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Cooling Energy Simulation and Analysis of an Intermittent Ventilation Strategy under Different Climates

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ABSTRACT

Energy use on heating, ventilation and air conditioning (HVAC) accounts for about 50% of building energy use. To have a sustainable built environment, energy efficient ventilation systems that deliver good indoor environmental quality are needed. This study evaluates the cooling energy saving potential of a newly proposed ventilation system called Intermittent Air Jet Strategy (IAJS) and compares its performance against a mixing ventilation (MV) system in a classroom located in three cities with different climates, Singapore with 'hot and humid', Ahvaz with 'hot and dry' and Lisbon with "moderate" climate. The results show a significant reduction of cooling energy need and flexibility in control strategies with IAJS as a primary system in hot and humid climates like Singapore. Hot and dry climate with short cool periods like Ahvaz show possible application and considerable energy savings with IAJS as a primary system under optimized variable setpoints, but moderate climates have an increased risk of occupant discomfort likely due to increased draft especially during the cool season. Thus, IAJS as a secondary system that operates only during cooling season may be conducive for moderate climates like Lisbon. Additionally, the results show that supply fan energy savings can also be realized if well implemented.

Keywords: Intermittent air jets; IDA-ICE simulation; Energy savings, Convective cooling, Hot and humid climate, Hot and dry climate, Moderate climate

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. Global trends [4] show that much of cooling and air conditioning is achieved by electricity driven systems which increases the burden and cost on electrical power systems. Because of the correlation between building energy use and surrounding climate conditions, cooling energy consumption/demand in buildings is expected to increase due to climate change [5]. For example, in Europe climate change is considered as one of the major drivers for increased cooling requirements and HVAC energy use [6,7].

Energy efficient HVAC systems that do not compromise the indoor environmental quality (IEQ) are necessary and needed. Research has demonstrated ways that different HVAC technologies, configuration and approaches can be effective for energy conservation without compromise on thermal comfort [8]. Common consensus in literature shows that changes on HVAC *modus operandi* can yield substantial energy savings more so on cooling requirements [9]. Research [10–12] shows that strategies that offer possibilities to extend air temperature setpoints have a high energy saving potential on building energy use.

Indoor operative temperature setpoints or the HVAC deadband (thermostat setpoint range) is critical for indoor climate control and has consequences on occupant thermal comfort and the HVAC energy use. Widening the deadband, either by reducing the lower setpoint during heating season or increasing the upper setpoint during cooling season, can result in energy savings as it reduces the heating/cooling demand [10]. Aynsley [13] discussed that adjusting the upper thermostat setting even by 1 °C can extensively increase the annual cooling energy savings by as much as 10 – 14%. Hoyt et al., [10] has also shown through a simulation of San Francisco, among other cities, that increasing the upper setpoint from 22.2 to 25 °C would result in 29% of cooling energy saving and 27% on total HVAC energy savings. Research has proposed and shown the potential of strategies that can offer opportunities to extend the HVACs upper operative temperature setpoint by incorporating higher air speeds in the occupied zone [11,12,14–23].

Standards [24–26] present guidelines on air speed limits and indoor temperature conditions, in air-conditioned spaces, within which occupant comfort is attained based on Fangers' predicted mean vote (PMV) model [27,28]. The recommended operative temperature limits with traditional ventilation systems for comfortable sedentary function is with air speed limit of less than 0.20 m/s to reduce the risk of draft. A close control of traditional HVAC systems within the stipulated conditions for occupant satisfaction implies a higher energy use [29]. On the other hand, the standards also state that increasing the air speeds in the occupied zone can offset thermal discomfort at elevated temperatures consequently reducing the cooling energy use on the HVAC system. Literature offers numerous examples were increased air speeds are used to reduce cooling energy demand without significantly affecting occupants thermal comfort at elevated temperatures [11,12,15,30–32].

Thermal comfort is not only influenced by the magnitude of air speeds but also air speed characteristics such as fluctuations and direction (target area). For example, fluctuating air speeds have a higher perceived cooling effect than steady air speeds [33–35], and the head is the most sensitive region of a fully dressed person to convective heat loss. Thus exposing the head to high air speeds results in a higher overall perceived cooling effect [36,37]. With this understanding, Kabanshi [38] proposed a novel ventilation strategy called intermittent air jet strategy (IAJS).

IAJS is a high-momentum air distribution system proposed for use in high occupancy spaces. The strategy optimises intermittent air speeds to increase convective cooling and penetration of the supply airflow into the sitting zone [17,39]. Kabanshi [38] explained the operational construct and proposed 0.4 m/s and 0.8 m/s as minimum and maximum operational velocities based on minimum air speed needed to fully distort the human thermal plume and the maximum allowable air speed without personal control, respectively [24,40,41]. Details of the system are presented in the objective measurement study [39]. Figure 1 illustrates the implementation possibilities either as a primary system (Fig. 1A) or as a secondary system (Fig. 1B; for spaces with existing HVAC systems or in climates where cooling is occasionally needed).

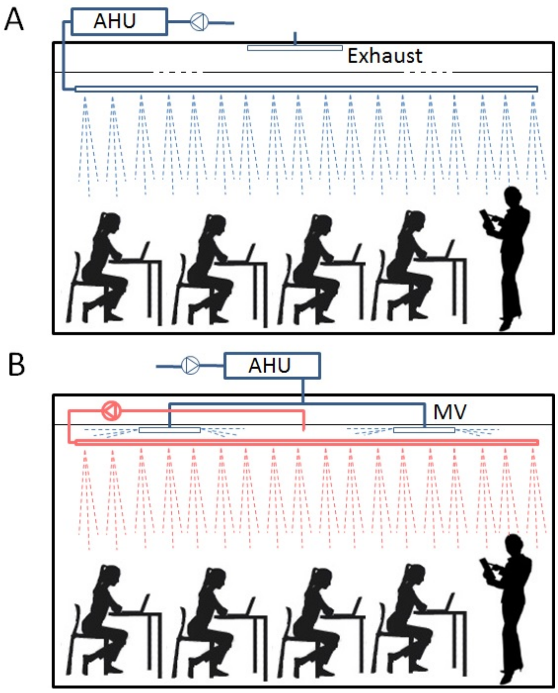


Figure 1: (A) IAJS as a primary system. (B) IAJS as a secondary system; AHU-air handling unit.

