Building and Environment 59 (2013) 76–90

Contents lists available at SciVerse ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

The hydraulics of exchange flow between adjacent confined building zones

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ARTICLE INFO

Article history:
Received 9 March 2012
Received in revised form
22 July 2012
Accepted 10 August 2012

Keywords:
Buoyancy-driven exchange flow
Boussinesq flow
Natural ventilation
Plumes
Gravity currents
Internal bores

ABSTRACT

Buoyancy driven flow between two finite zones containing fluid of slightly different density is investigated. The two zones are connected through a common rectangular doorway spanning the channel width so that a two-layer exchange flow develops once the barrier is removed. In the zone that initially contained dense fluid, a buoyant plume of light fluid mixes with the dense fluid leading, over time, to the development of non-trivial ambient density stratification. Meanwhile, dense fluid flows as a gravity current into the zone that initially contained light fluid. This gravity current reflects from the end wall and propagates back toward the opening in the form of an internal bore. When the bore reaches the opening the dynamics of the exchange flow (and consequently the source conditions of the buoyant plume) are substantially altered. Such dynamics are modeled using elements of gravity current, internal bore and plume theory. The flow dynamics of the two zones are linked using two-layer exchange flow theory whereby a maximal exchange flow rate is prescribed only before the bore reaches the opening. The velocity and density jump across the first front decrease substantially once the exchange flow becomes sub-maximal. Depending on the geometrical parameters, the terminal elevation of the first front may lie above, at or below the top of the opening; here, we focus on the former scenario. Experiments have been carried out to validate the model. The comparison between theory and experiment plus the application of the research to architectural fluid mechanics is discussed.

1. Introduction

The exchange of a buoyant fluid of finite volume through one or more openings with an adjacent volume of ambient fluid is a common problem in fluid mechanics with numerous examples in natural, industrial, and architectural settings [1]. Important examples in the latter circumstance include the exchange of hot and cold air between the inside and outside of a building and between different zones within the same building. The temperature difference between such zones produces buoyancy forces that drive the flow. Knowledge of the mixing process associated with such an exchange flow is important for the design of HVAC (heating, ventilation, and air conditioning) systems or for increasing the efficiency of natural ventilation [2–6].

Consider two zones with different temperatures in a one-storey building. The temperature difference can be a consequence of a difference of zone orientation relative to the sun or because in one zone high load (i.e. heat generating) electrical devices are used. If the temperature difference is small, the Boussinesq assumption implies that

$$\beta(T_0 - T_c) = -\frac{(\rho_0 - \rho_c)}{\rho_{00}} \tag{1}$$

where β is the coefficient of volumetric expansion (for ideal gases $\beta \sim (1/T)$), T_0 and T_c are the temperatures in the dense and light zones respectively, with the densities ρ_0 and ρ_c similarly defined, and ρ_{00} is a reference density, e.g. the density of the dense zone. In the simple model suggested by Fig. 1, the cold zone dimensions are $H \times \ell \times W$ with H as height, ℓ as length and W as width. The total length of both hot and cold zones is L.

Loosely mimicking the sudden opening of a doorway between the building zones,[1] let us suppose that the vertical barrier at $x = \ell$ is partially removed at time $t = 0$. As indicated schematically in Fig. 1, for $t > 0$ the barrier spans a distance $H - h$ measured from the ceiling. For $h < H$, two qualitatively different kinds of flow are

[1] To reiterate, and for simplicity, we herein restrict attention to cases where the opening spans the width, W, of the building zones. Based on the analysis of Dalziel and Lane-Serff [16], we expect qualitatively similar flow behavior when $\frac{w}{W} < 1$ in which w is the opening width.

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http://dx.doi.org/10.1016/j.buildenv.2012.08.009

