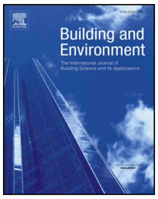
Building and Environment 141 (2018) 236–246

Contents lists available at ScienceDirect

Building and Environment

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



Study on thermal stratification of an enclosure containing two interacting turbulent buoyant plumes of equal strength

Xiaopan Gao, Angui Li[*], Changqing Yang

School of Environmental and Municipal Engineering, Xi'an University of Architecture and Technology, Xi'an, Shaanxi 710055, China

ARTICLE INFO

Keywords:
Interacting buoyant plumes
Ventilated enclosure
Thermal stratification
Separation threshold

ABSTRACT

The emptying-filling box model with two interacting turbulent buoyant plumes of equal strength is investigated in this paper using theoretical analysis and numerical simulation. Theoretical models are deduced and validated to quantitatively predict the thermal stratification height of an enclosure containing two interacting buoyant plume sources with different separations between the two plumes. The variation in the thermal stratification height with the separation between the two plumes is validated by numerical simulation. A threshold for the separation between two plumes is defined to determine whether the two buoyant plumes in the enclosure are interacting or independent, which is also confirmed by numerical simulation. Simultaneous equations containing height difference between the top and bottom openings of the enclosure and effective area of the top and bottom openings of the enclosure are proposed to predict the threshold. These results can be used as a reference on natural ventilation design for buildings with interacting heat sources to make use of the effect of indoor thermal plumes and create a suitable indoor environment.

1. Introduction

Thermal plumes are phenomena observed in buildings containing heat sources, such as occupants, lighting equipment and the heat treatment processes found in industrial buildings. In an enclosure with openings placed at both the top and bottom of the enclosure, thermal plumes will drive airflow upward and vertical thermal stratification will be generated within the enclosure, a phenomenon that has been gaining recognition in the engineering literature [1–6]. For engineering designers, the primary consideration on utilizing indoor thermal stratification is to make sure that the hottest region is above the occupied zone of an enclosure to improve indoor thermal comfort [7,8]. Besides, thermal plumes will drive pollutants upward with airflow and indoor thermal stratification can contribute to removing pollutants in displacement ventilation to improve indoor air quality [9–11].

A thermal plume rising from a single heat source has been studied extensively. The turbulent plume analysis is based on the classic point origin theory. In this regard, the self-similarity of the plume is achieved, and the mean vertical velocity profiles and temperature profiles in a turbulent plume are both taken as Gaussian [1,2]. The volume flux of a turbulent plume based on the point origin theory can be expressed as [1–3]:

$$Q = CB_0^{\frac{1}{3}}Z^{\frac{5}{3}} \tag{1}$$

where Q (m^3/s) is the volume flux of a plume, B_0 (m^4/s^3) is the buoyancy flux, $C = \frac{6}{5}\alpha\left(\frac{9}{10}\alpha\right)^{\frac{1}{3}}\pi^{\frac{2}{3}}$ is a universal constant based on the entrainment constant α [1], and Z (m) is the vertical-coordinate from the origin of the heat source. Additionally, thermal stratification is produced by a single buoyant plume in enclosed space. Studies on a single heat source in a free environment focus on the dynamic evolution of the rising thermal plume itself, including the plume velocity field, temperature field and the plume width and so on. In an enclosure with openings at both the top and bottom, a thermal plume will drive a thermal-driven flow and thermal stratification is generated because of the restriction of the enclosure framework. To understand the thermal-driven flow and thermal stratification in an enclosure, Linden, et al. [3] described theoretically the structure of a buoyant flow driven by a single point source in an enclosure. Openings in the enclosure were located at both the top and bottom of the enclosure, which creates the so-called "emptying filling box model". The results showed that a two-layer stratification is produced with a horizontal interface between the layers. The dimensionless height ξ of the horizontal interface in an enclosure of H is given by Ref. [3]:

$$\frac{A}{H^2} = C^{\frac{3}{2}}\left(\frac{\xi^5}{1-\xi}\right)^{\frac{1}{2}} \quad \left(\xi = \frac{h}{H}\right) \tag{2}$$

where A (m^2) is the effective area of the top and bottom openings of the

---

[*] Corresponding author.
E-mail address: liag@xauat.edu.cn (A. Li).

https://doi.org/10.1016/j.buildenv.2018.05.032
Received 21 January 2018; Received in revised form 13 May 2018; Accepted 14 May 2018

