Energy and Buildings 133 (2016) 185–196

Contents lists available at ScienceDirect

Energy and Buildings

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

Comparison of measured and simulated performance of natural displacement ventilation systems for classrooms

Nuno M. Mateus*, Gonçalo Nunes Simões, Cristiano Lúcio, Guilherme Carrilho da Graça

Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 5 August 2016
Accepted 23 September 2016

Keywords:
Displacement ventilation
Natural ventilation
Chimney
EnergyPlus
Model validation

ABSTRACT

Children spend the majority of their weekdays in classrooms that often have low indoor air quality and limited financial resources for the initial and running costs of mechanical ventilation systems. Designing effective natural ventilation (NV) systems in schools is difficult due to the intense use of the classroom spaces and the dependence of NV on building geometry and outdoor conditions. Building thermal and airflow simulation tools are fundamental to predict NV system performance in the design phase. These predictions of these tools must be validated (preferably with data from real buildings). This paper presents a set of detailed measurements of buoyancy driven natural DV systems of three classrooms located in two buildings in Lisbon (Portugal). The rooms are located in two educational buildings, a kindergarten and a university, and have different buoyancy driven natural DV systems (with and without chimneys). The experimental measurements are used to validate a three-node DV model implemented on the open-source thermal building simulation software EnergyPlus. The validation results show that the building thermal simulation model tested is able to predict bulk airflow rate with an average error of 16%. In addition, a good agreement is also obtained for the vertical temperature prediction: an average error of 4% corresponding (average deviation of 0.7 °C). Analysis of the kindergarten rooms results revealed, that as expected, increasing chimney height from 1 to 4 m has a significant positive impact in NV system performance. The performance of natural DV systems depends on the number of thermal plumes in the room. For the same sensible heat load, increasing the number of plumes lowers the average occupied zone air temperature and increases the bulk airflow rate. In light of the complexity of the cases tested, NV with uncontrolled boundary conditions, the results of the comparisons performed between measurements and simulations should contribute to increase confidence in the use of EnergyPlus to simulate buoyancy driven natural DV systems.

1. Introduction

Children spend the majority of their weekdays in classrooms that often have low indoor air quality (IAQ) due to insufficient outdoor airflow [1,2]. There are several studies that link low IAQ to reduced effectiveness of schoolwork and learning outcomes [3–7]. In response to this problem current classroom ventilation standards and guidelines recommend a minimum fresh air amount of 7–8 l/s per occupant [8,9] and an indoor-outdoor CO_2 concentration differential of less than 700 ppm [9,10]. Achieving these airflow rates with a mechanical ventilation system inevitably increases energy consumption and maintenance costs in schools that, in the majority of cases, have a limited budget. In many climates, a well-designed natural ventilation (NV) system can provide adequate IAQ with no running costs.

Implementing effective NV systems in schools is difficult due to the intense use of the classroom spaces and the dependence of NV on building geometry and outdoor conditions (weather, pollution and noise). NV airflow is driven by pressure differences generated by buoyancy effects, wind or a combination of these two mechanisms. These pressure differences drive airflow from high to low pressures zones, across different zones inside the building or between indoor and outdoor environment. To naturally ventilate a space there are three main approaches that can be employed: single-sided ventilation (SS), cross-ventilation (CV) and displacement ventilation (DV). SS ventilation is the most common NV system due its simplicity: it requires openings in a single façade [11]. Unfortunately, these systems often struggle to provide sufficient airflow away from the façade. CV uses openings in opposite façades and has the potential to provide large flow rates [12] but

---

* Corresponding author.
E-mail address: namateus@fc.ul.pt (N.M. Mateus).

