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Experimental investigation of heat transfer during night-time ventilation

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ABSTRACT

Night-time ventilation is seen as a promising approach for energy efficient cooling of buildings. However, uncertainties in the prediction of thermal comfort restrain architects and engineers from applying this technique. One parameter essentially affecting the performance of night-time ventilation is the heat transfer at the internal room surfaces. Increased convection is expected due to high air flow rates and the possibility of a cold air jet flowing along the ceiling, but the magnitude of these effects is hard to predict. In order to improve the predictability, heat transfer during night-time ventilation in case of mixing and displacement ventilation has been investigated in a full scale test room. The results show that for low air flow rates displacement ventilation is more efficient than mixing ventilation. For higher air flow rates the air jet flowing along the ceiling has a significant effect, and mixing ventilation becomes more efficient. A design chart to estimate the performance of night-time cooling during an early stage of building design is proposed.

1. Introduction

In many countries, a trend towards increasing cooling demand has been observed especially in commercial buildings in the last few decades [1,2]. More extreme summertime weather conditions [3,4], higher internal and solar heat gains and increased comfort expectations give rise to an increase in building cooling demand. One possibility to face the increasing energy demand of air conditioning systems is the passive cooling of buildings by night-time ventilation. The basic idea of the concept is to ventilate a building during the night with relatively cold outdoor air. In the simplest case this can be done by opening windows or, if necessary, by using a mechanical ventilation system. By night-time ventilation heat accumulated in the thermal mass of building elements is being removed. During the next day the cool building elements absorb heat gains, which prevents an extensive increase in indoor temperature.

Krausse et al. [5] recorded the energy consumption and the internal temperatures and CO_2 levels in the naturally ventilated Lanchester Library at Coventry University, UK. Due to the exposed thermal mass and the night ventilation strategy the building meets thermal comfort criteria even during prolonged hot spells, using 51% less energy than a typical air-conditioned office. Another example for a passively cooled building is the KfW office building in Frankfurt, Germany. A monitoring study conducted in this building by Wagner et al. [6] showed, that even under extreme climate conditions acceptable thermal comfort conditions can be reached with passive cooling.

Despite many successful examples, architects and engineers continue to be hesitant to apply this technique in commercial buildings because of high uncertainties in thermal comfort predictions [7]. One parameter obviously affecting the efficiency of night-time ventilation is the heat transfer at the internal room surfaces [8]. In a previous study [9] a high sensitivity was found for combined (convection and radiation) heat transfer coefficients below about 4 W/m^2 K. Depending on the direction of the heat flow, standard heat transfer coefficients for combined heat transfer are in the range from 5.9 to 10 W/m^2 K [10]. However, during night-time ventilation radiation does not contribute to the heat transfer from room surfaces to the air (as air is virtually transparent for infrared radiation), but in fact transfers heat from one surface to another. For convective heat transfer standard coefficients are 2.5 W/m^2 K for vertical walls, 5.0 W/m^2 K for upward heat flow and 0.7 W/m^2 K for downward heat flow [11]. This means that, especially at the ceiling – a concrete ceiling often represents a significant share of the thermal mass of a room – the convective heat transfer can be very limited (downward heat flow during night-time ventilation). On the other hand a higher convective heat transfer is expected due to the increased air flow rate and the possibility of a cold air jet flowing along the ceiling [12–14].

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Nomenclature

A	surface area (m^2)
ACR	air change rate (ACH)
Ar	Archimedes number
c, c_p	heat capacity (J/kg K)
CCP	climatic cooling potential (Kh)
F	view factor
H	room height (m)
h	heat transfer coefficient (W/m^2 K)
$\dot{m}$	mass flow (kg/s)
Q	heat (Wh)
$\dot{Q}$	heat flow (W)
$\dot{Q}_0$	reference heat flow (W)
$\dot{q}$	heat flux (W/m^2)
T	temperature (K), (°C)
ΔT	temperature difference (K)
ΔT_0	initial temperature difference (K)
$\dot{V}$	flow rate (m^3/s)

Greek symbols

γ	convection ratio
ε	emissivity
η	temperature efficiency
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
τ	dimensionless time

