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Field-based study on the energy-saving effects of CO_2 demand controlled ventilation in an office with application of Energy recovery ventilators

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ABSTRACT

Field studies were carried out to investigate the thermal performance of ceiling-based HVAC systems, which typically consist of package air-conditioners and an energy recovery ventilator (ERV), and to test the energy-saving efficiency of CO_2-demand controlled ventilation systems with integrated ERV systems. Measurements from sensors placed in both the occupied zone (0–1.8 m) and the upper ventilation zone (at ceiling height) were taken in an environmentally controlled, open-type office, configured with workstation furniture and partitions. The distributions of temperature, relative humidity (RH), and CO_2 concentration were assessed throughout the test site for four scenarios. Tests were conducted to investigate the effects of the ERV, heat loss from the ducts, CO_2 demand control strategies, and contaminant patterns generated in a real office. Measurements showed that, with the application of an ERV system, the energy consumption of the air conditioning system could be reduced by 20–30% and that of the ventilation system, i.e. outdoor air load, likewise reduced by 60–70%.

1. 1 Introduction

Regarding the use of heating, ventilation, and air conditioning (HVAC) systems to provide acceptable, healthy, and productive indoor environments, there is widespread agreement that energy consumption will be increased dramatically all over the world [1–6]. Higher energy usage in buildings implies higher carbon dioxide emissions, which contribute to global warming. Ventilation load providing outdoor air intake is one of the dominant heating/cooling loads in buildings and in some cases represents nearly half of the total heating/cooling costs. Violations of regulations can also be caused by inappropriate ventilation design and control [7,8]. Additionally, proper recovery of energy from exhausted air can contribute to the improvement of cost-efficiency and sustainable design of buildings, thereby reducing global energy consumption while providing better indoor air quality (IAQ) at the same time. More specifically, this not only protects our global environment, but also makes our buildings less susceptible to the risk of sick building syndrome (SBS) [9–11].

Increased ventilation rates play an important role in decreasing the percentage of subjects dissatisfied with IAQ and the intensity of odors, and in increasing the perceived freshness of air [12]. Ventilation strategies should be designed in accordance with building codes/standards and scientific knowledge; however, there are cases which demonstrate that inappropriate ventilation design can result in disproportionate increases in energy consumption. Furthermore, in times of disaster and/or contingency, a delay or time lag in outdoor air supply through the ventilation system might not be sufficient, especially to evacuate peak levels of hazardous contaminants in target spaces.

CO_2 concentrations are often used for evaluating the adequacy of building ventilation performance according to Pettenkofer's view, particularly as it is believed that it is related to the dilution of pollutants stemming from human metabolic activity. Several guidelines and standards have proposed the use of carbon dioxide (CO_2) as an air quality indicator to control the outdoor ventilation rate in order to maintain reasonable IAQ without resulting in excessive energy consumption [13,14]. In accordance with this scenario, a CO_2 demand controlled ventilation (DCV) approach, which incorporates an optimization algorithm for outdoor air intake by monitoring the CO_2 concentration in a target space, was adopted decades ago. However, traditional CO_2 DCV systems are risky since numerous assumptions including air flow patterns, contaminant and fresh air distributions, sensor accuracy (and/or placement), and so on, and inadequate design of CO_2 DCV systems presumably

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results in serious ventilation rate errors. Various properties were confirmed based on chamber tests or numerical simulation for flow patterns and subsequent contaminant concentration distributions [15–17]. In addition, there is a lack of detailed data in the literature for field studies and validation work conducted using sustainable devices and control algorithms under real and typical office conditions. In other words, arrangement and accumulation of measurement data in the field, specifically targeting ventilation systems, will contribute to the development and improvement of ventilation design/strategy.

Against this background, in this paper the thermal performance of a traditional ceiling-based HVAC system with package air conditioners and energy recovery ventilators (ERVs) was investigated, and the energy saving and contamination control performance of a CO_2 DCV system were also measured in a real and typical office building. A primary objective of this research was to provide fundamental information evaluating performance of commonly used ERV and CO_2 DCV systems with respect to energy savings based on field measurement of a real/typical office in Japan.

