Evaluation of Comfort Concepts with Tempered Air and Elevated Air Speed in Tropical Climate

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ABSTRACT

All too often today's buildings require massive resource input. The way we define the "comfortable" thermal conditions play a significant role in this environmental impact and the systems and energy required to air condition and cool our buildings. Adaptive comfort models, developed on the basis of field studies in tropical and subtropical climates, give evidence that extended operative temperature and humidity ranges are acceptable for indoor climate especially when combined with elevated air speed controlled by the occupants. Adaptive comfort typically can be achieved with less mechanical systems. The aim of this paper is to propose a low-energy, hybrid system design method as an alternative design strategy to "static" and deterministic HVAC control systems. In this context adaptive is not about changing people's comfort expectations, it is about changing environmental conditions, especially the air speed, to create comfort and to compensate for higher temperatures and humidities.

The non-governmental organization BRAC is planning a new university building in Dhaka, Bangladesh. To reduce resource consumption, technical systems and energy demand the design team is investigating alternative comfort strategies. The paper presents the design strategy, implementation in building simulation and analysis of thermal comfort concepts for a typical classroom. A conventional design for air conditioning according the static "comfort zone" is compared to a hybrid system design in regard to achieved comfort, required design of ventilation systems and energy demand. The thermal parameters of the building are assessed using the dynamical thermal simulation program TRNSYS 17 3D. Based on six environmental parameters the thermal comfort of the occupants is evaluated with the Standard Effective Temperature (SET) and the Predicted Mean Vote for elevated air speed (PMV_{eas}) according to the ASHRAE Standard 55-2013.

The design studies helped to develop a hybrid system comfort design which provides good fresh air quality and an excellent thermal comfort: A simple decentral mechanical system provides the room with tempered supply air of 20°C air temperature and dew point. In addition, ceiling fans provide air movement. Compared to conventional concepts of returned air with full heat recovery aiming on 26°C operative room temperature and 12 g/kg humidity ratio the energy demand is only about 75%. Both concepts provide the same comfort in terms of PMV_{eas}.

INTRODUCTION

Thermal comfort standards e.g. of ASHRAE [1] and ISO [2] are dominated by the studies and heat balance model works of O. Fanger, using the *Predicted Mean Vote (PMV)* as comfort index. Being carefully developed in mid-latitude climate regions systematic discrepancies were found, particularly in warmer zones, to explain observed thermal comfort in naturally ventilated buildings with the static "comfort zones" definitions based on the six comfort parameters in Fanger's PMV model [3]. Adaptive comfort models, developed on field studies in the tropics, as well as comparing naturally ventilated and air conditioned buildings give evidence that extended temperature and humidity ranges are acceptable [4].

Elevated air speed has long been used in practice as well as in the ASHRAE Standard 55 to offset higher temperatures in mechanically controlled indoor climates. With ASHRAE Standard 55-2013, Appendix G, a procedure for evaluating the cooling effect of elevated air speed using the *Standard Effective Temperature (SET)* is described. The *SET* can be calculated for a wide range of six environmental and personal parameters: *air temperature (T_{air}), mean radiant temperature (MRT), relative humidity (RH), average elevated air speed (v), clothing factor (clo) and metabolic rate (met).*

To evaluate the cooling effect of elevated air speed first the *SET* is calculated for the parameters and the given air speed (range: $0.15 \leq v \leq 3$ m/s). In a second step the air speed is replaced by still air (0.15 m/s) and an adjusted average air temperature is calculated to achieve the same *SET* as before. With this adjusted average air temperature, the air speed of still air and the four remaining parameters the *Predicted Mean Vote for elevated air speed (PMV_{eas})* is calculated and can be used for comfort evaluation and comparison [1, Appendix G and B]. This procedure was implemented into building simulation. To be useful for the evaluation and design of alternative comfort and climate concepts the method is implemented in a way that the required air speed to create the same perceived comfort - or in other words the same *Predicted Mean Vote for elevated air speed (PMV_{eas})* as for the reference case - could be determined by the simulation code representing an occupant controlled fan to increase air speed as required. An exemplified tool including PMV_{eas} is the Internet CBE Thermal Comfort Tool developed at the University of California Berkeley [5].