An earlier study demonstrated and compared the systems' airflow and temperature distribution, and PMV measurements with traditional systems: mixing ventilation (MV) and displacement ventilation (DV) [39]. Additionally, cooling effect of the generated air jets were assessed with a thermal manikin to compliment the understanding of fluctuating air jets on occupant comfort [42]. Further studies were performed with human subjects [17,43] and responses showed that the system was able to offset the upper operative temperature by 2.3 – 4.5 °C within the proposed air speed range (0.4 – 0.8 m/s) in the occupied zone. This translates to indoor operative temperature limits of 23.7 °C to 29.1 °C for sedentary activities at a clothing level of 0.51 clo. This is critical for comfort and system energy use as implementing the system means increasing the deadband of the traditional HVAC system [10]. 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 without inducing draft. We can deduce that IAJS as a primary system would be most effective in indoor climate were temperatures are above 23.7 °C throughout the year. As a secondary system or as a room induction unit, the strategy works in-conjunction with other systems (i.e., MV) but will only recirculate and increase room air speeds to offset thermal discomfort in increased room air temperatures. The induction system in-conjunction with a MV has been shown to improve perceived indoor air quality, thermal comfort and performance at elevated temperatures [44, 45]. As an 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.

So far, numerous studies have been done to evaluate the performance of IAJS in comparison with traditional mechanical ventilation systems, however, little has been done to evaluate its energy performance. The current study explores, by means of a simulation with IDA-ICE (Indoor Climate and Energy) software, the potential cooling energy savings associated with IAJS in a classroom if implemented in three different climates. An earlier version of this study was presented at the 10th International Conference on Sustainable Energy & Environmental Protection (SEEP) in Bled, Slovenia [46].

2 METHODS

IDA-ICE 4.7.1 simulation software [47] was used to evaluate all computational analyses reported herein. The software is versatile in building simulation analysis for thermal comfort, indoor air quality

(CO_2 modelling) and building energy use. Energy balance in the software considers the climatic variations and a dynamically varying time-step in accordance with model geometry, construction materials, HVAC conditions and internal heat loads (occupants, equipment, solar radiation etc.). The software has been widely used in validation studies of building energy use [48]. Other studies, more related to the current study, have used the software to evaluate the energy saving potential of personalized ventilation in hot and humid climates [49] and in cold climates [50]. Accordingly, herein the authors apply IDA-ICE simulation software to assess the energy saving potential of an intermittent ventilation system in classrooms. The simulation model used for the current study draws inspiration from the studies by Schiavon and others [11,49,50].

2.1 Room and HVAC Description

A single zone classroom with a lighting load of 10 W/m^2 and occupancy capacity of 30 students (activity level of 1.2 met, and clothing insulation of 0.55 clo.) 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 10 mm of cement plaster, 100 mm of glasswool, 240 mm of brick and 20 mm of external cement plaster. The room has four double pane windows (width = 1.2 m, height = 1.3 m), made of 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 (SHGC) 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. The resulting overall U-value of the external wall, inclusive of window properties, is 0.5977 W/(K.m^2). All walls except the outer wall were considered adiabatic and the effect of thermal mass was accounted for.

The ventilation system was set to run during weekdays between 6:00 AM and 7:00 PM, no public holidays were considered. 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 air change hours (ACH) when the pressure difference between the building envelop was 4 Pa. For simplicity, all cases were assumed fully occupied from 8:00 AM to 5:00 PM with an hour break at noon. Lighting load follows the occupancy schedule and works at full capacity.

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, an ideal cooling unit with a coefficient of performance (COP) of 3 and unlimited cooling capacity was used. Therefore, the energy cooling requirement were performed assuming a perfectly efficient HVAC system. The airflow networks and cooling units were not modelled, and humidity was monitored but not controlled.

2.2 Simulated Climates and Cases

The energy simulation model was run in three different cities with different climate characteristics: Singapore, Ahvaz and Lisbon. Singapore is a city-state off southern Malaysia characterised by hot and humid climate, Ahvaz is a city in the southwest of Iran with hot and dry climate and Lisbon is a Portuguese city on the western Iberian Peninsula on the Atlantic Ocean with a moderate climate characterised by mild winters and very warm summers. The cities were chosen to evaluate the potential application of IAJS in relation to different climatic conditions. The weather data were obtained from the ASHRAE IWEC 2 database, which contains "typical" weather files for 3012 locations (including the ones used in this study) available for direct downloading via the IDA-ICE program.

Table 1 shows the simulated cases. In all reference cases a perfectly mixed ventilation system (MV_{ref}) was assumed with airflow-rate (Q) of 10 l/(s.pr), [pr ~ person]. The airflow rate was based on ISO 7730 [15] for a Category I building. The minimum and maximum (T_{up}) allowed room temperature for Singapore, according to Schiavon et al., [49], is 22.5 °C and 24 °C. For Ahvaz and Lisbon, the minimum allowable room temperature is 20 °C and the maximum is 25 °C [51,52]. Iranian standard [52] stipulates that in hot and dry weather, the temperature setpoint for cooling should be 28 °C if the climate is hot and dry and 25 °C if the climate is hot and humid. Despite Ahvaz has rather a dominant hot and arid climate throughout the year, 25 °C is chosen as the cooling setpoint because it is closer to the neutral temperature in ISO 7730.

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 ventilation period. Three airflow rates 10 l/(s.pr), 15 l/(s.pr) and 20 l/(s.pr) are simulated corresponding to operational air speeds at head level: 0.4 m/s, 0.6 m/s and 0.8 m/s, respectively. Kabanshi et al.,[39] found that the generated air speed at head level within the jet centreline was proportional to the airflow rate (linear relationship). Fan settings of 10 l/(s.pr) resulted in air speed of 0.4 m/s, thus to generate 0.6 and 0.8 m/s the airflow rate should be 15 and 20 l/(s.pr), respectively. The maximum allowable indoor air temperatures under IAJS were expanded based on estimates from the overall thermal sensation (OTS) model [17] and air movements acceptability[43] proposed for IAJS shown below:

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

Where, V is the air speed measured at 1.1 m above the floor and To is the room operative temperature. Details of the model are discussed here [17]. At 0.4 m/s, 23.7 °C is the minimal temperature and at 0.8 m/s, 29.1°C is the maximum temperature in compliance with acceptable thermal sensation range (-0.5 to +0.5) as stipulated in ASHRAE Standard 55 [25]. Thus, 23.7 – 29.1 °C is taken as the operable indoor temperature range for IAJS. Based on Equation 1, 26.8 °C is used as the maximum allowable temperature in all cases with 0.4 m/s, 28 °C in all cases with 0.6 m/s and 29.1 °C in all cases with 0.8 m/s. The supply air temperatures (T_s) were varied to evaluate the energy saving possibilities of the system. No heating was done on either the supply air or room air. For all simulated climates an assumption taken was that the heating demand was offset by the internal heat load. Thus, supply temperature was the same as outdoor temperature in conditions when the outdoor air temperature dropped below the supply temperature setpoint. The intention was to optimise on the free cooling effect of outdoor air, so that part of the room cooling need is offset by the supply temperature. Additionally, only sensible cooling was done on the supply air temperature.

