Energy and Buildings 43 (2011) 2988–2997

Contents lists available at ScienceDirect

Energy and Buildings

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

Simulation of energy use, human thermal comfort and office work performance in buildings with moderately drifting operative temperatures

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ARTICLE INFO

Article history:
Received 7 September 2010
Accepted 10 July 2011

Keywords:
Building simulation
Thermal comfort
Work performance
Drifting temperature

ABSTRACT

Annual primary energy use in a central module of an office building consisting of two offices separated with a corridor was estimated by means of dynamic computer simulations. The simulations were conducted for conventional all-air VAV ventilation system and thermo active building system (TABS) supplemented with CAV ventilation. Simulations comprised moderate, hot–dry and hot–humid climate. Heavy and light wall construction and two orientations of the building (east–west and north–south) were considered. Besides the energy use, also capability of examined systems to keep a certain level of thermal comfort was examined. The results showed that with the moderate climate, the TABS decreased the primary energy use by about 16% as compared with the VAV. With hot–humid climate, the portion of the primary energy saved by TABS was ca. 50% even with the supply air dehumidification taken into account. The TABS working in a moderate climate kept the predicted percentage of dissatisfied (PPD) <10% during 60–80% of the working hours per year. Optimization of the TABS's control strategy (circulation pump dead-band, water supply temperature) resulted in significant reduction of the annual working hours with PPD > 10%; 1.4% in comparison to 17.5% h/yr. The highest estimated loss of occupants' productivity related to their thermal sensation hasn't exceeded 1% in whole year average.

1. Introduction

Current strategies for operation of buildings in developed countries often result in unsustainably high energy consumption. New types of climatic systems aim at low energy consumption and rely, for example, on a building's thermal mass in combination with night cooling/heating. Other systems provide cooling/heating by water circulated through pipes embedded in floors, walls or ceilings (thermo active building system – TABS). Such systems may be associated with daily drifts of indoor temperatures, but accepting some variation of temperatures during the day rather than to keep them steady, which is common in most air-conditioned buildings, has been shown to be a feasible means to reduce the building energy demand [1,2].

TABS offer the possibility to reduce the energy demand both on the "system" and "room side". On the system side, separation of ventilation and thermal conditioning of the space allows the ventilation system to be designed according to the desired indoor air quality. Thermal loads are extracted by the activated building construction (ceiling, floor or even walls) by means of radiation and partly convection [3]. At the same time, the thermal mass of the building construction accumulates thermal energy, which helps to reduce peak loads and justifies smaller installed heating or cooling capacity or, in some cases, even eliminates the need for mechanical cooling. Another advantage is that the temperature of the cooling/heating medium may be kept close to the room temperature, which allows utilization of renewable energy sources – heat pumps, ground heat exchangers, etc. [1]. On the room side, as a consequence of the heat accumulation, operation of the system does not keep a constant temperature, but may be associated with moderate drifts of indoor temperatures, also during the building occupancy period.

Recent research work by Kolarik et al. [4] has shown that moderate temperature ramps had no influence on the width of the comfort zone otherwise established under steady-state conditions [5], as long as the slope of the ramp was smaller than ±4.4 °C/h and continuous exposure to the ramp was shorter than or equal to 4 h. The study demonstrated that during continuous exposures lasting more than 4 h, temperature ramps contributed to enhanced intensity of headaches and other general SBS symptoms. This is in agreement with results of previous studies showing that increasing indoor temperatures in buildings may be associated with increased intensity of symptoms of fatigue, headache and difficulty in

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2011.07.008

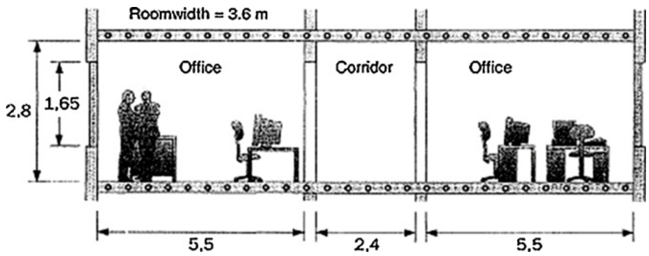

Fig. 1. Central room module used during the simulation, reproduced from Olesen and Dossi [2].

thinking clearly [6]. Also, a field study by Mendell et al. [7] found significant effects of temperature on the prevalence of SBS symptoms, even within the temperature comfort zone. Therefore, taking into account results of previous research, elevated intensity of SBS symptoms may be expected to negatively affect the performance of occupants' mental work. In the study by Kolarik et al. [4] increasing operative temperatures appeared to slightly decrease the speed of repetitive tasks that require mental efforts (addition and text typing). It has been shown that expenses incurred in employee salaries exceed building energy costs by a factor of 100 and maintenance costs by a factor of 10, and reduced energy consumption should therefore not be achieved at the expense of occupants' comfort, productivity or even health [8].

