Building and Environment 72 (2014) 44–52

Contents lists available at ScienceDirect

Building and Environment

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

Stack ventilation in multi-storey atrium buildings: A dimensionless design approach

Andrew Acred [a], Gary R. Hunt [b,*]

[a] Department of Civil and Environmental Engineering, Imperial College London, London SW7 2AZ, UK
[b] Department of Engineering, University of Cambridge, Cambridge CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 23 May 2013
Received in revised form
9 October 2013
Accepted 12 October 2013

Keywords:
Natural ventilation
Multi-storey buildings
Atrium
Stack effect
Buoyancy
Dimensionless design

ABSTRACT

Using a simplified mathematical model, a preliminary design strategy for steady stack ventilation in multi-storey atrium buildings is developed. By non-dimensionalising the governing equations of flow, two key dimensionless parameters are identified – a ventilation performance indicator, λ, and atrium enhancement parameter, E – which quantify the performance of the ventilation system and the effectiveness of the atrium in assisting flows. Analytical expressions are determined to inform the vent sizes needed to provide the desired balance between indoor air temperature, ventilation flow rate and heat inputs for any distribution of occupants within the building, and also to ensure unidirectional flow. Dimensionless charts for determining the required combination of design variables are presented with a view to informing first-order design guidance for naturally ventilated buildings.

1. Introduction

The atrium is a common architectural feature in both modern and historic naturally ventilated buildings [1,2], and serves to enhance the stack pressure driving ventilating flows by providing a tall vertical space in which buoyant air can accumulate. Fig. 1 shows an example multi-storey office building with an atrium. Other purpose-built vertical spaces such as solar chimneys and double façades are also increasingly incorporated into building designs with a view to assisting natural ventilation. Such multi-compartment buildings pose a particular design challenge due to the interaction of heat and air flows between different building zones, often due to the common connection with the atrium. This can lead to unforeseen flow phenomena and compromise the ventilation scheme [3,4]. As a consequence, the question of how to provide clear and helpful design guidance has remained open for some time now.

Simplified mathematical models, based on the fundamental physics governing heat and air flows through buildings, have proven particularly useful in preliminary design guidance – see Refs. [5,6], for example – due to their ease of use and minimal computational overhead. Simplified mathematical models have been successfully developed and validated using small-scale laboratory experiments in numerous studies of stack ventilation, including studies of atrium buildings. Holford and Hunt [7], for example, developed and experimentally validated a simplified mathematical model of stack ventilation flows in a room attached to an atrium. Livermore and Woods [8] experimentally validated a similar model of flows in a two-storey building with a ventilation stack. These models have been further validated in numerical studies. Ji et al. [9] and Ji and Cook [10] observed good agreement between CFD (computational fluid dynamics) and simplified mathematical models for modelling stack ventilation flows through atrium buildings.

These models have therefore proven to be robust, and for this reason have been extended and generalised to more complex building geometries in numerous studies. Etheridge [11], for example, extends the 'explicit method' – a simplified mathematical approach to preliminary design presented in CIBSE guidance [5] – to a number of example multi-compartment buildings. Acred and Hunt [12] also developed a general simplified mathematical model for stack ventilation in multi-compartment buildings which can be used to provide a number of qualitative 'rules-of-thumb' for preliminary design and ventilation control. A number of theoretical studies, with a specific focus on buildings with atria or ventilation stacks, are also underpinned by the extension of experimentally and numerically validated models [13–15]. Notably, Hunt and Holford [16] produced simple dimensionless expressions and

---

* Corresponding author. Tel.: +44 1223768449.
E-mail address: gary.hunt@eng.cam.ac.uk (G.R. Hunt).

0360-1323/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.buildenv.2013.10.007

Nomenclature

Symbols

A	vent area, m^2
A^*	effective vent area m^2
$\widehat{A^*}$	dimensionless effective vent area, –
$\mathcal{A}$	scaled vent area per person, –
B	buoyancy flux, m^4 s^{-3}
$\widehat{B}$	dimensionless buoyancy flux, –
β	thermal expansion coefficient, K^{-1}
c_d	discharge coefficient, –
c_p	specific heat capacity of ambient air, J kg^{-1} K^{-1}
E	atrium enhancement parameter, –
Fr	Froude number, –
g	gravitational acceleration, m s^{-2}
g'	reduced gravity, m s^{-2}
$\widehat{g'}$	dimensionless reduced gravity, –
H	storey height, m
ΔH	atrium height above top storey, m
$\widehat{\Delta H}$	dimensionless atrium height above top storey, –
i	storey number, –
λ	ventilation performance indicator (VPI), –
M	momentum flux, m^4 s^{-2}
n	number of people, –
N	total number of storeys, –
Q	ventilation flow rate, m^3 s^{-1}
$\widehat{Q}$	dimensionless ventilation flow rate, –
Re	Reynolds number, –
ρ	density of air, kg m^{-3}
T	temperature, K
W	heating rate, W

