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Dimensionless design approach, applicability and energy performance of stack-based hybrid ventilation for multi-story buildings

Dong Yang [a, b, *], Ping Li [a, b]

[a] Key Laboratory of the Three Gorges Reservoir Region's Eco-Environment, Ministry of Education, Chongqing University, Chongqing 400045, China
[b] National Centre for International Research of Low-carbon and Green Buildings, Chongqing University, Chongqing 400045, China

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ABSTRACT

The active building ventilation systems, which remove excess heat, humidity and contaminants from indoor environment, could be large energy consumers. To provide desired ventilation flow rates for all of the floors of a multi-story building and to reduce the resulting energy consumption, a stack-based hybrid ventilation scheme is proposed. This hybrid scheme is advantageous if the building has too many floors or the required ventilation flow rate is beyond the one that pure buoyancy-driven ventilation schemes can assist. A dimensionless design approach is developed using simplified mathematical analysis. The expressions for the optimal interface between the NVFs (naturally ventilated floors) and MVFs (mechanically ventilated floors) and the vent sizes of different NVFs, which guarantee an appropriate balance between the desired ventilation flow rate, room air temperature, and the heat inputs within the occupants' spaces, are derived. Energy performance analyses are carried out to obtain the dependence manners of the amount of energy consumption to the key design parameters. Differences in the applicability between this hybrid ventilation scheme and the other two low-energy ventilation schemes are presented. The design procedure for this stack-based hybrid ventilation scheme is presented. The dimensionless design approach has been validated with numerical simulations.

1. Introduction

The building sector has been the largest energy consumer in most countries. Energy consumption of buildings is responsible for about 30–45% of the global energy demand, in which most of the energy is used for maintaining thermally comfortable indoor environment, i.e., space heating or cooling (i.e., air-conditioning) of buildings. In Hong Kong, buildings even account for over 90% of the total electric energy consumption [1]. To reduce energy consumption of buildings, passive measures and technologies have been used for substituting for the air conditioning and mechanical ventilation systems. These passive measures include, for example, night-time ventilation [2], the use of ground as heat source or sink for buildings [3], ventilation heat recovery [4] and pre-cooling of buildings with thermal mass [3,5], etc.. Natural ventilation could contribute towards achieving nearly zero or very low energy buildings, especially for the transient seasons with thermally comfortable ambient climates [6,7]. For a heated single-floor space with a relatively large height, natural displacement ventilation, which is achieved by using two openings of sufficient vertical distance, could be sufficient for cooling the interior building spaces (see Fig. 1) [8,9]. For an occupant space with limited floor height, a ventilation stack can be incorporated into the building to provide an additional vertical space for increasing thermal buoyancy and enhancing natural ventilation flows [10–12]. This low-energy ventilation scheme is called as stack ventilation. In recent years, the principle of stack ventilation has been increasing applied to modern, multi-story buildings. Tall vertical structures, such as atriums, solar chimneys and double facades, are consciously being incorporated into multi-story buildings for assisting natural flows, playing a similar role as the ventilation stacks. Acred and Hunt have proposed a design strategy for stack ventilation of the entire occupant spaces of a multi-story building based on two key dimensionless parameters (ventilation performance indicator and atrium enhancement parameter) [13]. The schematic of this ventilation scheme is shown in Fig. 2 (Mode II). The use of stack ventilation for all the floors of a multi-story building is the most

* Corresponding author. Faculty of Urban Construction and Environmental Engineering, Chongqing University, Chongqing, 400045, China. Tel.: +86 23 65120750; fax: +86 23 65120773.
E-mail address: yangdong@cqu.edu.cn (D. Yang).

