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Indoor air environment and night cooling energy efficiency of a southern German passive public school building operated by the heat recovery air conditioning unit

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ABSTRACT

The recently built school building has adopted a novel heat recovery air conditioning system. Heat recovery efficiency of the heat recovery facility and energy conservation ratio of the air conditioning unit were analytically modeled, taking the ventilation networks into account. Following that, school classroom displacement ventilation and its thermal stratification have been numerically investigated concerning the effects of the heat flow flux of passive cooling within the ceiling concrete in the classroom due to night ventilation in summer which could result in cooling energy storage. Numerical results indicate that the promotion of passive cooling can simultaneously decrease the volume averaged indoor temperatures and the non-uniformity of indoor thermal distributions. Subsequent energy performance analysis demonstrates that classroom energy demands for ventilation and cooling could be reduced with the promotion of heat recovery efficiency of the ventilation facility, and the energy conservation ratio of the air-cooling unit decreases with the increasing temperatures of exhaust air and the heat flux value for passive cooling within the classroom ceiling concrete. Fitting correlations of heat recovery ventilation and cooling energy conservation have been presented.

1. Introduction

Nowadays, world energy crisis and carbon emission have put heavy pressures on the building energy reductions, particularly on those high-energy consumption buildings [1,2]. Recently, avalanche energy consumptions of public school buildings have pushed government administrators in southern Germany to design and build up passive school buildings or the ultra-low energy school buildings, where high level insulations, energy efficient windows, low air infiltration (extremely airtight building envelopes), and mechanical heating/cooling recovery ventilation systems as well as night ventilation in summer were simultaneously applied. In addition, in order to make full use of the advantages of mechanical heating/cooling recovery ventilation systems and extremely airtight building envelopes, all the windows in the classrooms are normally closed for the sake of avoiding indoor heating/cooling energy losses in winter/summer [3,4]. Furthermore, it is well-known that thermal mass with night ventilation in summer could shrink the maximum daytime indoor temperature in buildings, particularly, which is suitable for those unoccupied public school buildings at night [5].

Due to the thermal response of passive low energy school building, with intensive night ventilation the building elements (such as the walls, service equipments and ceiling) could be cooled down, it will then provide more appropriate living conditions for the following day, and at the same time it could save lots of energy costs for cooling at day [6,7]. Such night ventilation cooling is especially efficient in moderate climatic conditions, where the outdoor temperature difference between day and night is intensely large such as southern German city Munich, whose outdoor temperature difference between day and night in summer is normally more than 10 °C, which is exceedingly suitable for night ventilation cooling. In addition, in order to obtain much more cooling energy storage in the building elements and allow those cooling energy to transfer conveniently into indoor air and envelopes, suitable thermo-physical

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properties of the building element materials could be required, including high density, specific heat capacity and thermal conductivity. The concrete is usually selected as the primary material for the walls/ceiling [5,7,8], and thus it will be the primary materials for the building elements investigated here.

Healthy and comfortable indoor air climate conditions are essential for any type of building environment. Particularly, classroom environment and thermal comfort has an important role in the teaching and learning process as it could be engaging students in activities that promote their performances, such as understanding of concepts, abilities of problem solving, and attitudes toward learning [9]. 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 [10]. Therefore, for the new-built passive low energy school buildings, indoor human thermal comfort should be particularly paid more attentions due to the fact that these new school buildings adopted close-type windows and airtight building envelopes.

In the present work, heat recovery ventilated air motions in a representative classroom embedded in a new-built passive low energy school building will be investigated, where the displacement ventilation system has already been put into operations. Displacement ventilation essentially belongs to energy efficient air distribution strategy where fresh and conditioned air will be delivered at floor level and heated and polluted by indoor occupants, naturally flowed upward and then extracted from upper exhausts. With such advantages, displacement ventilation is favorably suitable for improving indoor air quality in the occupied classroom spaces. On the other hand, displacement ventilation may be a cause of discomfort due to large vertical temperature differences and ventilation drafts [11,12]. Therefore, it is essential for us to investigate the thermal comfort of occupants in the low energy school building with displacement ventilation.