To summarize: the implemented procedure allows evaluating the different design strategies with the 7-point scale of thermal sensation, defined as follows: hot (+3), warm (+2), slightly warm (+1), neutral (0), slightly cool (-1), cool (-2), cold (-3) and compare with the analytical comfort zone model of Standard 55-2013, chapter 5.3.2. Compliance is achieved when $-0.5 < PMV_{eas} < 0.5$, which is equivalent to a satisfaction of 90% of the occupants with the environmental conditions.

THE PROJECT

The non-governmental organization BRAC is currently planning a new university building in Dhaka, Bangladesh. BRAC is particularly interested in a sustainable building concept which creates best comfort in the local context. The architects commissioned are WOHA, Singapore, who are experienced in the design of naturally ventilated buildings in the tropics. For comparison study, the School Of The Arts (SOTA) in Singapore, also designed by WOHA Architects, serves as a role model: Wherever appropriate, the classrooms are naturally ventilated and thermal comfort is enhanced with ceiling fans to elevate air speed in the occupied zone. The passive building design and the elevation of the classrooms above ground reinforce natural ventilation by prevailing wind directions. Air conditioned zones are reduced to a minimum.

To cross check the proposed design strategy and to familiarize the design team with the strategy evaluating thermal comfort with the *SET* and PMV_{eas} a short comfort survey was made at SOTA. The classroom (Figure 1) was surveyed for an ambient air temperature of 30°C and an air humidity ratio of 17.5 g/kg. This represents a typical outdoor climate of Singapore's summer period. The measured local air speeds are in the range of 0.4 to 1.0 m/s (Figure 1). The results showed that for the given parameters the environment is comfortable (none of the occupants wanted to change clothing nor to change air speed). The survey provides an additional confirmation that the proposed design parameters *SET* and PMV_{eas} can be used for comfort evaluation in the tropics. Mentioned work on adaptive comfort models underlines this conclusion [4].

Occupancy
23 pupils
1 teacher

Room geometry
Area: 80 m²
Height: 3.5 m

Doors
operable, on two sides of the room

Windows
opposite on two sides of the room

Six ceiling fans

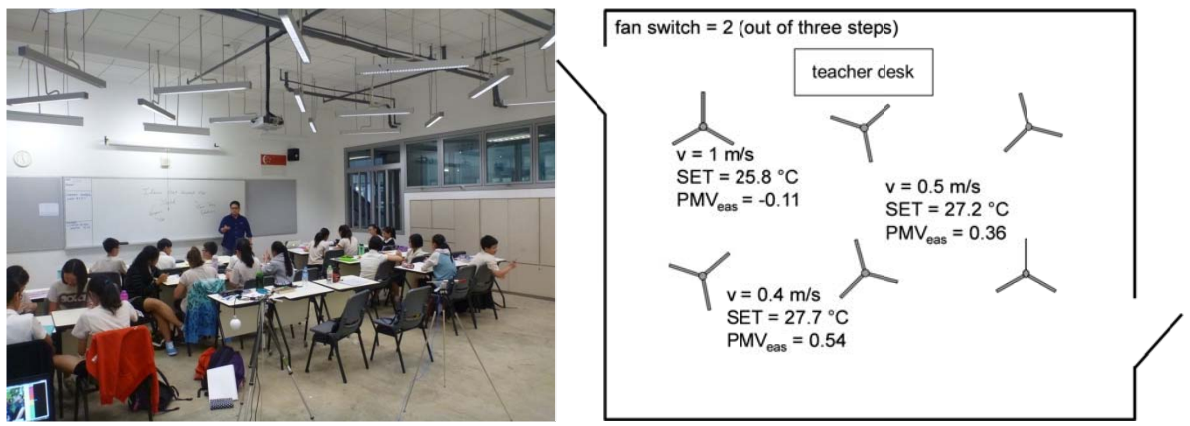

Figure 1 left: classroom at SOTA; right: local air speed and comfort measurements, top view plan of the classroom [6].

