Ventilation Performances of Mixing, Displacement, and Impinging Jet System under Different HVAC Scenarios: Part II

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ABSTRACT

See Part I.

KEYWORDS

Impinging Jet Ventilation, Energy Conservation, Thermal Comfort, CFD, HVAC, IAQ.

VENTILATION PERFORMANCES

In general, the ventilation effectiveness is used to describe the overall space performances. Ventilation effectiveness is based on heat and pollutant removal (Awbi, 1998). Higher ventilation effectiveness means higher ventilation performances. However, these criteria do not include the local human configuration. Therefore, five ventilation criteria including room energy conservation, stratification discomfort, draft, CO_2 level, and RH are used. See **Equation 1** to **Equation 5** respectively. Since the space is utilized only within the breathing zone (0-1.8m), measurement points at different room heights of 0.1, 0.6, 0.9, 1.1, 1.6m are selected. Within the breathing zone, three activities including standing, sitting, and sleeping are common. Sleeping has the lowest height, while standing has the highest height. **Table 2** shows the planes selection to represent these activities.

Table 1: Equations for ventilation performances criteria

Equation 1	**Equation 2**	**Equation 3**	**Equation 4**	**Equation 5**
Energy Conservation	RH	Stratification discomfort	Draft	CO2
$\frac{Q_{cfd}}{Q}$, $\frac{(T_a - T_{cfd})}{(T_a - T_s)}$	$\frac{w_a}{w_{sp}}$	$\frac{A_{t>3C}}{A}$	$\frac{A_{V>0.15m/s}}{A}$	$\frac{C_{cfd}}{C_{1000ppmv}}$
Q_{cfd} =CFD flow rate Q =peak load flow rate T_a =control temp T_{cfd} =CFD supply temp T_s =peak load supply temp	W_a =humidity ratio W_{sp}=saturate humidity ratio at a given air temperature	$A_{t>3c}$ =area of selected plane where temperature of 1-0.1 m exceeding 3°C A = room area	$A_{v>0.15m/s}$ =area of selected plane where velocity exceeding 0.15 m/s A = room area	C_{cfd}=CO_2 concentration of selected plane $C_{1000ppmv}$ = CO_2 at 1000ppmv

Table 2: CFD grid points/planes selections

	Standing	Sitting	Sleeping
Average Temperature and RH	0.1, 0.6, 1.1, 1.6m	0.1, 0.6, 1.1m	0.1, 0.6m
CO_2 and draft	1.6 m	0.9 m	0.6m
Stratification discomfort	1.1-0.1m		

Energy conservation directly relates to supply conditions. Either reducing the flow rate (VAV) or increasing the supply temperature (CAV without reheat) provides energy conservation as described by **Equation 1**. Peak scenario of 160 W/m^2 is used as a reference for cooling energy conservation. For all activities, satisfying the temperature and RH criteria requires all points at a given height to be calculated. Draft usually occurs at sensitive locations on the human body such as the neck and ear, (Awbi, 2003) while CO_2 is most important at the nose level within a space. Thus, only typical head height planes are used for both parameters. Stratification discomfort occurs when temperature at 0.1-1.1m differs with more than 3°C, while wind velocity of 0.15 m/s (ambient temperature of 23.5°C) can causes draft dissatisfaction of 10%. (ASHRAE, 2005) The room area which exceeds this temperature threshold can be use as an indicator. See **Equation 3** and **Equation 4**. Theoretically speaking, the ventilation performances parameters should be close to zero except for RH where a value of 50% is preferred.

VENTILATION STRATEGIES COMPARISON

In **Figure 4 of Part 1**, IJV shows the temperature stratification. Typically, the cool air is located adjacent to the floor surface. Temperature gradually increases with height. High cooling load increases the temperature difference which can be both an advantage and a disadvantage. If the stratification is too strong, discomfort follows. At the same time, the preserved cool air layer within the breathing zone reduces the cooling energy consumption. A good ventilation strategy should minimize the stratification discomfort and maximize the energy conservation. Since sleeping, sitting, and standing activities require different spatial heights, the low activity level such as sleeping might require less cooling energy than the high activity level such as standing. IJV performances can be compared with those of DV and MJV by using ventilation performances described in the previous session.