Table 1. Simulated cases

No.	Case	Singapore T_S [°C]	Singapore T_{UP} [°C]	Singapore Q [l/(s.pr)]	Singapore V [m/s]	Ahvaz/Lisbon T_S [°C]	Ahvaz/Lisbon T_{UP} [°C]	Ahvaz/Lisbon Q [l/(s.pr)]	Ahvaz/Lisbon V [m/s]
1	MV_{ref}	16	24	10	0.2	16	25	10	0.2
2	IAJS-0.4-16	16	26.8	10	0.4	16	26.8	10	0.4
3	IAJS-0.6-16	16	28	15	0.6	16	28	15	0.6
4	IAJS-0.6-18	18	28	15	0.6	18	28	15	0.6
5	IAJS-0.6-20	20	28	15	0.6	20	28	15	0.6
6	IAJS-0.6-22	22	28	15	0.6	22	28	15	0.6
7	IAJS-0.6-24	24	28	15	0.6	24	28	15	0.6
8	IAJS-0.8-16	16	29.1	20	0.8	16	29.1	20	0.8
9	IAJS-0.8-18	18	29.1	20	0.8	18	29.1	20	0.8
10	IAJS-0.8-20	20	29.1	20	0.8	20	29.1	20	0.8
11	IAJS-0.8-22	22	29.1	20	0.8	22	29.1	20	0.8
12	IAJS-0.8-24	24	29.1	20	0.8	24	29.1	20	0.8

2.3 Energy analysis

In the current study, the energy analysis is made based on the system ‘‘cooling energy need” in order to assess the applicability and potential of IAJS to save energy by optimising enhanced convective cooling. The cooling energy needed to meet the specified ventilation conditions is defined, as cited by Schiavon et al., [49] 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. The use of the “energy need” in the current analysis is critical because the predicted results are independent of the specific characteristic of the HVAC system [49].

For example, in the current study the influence of equipment performance, duct system characteristics and chiller part load curves are not accounted for. In applied practice, delivered energy is considered so that the HVAC system characteristics are all included in the analysis.

Generating conditions conducive for occupant thermal comfort is the desired goal of climate control. Therefore, the current study makes the energy simulation analysis in relation to PMV estimates in the occupied zone for design and assessment of energy performance of buildings, specifically focusing on the thermal environment. Standards present categories according to thermal sensation estimates with ASHRAE standard 55 [24] giving +0.5 to −0.5 as the acceptable range, while EN 15251 [25] and ISO 7730 [26] present categories as indicators of 'quality' and occupant expectation [23]. The categories as explained by Nicol and Wilson [29] are: Category I (−0.2 < PMV < +0.2) is for high level of expectation only used for spaces occupied by very sensitive and fragile persons; Category II (–0.5 < PMV < +0.5 and outside the range of Category I) is the normal expectation for new buildings and renovations unless the building is clearly from a different category, Category III (−0.7 < PMV < +0.7, and outside Category I & II) is for moderate expectation and applied to existing buildings; values outside the criteria for the above categories refer to Category IV.

3 RESULTS AND DISCUSSION

The 2016 simulation indicate that the reference case (MV_{ref}) for Ahvaz and Lisbon has a mild cool season requiring 13 kWh/yr.m^2 and 28.6 kWh/yr.m^2 of heating to satisfy the supply air temperature setpoint, respectively. Since the simulation cases with IAJS did not incorporate any heating, the current section present results and discussion of only the cooling energy requirements.

3.1 Hot and humid climate (Singapore)

Figure 2 shows the annual cooling energy per square meter for Singapore. The simulated energy need for the reference case is 652.4 kWh/m^2: 21.6 kWh/m^2 from room cooling and 630.8 kWh/m^2 from AHU cooling. Comparing cases with IAJS shows a potential reduction in the total energy use in the range of 3.6 – 52.6%. However, assessment of PMV from Table 2 shows that six out of eleven cases under IAJS (No. 2, 3, 4, 8, 9 and 10) complied with the comfortable Categories (I – III) in EN 15251. Table 2 present the number of months with a monthly mean (PMV) falling within the respective Category based on boxplots in Appendix A, which give more details on the monthly distribution of PMV across the simulated period.

Case No. 2 (IAJS with 0.4 m/s) is interesting because it has the same settings as MV_{ref} but higher operative setpoint. As seen in Figure 2, implementing the strategy allows increase in upper operative temperature setpoint by 2.8 °C translating to a total saving of about 44.5%. However, it increases room cooling requirements by almost 80% even though there is a 50% reduction on AHU cooling. This will consequently increase operational costs to meet room cooling requirements and may require installing a bigger chiller compared to the reference case. Additionally, the comfort quality or expectation drops from Category I (MV_{ref}) to Category III. The results also show that much of the cooling energy in hot and humid climate is on AHU due to both sensible and latent cooling requirements of humid air.

Case No. 4 (IAJS-0.6-18) and No. 10 (IAJS-0.8-20) equally offer higher energy saving possibilities and with a huge reduction on room cooling requirements. IAJS-0.6-18 has a 39.5% reduction on total cooling energy need with a saving of 90.9% on room cooling and 37.8% on AHU cooling. IAJS-0.8-20 results in a total reduction of about 36.4% with almost 100% savings on room cooling and 34.3% on AHU cooling. In both cases, the resulting comfort Category is III (Table 2).

For better quality and expectation of the indoor thermal climate, Case No. 3 (IAJS-0.6-16) and 9 (IAJS-0.8-18) generate better comfort categories; some months in a year have Category I and others Category II. IAJS-0.8-18 has eight months in a year with Category I and the remaining months have Category II, but only result in 19.8% savings on total cooling requirements, while IAJS-0.6-16 offers 27.1% total savings but with one month in a year having Category I and the remaining months with Category II. In both cases the need for room cooling requirements is fully removed. Alternatively, Case No. 8 (IAJS-0.8-16), generates yearly comfort conditions with Category II but offers only 3.6% total energy saving, accounting for 100% reduction on room cooling.