http://dx.doi.org/10.1016/j.enbuild.2016.09.057
0378-7788/

Nomenclature

NV	Natural ventilation
IAQ	Indoor Air Quality
CO_2	Carbon dioxide
SS	Single-sided ventilation
CV	Cross-ventilation
DV	Displacement ventilation
CFD	Computational fluid dynamics
DSF	Double skin façade
F	Inlet flow rate (m^3/s)
α	Plume entrainment constant
g	Acceleration of gravity (m/s^2)
β	Coefficient of thermal expansion (K^{-1})
W	Heat flux plume (W)Heat flux plume (W)
h	Neutral height (m)
ρ	Air density (Kg/m^3)
C_p	Thermal capacity of air at constant p ($W\,m^3/(kg\,K)$)
n	Number of thermal plumes
A*	Effective opening area
a_t	Top opening area
a_b	Bottom opening area
H	Total room height (m)
UL	University of Lisbon
A_{in}	Inlet opening area
A_{out}	Outlet opening area
C_d	Discharge coefficient
T_{OC}	Temperature of room air in the occupied zone (°C)
T_f	Temperature of floor surface (°C)
T_{Af}	Temperature of room air in the horizontal layer adjacent to the room floor (°C)
T_{wl}	Temperature of lateral surface that is below the mixed layer (°C)
T_{wu}	Temperature of lateral surface that is above the mixed layer (°C)
T_{MX}	Temperature of mixed layer node (°C)
T_c	Temperature of ceiling surface (°C)
T_{in}	Inflow air temperature (°C)
A_f	Floor surface area (m^2)
A_{wl}	Lateral area exposed to the lower zone surface area (m^2)
A_{wu}	Lateral area exposed to the upper zone surface area (m^2)
A_c	Ceiling surface area (m^2)
h_f	Heat transfer coefficient of floor surface ($W/(m\,K)$)
h_{wl}	Heat transfer coefficient of the lateral surface that is below the mixed layer ($W/(m\,K)$)
h_{wu}	Heat transfer coefficient of the lateral surface that is above the mixed layer ($W/(m\,K)$)
h_c	Heat transfer coefficient of ceiling surface ($W/(m\,K)$)
h_{rc}	Radiative heat transfer coefficient of ceiling surface ($W/(m\,K)$)
h_{Rf}	Radiative heat transfer coefficient of floor surface ($W/(m\,K)$)
h_{rwl}	Radiative heat transfer coefficient of the lateral surface that is below the mixed layer ($W/(m\,K)$)
h_{rwu}	Radiative heat transfer coefficient of the lateral surface that is above the mixed layer ($W/(m\,K)$)
G	Total internal heat gains (W)
F_{MO}	Fraction of the convective heat gains that is mixed into the occupied zone
F_{GC}	Fraction of total heat gains that are convective
F_{GR}	Fraction of total heat gains that are radiative
I_M	Inflow degree of mixing
h_{TMX}	Room height where zero temperature gradient region begins
Avg.	Error average error
Avg.	Dif. average difference
Avg.	Bias averaged bias
ΔP	Pressure difference

is difficult to implement in schools due to potential draft induced discomfort, noise propagation and the prevalence of single sided room configurations. In DV systems air is introduced near the room floor with low velocity. Buoyancy forces induced by temperature differences between inflow and room air heated by internal gains promote airflow across the floor towards the heat sources where the ventilation air expands and moves upward. Ideally, the air movement induced by buoyancy is capable of transporting heat and pollutants away from the occupied zone, promoting stratification, creating a warmed mixed layer in the upper part of the room [13]. In order for the buoyancy forces to be effective, DV systems require a height difference between inflow and outflow that is difficult to achieve without chimneys. For single story buildings chimneys can be placed in the roof, any other configurations require internal voids or individual chimneys that may be difficult to integrate in the building.

The performance of NV in schools can be evaluated using thermal and occupant comfort simulations, field questionnaires or measurements. In 2004, a questionnaire based study [14] performed in two schools confirmed that, when NV is used, there is a higher tolerance to elevated indoor temperatures, exceeding the thermal comfort limits imposed by building regulations. A recent study analyzed the impact of the type of ventilation system on student performance, concluding that a well-designed NV system can as good as a mechanical ventilation system [15]. When the room CO_2 sources are known, the CO_2 concentration differential between indoor and outdoor can be used as an indirect method to determine room airflow change rates, this bulk airflow measurement approach is often used in schools [16]. In 2008, a large field study measured CO_2 concentration and airflow rates in 62 classrooms [17], showed that in 77% of the time the airflow rates were below 8l/s/occupant. Further, as expected, in the NV systems measured, high indoor CO_2 concentrations occurred predominantly when the windows were closed. This trend was also observed by other authors, mainly during winter when outside air is too cold to allow for open windows without cold draft discomfort [18]. It is increasingly consensual that window operation is predominantly driven by thermal comfort and not IAQ [19]. Existing IAQ problems may be aggravated in schools located in cold climates that are retrofitted with envelopes that have very low infiltration [20].

The world population is increasingly urban and, therefore, the majority of schools are located in dense or semi-dense urban areas. Using wind driven ventilation in dense areas is difficult due to the wind velocity attenuation that characterizes these environments. In response to this limitation, designers often prefer buoyancy driven systems in SS or DV configurations that can still benefit from winds effects but are mostly driven by temperature difference between indoor and outdoor of at least 2–3 °C. This requirement restricts the use of these systems to outdoor temperatures below ≈25 °C [21]. To extend the outdoor temperature range for buildings NV designers can use chimneys that increase the vertical distance between inlet-outlet and decrease the indoor-outdoor temperature difference in the occupied zone [22,23]. An effective chimney lowers room temperatures, reduces outdoor noise ingress