Hence, human thermal comfort inside the classroom of one passive low energy school building will be investigated. In the following sections, a classroom in a low-energy school building operated by the heat recovery displacement ventilation unit (occupied) and with night ventilation (unoccupied) will be firstly introduced and analyzed. Subsequently, three-dimensional room thermal airflow in the classroom operated with displacement ventilation will be simulated by the methodology of computational fluid dynamics [13–15]. Concerning the uncertainties inherently existing in the numerical models, some representative CFD results will be validated by the on-site measurements. Thermal comfort parameters will be analyzed, including percentage dissatisfied and vertical temperature difference between human-body parts, etc. Finally, the energy conservation ratio of air handling unit through the heat recovery ventilation will be correlated with functions of variable heat flux value of passive night ventilation cooling, and the temperature difference between exhaust air and entraining fresh air temperatures.

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 one of 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, who are distributed in 5 Lines and 6 Rows and 1.20 m in height. In addition, one teacher is 1.70 m in height and standing before the students and 6 slender tables sitting by 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 is a large window sizing of 6.25 m × 2.10 m and an entrance with 1.25 m × 2.85 m. As such low energy school building, external walls are composed of interior plaster, reinforced concrete, and heat insulation, whereas the roof was is formed by the reinforced concrete and heat insulation. Insulation material of WLG 035 is applied in the wall insulation layers, and triple level thermal insulation glasses (from UNIGLAS corporation) are adopted for the windows, such that heat transfer coefficients (*U*-values) of the classroom envelopes are maintained at lower values, i.e., front wall (external wall) 0.128 W/m^2 K, other vertical walls (interior walls) 4.357 W/m^2 K, floor 2.450 W/m^2 K, ceiling 0.095 W/m^2 K, and window 0.870 W/m^2 K. The specific heat capacity of concrete within the ceiling, which is applied in night ventilation cooling energy storage, is 0.8 kJ/kg K and its density is 2400 kg/m^3.

Three diffusers of same size (2.50 m × 0.15 m) are installed side by side in the lower part of the front wall (beneath the window and immediately 0.10 m above the floor) and they horizontally deliver fresh and cold air into the space. On the backward side opposing to the front wall, the exhausting port sizing of 0.825 m × 0.325 m is positioned in the high altitude and lying 0.60 m below the ceiling. With such arrangement, displacement ventilation then will be established, i.e., fresh and cold air will be supplied by the diffusers into the classroom and spread along the floor; after being heated and polluted by the indoor occupants, it will become warm and travels upward to the top exhaust.

In this representative classroom, averaged heat emission 75 W is produced by each seated student, while that 100 W is generated by the standing teacher. Heat generated by the occupants will be removed simultaneously by both thermal radiation and convective modes, and their contribution ratio was assumed by 20/80. That is to say, the convective heat gains are 60 W and 80 W, respectively, for a seated student and a standing teacher. Solar radiation from the windows of such school buildings is almost avoided with the shading systems installed outward from the windows.

3. Night cooling energy storage preliminary analysis

For the whole night ventilated classroom in summer, the night cooling energy Q_{cool} (kJ) due to night ventilation is determined by the following relation,

$$Q_{cool} = \int_{t_1}^{t_2} [Q_{fresh}\rho_{fresh}C_{fresh}(T_{indoor} - T_{fresh})]dt \quad (1)$$

where Q_{fresh} represents the supplying fresh airflow rates (m^3/h) by the night ventilation in the investigated classroom. Its specific thermo-physics have been respectively determined by the supplying air density ρ_{fresh} (kg/m^3) and the specific heat capacity of air C_{fresh} (kJ/kg K). The difference between indoor air temperature and exterior surrounding air temperature is $(T_{indoor} - T_{fresh})$ (K). t_1 and t_2 represent the start and end charging time of the night cooling energy in the investigated classroom (h).

With energy conservation, the night cooling energy Q_{cool} due to night ventilation equals the night cooling energy stored by the concretes within the ceiling $Q_{concrete}$ (kJ) and the night cooling energy stored by the other envelopes Q_e (kJ) in the investigated classroom as well as the energy loss during the process of energy conversion Q_l (kJ), i.e., being written as,

$$Q_{cool} = Q_{concrete} + Q_e + Q_l \quad (2)$$

Due to the thermo-physical properties of the concretes e.g., high density $\rho_{concrete}$ (kg/m^3), specific heat capacity $C_{concrete}$ (kJ/kg K) and thermal conductivity [5,7], meanwhile, Q_e and Q_l only occupy