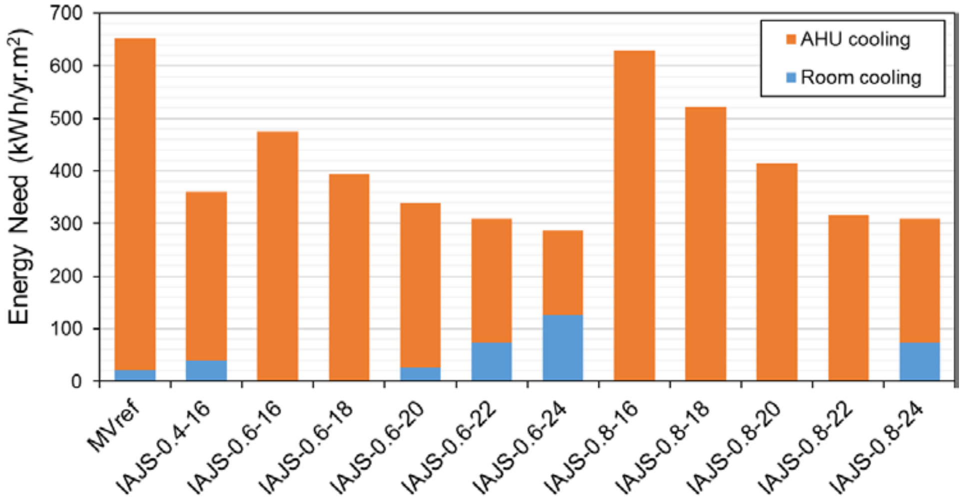


Figure 2: Annual cooling energy need for Singapore

Further analysis of the simulation results with IAJS revealed that more energy savings and improved indoor conditions can be realised by varying the system operation (airflow rate and supply temperature) across the year. To illustrate, we increased the upper setpoint to 29.1°C and re-simulated the cases. Comparing the resulting PMV, we picked cases with the distribution close to neutral for each month. Figure 3 shows the resulting PMV estimates and the three control strategies: Q = 15 l/(s.pr) (0.6 m/s) at T_s = 16 °C from January to May, increase T_s = 18 °C from June to September, and from October to December operate with Q = 10 l/(s.pr) (0.4 m/s) at T_s = 16 °C. This variation results in a total of 36.7% reduction on cooling requirements; no room cooling requirement was needed and 34.5% savings on AHU cooling were realised. From Figure 3, we see that all months except January and February are within Category I, and this can be corrected with personal adjustment i.e., increase clothing from 0.55 clo (used in the simulation) to 0.7 clo.

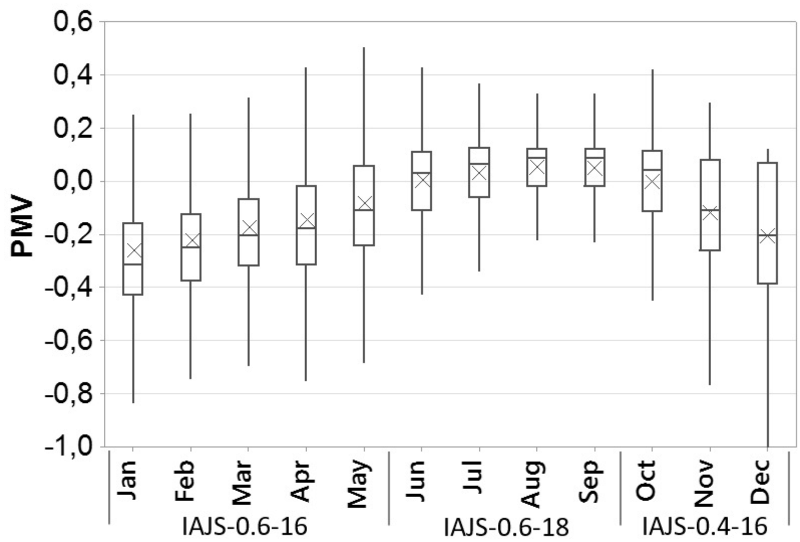


Figure 3: Monthly PMV trends and the respective control strategy for each period with the upper operative setpoint at 29.1°C.

For economical and operational purposes, implementing IAJS with a total removal of room cooling is desirable. From practice, it is easier and cheaper to handle all cooling requirements through the AHU as it removes the need of installing and operating room chillers or cooling units.

3.2 Hot and dry climate (Ahvaz)

Figure 4 shows the annual cooling energy per square meter for Ahvaz. As seen, the reference case has a total cooling energy need of 284.2 kWh/m^2: 7.4 kWh/m^2 from room cooling and 276.8 kWh/m^2 from AHU cooling. The simulated cases with IAJS shows a total energy saving potential in the range of 3.5

– 44.7%. Table 2 indicates that of these, only two cases (No. 2 and 6) satisfy the comfort categories. In both cases, IAJS-0.4-16 and IAJS-0.6-22, there is a reduction on AHU cooling by 46.6% and 54.3%, respectively. However, there is an increase in the room cooling requirements by about 311% for IAJS-0.4-16 and 376% for IAJS-0.6-22, which as stated earlier is not desirable.