Supply Condition and Energy Conservation

In **Figure 1**, the average temperature for the different activities is plotted. MJV, DV, and both IJVs are compared. When the flow rate is reduced, the temperature increases linearly. Overall, the temperature strongly depends on flow rate (steeper slope) for low cooling loads (9 W/m^2). Also, all strategies perform similarly (Each line moves closer). DV is the most energy efficient strategy (less flow rate required). Low activity level reduces the energy consumption of DV and IJV respectively. IJV#2 performs worst in peak and low cooling loads, but performs similar to IJV#1 in high and medium cooling loads (47, 116 W/m^2). Since the IJV#2 velocity is twice that of the IJV#1, the supply velocity might be too high in peak cooling load (160 W/m^2).

In CAV, the supply temperature can be determined by using the same method as with VAV. The flow rate of 11.12 ACH is fixed. When the supply temperature increases, the average temperature increases. In contrast with VAV, in **Figure 3**, when the cooling load is low, a constant flow rate reduces the effect of supply temperature variations (less steep slope). In DV and IJV, warmer supply temperature can be supplied for the low activity level. Overall, DV requires the warmest supply temperature. From a building operation perspective, warm supply temperature does not necessary consume less energy. In the CAV reheat system, the typical duct temperature is 13-15°C (55-60°F). The thermostat in each zone activates the reheat unit to control the room temperature. Thus, the warm air supply leads to reheat energy waste. However, for hot-humid climates, the heating system is not necessary. CAV can be operated by shutting down the cooling cycle, while the fan is still activated. Since the cooling coil can not maintain the temperature at the dew point all the time, the moisture condensation rate is reduced. If fresh air intake has high humidity level, the supply air can be too humid. Thus, RH in the room can become problematic. Detailed discussion can be found in HVAC handbooks such as *Mechanical and electrical equipment for buildings* (Stein et al., 1992). IJV#1 generally requires moderately warm supply temperature (warmer than MJV but cooler than DV). IJV#2 requires coolest supply temperature. Therefore, in CAV with reheat terminal, high IJV supply velocity (IJV#2) is suitable, while, in systems without reheat terminal, lower IJV supply velocity (IJV#1) is more appropriate (the humidity control must be carefully investigated). In the heating mode, both IJV perform distinctly. In **Figure 2**, the jet streamline of DV and MJV tilts toward the ceiling, while IJV streamline still attaches to the floor. Thus, the heat delivery mechanism of IJV is better and conserves more heat energy (cooler supply temperature).