Nomenclature

A	effective opening area (m^2)
A_{in}	area of the bottom openings (m^2)
A_{out}	area of the top openings (m^2)
A_h	area of the heat source (m^2)
B_0	buoyancy strength (m^4/s^3)
b_G	Gaussian plume width (m)
b_T	top-hat plume width (m)
C	constant to calculate the volume flux of a plume (−)
C_{eff}	constant to calculate the volume flux of two interacting plumes (−)
c	pressure loss coefficient (−)
c_d	discharge coefficient (−)
c_p	specific heat capacity of the air at constant pressure (J/kgK)
H	height difference between the top and bottom openings (m)
H_{UP}	upper bound of the dimensionless thermal stratification height
H_L	lower bound of the dimensionless thermal stratification height
h	thermal stratification height (m)
G'	reduced gravity in the region above the interface and outside the plume (m/s^2)
g	acceleration due to gravity (m/s^2)
g'	reduced gravity (m/s^2)
l	typical length scale (m)
Q	total volume flux of two interacting plumes (m^3/s)
Q_0	volume flux of one plume (m^3/s)
	volume flux into the enclosure (m^3/s)
$Q*$	dimensionless volume flux (−)
r	radial distance from plume-axis (m)
V_G	Gaussian velocity (m/s)
V_T	top-hat value for velocity (m/s)
x_0	separation between two plumes (m)
x_T	threshold for the separation between two plumes (m)
Z	z-coordinate from the origin of the heat source (m)
Z_T	height where the plumes touching begins (m)
Z_M	height where the plumes merging begins (m)
α	plume entrainment constant (−)
α_{eff}	effective entrainment constant (−)
β	thermal expansion coefficient (1/K)
θ	temperature difference between the upper layer and the ambient air (°C)
λ	thermal conductivity (W/mK)
μ	molecular viscosity (kg/ms)
ξ	dimensionless thermal stratification height (−)
ρ	density (kg/m^3)
ρ_p	density of the plume (kg/m^3)
ρ_a	ambient density (kg/m^3)
ρ_0	reference density (kg/m^3)

enclosure, and H (m) is the height difference between the top and bottom openings, and h (m) is the interface height [3,7]. The constant $C = \frac{6}{5}\alpha\left(\frac{9}{10}\alpha\right)^{\frac{1}{3}}\pi^{\frac{2}{3}}$ is the same constant as that used in equation (1).

Other aspects of the emptying-filling box model have also been studied. The modifications to the emptying-box model were developed by Coffey and Hunt [12] and localized mixing within the emptying box at the thermal stratification interface was observed. Kaye and Hunt [13] developed a theoretical model to predict, as functions of time, the thermal stratification and the volume flow rate through the openings in the time-dependent flows of an emptying filling box. Crouzeix et al. [14] investigated the thermal stratification induced by thermal plumes in a non-adiabatic context. Emptying non-adiabatic filling boxes were also investigated by Lane-Serff and Sandbach [15] to study the effects of heat transfer on the fluid dynamics of natural ventilation. Jun Gao [16] described multi-layer thermal stratification under natural ventilation in high and large spaces, and the thermal plume developed in the multi-layer environment was investigated based on its development across each density interface. A multi-layer stratification model for displacement ventilation was also presented by Chen et al. [17] and Li [18]. Using theoretical and experimental analysis, Flynn [19,20] examined the flows that were forced in one chamber by an isolated point source of buoyancy and developed within a multi-chamber domain in contrast to within a single chamber. They observed a complex internal stratification of buoyancy, the details of which depend upon the relative sizes of the adjacent chambers and the size/vertical location of the internal/external openings. Tovar et al. [21] studied the hybrid ventilation in two interconnected rooms with a forced buoyancy source with a finite volume flux located in the ceiling of one-room. Kosonen et al. [22] studied the effect of typical buoyant flow elements and heat load combinations on room air temperature profile in office buildings. Lin et al. [23] investigated the emptying-box problem with horizontal and vertical inflow directions, and a modified theoretical model is proposed on the transient stratified flow. Espinosa [24] performed computational fluid dynamics (CFD) simulations in a typical occupied office to study the effects of ventilation parameters and inlet geometry on thermal stratification. Comparisons of the CFD and experiment in the same practice were made by Cook and Cook & Lomas on the emptying-filling box model [25,26]. The results have shown that the calculation by CFD was in agreement with the experimental results of Linden et al. [3]. CFD simulations for stratification of indoor temperature were also carried out by Gilani et al. [27] and a sensitivity analysis was performed to investigate the impact of computational grid resolution, turbulence model, discretization schemes and iterative convergence on the predicted temperatures of the emptying-filling box model.

Studies on two plumes in a free environment and in an enclosure were also carried out. Linden [7] pointed out that two plumes in a free environment would entrain the ambient fluid between them and that they are naturally drawn together and merge if sufficiently close together as they rise. Kaye and Gregory [28] found that the merging height has a relationship with the separation of the heat sources and that for plumes of equal strength, merging occurs approximately three to four source separations above the source. Kaye and Linden [29] first studied the conditions of interacting and merging for two fully developed turbulent plumes in a free environment. The point of coalescence was defined as the location at which only a single peak appears in the horizontal buoyancy profile, and a prediction was made for its height. A model was then developed to describe the resulting single plume and predict its virtual origin. Then, Cenedese & Linden [30] extended this work and divided the space above the two heat sources in free environment into three regions. An effective entrainment constant was therefore proposed to describe the parameters in the three regions of plumes coalescence. Aiming at two plumes in an enclosure and thermal stratification, Cooper and Linden [31] studied two buoyant point sources in a naturally ventilated enclosure and analysed the thermal stratification of two independent buoyant sources. It was found that two sources of unequal strength produce a vertical density profile consisting of three distinct, fully mixed layers. The case of multiple buoyant sources in a naturally ventilated enclosure was also studied by Linden and Cooper [32], and it was shown that the multiple sources produce a multiple layered stratification with each plume terminating in a given layer. However, it is worth noting that in references [3,7,13–16,25,26,31,32], a single point source, two point sources or multiple point sources of buoyancy in an enclosure were assumed to be isolated or independent of each other.