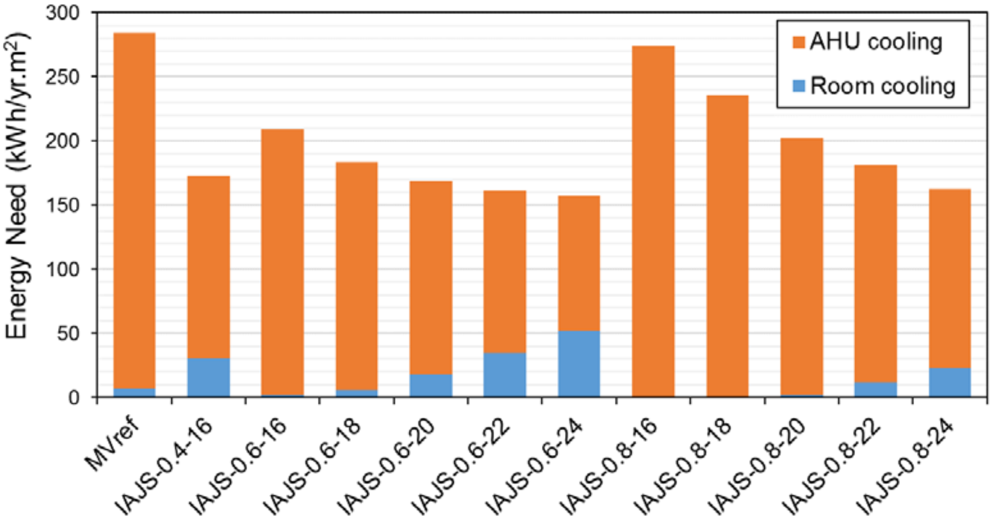


Figure 4: Annual cooling energy need for Ahvaz

Comfort analysis in Table 2 show that IAJS-0.4-16 has a 5 months shift in comfort Category from I into II in comparison with the reference case (MV_{ref}). IAJS-0.6-22 had 4 months with Category II and the remaining in the year had Category III. Further assessment of the thermal sensation estimates shows skewness towards cool, mostly for January, February and December (cool season in Ahvaz) in cases with IAJS with air speeds above 0.4 m/s (see Appendix A). One way to improve thermal sensation under IAJS is to introduce heating on the AHU so that the delivered supply air temperature satisfies the setpoint during cool season. However, this introduces periods of concurrent heating and cooling, whereas the delivered supply air temperature adds to the internal heat load. Another way is to encourage personal adjustment i.e., clothing level. This does not affect the energy use but can significantly improve thermal climate. To illustrate, we re-simulated IAJS-0.6-16 (had 26.4% total cooling energy saving: 74% on room cooling and 25.2% AHU cooling) with clothing level of 0.7 clo instead of the initial 0.55 clo. for January, February and December. The resulting indoor thermal climate for the re-simulated period improved to Category II. A similar observation was made with IAJS-0.6-18.

Alternatively, having a variable control strategy with varying setpoints can be critical in improving thermal climate and reduce energy use. In the current study, we assessed the effect of varying control strategies by focusing on cases with monthly PMV in Category I. Figure 5 shows: (A) operating schedule for selected cases and months, and (B) the resulting PMV distribution. As seen, the comfort Category improves to Category I for the entire year. Furthermore, this operating schedule and the respective setpoints (Table 1) results in total energy savings of about 11.6%; a reduction of 83% on room cooling and 9.7% on AHU cooling. From this result, we can deduce that implementing variable strategy in climates with slight variations can have benefits on controlling indoor climatic conditions. Additionally, building managers and HVAC engineers can compromise between optimal energy savings and thermal comfort level depending on what is desired for the system operation.

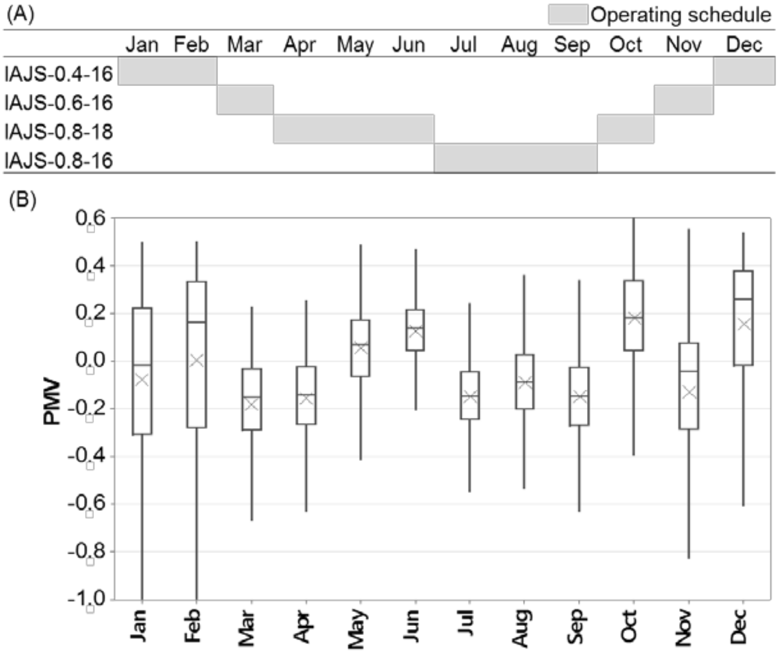


Figure 5: (A) Operating schedule for given cases. (B) The result thermal sensation

3.3 Moderate climate (Lisbon)

Figure 6 shows the annual cooling energy need for the simulated cases in Lisbon. The total annual energy need for the reference case (MVref) was 87.7 kWh/m^2, with much of the cooling done through the AHU (87.58 kWh/m^2) and a negligible amount in room cooling (0.12 kWh/m^2). The total annual cooling energy need is within agreeable range to what is reported in other studies [6]. Comparing conditions under IAJS shows the cooling energy potential of the simulated cases with IAJS. However, the results show that all case with IAJS except case No. 2 (IAJS-0.4-16) result in occupant discomfort. Assessing PMV distribution (Appendix A) reveal that the sensations are skewed towards slightly cool for seven months and around neutral for five months under the reference case. This suggests that introducing IAJS will likely increase the risk of draft or thermal discomfort especially for the seven months (January, February, March, April, May, November and December) with slightly cool sensations.

Unlike in Ahvaz were clothing adjustment can be used to offset discomfort during cool season, the climate in Lisbon did not yield much improvement under IAJS. However, variable control strategies with IAJS-0.4-16 operating during the seven months (cool period) and IAJS-0.8-20 used in the remaining five months (June-October; comfort Category I) show promise on both energy savings and thermal comfort. An overall 54.3% total cooling energy saving was recorded even though room cooling increased, it was still negligible (0.32 kWh/m^2). The reduction was mostly observed in the summer period when cooling with air movements allows operation at elevated temperatures. The months in cool season had January with Category III, and November and December with Category II. The sensations were still skewed towards slightly cool. The remaining months in the year had Category I.