Nomenclature

b	non-dimensional buoyancy
b_∞	terminal non-dimensional buoyancy
b_p	effective half-width of the plume (m)
Cr	Courant number
C_d	discharge coefficient
Fr	Froude number
g'	reduced gravity (m s^{-2})
h	height of removal (m)
k	function in exchange flow equation (5)
ℓ	lock length (m)
P	pressure (Pa)
Q_e	exchange volume flux per unit width (m^2 s^{-1})
R	non-dimensional distance where the first front halts above the source
t	time (s)
t_1	time taken for the gravity current to reach to the end-wall (s)
t_2	time taken for the internal bore to reach to the doorway (s)
T_0, T_c	initial temperature of the dense and light zone (K), respectively
z_{ff}	elevation of the descending first front (m)
α	entrainment coefficient
β	volumetric expansion coefficient (K^{-1})
Γ_d	discharge parameter
λ	empirical factor for density profile within plume
ρ_0	initial density of the dense zone (kg m^{-3})
ρ_c	initial density of the light zone (kg m^{-3})
ρ_{00}	reference density (kg m^{-3})
H, L, W	height, length, width of the rooms (tank), respectively (m)
Q, M, F	volume (m^2 s^{-1}), momentum (m^3 s^{-2}), buoyancy (m^3 s^{-3}) flux within plume, respectively
u_{01}, h_{01}	velocity (m s^{-1}) and depth (m) of the bottom layer at doorway, respectively
u_{02}, h_{02}	velocity (m s^{-1}) and depth (m) of the upper layer at doorway, respectively
u_1, h_1	dense gravity current velocity (m s^{-1}) and depth (m), respectively
u_2, h_2	light gravity current velocity (m s^{-1}) and depth (m), respectively
u_b, h_b	internal bore velocity (m s^{-1}) and depth (m), respectively
x, z	horizontal and vertical coordinates (m)
$\overline{w}$, Δ	characteristic axial velocity (m s^{-1}) and density (m s^{-2}) within plume, respectively
ρ_a, Δ_a	density (kg m^{-3}) and characteristic density (m s^{-2}) of the ambient of the plume (dense zone), respectively
ρ_p, w_p	density (kg m^{-3}) and velocity (m s^{-1}) within the plume, respectively

observed: a gravity current of dense fluid traveling at constant speed from left to right at the base of the hot zone and a buoyant plume rising through the cold zone. In the latter case, ambient (dense) fluid is entrained into the plume, which forms a (light) gravity current of its own when it reaches the ceiling. Over time and as the buoyant convection and entrainment continues there will develop a stable stratification of density in the ambient in a manner described by the “filling-box” theory of Baines and Turner [7]. Accordingly dense fluid of density ρ_0 is separated from fluid originating from the plume by a horizontal “first front” of elevation z_{ff} that descends over time. Meanwhile to the other side of the vertical barrier, and after some elapsed time, say, $t = t_1$, the (dense) gravity current will reflect from the right end wall whereupon a right-to-left traveling internal bore will be generated. The bore has a total height, h_b, travels at constant speed, u_b, and reaches the opening at $x = \ell$, at $t = t_2$, say. For $t \geq t_2$, the source conditions of the buoyant plume will be different from those for $t < t_2$ and slowly varying in time in a manner to be described below. Phillips and Woods [8] analyzed the exchange flow between an interior space and the external ambient through a single doorway. They carried out similitude experiments that characterized the room filling time as a function of doorway and room geometry. They also examined the impact of the source buoyancy on the interface height. In their analysis, however, Phillips and Woods [8] considered an exchange flow that remained critical (i.e. fully controlled) for all time. Moreover, Phillips and Woods [8] did not consider the details of the (evolving) interior stratification in the context of a filling box analysis. This latter simplification was relaxed in the follow-up investigation by Caulfield and Woods [9], who investigated the transient evolution of an

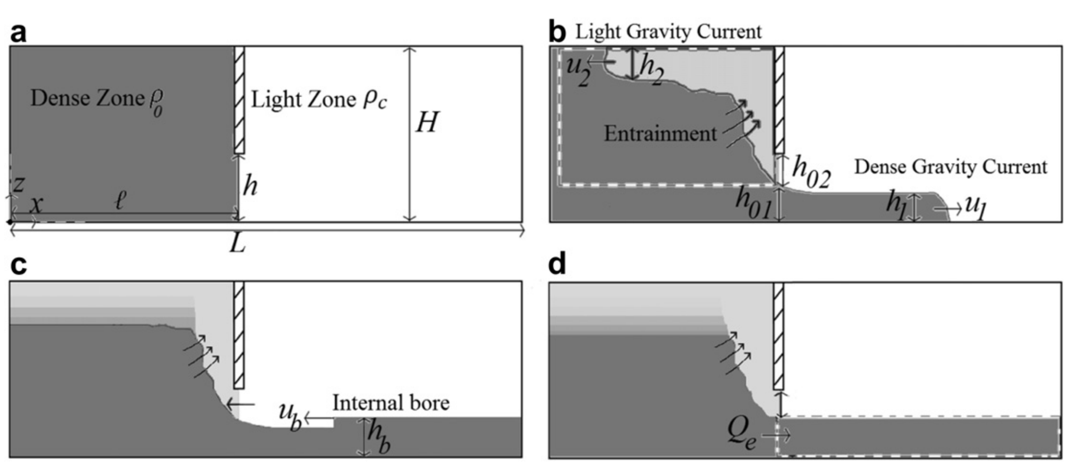

Fig. 1. Schematic of the exchange flow at (a) $t = 0$, the instant when buoyancy-driven motion begins, (b) $t < t_1$, before the dense gravity current reaches the right end wall, (c) $t_1 < t < t_2$, after reflection of the dense gravity current as an internal bore, and, (d) $t \geq t_2$, after the bore has reached the horizontal position of the opening, $x = \ell$.