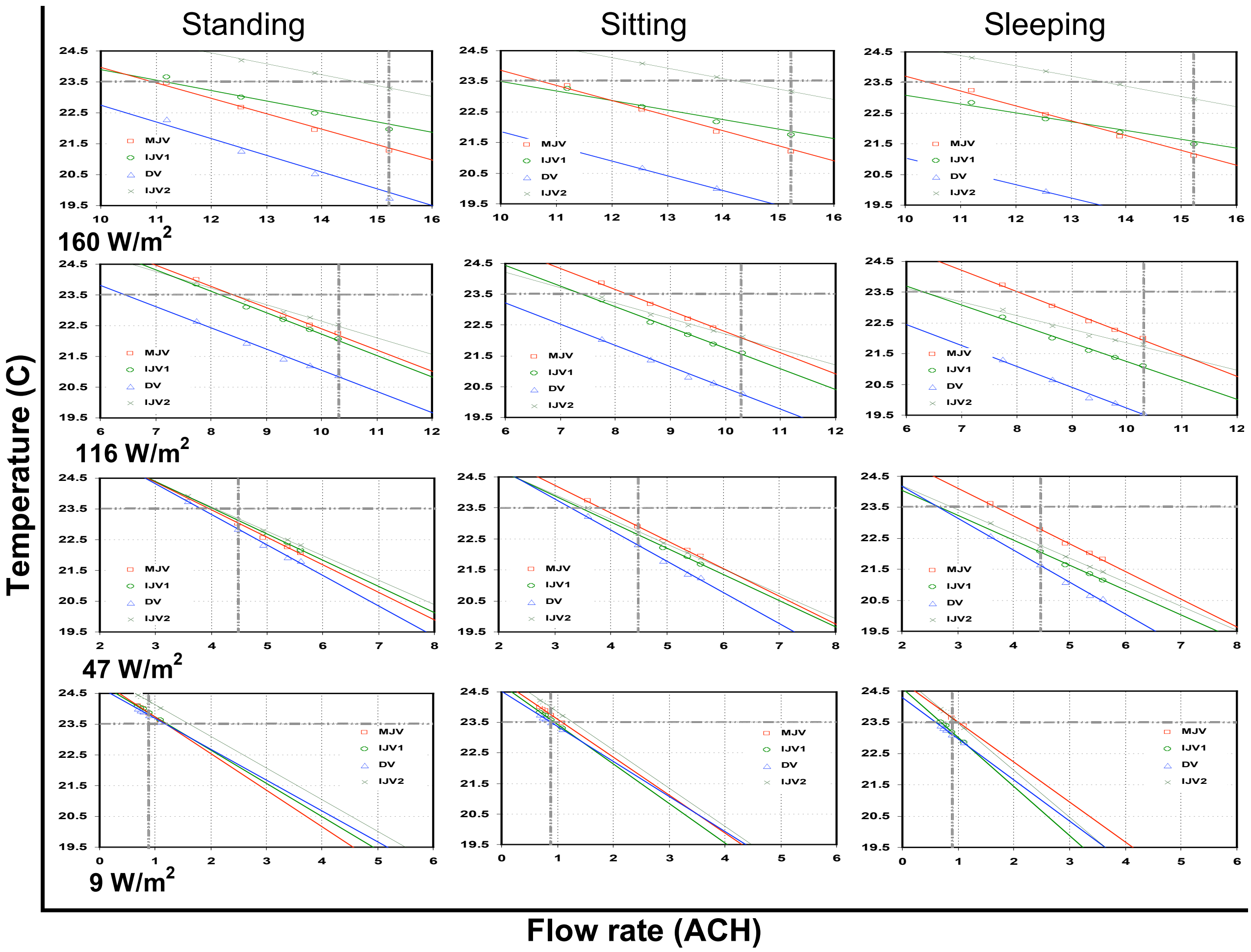


Figure 1 : Average air temperature analysis of VAV system:

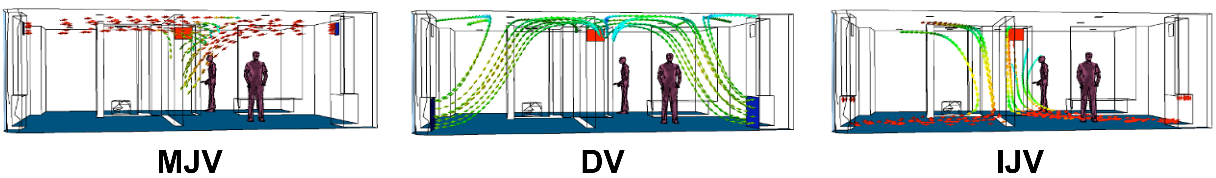


Figure 2 : the streamline plot of ventilation strategies in heating mode:

Once the supply conditions of all CFD scenarios are specified, the ventilation performances can be plotted in **Figure 4**. Using **Equation 1** to **Equation 5**, each performance can be graphed depending on the occupants' activities.