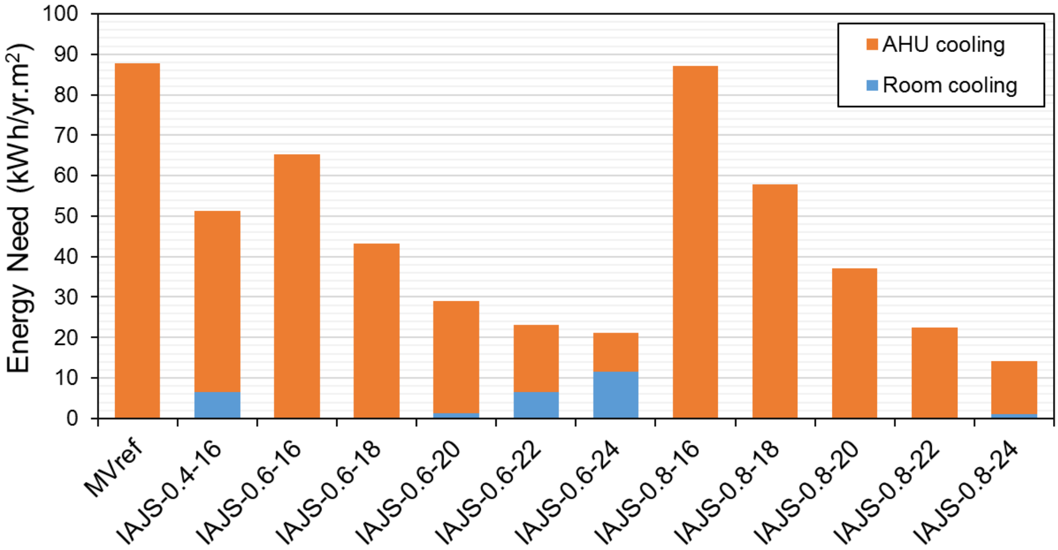


Figure 6: Annual cooling energy need for Lisbon

The results of the present analysis revealed that IAJS may not be conducive as a primary ventilation system in moderate climates with cold seasons like Lisbon. The strategy would increase the risk of draft and consequently thermal discomfort. Earlier [38] it was suggested that IAJS as a secondary ventilation system may be appropriate in cities with climates like Lisbon. The system can be integrated as an induction unit with a traditional system i.e., MV or DV, but can be operated when the indoor temperature increases to necessitate cooling. This configuration can also be used in cold climates whereby the traditional system provides primary ventilation and IAJS is used to aid the system during cooling demands. Due to limitations with the simulation software, no secondary configurations were performed for this scenario.

Table 2: Simulated cases and number of months with PMV within respective Categories of EN 15251

		Number of months with comfort Categories under EN 15251											
		Singapore				Ahvaz				Lisbon			
No.	Case	I	II	III	IV	I	II	III	IV	I	II	III	IV
1	MV_{ref}	12	0	0	0	8	4	0	0	5	7	0	0
2	IAJS-0.4-16	0	0	12	0	3	9	0	0	4	7	1	0
3	IAJS-0.6-16	1	11	0	0	4	5	2	1	4	2	3	3
4	IAJS-0.6-18	0	0	12	0	2	3	6	1	3	3	3	3
5	IAJS-0.6-20	0	0	0	12	0	4	7	1	2	5	2	3
6	IAJS-0.6-22	0	0	0	12	0	4	8	0	2	4	3	3
7	IAJS-0.6-24	0	0	0	12	0	4	6	2	2	4	3	3
8	IAJS-0.8-16	0	12	0	0	3	3	2	4	0	0	4	8
9	IAJS-0.8-18	8	4	0	0	4	5	0	3	3	2	1	6
10	IAJS-0.8-20	0	0	12	0	2	2	5	3	3	3	0	6
11	IAJS-0.8-22	0	0	0	12	2	0	1	9	1	4	1	6
12	IAJS-0.8-24	0	0	0	12	0	2	0	10	0	4	2	6

3.4 Fan Energy Use

Figure 7 shows the fan annual energy need for each supply airflow rate. MV_{ref} had an annual energy need of about 27.2 kWh/m^2. Implementing IAJS with 10 l/(s.pr) (corresponding to 0.4 m/s) would result in 68.1% savings on fan energy need while IAJS with 15 l/(s.pr) (corresponding to 0.6 m/s) would save about 51.3% and IAJS with 20 l/(s.pr) (corresponding to 0.8 m/s) about 36.1%. These results marry the hypothesis [39] that theoretically in certain applications/setups, fan energy savings close to 50% can be achieved with IAJS as a primary system. 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. The current study has not accounted for the influence of HVAC system behaviour, for example, with MV a low-pressure fan can satisfy the air delivery requirements while a high-pressure fan is required to deliver elevated air speeds in the room consequently increasing the influence of duct characteristics (i.e., airflow resistance), which eventually will lead to a higher energy use. Realistically, the fan energy use due to intermittency operation would not be the same as the ones obtained in this study. For this reason, the fan energy savings obtained herein should be interpreted with caution. Additionally, with IAJS as a secondary system the total fan electrical energy use is expected to increase since it is an addition to the primary fan.

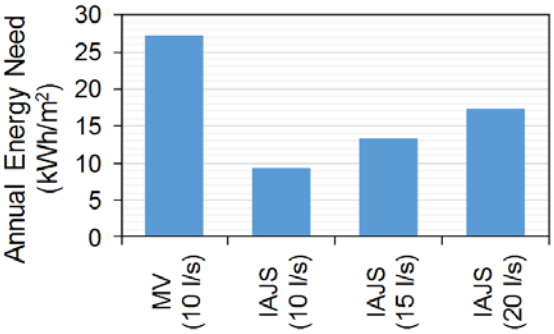


Figure 7: Fan energy need

3.5 General Discussion

The present study reveals that under IAJS the reduction on the total energy need increases with increase in supply temperature for the same airflow rate. Schiavon et al., [49] and Yang et al., [12] reported that under personalized ventilation, supply temperature has minimal influence on total energy use in hot and humid climates, this is was not observed under IAJS herein. IAJS in hot and humid climates show that increasing the supply temperature for the same supply flowrate has a considerable effect on the energy need for AHU cooling as it reduces both sensible and latent heat in the humid air. However, this effect is dependent on the supply airflow. For example, with airflow at 15 l/(s.pr) the savings reduce with increase in temperature and the transfer of the cooling demand from the AHU to room cooling is easily observed. On the other hand, airflow with 20 l/(s.pr) show an increase in savings with increase in supply temperature until after T_s = 22°C. At high airflow rates the cooling capacity of the supply increases thus offsetting the room cooling need. The same effect is observed on the other considered climates, i.e., Ahvaz and Lisbon.

IAJS offers advantages of a wider operational room temperature range 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 desired 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 [18].