Compared to Singapore, Dhaka's summer climate differs significantly in terms of humidity ratio and ambient air temperature (Figure 2).

As a consequence, the BRAC University comfort design could rely on natural ventilation for the winter period, but not for the hot and humid summer time.

Thus, based on the original design concept of the SOTA classrooms energy efficient comfort design strategies for a typical classroom of BRAC University have been compared, analyzing the difference between a conventional fully air conditioned and a hybrid system concept for the Dhaka summer period.

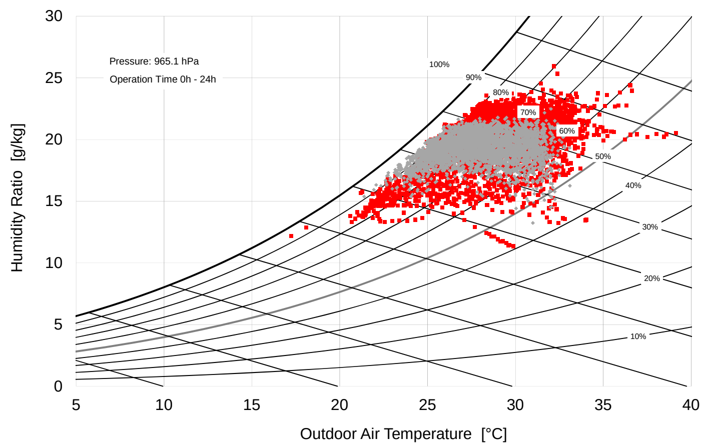

Figure 2 Psychrometric chart with IWEC Singapore (grey) and SWERA Dhaka (red) summer climate data

IMPLEMENTED BUILDING SIMULATION METHOD

All environmental parameters (room geometry, internal and external loads, occupancy, buildings physics, ventilation, cooling power, etc.) are modelled with the dynamical thermal simulation program TRNSYS 3D on an hourly base. In a second step the thermal comfort is modelled based on the calculated environmental parameters and the control strategy of the fans using the *Engineering Equation Solver (EES)* where the codes for SET and PMV_{eas} have been implemented according to the ASHRAE Standard 55-2013.

The simulation model

The thermal simulation work was carried out for a typical classroom model of BRAC University in Dhaka with dimensions 9.0*9.0*3.1 m³. The east and west façades are 30% glazed, semi-outdoor hallways affiliate on the outside. The hallways are naturally shaded by façade plants. For a typical university schedule, the classroom's operation time includes weekdays from 07:00 to 17:00, fully occupied by 40 students. Sedentary activity with 70 W sensible and 65 g/h (40 W) latent load per student as well as adaptive clothing from 0.5 to 1 clo were assumed. In Table 1 the major characteristics of the classroom model are summarized.

Table 1. Simulation settings for the classroom model used in TRNSYS 17 3D

Climate, Shading & Geometry		Time Settings & Occupants		Internal Loads & Air Supply		
Climate Data	SWERA Dhaka	Time	May - Oct	Occupants	110	W/Pers
Shading West/East	External	Operation Day	07:00 - 17:00	Electrical Loads	5	W/m²
Classroom Area	81 m²	Total Operation Hours	1320 h	Artificial Light	10.5	W/m²
Classroom Volume	251 m³	Occupants Number	40	Air Supply	30	m³/Pers

Conventional comfort design with full air conditioning and fan coil cooling

In the tropics, the typical climate concept for offices and public buildings is closed façades combined with full air conditioning. So for the conventional case, a climate concept with conditioned supply air and heat recovery from the returned air combined with fan coil cooling was chosen (Figure 3). Aiming at 26°C operative temperature and 12 g/kg humidity ratio, this system fulfills the conventional "static" PMV comfort standard. For evaluation the following design assumptions are made: Fresh air supply is set to 30 m³/h*pers in order to achieve good air quality for an university environment. Fresh air is supplied with 20°C and a dew point temperature of 14°C (10 g/kg), the latent and sensible heat recovery is 75%. The fan coil unit is designed to cool the room air to maximum 26°C operative temperature and to keep room air humidity ratio below 12 g/kg. Infiltration is set to 0.2/h. In this system the air conditioning is introducing fresh air, cooling, dehumidification and air circulation (to be distinguished from the air movement in the hybrid system: see next sub-chapter).

