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ENERGY SIMULATION AND ANALYSIS OF AN INTERMITTENT VENTILATION SYSTEM UNDER TWO CLIMATES

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Abstract

Energy use on heating, ventilation and air conditioning (HVAC) accounts for about 50% of total energy use in buildings. Energy efficient HVAC systems that do not compromise the indoor environmental quality and at the same time meet the energy reduction directives/policies are necessary and needed. The study herein, evaluates the energy saving potential of a newly proposed ventilation system in spaces with high occupancy density, called Intermittent Air Jet Strategy (IAJS). The aim of the study was to evaluate through simulations the potential energy savings due to IAJS as compared to a mixing ventilation (MV) system in a classroom located in a 'hot and humid' climate (Singapore), and in a 'hot and dry' climate (Kuwait). The analysis is based on IDA Indoor Climate Energy simulation software. The results herein demonstrate significant reduction of cooling energy use of up 54.5% for Singapore and up to 32.2% for Kuwait with IAJS as compared to MV. Additionally, supply fan energy savings can also be realized if well implemented.

Keywords: Intermittent air jets; Energy simulation; Energy saving, Setpoint extension, Convective cooling

1 INTRODUCTION

Energy concerns are a daily ubiquitous topic due to challenges of our current energy economy and its impact on climate change. The rising energy demand necessitates aggressive reforms on energy use, conservation and efficiency, especially so because of validated assertions of a causal relationship between energy demand and greenhouse gas (GHG) emissions [1, 2]. One sector with a rising energy demand is the built environment, which currently uses more than 40% of primary energy and accounts for 30 – 40% of GHG emissions [3], of which heating, ventilation and air conditioning (HVAC) takes about 50 % of the total building energy use. Common consensus in literature shows that changes on HVAC *modus operandi* can yield substantial energy savings more so on cooling requirements. Studies [4, 5] have shown that strategies that offer possibilities to extend air temperature setpoints have a high energy saving potential on building energy use.

Intermittent air jet strategy (IAJS), which is a high-momentum air distribution system, was recently proposed for use in high occupant spaces. The strategy optimises intermittent air speeds to increase convective cooling and penetration of the supply airflow into the sitting zone [6, 7]. Figure 1 illustrates the implementation possibilities either as a primary system (Fi. 1A) or as a secondary system (Fi. 1B; for spaces with existing HVAC systems or in climates where cooling is occasionally needed).

Kabanshi et al., [6] introduced and evaluated the concept of IAJS with objective measurements. Using the air jet diffuser made out of a 160 mm diameter ventilation duct fitted having a single row of specially designed circular nozzles (d_0 = 10 mm, equidistant spacing of 1.4d_0) and placed overhead at 1.2 m and 2.3 m from the breathing height and the floor, respectively. The diffuser installation covered the sitting column of the occupied zone. He explained the operational construct and proposed 0.4 m/s and 0.8 m/s as minimum and maximum operational velocities.

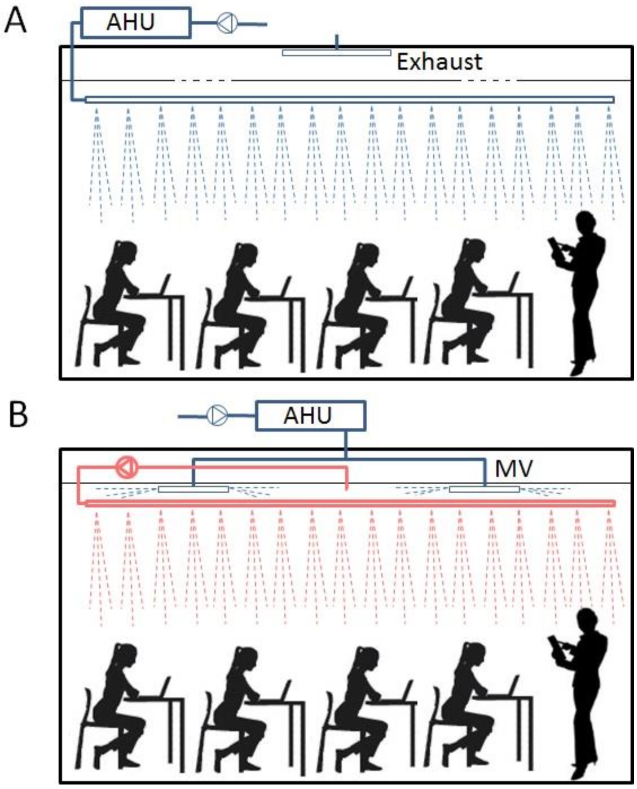

Figure 1: (A) IAJS as a primary system. (B) IAJS as a secondary system

A human response study to IAJS [7], showed that the system can offset the upper operative setpoints by 2.3 – 4.5 ºC by introducing intermittent air speeds between 0.4 and 0.8 m/s in the occupied zone. This translates to indoor operative temperature limits of 23.7 ºC to 29.1 ºC. This is critical for comfort and system energy use as the HVACs deadband or the indoor operational setpoints can be increased [4].