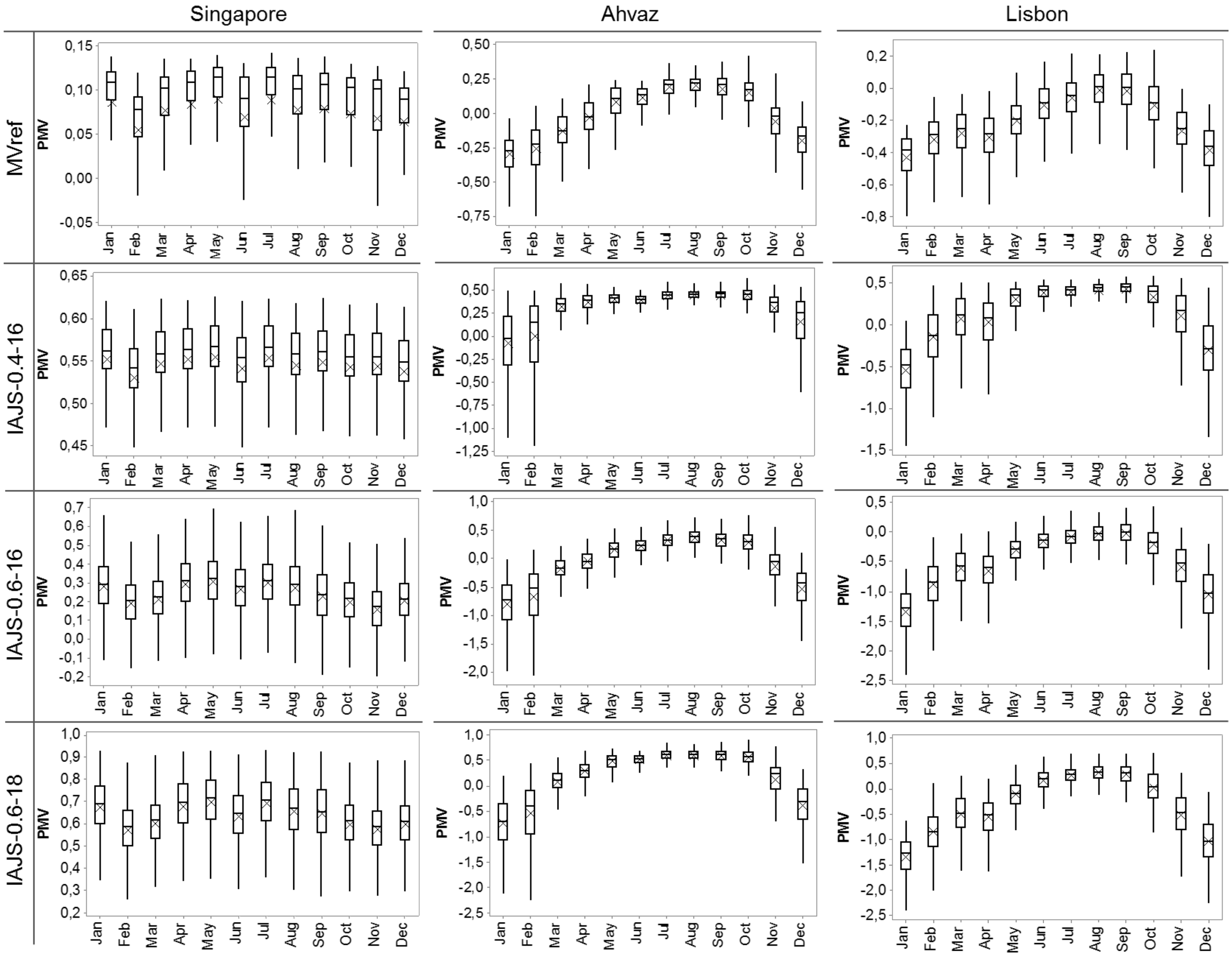
The cooling energy need of the simulated cities differed depending on the climate. Singapore had the highest need because cooling is required throughout the year while Lisbon, of the simulated cities, had the least cooling period. Additionally, Singapore is very humid which increases the cooling energy need of the AHU because you are required to remove both the sensible and latent heat of the supply air. From the results here in, Implementation of IAJS as a primary ventilation system has the highest potential in climates with a year-round cooling demand, while an IAJS as an induction system seems logical in moderate climates of which during cool season, high room temperatures can be offset by other techniques like opening the windows if it doesn’t compromise on indoor air quality.

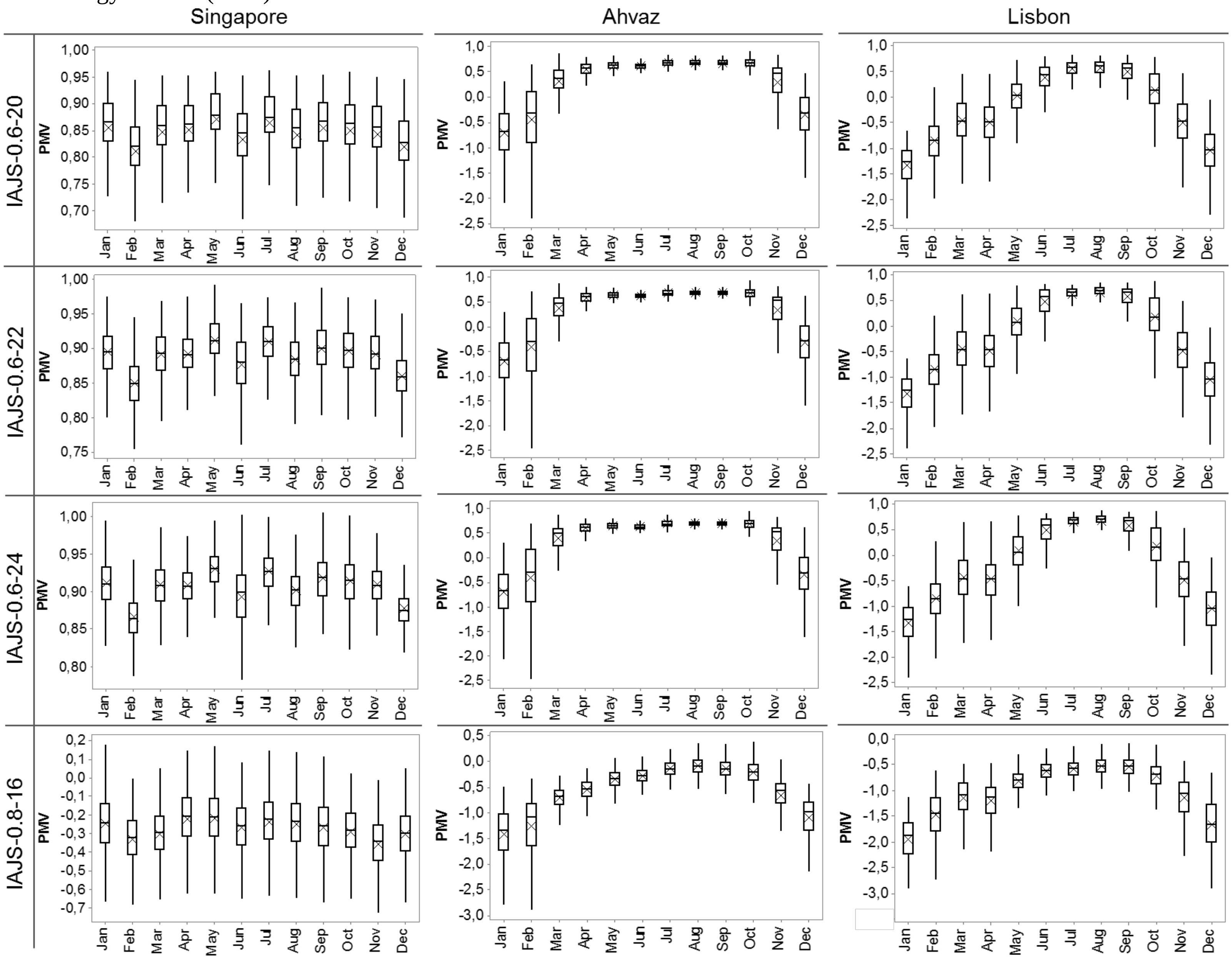
The results of current simulation demonstrate the cooling energy saving potential of intermittent air jet strategy. It is noteworthy that the study considers several approximation and simplifications, discussed herein, which in practice may alter the results. For example, the current study assumes a standard annual clothing level, but in reality, indoor clothing level may be influenced by seasons and occupant behaviour or expectations. Therefore, the authors recommend detailed research on measured energy use of IAJS in applied practice both as a primary ventilation system and a secondary system. This will quantify the energy saving possibilities and address the practical challenges of implementing IAJS.