Subscripts

a	atrium
c	ceiling-level
crit	critical
d	design value
e	external environment
eff	effective
f	floor-level
i	storey number
isolate	equivalent isolated storey
N	top storey
p	per person
s	bulk value for storeys
tot	total

design charts for sizing vents in a multi-storey building with an atrium and top-down chimneys.

The use of dimensionless parameters in analysis – a technique routinely employed in fluid dynamics – is particularly powerful, since it can be used to generalise results to a wide range of buildings. A dimensionless approach to natural ventilation design is advocated by Etheridge [17] and has also widely been used in fundamental studies of the fluid dynamics of natural ventilation [18,19], for example. As Hunt and Holford [16] demonstrated, a dimensionless approach lends itself to the use of simple algebraic expressions and design charts and is therefore capable of providing extremely rapid and intuitive guidance.

In this paper, we build on this existing work to develop a new dimensionless design approach for naturally ventilated buildings, focussing on multi-storey buildings with an atrium, solar chimney, or similar vertical space which links multiple storeys. In particular, we use dimensionless parameters to quantify the performance of the ventilation scheme and balance key design criteria to inform the sizing of ventilation openings.

Since a key objective of this work is to provide rapid and intuitive first-order guidance – for use in preliminary design only – the mathematical model used is deliberately simple and is based only on the balance between driving stack pressure and pressure losses at ventilation openings. Additional effects such as wind, leakage through adventitious openings and pressure losses due to friction are not explicitly modelled but could, in principle, be included in the pressure balance following the general approach discussed in Ref. [12] (Appendices), for example. Although simple, this class of model has shown good agreement with small-scale laboratory experiments (e.g. Refs. [7,20,21]), allowing for explicit validation of the results presented herein in later experimental work. As effective building designs typically harness wind to assist stack ventilation, analysing the case of stack effect only can be thought of as a 'worst-case scenario; vent sizes determined herein therefore give conservative design estimates (i.e. providing the maximum required vent sizes).

In §2 and §3 we use the example of buoyancy-driven ventilation of a single room to identify a key dimensionless 'ventilation performance indicator', which is linked to design requirements for fresh air supply rate per person and internal air temperature. In §4 and §5 we extend the dimensionless approach to multi-storey atrium buildings and, by defining a measure for the ventilation performance of the atrium, derive simple analytical expressions for the vent areas required to provide the desired ventilation rate and air temperature for all occupants, regardless of their distribution within the building. In §6, we place a constraint on the atrium vent area, such that exchange flows are avoided; and in §7 the design process for sizing vents in a multi-storey atrium building is summarised.

2. Buoyancy-driven ventilation of a single room

2.1. Buoyancy-driven ventilation model

To illustrate the development of a dimensionless 'ventilation performance indicator', we consider first the case of steady

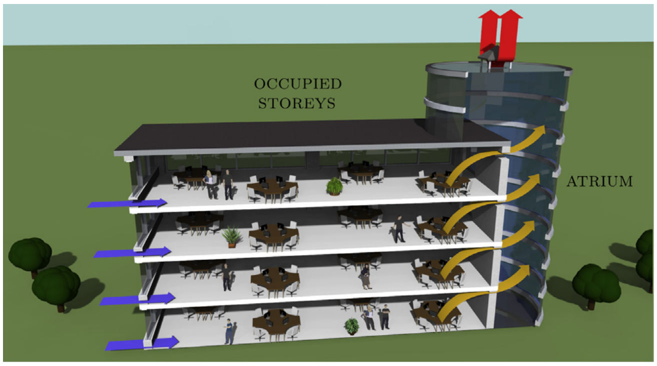

Fig. 1. Visualisation of an example four-storey atrium building, with open-plan occupied spaces and a glazed atrium. Arrows show the intended flow pattern. From left to right: cool air is supplied to the occupied storeys by floor-level vents (blue arrows); warm air exits the storeys through ceiling-level vents (yellow arrows) and exits the atrium through a high level vent (red arrows). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)