The predicted temperature range, gives insight on applicable climatic conditions suitable for implementation of IAJS as a primary ventilation system or as a secondary system. We can deduce that IAJS as a primary system would be most effective in indoor climate were temperatures are around/above 23.7 ºC throughout the year. As a secondary system or as a room induction unit, the strategy can work in almost all climates and it is easy to implement in buildings with existing HVAC or other air distribution systems and will only recirculate and increase room air speeds to offset increased room air temperatures.

The current study explores, by means of simulation with IDA Indoor Climate and Energy (ICE) software, the energy saving potential associated with IAJS if implemented as a primary air distribution system in “hot and humid” and in “hot and dry” climates.

2 METHODS

2.1 Room and HVAC Description

A single zone classroom with a lighting load of 13 W/m^2 and occupancy capacity of 30 students was simulated. The room has a floor area of 10 m x 6.4 m, and a ceiling height of 3 m. External wall is made of 280 mm medium-weight concrete (0.66 W/m·K) and the wall has 20 mm cement plaster (1.4 W/m·K) on both sides, resulting in an overall U-value of 1.8 W/(m^2·K). The room has four double pane windows (width = 1.2 m, height = 1.3 m), made of a 12 mm air gap with 4 mm glasses on both sides, and each has an overall U-value of 2.54 W/(m^2·K). The windows are on the wall facing south and have a solar heat gain coefficient of 0.37 and a light transmittance of 0.44. They are integrated with shading blinds between the panes, which activates when the incident light hitting the windows is higher than 100 W/m^2. All walls except the outer wall were considered adiabatic.

The ventilation system was set to run during weekdays between 6:00 AM and 7:00 PM. For simplicity, all cases were assumed fully occupied during this time. There was no ventilation at night and during weekends, but the model was integrated with an infiltration leakage equivalent to 0.012 m^2, amounting to a wind driven air change rate of about 0.52 ACH when the pressure difference across the between envelop was 4 Pa.

Supply air conditions were met with the air-handling unit (AHU) and the room had an internal cooling unit to keep the room temperature within the specified air temperature limits. In the simulation, we used an ideal cooling unit with a coefficient of performance (COP) of 3 and unlimited cooling capacity. No heating was done on either the supply air or room air. Thus, supply temperature was the same as outdoor temperature in conditions when the outdoor air temperature dropped below the supply temperature setpoint. Additionally, only sensible cooling was done on the supply air temperature.

2.2 Simulated Climates and Cases

Two climates characterised by hot and humid (Singapore), and hot and dry (Kuwait) were simulated. ASHRAE weather files were used as input data and simulations were done for 2016. Comfort conditions used for Singapore were based on values used by Schiavon et al., [8], room temperature setpoints of 22.5 °C to 24 °C under MV. For Kuwait, the maximum indoor temperature used was 25.6 °C based on neutral temperature estimated with ASHRAE *Standard* 55 [9] at clothing level of 0.51, 1.2 met and relative humidity of 30%.

Table 1 shows the simulated cases, MV_{ref} is mixing ventilation with 10 l/(s.pr) airflow-rate (Q), 16 °C supply temperature (T_s), 24 °C and 25.6 °C maximum allowed room air temperature (T_{max}) for Singapore and Kuwait, respectively. The airflow rate was based on ISO 7730 [10] for a Category I building.

Cases with IAJS are represented as shown in Table 1. For example, IAJS-0.4-16 means IAJS with room air speeds of 0.4 m/s and supply temperature at 16 °C. Intermittency was generated by scheduling the supply fan to run with a cycle of 6 min (3 min on and 3 min off) for the occupancy period. Two airflow rates are simulated based on proposed operational velocity limits: 0.4 – 0.8 m/s. Kabanshi et al.,[6] found that the generated velocity at breathing height within the jet was proportional to the air flowrate. Fan settings of 10 l/(s.pr) resulted in air speed of 0.4 m/s, thus to generate 0.8 m/s the airflow rate extrapolates to 20 l/s. The maximum allowable indoor air temperatures under IAJS were expanded based on estimates from the overall thermal sensation (OTS) model proposed for IAJS shown below:

$$OTS = 0.31ta - 1.72V - 7.15 \quad (1)$$

Where, V is the air speed measured at 1.1 m from the floor and ta is the room air temperature. Details of the model are discussed here [7]. At 0.4 m/s, 23.7 °C was the minimal temperature and at 0.8 m/s, 29.1°C was the maximum temperature in compliance with acceptable thermal sensation range (-0.5 to +0.5) as stipulated in ASHRAE *Standard* 55 [9]. Thus, 23.7 – 29.1 °C is taken as the operable indoor temperature range for IAJS. 24 °C is used as the T_{max} in all cases with 0.4 m/s and with 0.8 m/s the temperature range is 23.7 – 29.1 °C, simulated with different supply air temperatures.

Table 1. Simulated cases

Singapore			
Case	T_s [°C]	T_{max} [°C]	Q [l/s.pr]
MV_{ref}	16	24	10
IAJS-0.4-16	16	24	10
IAJS-0.8-16	16	29.1	20
IAJS-0.8-18	18	29.1	20
IAJS-0.8-20	20	29.1	20
IAJS-0.8-22	22	29.1	20
IAJS-0.8-24	24	29.1	20
Kuwait			
Case	T_s [°C]	T_{uo} [°C]	Q [l/s.pr]
MV_{ref}	16	25.6	10
IAJS-0.4-16	16	24	10
IAJS-0.8-16	16	29.1	20
IAJS-0.8-18	18	29.1	20
IAJS-0.8-20	20	29.1	20
IAJS-0.8-22	22	29.1	20
IAJS-0.8-24	24	29.1	20

* Velocity in m/s at breathing height.

3 RESULTS AND DISCUSSION

The energy needed to meet the specified ventilation conditions is defined, as cited by Schiavon et al., [8] from CEN/TR 15615-2007 as, the sum of energy needed to cool the supply air (AHU Cooling) and to cool the room air (Room Cooling) in order to obtain and maintain the specified conditions for a given occupancy period. This section presents the energy simulation results and analysis of the considered cases.

3.1 Hot and Humid climate (Singapore)

Figure 2 shows the annual energy use per square meter for the simulated cases based on 2016 climatic conditions for Singapore. As shown, the simulated annual energy use for the reference case was 731.7 kWh/m^2. Comparing cases with IAJS shows a reduction in the total energy use by 13.5 – 54.5%. While in most cases the AHU cooling energy use reduced, the room cooling energy use increased. Case IAJS-0.8-16, IAJS-0.8-18 and IAJS-0.8-20 show minimal requirements on room cooling as there was a reduction of 100%, 16.8% and 33.8% on room cooling compared to the supply case, respectively. This offers an option to reduce installation costs or sizing on room cooling units.

Case IAJS-0.8-24 gave the highest total energy savings of about 52.4%, resulting in an increase of 16.2% in room cooling and 65.7% reduction on AHU cooling energy need. However, *PMV* (Predicted Mean Vote) and *PPD* (Predicted Percentage of Dissatisfied) were slightly above +0.5 and 10% respectively (See Table 2). All other cases had met the requirements of -0.5 < *PMV* < +0.5 and *PPD* < 10%. Case IAJS-0.8-22 had a reduction on both room cooling (88.4%) and AHU cooling (33.8%) resulting in a total energy saving of 41.4%.

Interestingly, IAJS with 0.4 m/s (IAJS-0.4-16) and same settings as MVref, had a total energy reduction of 29%, although room cooling requirements increased twice as much but AHU cooling reduced almost by half (49.8%). However, CO_2 concentration were higher (1485.6 ppm) compared to MVref (1070.7 ppm). Kabanshi et al.,[6] found that IAJS running at 10 l/s was equivalent to a system running continuously with airflow of 8 l/(s.pr). Simulation of a continuous system with 8 l/s (not reported here) showed a drop in CO_2 concentration to 1102.8 ppm. All other cases with IAJS (0.8 m/s) had CO_2 concentration similar to the reference case.