2. 2 Method

2.1. Field measurement

The field measurements were carried out in an open-type office, the first floor of a typical two-storey office building located in Gifu prefecture, Japan. In this testing office, the overall heat transfer coefficient (generally called a *U* value) of the walls was estimated at 3.5 W/m^{2}K, and was associated with the thickness of constructed material, the sequence in which they were positioned, the conductivity of each building material, and the internal and external resistances of the construction elements (see in Table 1). The floor area of the target room was 418 m^2 (28.225 m × 15.45 m), and the height was 2.4 m. The target office space consisted of three zones: the main working space and two fitting rooms. Double-glazed windows were installed on the north and east walls of the main office space. The proportions of windows compared with the total area were 0.297 for the north wall and 0.251 for the east. Adjoining room spaces are partitioned by interior walls, and their air conditioning and ventilation systems are also separated. Overall, 44 workers were inspected in the office in typically sedentary conditions during normal working periods. This target office is a typical and featureless medium-scale office space in Japan. For detailed dimensional information and set up, please refer to our previous reported paper [18].

Four ERV units were implemented on the ceiling, with rated temperature exchange efficiency at 79% and enthalpy exchange efficiency at 70% respectively, and they provided 350 m^3/h ventilation rates and consumed 164 W rated power each. The ventilation system consisted of an exterior fan placed outdoor to exhaust contaminated air; ductwork with a diameter of 200 mm supplied fresh air into the ERV for sensible and latent heat recovery.

Each package air conditioner, or PAC (terminal units of an air-source heat pump system in an indoor space), was installed on the ceiling with a supply jet diffuser and a return slit; this supplied air more directly to the occupied zone instead of attempting to control the whole space. The air volume of each air conditioner was 1620 m^3/h and, in total, 7 air conditioning units were attached to the ceiling in the working office space as shown in Fig. 1. The air change rate, estimated as the air flow rate of the PAC system divided by the room volume, was 13.94 ACH.

During the field measurements, PACs were employed and operated to achieve indoor environmental conditions that comply with the Japanese energy conservation campaign (COOLBIZ campaign promoted by Ministry of the Environment (Japan) from 2005 [19]), with target temperatures of 28 °C in summer and 20 °C in winter. For the cooling and heating system in the site test, the coefficient of performance (COP) of the air source heat pump was 2.53–3.78 during the summer and 2.13–3.30 during the winter.

2.2. Instrumentation and layout

Continuous measurements of air temperature, relative humidity (RH), and CO_2 concentration within the target office were accomplished using lightweight sensors positioned at desired measurement heights to represent the occupancy condition in the space and located inside the ERV system. Table 2 summarizes the properties and the accuracies of the experimental apparatus. The air temperature and RH (HIOKI 3641; −40 to 85 °C, ±0.5 °C; 10–90%, ±5%, respectively) and CO_2 concentration (KNS-CO_2; 0–2000 ppm ± 50 ppm + 3% (at 25 °C)) were continuously monitored at 10 min intervals in the interior office space and also in the duct within the ERV. Power consumption (CK-F ±2%; TS4 ±5%) of the ERV and PACs were also continuously measured at 1 min intervals.

In the center of the office space, air temperature, relative humidity (RH), and CO_2 concentration were measured at a height of 1.5 m corresponding to the human breathing zone for sedentary subjects in compliance with 0.75–1.8 m above the floor as stated in the ASHRAE Standard 62.1 [1]. Measurements were carried out at representative locations that were secure from interference. To map a vertical section of temperature distribution in the testing room, a sensor was located on the ceiling with respect to the traditional overhead cooling supply air conditioning system. For testing the air properties at the supply inlet and exhaust outlet openings, sensors were placed on the duct terminal of a specific ERV unit and a PAC device. The plan view and spatial distribution of the measurement points for an ERV and a PAC are summarized in Fig. 1. Meanwhile, an internal view of the working space is also shown in Fig. 1.

2.3. Calibrations

All sensors were calibrated prior to taking field measurements. Regarding the accuracy, acceptable uncertainties of measurement were checked representing the actual value being measured during the pre-testing processes.

At the testing office, on-site investigation was carried out for a minimum of one week per condition. The first day was reserved for monitoring the environmental conditions without modifying any of the indoor climatic parameters. During four consecutive days, resistance–temperature detectors (RTD) were simultaneously used for temperature and humidity measurement to secure the measurement accuracy of temperature/humidity sensors in the office space. Calibration of the CO_2 sensors was performed using standard gas mixtures (0 and 1000 ppm) from cylinders and on random samples taken from each of the four sensors in the room. We then performed further relative sensor calibration in the early morning to ensure that the room had been unoccupied for at least eight hours, adjusting each sensor until all sensors were within an accuracy of ±2.5% of that of the outside CO_2 sensor.

In the subsequent results, the field measurement data, i.e. time series of temperature, humidity, CO_2 concentration and power consumption, were shown directly and the averaging operation was not given for the measurement results.

2.4. Experimental design

For investigating the energy consumption and the thermal and ventilation performance after the ERV implementation, a series of field measurements were collected in the real office space