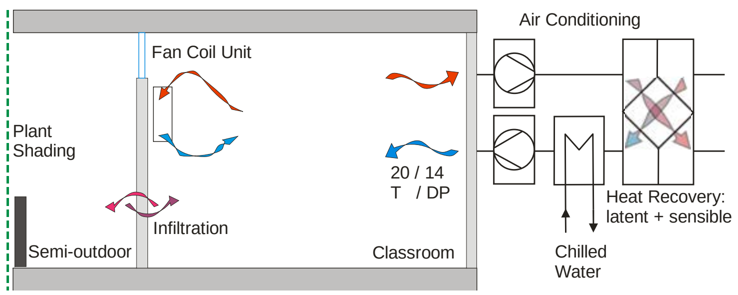

Figure 3 Conventional comfort design with full air conditioning and fan coil cooling

Hybrid system comfort design, decoupling cooling from air movement, with tempered air and elevated air speed

For the hybrid system comfort concept fresh air is supplied with also 30 m³/h*pers to the room. The supply air is tempered, meaning cooled to 20°C (resp. 22°C) air temperature and dew point (equal to 14.7 resp. 16.7 g/kg) only. The supplied air is pressurizing the room and spilling over to the hallways, which minimizes infiltration (Figure 4). The condensate from the decentralized supply air units is used for irrigation of the façade plants.

To establish constant comfort, six ceiling fans with controlled air speed are used in addition. Air velocity is automatically elevated in two steps from 0 to 0.7 to 1.2 m/s, if perceived comfort exceeds 0.5 PMV_{eas}. This is set to be in line with recommended limits for air speed of sedentary work (0.7 m/s) and maximal air speed under occupant control (1.2 m/s) according to ASHRAE Standard 55.

For further comparison a design without any mechanical ventilation but natural window ventilation (air change rates, driven by thermal boundary conditions, range from min. 4.8/h to about 10/h) and elevated air speed with ceiling fans has been compared (see next chapter).

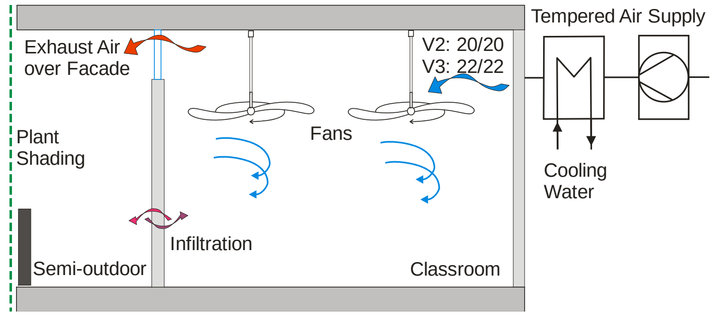

Figure 4 Comfort design with tempered air and elevated air speed

RESULTS AND DISCUSSIONS

In Table 2 the four variants of different comfort designs are compared. The first variant V1 stands for the conventional comfort concept of full air conditioning and fan coil cooling. The variants V2 and V3 are based on the comfort design of tempered air and use of fan. V4 represents the fully natural ventilated design with no air tempering but use of fans.

