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Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building

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ABSTRACT

Natural ventilation is an effective method to simultaneously improve indoor air quality and reduce energy consumption in buildings, especially when indoor temperature is close to ambient temperature e.g. the transitional seasons in Germany. Heat loss due to opened window and ventilation effectiveness ratio were analytically modeled. Following that, the effects of thermal buoyancy on the steady classroom airflow and thermal stratification comfort as well as the contaminant dispersion were discussed. Classroom displacement ventilation and its thermal stratification as well as indoor air quality indicated by the CO_2 concentration have been investigated concerning the effects of supplying air temperature and delivering ventilation flow velocity. Representative thermal comfort parameters, percentage dissatisfied and temperature difference between ankle and head have been evaluated. Subsequent energy consumption efficiency analysis illuminates that classroom energy demands for natural ventilation not only in transitional seasons but also in winter could be decreased with the promotion of the ventilation effectiveness ratio for heat distribution when the natural ventilation rate maintains a constant, and with the shrinking of the ventilation effectiveness ratio for heat distribution when the supplying air temperature is not variable. Detailed fitting correlations of heat loss resulted from opened window and ventilation effectiveness of natural ventilation inside the classroom have been presented.

1. Introduction

Natural ventilation is an effective way to simultaneously enhance indoor air quality and reduce energy consumption of buildings [1–5], although it is not popular than mechanical ventilation [5]. This is mainly contributable to the facts that natural ventilation could not easily maintain a stable indoor air environment, and the operation of natural ventilation could not be controlled conveniently by the occupants, who usually enjoy the easy control of mechanical ventilation system. However, the energy consumption depending on the mechanical ventilation and its air conditioning system should be the largest portion of building energy consumptions. With the most recent studies, air conditioning system and its mechanical ventilation network could consume over 50% of total final energy supplied into the service and residential buildings [6,7].

With the global energy and environment issues, natural ventilation, this very old and traditional technology for enhancing building environment, has attracted great attentions. Natural ventilation has been regarded as an efficient built air delivery mode to shrink the building energy consumption, especially in the transitional seasons when the indoor air temperature level approaches the surrounding environment temperature level [1]. Consequently, in the recent decades, many researchers have investigated the airflow patterns, the temperature and contaminant distributions, and thermal stratification comfort as well as the effects of thermal buoyancy and wind force for naturally ventilated rooms or buildings [4,5,8–15]. However, the aforementioned most of researches and experiences of natural ventilation were focusing on the residential and office buildings, but almost nothing has been done for the natural ventilation in the school buildings.

Classroom environment and thermal comfort has an important role in the teaching and learning as it could be engaging students in activities that promote their performances, such as understanding of concepts, abilities of problem solving, and attitudes towards

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Nomenclature

c	specific heat capacity of air (J/kg K)
C	contaminant concentration (ppm)
N	natural ventilation rate (1/h)
PD	percentage dissatisfied
q	heat loss (W)
$\boldsymbol{Q}$	air flow rate (m^3/h)
$\boldsymbol{S}$	source term
$\boldsymbol{T}$	temperature (°C)
$\boldsymbol{V}$	air velocity (m/s)
X, Y, Z	Cartesian coordinates (m)
Δ	difference
Γ	digression coefficient
ρ	density (kg/m^3)
φ	general variable
ε	ventilation effectiveness
u	momentum equation
-	volume averaged

Subscripts

a,v	difference between ankle and head
C	contaminant removal
exhaust	exhausting port of the classroom
heat	heating
in	indoor air
supply	supplying port of the classroom
t	heat distribution

learning, and etc [16,17]. Due to the crowded living and learning environment, recent researches have found that more than half of school children have some kinds of allergy and asthma, after extensive surveys in the traditional school buildings [18]. Consequently, for the new-built low energy school buildings, indoor air quality and thermal comfort by the natural ventilation should be particularly investigated to solve the common doubts on the classroom air quality by the airtight building envelopes and crowded students.