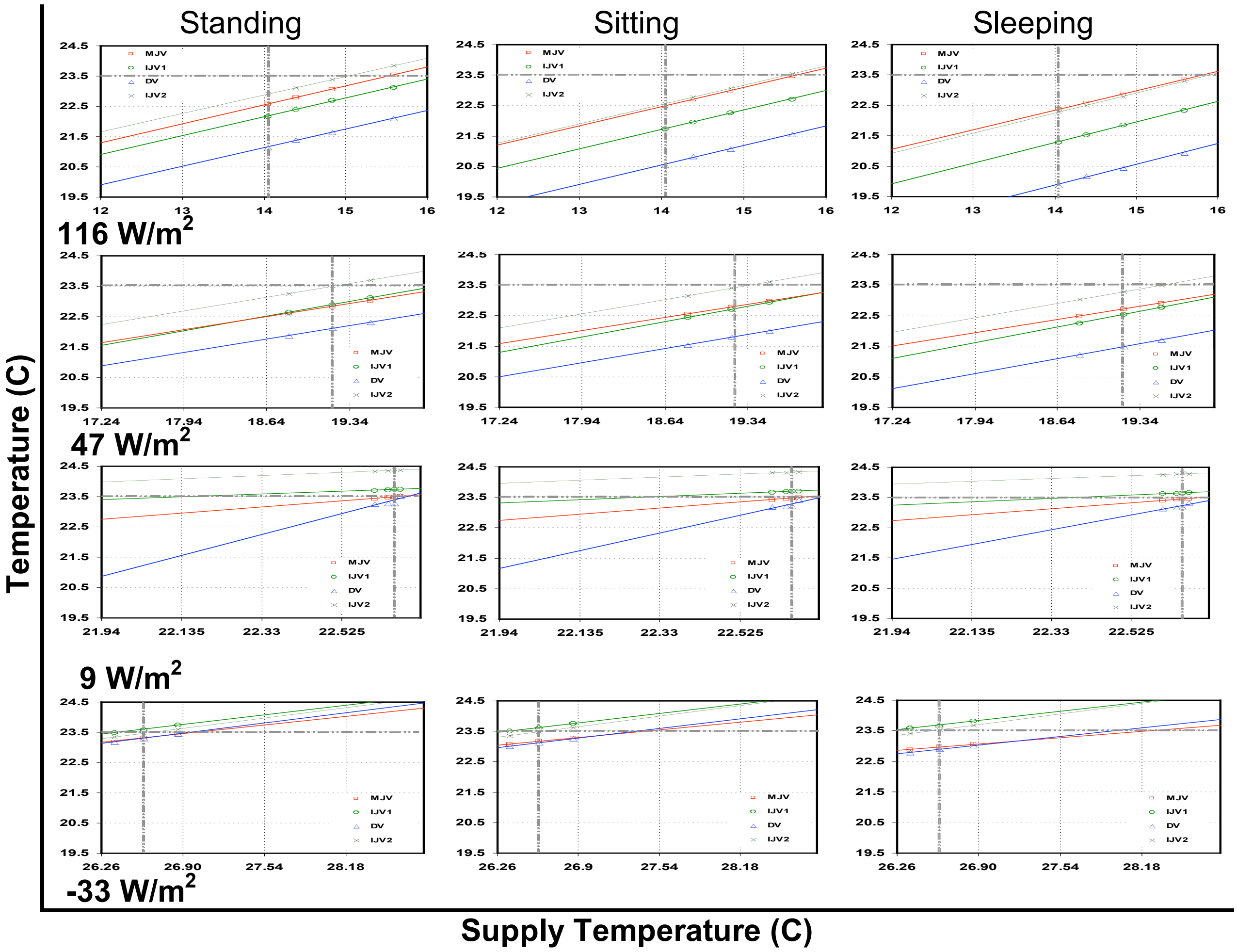


Figure 3 : Average air temperature analysis of CAV system:

Stratification Discomfort

Due to the low supply temperature of VAV, stratification discomfort is a shortcoming of DV. In peak to mid cooling load, stratification discomfort reaches 0.4 (**Equation 2**) or 40% of room area. MJV minimally remedies stratification discomfort in all cases. IJV has a moderate performance. The worst stratification discomfort does not occur at peak load condition, but at mid load condition. The key to solving stratification discomfort is to increase the supply velocity. The high velocity mixes the cool supply air with the ambient air faster. Another way to reduce stratification discomfort is to increase the supply temperature which is applicable in CAV. By supplying a slightly warmer temperature (14°C), stratification discomfort drastically drops to less than 0.1. However, DV requires the warmest temperature to solve this problem; therefore, higher reheat energy is needed. The finding is similar to the previous studies. The suggested supply temperature of DV should be higher than 19°C (66.2°F) or 2-3°C lower than the room temperature. (Skistad, 1994). In the heating mode, since humans are less irritated by warm floor temperature (Awbi, 2003), the stratification discomfort is not found.

Draft

Supply velocity of MJV constantly faces severe draft problem, while draft of DV is almost unnoticeable. Since nozzles of IJV are tilted toward the floor, the room average draft is significantly reduced. IJV#2 velocity is almost triple that of MJV but draft is less presented. In CAV, due to the supply temperature variations, the stratification affects the draft consequences. In IJV, the maximum draft occurs in low activity level and is significantly reduced in high activity level. When the supply temperature is low, IJV preserves its boundary layer close to the floor. When the supply temperature increases, the jet spreads more upward, and causes more draft in standing activity. Therefore, in a heating mode, IJV is slightly draftier than others.