Table 2.Variants of comfort design for a typical classroom

Variant	Ceiling Fan	Fan Coil Unit	Mechanical Ventilation T_{supply} [°C]	Mechanical Ventilation $T_{dewpoint}$ [°C]	Heat recovery [%]
V1	No	Yes	20	14	75
V2	Yes	No	20	20	-
V3	Yes	No	22	22	-
V4	Yes	No	-	-	-

All four variants have been evaluated on the same basis with PMV_{eas} for the purpose of comparing the achieved comfort. Figures 5 and 6 show that for V1, V2 and V3 the achieved PMV_{eas} is in the range of 0.2 to 0.5. Thus, those variants provide excellent comfort. In contrast, V4 provokes uncomfortably warm conditions, even though fans are at high air speed of 1.2 m/s (Figure 8). Its PMV_{eas} increases up to typically 2, in maximum to 3. Thus, V4 is not discussed any further.

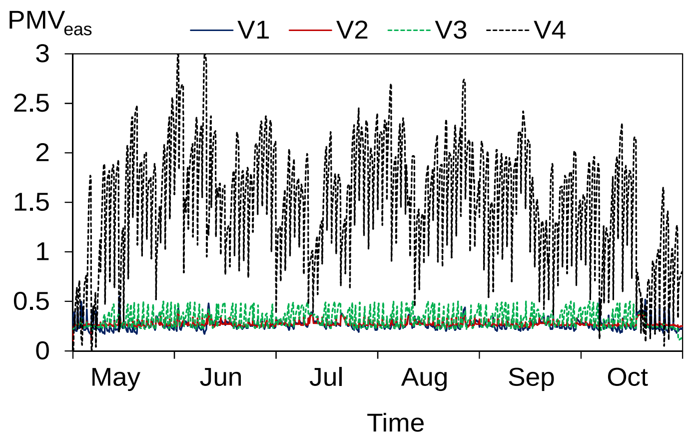

Figure 5 PMV_{eas} curves of comfort design variants over Dhaka's summer period

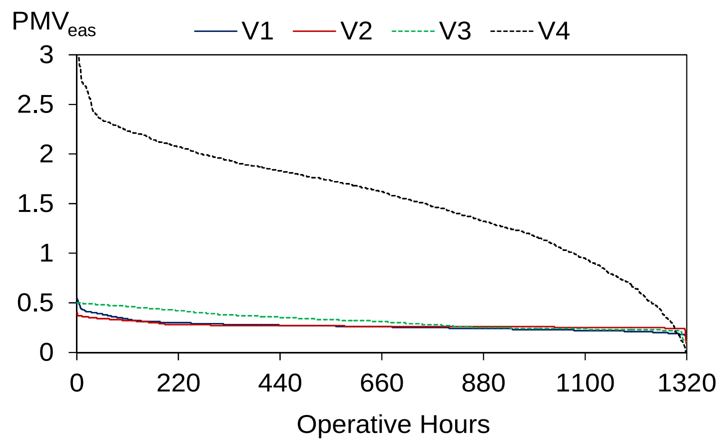

Figure 6 Sorted PMV_{eas} curves of comfort design variants over Dhaka's summer period