This paper summarizes results of computer simulations of energy consumption and indoor thermal environment of the building conditioned by means of the different HVAC systems: a commonly used all-air system and system involving activation of the building's thermal mass. The potential influence on office work performance of the thermal conditions resulting from using the selected systems was estimated.

2. Methods

The simulations, described in the present paper, were performed using the IDA Indoor Climate and Energy building simulation tool [9]. It allows simultaneous performance assessments of all building issues such as facade and wall construction, window glazing, HVAC systems, controls, indoor air quality, human thermal comfort and energy consumption.

2.1. Building model

The model used in all simulations included a central module of an office building with two offices separated by a corridor (Fig. 1). Both the corridor and each of the offices were treated as separate zones. The selection of the building module was based on earlier work by Olesen and Dossi [2]. Thermal characteristics of the building components are given in Table 1.

The building module was conditioned by three different systems – all-air variable volume system and thermo active building system with two different water pump operation schedules. Two types of wall construction (both internal and external walls) were examined. The heavy (320 kJ/m^2) construction was designed to have a higher thermal mass, while the light (14 kJ/m^2) construction consisted only of a steel frame and thermal insulation. Two orientations of the building module were examined – with windows facing east–west and north–south. All spaces adjacent to the central module were assumed to have the same internal temperatures as the test space, wherefore only heat transmission through external walls was considered.

2.2. Locations and meteorological data

Simulations were performed for three locations in the USA, each representing a different climate: San Francisco, Miami and Phoenix (Table 2). Typical Meteorological Year Version 2 (TMY2) [10] was used as climate data input. TMY2 was produced using an objective statistical algorithm to select the most typical month from long-term meteorological observations. The duration of cooling/heating period for each particular location was established using monthly average outdoor temperatures ($\theta_{m,aver}$); Table 2.

Total internal heat load in the office zones was considered approximately 630 W/zone (32 W/m^2). The load included heat production by two occupants, present in the building during week days from 8^{00} to 12^{00} and from 13^{00} to 17^{00}. Occupants' metabolic rate was considered to be approximately 1.2 met; that corresponds to about 238 W [13]. Office equipment (two computers and printer) were estimated to produce 350 W (long wave radiation fraction 50%) and ceiling light 50 W (convective fraction 50%) of heat. Heat loads from equipment and light had the same time schedule as occupants as it could be assumed that people switched off the light and their computers during the lunch break. Moisture production by occupants was taken into account in the zone model, calculation of the moisture load was done according to EN ISO Standard 7730 [13]. In addition, there was 100 W ceiling light as the only heat source in the corridor zone.

The windows in the office zones were equipped with two types of solar shading devices. When the solar radiation incident on an inside glass pane exceeded 100 W/m^2, an external window shading screen in dimensions 0.9 m × 3 m shaded the upper part of the window. Further increase of the solar heat gain above 200 W/m^2 activated internal blinds. When the internal blinds were drawn, the total shading coefficient of the window was multiplied by a factor of 0.65 and the short-wave shading coefficient of the window by a factor of 0.16. No effect of the internal blinds on the *U*-value of the window was considered. Both types of solar shading devices had simple two-position (on/off) control.

2.3. Description of the simulated climatic systems

(a) *Corridor* – CAV system (operation: weekdays 6^{00}–18^{00}); outdoor air change rate: 0.5 ACH (3.4 L/s); supplied air temperature: 19 °C; supply/exhaust airflow ratio: 1.
(b) *Office zones* – all-air ventilation (further abbreviated as VAV): VAV system with heat recovery (operation: weekdays 7^{00}–18^{00}; Sundays 8^{00}–24^{00}); maximum possible airflow: 16 L/s m^2 – 10 ACH/zone (for Phoenix increased to 30 L/s m^2 – 19 ACH/zone); minimum supply airflow: 2 L/s m^2 (39.6 L/s) (to keep acceptable indoor air quality [14]); on Sundays 70% of the required airflow was used; temperature of the supplied air: 19 °C; zone temperature set-point: 24.5 ± 1.5 °C (cooling period), 22 ± 2 °C (heating period).
(c) *Office zones* – thermo active building system (abbreviated as TABS): ceiling/floor concrete core conditioning was complemented with a CAV ventilation system with heat recovery (operation: weekdays 8^{00}–12^{00} and 13^{00}–17^{00}); supply airflow: 2 L/s m^2 (39.6 L/s) (to keep acceptable indoor air quality [14]); temperature of the supplied air: 19 °C; water circulation pump operation: 24 h/day with 22–23 °C dead-band; water mass flow rate 350 kg/h; inlet water temperature (θ_s) control: according to Eq. (1) established by Olesen and Dossi [2].

$$\theta_s[^\circ\mathrm{C}] = 0.52 \times (20 - \theta_e) + 20 - 1.6 \times (\theta_o - 22) \quad (1)$$

where θ_e is ambient air temperature [°C], θ_o operative temperature in the reference zone [°C]. The inlet water temperature was