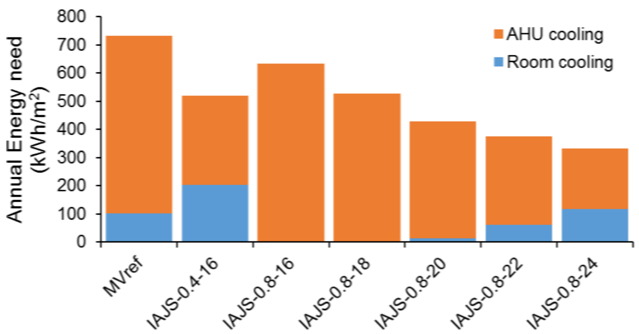

Figure 2: Annual cooling energy need

3.2 Hot and Dry climate (Kuwait)

Figure 3 shows the annual energy use per square meter for Kuwait based on 2016 climatic conditions. The total annual energy need for a MVref was 319.3 kWh/m^2. Introducing IAJS with a lower room setpoint (IAJS-0.4-16) increased room cooling needs (200%) but reduced AHU cooling needs (49.8%) resulting in an overall reduction on total energy need of 21.6%. IAJS with air speed of 0.8 m/s gave a reduction in energy need from 8.4 to 32.3%. As shown, above supply temperature of 20 ^{o}C, any increase in the supply temperature had little influence on the total energy saving but an influence on the room cooling requirements.

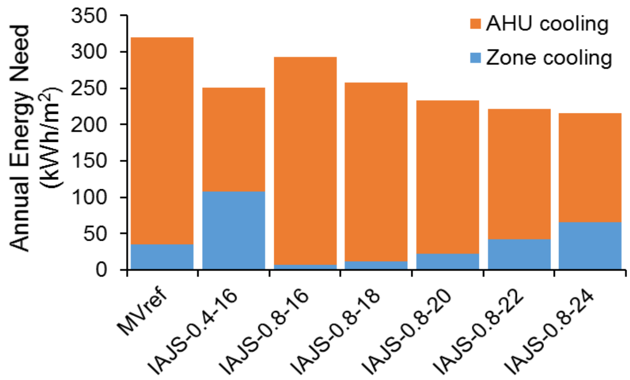

Figure 3: Annual cooling energy need

Comfort analysis showed that *PMV* ranged between -0.33 and +0.35, and *PPD* ranged between 4.22 and 8.74. In January, the average indoor operative temperature was 22.8 ^{o}C, lower than the limit of 23.1 ^{o}C proposed for IAJS. Relative humidity was between 24.6 and 43.7%. CO_2 concentration were similar to the results for Singapore.

3.3 Fan Energy Use

Figure 4 shows the fan annual energy need for each supply airflow rate. MVref had an annual energy need of about 27.2 kWh/m^2. IAJS with 10 l/s (corresponding to 0.4 m/s) gave a 68.1% reduction in fan energy use while IAJS with 20 l/s (corresponding to 0.8 m/s) had a 35.2%. These results marry with the hypothesis by Kabanshi et al.,[6] that IAJS as a primary system would offer energy saving on the supply fan close to 50%. However, realistically the instantaneous power demand on the supply fan is expected to increase due to an increase in system pressure and delivery of elevated air speeds in the room, thus energy savings due to intermittency operation would not be as high as the ones obtained in this study. The fan energy savings obtained in this simulation should be interpreted with caution, as it is unclear whether the simulation software accounts for the increase in room air speeds on the supply fan energy use.

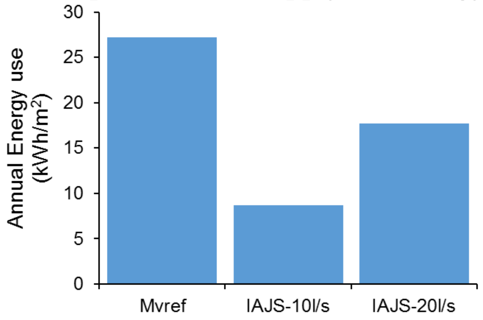

Figure 2: Fan energy use

3.4 General Discussion

Under Hot and humid climate, increasing the supply temperature with IAJS has a larger effect on the energy need for AHU cooling as it reduces both sensible and latent heat in the humid air. Thus if we compare Fig. 2 and 3, we see that the reduction on the total energy need increases with increase in supply temperature for Singapore than for Kuwait (dry air) were the supply temperature has a little influence on the total energy use but has an effect on the room cooling requirements.

Schiavon et al., [8] and Yang et al., [11] reported that under personalized ventilation supply temperature has minimal influence on total energy use in hot and humid climates, this is opposite to the results obtained under IAJS herein. One explanation could be because IAJS has a wider operational room temperature range as compared to that used by Schiavon and Yang. The wider room temperature range can also be an advantage to encourage personal adjustment. Whereas, the system air speeds can be varied automatically based on the relationship between air speed and room temperature defined by Equation 1 for a neutral thermal sensation. Occupants would have freedom to adjust their comfort outside the neutral condition settings. This will reduce on complaints of over cooled indoor spaces, which is usually the case in places like Hong Kong and Singapore [12].