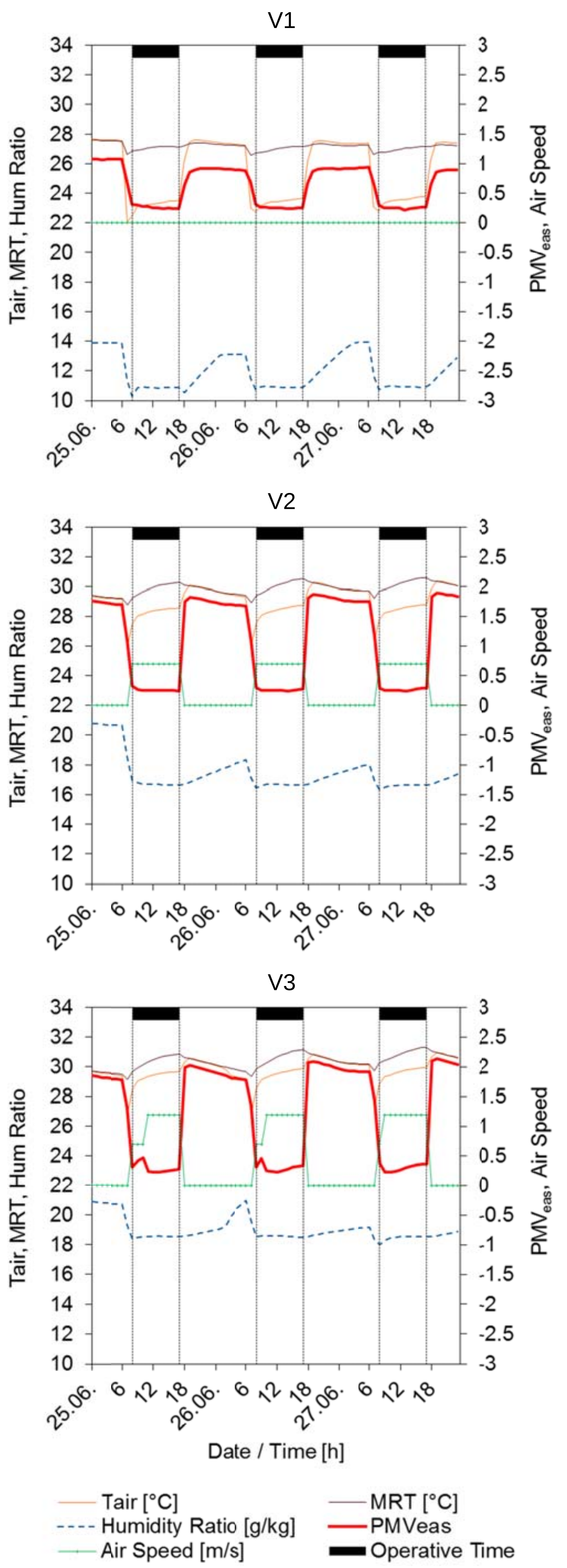

Figure 7 Design day chart showing the achieved PMV_{eas} and its major parameters for the compared variants [7]

Figure 7 on the left gives a detailed comparison of the parameters' interaction for variant V1, V2 and V3. Three design days in June were chosen to represent a typical summer situation in Dhaka. The results from the thermal simulation were used as input parameters for comfort calculation [7]. T_{air}, MRT and humidity ratio are plotted on the left ordinate. Determined fan step as well as resulting PMV_{eas} are shown on the right scale. Black plotted bars at the diagram's top indicate the occupants' operative time.

V1 leads to average values for T_{air} with 23.5°C and MRT with 27°C, and to a reduced average humidity ratio of 11 g/kg (Figure 7, diagram at the top).

In contrast, the hybrid variants allow higher T_{air} and MRT values between 28°C and 31°C and higher humidity ratio of 16 to 18 g/kg. The impact of high temperatures and humidities is compensated by elevated air speed causing comparable PMV_{eas} values in the range of 0.2 to 0.4 during occupation.

The comparison of V2 and V3 shows that a fan speed of maximal 0.7 m/s is sufficient for V2, whereas the slightly warmer and more humid environment in V3 requires 1.2 m/s for most of the operative time in order to keep the PMV_{eas} at the same range (Figure 7, middle and bottom diagram). To provide the same comfort in all variants with fan, the six ceiling fans run constantly during the 1320 h of occupation (Figure 8).

V2 establishes good thermal comfort while constantly using the lower fan step of 0.7 m/s at all 1320 hours of operative time. With V3 a higher average air speeds is necessary due to the reason mentioned above. Almost one third of operative time the higher fan step of 1.2 m/s is required. If this would be acceptable to the users the energy savings would be about - 42% (Figure 9).

But as ASHRAE 55 recommends limiting air speed for sedentary activity in the occupied zone, V2 with 0.7 m/s air speed is the preferred variant even though the energy savings are less with - 25%.

The comparison of the variants' energy demand (Figure 9) gives evidence that substantially less mechanized concepts can achieve significant energy savings even though no heat (cold) recovery is installed.