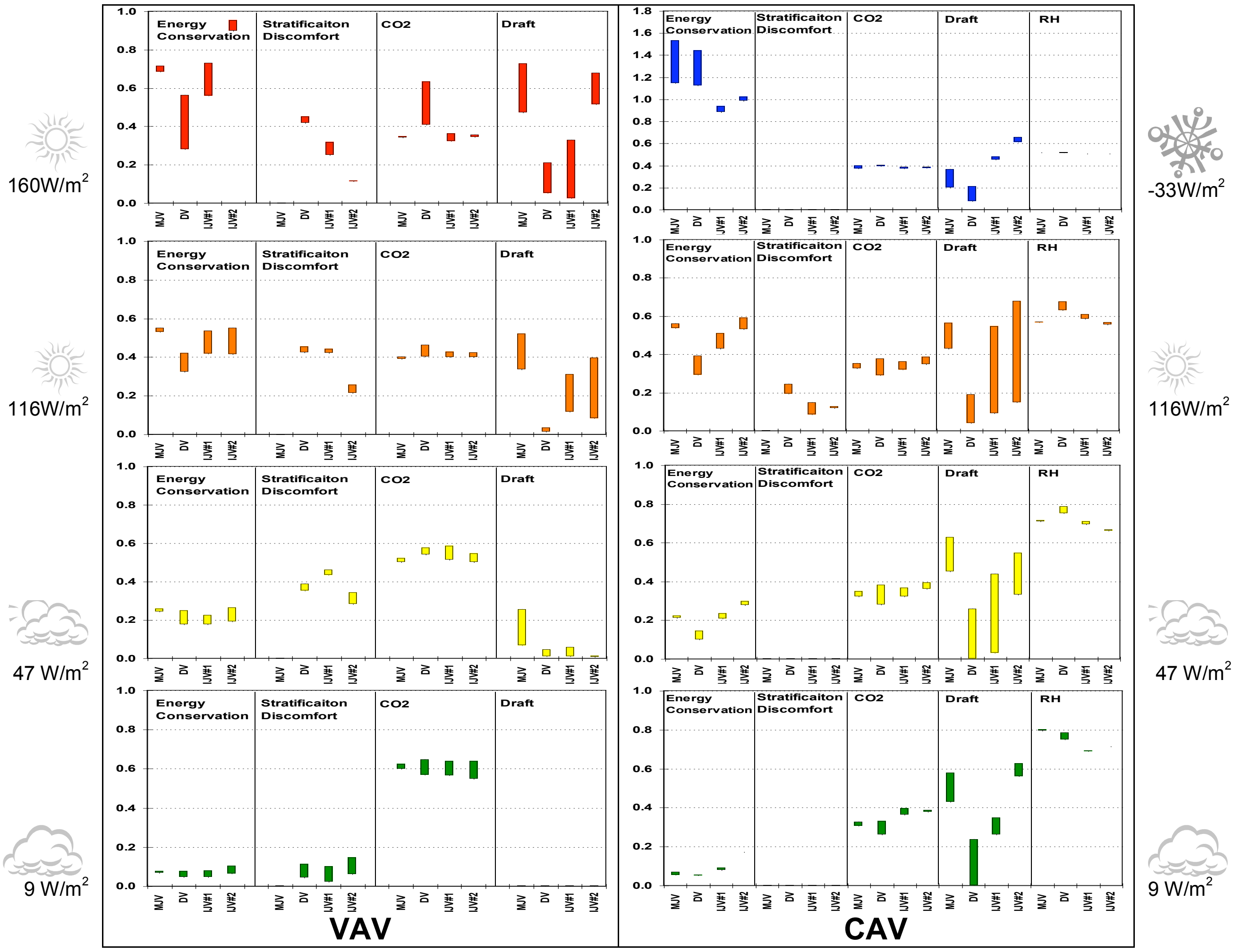


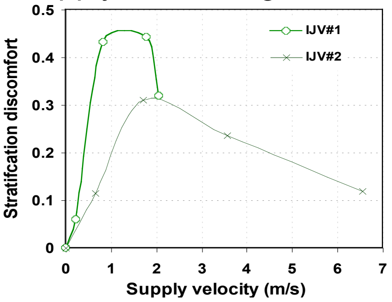
Figure 4 : Ventilation performances summary given five indices:

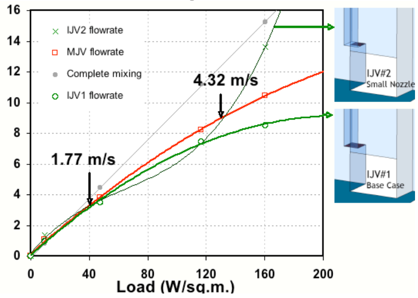
Indoor Air Quality

In VAV, IJV and DV require less flow rate; however, the CO_2 level remains similar or lower than MJV. Except in the peak cooling load case, high CO_2 level of DV is a result of inadequate flow rate. The previous research suggests that stratification helps improving IAQ (Skistad, 1994). In this study, the IAQ improvement is found only in sitting and sleeping activities. In standing activity, CO_2 levels of DV and IJV are slightly higher than those of MJV. Thus, MJV does not always have the worst IAQ. To improve IAQ of standing activity, DV and IJV need higher flow rates; therefore, the waste of energy by fan and reheat operation is a tradeoff. In CAV, DV performs best. IJV slightly reduces the pollutants in high and mid cooling load. In the heating mode, the effect on the CO_2 level is indifferent.

Relative Humidity

To understand humidity behavior, supply humidity without reheat system is set up. In low cooling load, since the supply temperature in CAV is warm and humid, the supply humidity exceeds the appropriate level. As a result, RH exceeds the recommended threshold (75%) (ASHRAE, 2005). Overall, DV has the highest RH for high and mid cooling loads, while RH for both MJV and IJV cases are similarly lower. Thus, warm supply temperature is more appropriate for both MJV and IJV. In the heating mode, dry supply air is assigned. Overall, all strategies are able to maintain 50% RH.





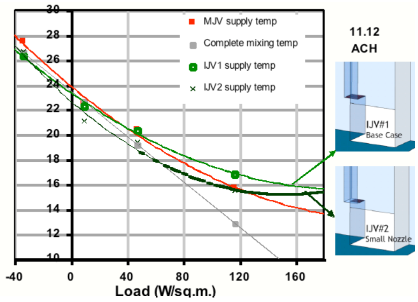


Figure 5 : Stratification discomfort of IJV analysis (left):
Figure 6 : IJV supply velocity threshold for energy conservation (mid):
Figure 7 : IJV supply temperature for energy conservation (right):

DISCUSSION

In DV and IJV ventilation strategies, stratification discomfort is always an issue as cold air is supplied near the floor surface. This major disadvantage limits the possibility of conventional MJV replacement. To solve this problem, either increasing the supply velocity or temperature helps. In **Figure 5**, IJV#2 reduces the stratification discomfort drastically. Although the reheat system wastes energy, it significantly helps reduce the stratification discomfort. Compared to DV, IJV requires less reheat energy. Supply temperature of 15-16°C strongly minimizes the problem. In **Figure 6**, yellow area indicates energy conservation range for IJV#2. IJV shows energy conservation potential with a supply velocity higher than 1.8 m/s and not exceeding 4.3 m/s. In CAV with reheat system, the high IJV supply velocity is preferred because less reheat energy is required. (The threshold of 4.3 m/s should be not exceeded) See **Figure 7**. In heating mode, IJV demonstrates that cooler supply temperature is applicable. In **Figure 7**, Blue area indicates heat energy conservation for heating phase. In HVAC without a reheat system, IJV with low supply velocity is more appropriate because warm supply air is recommended (yellow area).

CONCLUSION

With the appropriate settings presented in this research, IJV can be a new ventilation alternative for both heating and cooling purposes. Using five ventilation performances, i.e. energy conservation, stratification discomfort, draft, IAQ, and RH; IJV is suited for spaces in with low activity levels dominate, such as sitting and sleeping. As never before, CFD allows researchers to understand room ventilation better. Forthcoming publications will be focused on IJV performances under different space configurations such as large hall, office cubicles, etc.

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