4 CONCLUSION

The results here in give an insight on the energy saving potential of IAJS if implemented as a primary system in high occupant spaces. Based on the simulated cases and setup, the results shows that widening of the room temperature setpoints under IAJS increases the energy savings possibilities in hot and humid climate of Singapore by 13% to 54.5%, and in hot and dry climate of Kuwait by 8.4% to 32.2%. The system also offers energy saving on the supply fan amounting to 68.1% (based on the simulation results) as compared to a MV system. Overall, the study shows the potential energy benefits of implementing IAJS.

REFERENCES

[1] L. Schipper, M. Ting, M. Khrushch, and W. Golove, "The evolution of carbon dioxide emissions from energy use in industrialized countries: an end-use analysis," *Energy Policy*, vol. 25, no. 7–9, pp. 651–672, 1997.

[2] P. Linares and X. Labandeira, "Energy efficiency: economics and policy," *J. Econ. Surv.*, vol. 24, no. 3, pp. 573–592, 2010.

[3] A. Mardiana and S. B. Riffat, "Building energy consumption and carbon dioxide emissions: threat to climate change," *J. Earth Sci. Clim. Change*, no. S3, p. 1, 2015.

[4] T. Hoyt, E. Arens, and H. Zhang, "Extending air temperature setpoints: Simulated energy savings and design considerations for new and retrofit buildings," *Build. Environ.*, vol. 88, pp. 89–96, 2015.

[5] S. Schiavon and A. K. Melikov, "Energy saving and improved comfort by increased air movement," *Energy Build.*, vol. 40, no. 10, pp. 1954–1960, 2008.

[6] A. Kabanshi, H. Wigö, and M. Sandberg, "Experimental evaluation of an intermittent air supply system - Part 1: Thermal comfort and ventilation efficiency measurements," *Build. Environ.*, vol. 95, pp. 240–250, 2016.

[7] A. Kabanshi, H. Wigö, R. Ljung, and P. Sörqvist, "Experimental evaluation of an intermittent air supply system – Part 2: Occupant perception of thermal climate," *Build. Environ.*, vol. 108, pp. 99–109, 2016.

[8] S. Schiavon, A. K. Melikov, and C. Sekhar, "Energy analysis of the personalized ventilation system in hot and humid climates," *Energy Build.*, vol. 42, no. 5, pp. 699–707, 2010.

[9] ASHRAE 55, *Thermal environmental*

conditions for human occupancy. Atlanta. GA: American Society of Heating, Refrigeration and Air-Conditioning Engineers, 2013.

[10] ISO 7730, *Moderate thermal environment -Determination of the PMV and PPD indices and specification of the conditions for thermal comfort*. Geneve: International Organization for Standardization., 2005.

[11] B. Yang, C. Sekhar, and A. K. Melikov, "Ceiling mounted personalized ventilation system in hot and humid climate—An energy analysis," *Energy Build.*, vol. 42, no. 12, pp. 2304–2308, 2010.

[12] S. C. Sekhar, "Thermal comfort in air-conditioned buildings in hot and humid climates – why are we not getting it right?" *Indoor Air*., vol. 26, no. 1, pp. 138–152, 2016.

Table 2. Annual average conditions in the room

	T_o [ºC]	RH [%]	PMV	PPD [%]	CO_2 [ppm]
MV_{ref}	24.76 (0.02)*	61.2 (0.4)	0.11 (0.003)	2.9 (0.1)	1066.5 (3.44)
IAJS-0.4-16	24.76 (0.02)	59.8 (0.2)	-0.06 (0.002)	2.5 (0.1)	1485.6 (8.98)
IAJS-0.8-16	27.90 (0.02)	57.2 (0.3)	0.13 (0.002)	3.3 (0.1)	1063.6 (7.57)
IAJS-0.8-18	28.74 (0.02)	57.9 (0.4)	0.26 (0.002)	5.6 (0.1)	1058.3 (5.04)
IAJS-0.8-20	29.29 (0.02)	55.3 (0.7)	0.39 (0.010)	9.2 (0.3)	1079.2 (4.64)
IAJS-0.8-22	29.45 (0.02)	56.1 (0.8)	0.45 (0.010)	11.6 (0.4)	1073.9 (4.13)
IAJS-0.8-24	29.63 (0.02)	53.9 (0.9)	0.53 (0.010)	16.8 (0.4)	1086.24 (4.88)

*mean monthly standard deviation