As room air temperature and humidities are higher compared to conventional systems additional sensible and latent heat recovery would be less effective. For V2 cooling energy could be reduced e.g. from 66 to 45 kWh/m²a, but a full sensible and latent hreat recovery system (75%) would be required.

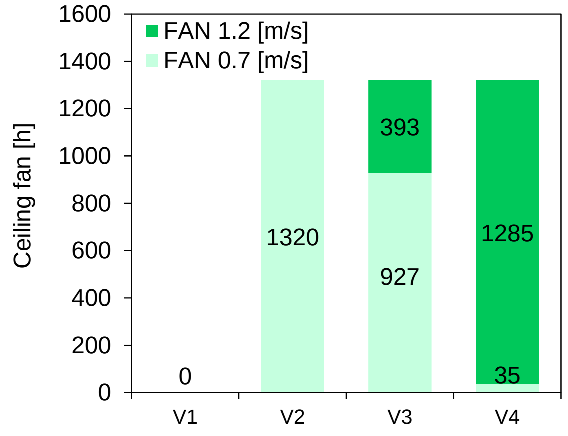

Figure 8 Running hours of fans of each variant, accumulating to 1320 h of total operative time

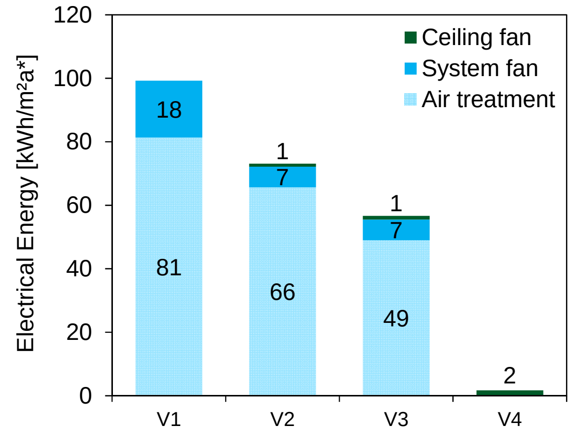

Figure 9 Electrical energy demand of each variant for ventilation, cooling and dehumidification (COP 3)

CONCLUSIONS

The paper's purpose is to investigate whether a hybrid system comfort design can lead to significant energy savings while providing equal comfort compared to the conventional concept of full air conditioning and fan coil cooling.

Methodology, implementation in building simulation, and analysis of thermal concepts for a typical university classroom in Dhaka, Bangladesh, have been carried out. The implemented method based on ASHRAE's SET-PMV comfort evaluation for elevated air speed proved to be a powerful tool to explain thermal comfort achieved with 100% fresh air supply of tempered air and the use of ceiling fans as typically installed.

Based on the results, a hybrid system comfort concept with dedicated fresh air supply is proposed which provides good fresh air quality with 30 m³/h*pers and excellent thermal comfort. A simple decentral mechanical system is proposed to supply the fresh air at 20°C temperatures and dew point. In addition, ceiling fans provide acceptable air movement during operative time. Compared to the conventional concept of conditioned air with full heat recovery aiming on 26 °C operative temperature and 12 g/kg humidity ratio, energy savings are about 25%.

The supply air systems can be installed decentral and operated per room in case of occupation only. Typical installations for mechanical rooms with central air conditioning systems, heat recovery, insulated supply and return air ducts in false ceilings, vertical shafts etc. are not required. The substantially lighter hybrid system will have lower investment costs of the system itself as well as for the building as less space is used for the air handling systems and will allow a more simplified building envelope design and thermal zoning of the university building.

It is to be noted that achieved comfort of the systems analysed is comparable, while their influencing environmental parameters configure in two complete different ways: the hybrid system variant provides comfort with high operative temperatures and high humidity compensated by elevated air speed, whereas systems with full air conditioning and fan coil cooling run on low operative temperatures and low humidity without elevated air movement.

While similar built examples of hybrid systems exist, the paper's outcome fills the gap of a missing methodology to assess hybrid comfort designs in tropical climates. The method proved to be useful for these design evaluations.

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