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Nomenclature

A_{in}	area of the floor-level vent (m^2)
A_{out}	area of the ceiling-level vent (m^2)
A^*	the combined effective vent area (m^2)
$\widehat{A}^*$	the dimensionless vent size(dimensionless)
$A_{in,i}$	vent area of the ith floor (m^2)
A_i^*	effective area of the ith floor (m^2)
$\widehat{A}_i^*$	the dimensionless vent size of the ith floor(dimensionless)
A_r	the vent area of the top NVF (m^2)
A_r^*	the effective area of the top NVF (m^2)
$\widehat{A}_r^*$	the dimensionless vent size of the top NVF (dimensionless)
$\widehat{A}_{r,\max}^*$	the maximum available dimensionless vent area of the top NVF (dimensionless)
$A_{s,out}$	area of stack top vent (m^2)
$A_{s,out}^*$	effective area of stack top vent (m^2)
$\widehat{A}_{s,out}^*$	the dimensionless area of the stack top vent (dimensionless)
$\widehat{A}_{s,out,\max}^*$	the maximum available dimensionless area of the stack top vent (dimensionless)
$\widehat{A}_n^*$	the dimensionless vent size of the nth floor (dimensionless)
A_0	vent area of the MVF (m^2)
A_0^*	effective area of the MVF (m^2)
$\widehat{A}_0^*$	the dimensionless vent area of the MVF (dimensionless)
$A'_{0,j}$	the cross-sectional area of the jth part of the mechanical ventilation system (m^2)
$C_{d,in}$	discharge coefficient of floor-level vent (dimensionless)
$C_{d,out}$	discharge coefficient of ceiling-level vent (dimensionless)
$C_{d,s,out}$	discharge coefficient of stack top vent (dimensionless)
$C'_{d,j}$	discharge coefficient of the jth part of the mechanical ventilation system (dimensionless)
C_p	specific heat of air (J/kg K)
E	heat input of each floor (W)
g	gravity acceleration (m/s^2)
g'	reduced gravity acceleration(m/s^2)
g'_0	the reduced gravity that corresponds to the required ventilation flow rate(m/s^2)
h	story height (m)
h_c	height between the neutral level and upper vent of a room without stacks
H	total height of building (m)
H_{ne}	height of the stack neutral plane (m)
ΔH	height of the stack extending the top floor (m)
$\Delta\widehat{H}$	the dimensionless height of the stack extending the top floor (dimensionless)
n	total number of the floors of the building
N	the number of people in each floor
$\Delta P_{fa,i}$	fan pressure for the ith floor of a pure mechanical ventilation scheme(Pa)
$\Delta P'_{fa,i}$	fan pressure for the ith floor of the proposed hybrid scheme (Pa)
ΔP_i	pressure difference between the stack and ambient air for the ith floor (Pa)
Q	ventilation flow rate (m^3/s)
Q_0	required ventilation flow rate for a single room (m^3/s)
Q_p	the minimum fresh air rate required by per person (m^3/s)
Q_i	buoyancy-driven ventilation flow rate of the ith NVF (m^3/s)
Q_{out}	total flow rate through the stack top vent (m^3/s)
r	the number of the top NVF
t_y	annual cycle (s or day)
T_i	indoor air temperature (K)
$T_{i,c}$	comfortable indoor air temperature for occupants (K)
T_0	environment temperature (K)
W_{fa}	the work input rate of a pure mechanical ventilation scheme (W)
W'_{fa}	the work input rate of the ventilation system of this proposed hybrid scheme(W)
Z_{ne}	the number of the floor where the neutral plane locates

Greek symbols

β'	the expansion coefficient (1/K)
η_v	the normalized energy consumption
λ	ventilation performance indicator(dimensionless)
λ_0	required ventilation performance indicator (dimensionless)
λ_0^u	the upper limit value of λ_0 (dimensionless)
λ_0^l	the lower limit value of λ_0 (dimensionless)
λ_0^m	the third value of λ_0 (dimensionless)
ρ	density of indoor or stack air (kg/m^3)
ρ_0	density of ambient air (kg/m^3)

Subscript

p	per person
0	ambient
i	floor number
ne	neutral plane
r	the floor number of the top NVF
s,out	stack top vent
u	upper limit
l	lower limit
m	third limit
fa	fan

advantageous scheme for energy conservation; however, it could be unachievable in many circumstances. The main reason is that, to ensure negative hydrostatic pressures in all occupant spaces, the stack should be significantly extended above the building. Otherwise, contaminated air could enter the higher-level occupant spaces from the ventilation stack (see Fig. 3 (a)). For buildings with too many stories or with relatively high desired ventilation flow rates, a competent ventilation stack could be much higher than the ventilated building. However, an extremely high stack could be contradictory to the requirements for both building structure and architectural appearance. The use of an active stack [14], which is attached with a controllable fan, could increase the exhaust effect to generate negative pressures in the entire building and may avoid the flow behavior shown in Fig. 3(a). The active stack has been used for ventilating a single-floor building [14]. However, for a building with several floors, it may be required that the fan attached to the