_m C_{pm} V_m \frac{d\Delta T_m}{dt} = Sf(\Delta T - \Delta T_m) \tag{3}$$

Here the subscript m indicates a property of the thermal mass.

It is convenient to scale the temperature relative to the initial steady state buoyancy-dominated flow with no wind and no thermal mass. This is given by

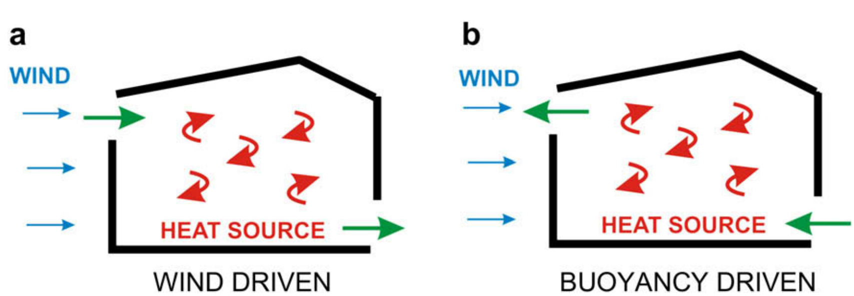

Fig. 1. Schematic illustrating the wind-dominated and the buoyancy-dominated equilibrium flow regimes.