Subscripts

cond	conduction
conv	convection
d	day
rad	radiation
tot	total
vent	ventilation

Several studies deal with the heat transfer at internal room surfaces. Different correlations were proposed for natural (e.g. Alamdari and Hammond [15], Khalifa and Marshall [16], Awbi and Hatton [17]) and mixed convection (e.g. Chandra and Kerestecioglu [12], Spitler et al. [18], Awbi and Hatton [19]) from horizontal and vertical surfaces. Based on such empirical correlations Beausoleil-Morrison developed an adaptive algorithm for the simulation of the convective heat transfer at internal building surfaces [20]. However, many of these correlations are based on experiments on small heated plates. A review comparing natural convective heat transfer at isolated surfaces and surfaces in enclosures revealed clear discrepancies [21,22]. This demonstrates the necessity of considering a room as a whole.

Geros et al. [23] compared monitoring data from a very heavy, massive and free floating building, where night ventilation was applied by natural cross-ventilation with thermal simulations. When the measured air flow rate was used as an input, the simulation model overestimated the performance of the night ventilation. The authors attribute this mainly to the non-efficient coupling of the air flowing through the building to the thermal mass (short circuit air flow). The effective flow rate was then found by adjusting the simulation model to result in the measured indoor air temperature. The ratio between the measured and the effective flow rate was found to be close to 0.3.

The effect of different flow patterns on the storage efficiency during night-time ventilation has been investigated by Salmerón et al. [24] using a 2-dimensional computational fluid dynamics model. A variation by a factor of 6 was found between different configurations of air in- and out-let openings. However, radiation between internal room surfaces was not considered. Furthermore, the impact of the air flow rate on the storage efficiency was not investigated.

This study provides a detailed analysis of convection and radiation during night-time ventilation depending on the air flow rate and the initial temperature difference between the inflowing air and the room. Heat transfer in case of mixing and displacement ventilation has been investigated in a full scale test room.

2. Setup of the test room

A test room at Aalborg University – a wooden construction insulated with 100 mm rock wool – was rebuilt for the experimental investigation of the heat transfer during night-time ventilation. For increased thermal mass a heavy ceiling element consisting of 7 layers of 12.5 mm gypsum boards was installed [25]. The walls and the floor were insulated with 160 mm (floor: 230 mm) expanded polystyrene (EPS). After installation of the insulation the internal dimensions were 2.64 m × 3.17 m × 2.93 m (width × length × height) resulting in a volume of 24.52 m^3. A vertical section of the test room is shown in Fig. 1, a detailed description can be found in [26].

The thermal properties of the materials used at the internal surfaces of the test room were measured or taken from literature (see [26] for details). The values used for calculations including estimated uncertainties are summarised in Table 1.

A mechanical ventilation system was installed to supply air at a defined temperature to the test room. The ventilation system was capable of providing an air flow rate of about 56–330 m^3/h, corresponding to 2.3–13 air changes per hour (ACH). For measuring the air flow rate, an orifice was installed in the supply air pipe to the test room. The pressure difference over the orifice was measured using a micro-manometer. The accuracy of the air flow measurement was about ±5%.

Two different configurations of the air in- and out-let openings of the test room representing mixing and displacement ventilation were investigated (Fig. 2). In case of mixing ventilation the air inlet to the test room was a rectangular opening of 830 mm width and 80 mm height located directly below the ceiling (Fig. 3). To obtain a more uniform velocity profile, two fleece filters were placed approximately 25 and 35 cm before the opening. For the air outlet there were two circular openings with a diameter of 110 mm close to the floor.

For displacement ventilation the same rectangular opening below the ceiling was used as outlet and a semicircular displacement inlet device was placed at the floor on the same side of the test room (Fig. 4).

3. Measurement instrumentation and location of sensors

For temperature measurements type K thermocouples connected to two Fluke Helios Plus 2287A data loggers with 100 channels each were used. The setup of the Helios data loggers using 178 channels for temperature measurement and 17 channels for temperature difference measurement is described in detail in [27]. The accuracy of the measurement system using the Helios data loggers was estimated to be ±0.086 K. The data loggers were configured to record temperatures at a sampling rate of 0.1 Hz.

The ceiling was divided into 22 sections (Fig. 5). At each of the 22 positions 5 thermocouples were installed in different layers (see