In the present work, school building energy conservation performance and classroom air quality with natural ventilation in the transitional seasons and winter will be simultaneously discussed, through which the ventilation effectiveness and air flow motions in a representative classroom in a new-built low energy school building will be, respectively, investigated. Within the classroom, the displacement ventilation flow will be established, where the fresh air will be delivered from a window and polluted by indoor occupants, and finally extracted from the upper exhausts. Displacement ventilation essentially belongs to an energy efficient air delivery and distribution strategy, and it is well suitable for improving indoor air quality in the occupied space of buildings [19–21]. Coins have two sides. Past researches concerning the displacement ventilation have shown that it may be a cause of discomfort due to large vertical temperature differences and ventilation drafts [19,20]. Therefore, the classroom displacement ventilation should be further investigated, such that the classroom air environment and thermal comfort of students and teachers could be enhanced, with the operation of natural ventilation system.

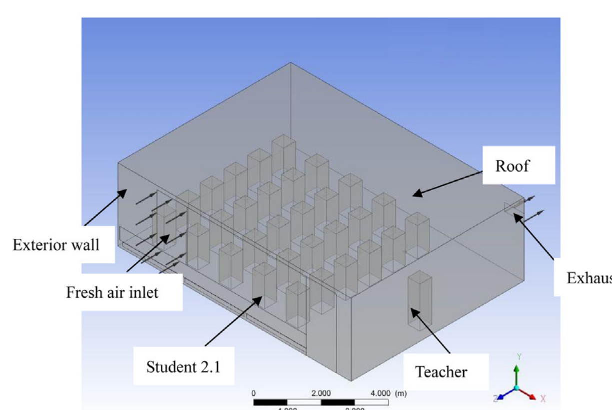
In the following section, a classroom in the low energy school building will be firstly introduced, where it is operated by the displacement natural ventilation system. Sequentially, theoretical analysis of ventilation effectiveness and heat loss due to natural ventilation will be presented. Following that, mathematical modelling of displacement ventilation airflow in the classroom will be briefly stated [22–26], and the corresponding computational fluid dynamics (CFD) program will be validated by the on-site measurements. Subsequently, displacement natural ventilation air flow motion, thermal transport and indoor CO_2 dispersion with and without thermal buoyancy will be fully simulated by the validated numerical codes, respectively. Effects of natural ventilation parameters on the classroom volume averaged temperature, vertical thermal gradient as well as classroom CO_2 concentration reductions, will also be included. Typical thermal comfort parameters will be analyzed, including percentage dissatisfied rate, and the volume averaged temperatures as well as vertical temperature difference between human head to ankle in the classroom. Finally, the heat loss resulted from natural ventilation will be correlated with functions of the ventilation effectiveness ratio.

2. Physical model of the investigated classroom

A representative classroom of 9.77 m (length) × 7.25 m (width) × 3.00 m (height) was extracted from the low-energy school building situated in the region of southern Germany, as illustrated in Fig. 1(a). This classroom has been fully modeled as a rectangular parallelepiped enclosure, as indicated in Fig. 1(b). The enclosure space totally accommodates 30 students, whom are distributed in 5 Lines and 6 Rows and 1.20 m heights. In addition, there is one teacher of 1.70 m standing before the students. All occupants were described by the hexagonal shapes in the research model.

The objective classroom is located in the top floor, such that the roof and front wall both expose to the surrounding environment. On the front wall, there are a large window sizing of 5.00 m × 2.10 m and a small window with 1.25 × 2.10 m (as a fresh air inlet) as well

(a) Low energy school building in Bavaria, Germany



(b) Modeling classroom extracted from the low energy building

Fig. 1. Façade picture of low energy building and the geometry of the modeled classroom, where all the occupants (students and teacher) were simplified into cuboids and the symbol student 2.1 represents that the student sits at line 2 and row 1.