4 CONCLUSION

The results herein give an insight on the energy saving potential of IAJS if implemented as a ventilation strategy in high occupancy spaces. Based on the simulated cases and setup, the results show that widening of the room temperature setpoints under IAJS increases the energy savings possibilities. The strategy can be used as a primary ventilation system in climates with an annual cooling requirement like in hot and humid climate of Singapore, and in hot and dry climate like Ahvaz. Optimized controlled setpoints can be varied based on outdoor climate or seasons for the upper operative room temperature, air speed and supply temperature to ensure comfortable climate and/or optimal energy savings. In moderate climates like Lisbon, it is reasonable to implement IAJS as secondary system operating only during cooling demand periods. The system also offers energy saving possibilities on the supply fan if well implemented as a primary ventilation system. Overall, the simulation study shows the potential energy benefits of implementing IAJS in classrooms.

Appendix A: Full set of boxplots for PMV for the simulated cases in Table 1.





Singapore
Ahvaz
Lisbon
IAJS-0.6-20
IAJS-0.6-22
IAJS-0.6-24
IAJS-0.8-16
PMV
Jan
Feb
Mar
Apr
May
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Nov
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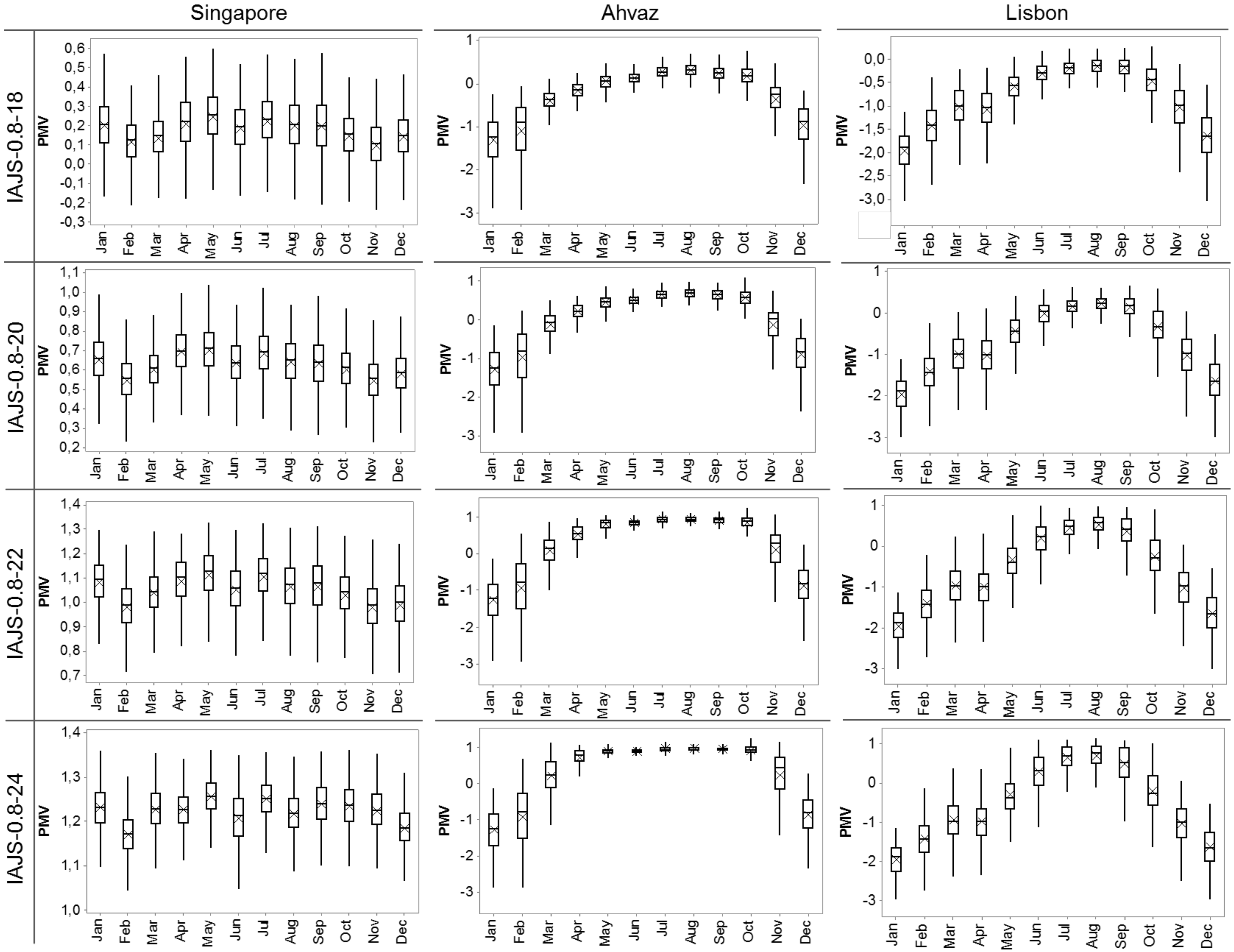
Singapore
Ahvaz
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IAJS-0.8-18
IAJS-0.8-20
IAJS-0.8-22
IAJS-0.8-24
PMV
Jan
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Dec

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