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Transient buoyancy-driven ventilation: Part 1. Modelling advection

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ABSTRACT

The unsteady development of the vertical temperature profile in a ventilated space containing a heat source is modelled. The buoyant fluid released from the heat source is modelled as a turbulent buoyant plume, using a standard integral plume model with a fixed entrainment coefficient. Two types of natural ventilation flow are considered, with the flow driven entirely by the density contrast between the fluid inside and outside the space (stack effect). The ventilation types are (a) classic displacement ventilation, with outflow of warm air through upper openings and inflow of cool air through lower openings; and (b) doorway ventilation, with an exchange flow through the doorway. An improved version of the doorway exchange flow model is given as compared to previous studies. The boundaries of the space are considered to be perfectly insulating, so that heat is transported entirely by the fluid motion. The temporal stratification that develops within the space (outside the plume) is calculated using a modified filling-box model, with successive layers added to the top of the space over time. Laboratory experiments giving reduced-scale simulations of the flows were also conducted, where saline solution and fresh water are used to model fluid of different density. The developing density profiles in the laboratory experiments compare very well with the model predictions. The use of this type of model, capturing the main physical flow features, allows rapid and accurate calculations of transient stratification in ventilated spaces.

1. Introduction

Inhabited spaces generally contain heat sources, derived for example from the occupants, electronic equipment (computers, printers, televisions, etc) or heating systems (radiators, fires, etc). To maintain thermal comfort and remove contaminants, these areas are normally provided with some form of ventilation. This ventilation may be driven by mechanical means, by natural pressure differences (wind/temperature) or by some combination of natural and mechanical forcing. In spaces containing heat sources, the resulting buoyancy within the room can be used to drive the flow, and we concentrate on these naturally driven flows in this paper.

The magnitude of the buoyancy forces scales with the density differences, and accelerations scale with the so-called reduced gravity ($g' = \Delta\rho g/\rho$, where $\Delta\rho$ is the density difference and ρ a typical fluid density). We use this approach here, with the density of the ambient external air taken as our reference density. For typical temperatures in buildings, the density differences, and thus reduced gravity, are proportional to temperature differences, so the reduced gravity is a measure of the temperature relative to the external ambient temperature.

The resulting ventilation flows may be divided into two broad types: mixing flows and displacement flows. In mixing flows, the incoming fresh air is mixed throughout the space, producing a uniform distribution of thermal energy and contamination within the space. In displacement flows, cool air is introduced at a low level and exhaust air extracted at a high level. Here we concentrate on two types of displacement flow in a space containing a single heat source. The first is the "classic" displacement-ventilation flow described by Linden et al. [1], with openings near the top of the space to allow warm air to exit and openings near the bottom to allow cooler air to enter the space. The second is a space ventilated by an open doorway [2,3], where there is inflow of cooler air through the lower part of the doorway and outflow of warm air through the upper part of the doorway.

Methods for evaluating ventilation strategies include experimental and numerical modelling. In most cases, full-scale experimental representation of these flows is not practical, and scaling considerations [1,4] make it difficult to conduct reduced-scale experiments (for thermally driven ventilation). Salt water bath experiments overcome some of these issues, where saline solution and fresh water is used to model density contrast [1,5]. This type of

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Nomenclature

Dimensional parameters

A	cross-sectional area of the ceiling/floor (m^2)
A_u and A_l	upper and lower ventilation opening areas (m^2)
A^*	effective opening area as defined by Linden et al. [1] (m^2)
B_0	source buoyancy flux ($m^4\,s^{-3}$)
g	gravitational acceleration ($m\,s^{-2}$)
g'	reduced gravitational acceleration due to density differences ($m\,s^{-2}$)
H	height measured above the floor (m)
H_d	height of the doorway (m)
H_{int}	the exchange flow interface relative to the floor (m)
H_r	height of the room (m)
$H_{r,eff}$	effective height of the room, this is the rise height of the plume measured from the hypothetical point source to the ceiling (m)
H_s	height of the buoyancy source above the floor (m)
H_{vir} and L_{vir}	distance above the hypothetical point source relative to the floor and the buoyancy source (m)
$\overline{H}$	height of the neutral level above the floor (m)
M_v	momentum flux of the ventilation flow ($m^4\,s^{-2}$)
Q_p and Q_v	plume and ventilation flow rate ($m^3\,s^{-1}$)
t	time (s)
U_u and U_l	upper and lower ventilation velocities ($m\,s^{-1}$)
W	width of the doorway(s) (m)
Z	vertical height above the plume hypothetical point source (m)
ρ	density ($kg\,m^{-3}$)
g'_s, M_s, Q_s, t_s and Z_s	scales used to non-dimensionalise reduced gravity, momentum flux, volume flow rate, time and vertical lengths (see in Eqs. (1) and Eq. (A3))

Non-dimensional parameters

$a^* \ (= A^*/H^2_{r,eff})$	effective opening area normalised by the effective height of the room
f	function dependent on the stratification interface
$h_d \ (=H_d/H_{r,eff})$	dimensionless doorway height
$m_v \ (=M_v/M_s)$	dimensionless ventilation momentum flux (scale defined in Eq. (A3))
$q \ (=Q/Q_s)$	dimensionless volume flow rate (scale defined in Eq. (1))
$w \ (=W/H_{r,eff})$	dimensionless doorway width
Δ	dimensionless parameter that is proportional to the hydrostatic head (see Eq. (8))
$\delta \ (=g'/g'_s)$	dimensionless reduced gravity (scale defined in Eq. (1))
$\tau \ (=t/t_s)$	dimensionless time (scale defined in Eq. (1))
$z \ (=Z/Z_s)$	dimensionless vertical height above the plume hypothetical point source (m)
$\widehat{m}, \widehat{q}, \widehat{z}$ and $\widehat{\delta}$	dimensionless momentum, volume flow rate, vertical plume height and reduced gravity as defined above where: $Z_s = H_d$ in Eq. (1)
$\widehat{f}\,(=f/h_d^3)$	function dependent on the stratification interface defined using $\widehat{z}$ rather than z

Constants

C_d, C_c and C_v	discharge, vena contracta and velocity coefficients used to include energy losses in the displacement-ventilation model
$C_{en} \ (= 4\pi^{2/3}\alpha_{en}^{4/3})$	an entrainment coefficient defined to simplify the scales defined in Eq. (1)
$C_p \ (=(243/2500)^{1/3}C_{en})$	a further entrainment coefficient similar to C_{en} typically used in the definition of the plume equations and solutions (*cf.* [1,2,5,9])
n and n_p	number of stratification layers and plumes
α_{en}	plume entrainment constant defined as the ratio between the mean centreline velocity and the mean entrainment velocity
γ	parameter used to relate the location of the stratification interface and the exchange flow interface

experiment captures the details of the flow, but does not simulate any heat transfers at the boundaries of the space.

Numerical models range from those based on simplified or averaged plume equations, referred to in this paper as mathematical models, to more complicated simulations using computational fluid dynamics (CFD). Using CFD, detailed flow patterns and temperature variations can be resolved and in principle these models include many of the important physical processes. However, in practice a degree of simplification is required and computational demands mean that these calculations are very time consuming. Simplified mathematical models offer an advantage of reduced time scale to calculate the solution as compared to CFD models, at the expense of physical complexity. For this reason, mathematical models are more useful in the early stages of design, as different ventilation strategies and configurations can be evaluated rapidly, with a more detailed CFD analysis later. In addition mathematical models help to identify functional dependencies that are not immediately clear from numerical experiments.

Mathematical models range in complexity. The main differences relate to the assumed temperature profile and the amount of physical processes modelled. There are three basic assumed temperature profiles: *i*) fully mixed [6–8]; *ii*) fully mixed two-layer [1,5,9]; and *iii*) linear [9,10]. The two-layer and linear models are primarily based on experimental investigations. Some of these models include the effect of heat transfer at the boundaries, including radiative redistribution [9–11] and conductive heat transfer [10,11], and they generally model only the steady-state flows.

In this paper, a new mathematical model for unsteady buoyancy-driven ventilation is proposed, giving the full detailed transient vertical stratification within the space. The model was developed and validated using experimental results obtained from