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

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ABSTRACT

In most conditioned spaces, the Mixing Jet Ventilation (MJV) systems are commonly installed. Relying on turbulent mixing, MJV homogeneously controls the room environment. However, Indoor Air Quality (IAQ), draft, and noise can sometimes be drawbacks of MJV systems. In late the 70's, Displacement Ventilation (DV) was first introduced. By supplying low supply velocity air from the floor or lower wall, a stratification zone is formed which forces pollutants to be collected near the ceiling and allows clean air to remain in the breathing zone. To avoid discomfort associated with stratification, a warm supply temperature is suggested. Accordingly, the dehumidification and reheat energy become obstacles. Recently, a new concept, Impinging Jet Ventilation (IJV), has been introduced. By placing the supply terminal toward the floor within the impinging range, IJV successfully utilizes the advantages of MJV and DV. A supply temperature of 55°F can be commonly applied. Previous studies show that IJV is particularly appropriate for space with fixed seating arrangements. Since IJV is new, this research aims quantify IJV ventilation performances including energy conservation, stratification discomfort, draft, IAQ, and relative humidity under both cooling and heating conditions. Using Computational Fluid Dynamics (CFD) as a primary research tool, 96 different scenarios were simulated. Under appropriate supply velocity and temperature, IJV reduces energy consumption and improves a room's IAQ.

KEYWORDS

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

INTRODUCTION

Similar to Mixing Jet Ventilation (MJV), Impinging Jet Ventilation (IJV) relies on high/moderate supply velocity. The supply terminal faces the impinging surface (floor) within an impinging range of 0.3 to 1m. After reaching the floor, the jet forms a thin boundary layer along the floor surface. The jet velocity is drastically reduced and behaves as a wall jet. Ultimately, stratification occurs within the room due to the difference in temperature and lack of mixing between the supply and the ambient air. Heat and pollutants are usually concentrated in the top layer toward the ceiling where exhausts are located (Awbi, 2003). In a typical classroom application, IJV has shown promising results. The system indicates a similar Predicted Percentage of Dissatisfaction (PPD) (Fanger, 1972) to Displacement Ventilation (DV) (Karimipanah and Awbi, 2002). However, previous studies only studied limited load conditions, and environmental parameters such as humidity were excluded.

In this paper, the various load scenarios are tested for all ventilation configurations: MJV, DV, and IJV. The ventilation performances under both Variable Air Volume (VAV)

and Constant Air Volume (CAV or CV) of both cooling and heating modes will be discussed. The space used in this case study is a typical high rise residential unit in Henderson, Nevada. See **Figure 1**. This unit includes bed room, living room, and rest room. This project aims at obtaining LEED certification. Since energy and Indoor Air Quality (IAQ) are among the scoring criteria (USGBC, 2003), the selection of ventilation strategies becomes a major design concern. To respond to the design process effectively, Computational Fluid Dynamics (CFD) is used. The current volume of ASHRAE fundamentals dedicates chapter 34 to discussing CFD simulation methods (ASHRAE, 2005). This confirms that CFD is increasingly accepted in ventilation practices. The CFD model of the study space with MJV, DV and IJV configurations is presented in **Figure 1**.

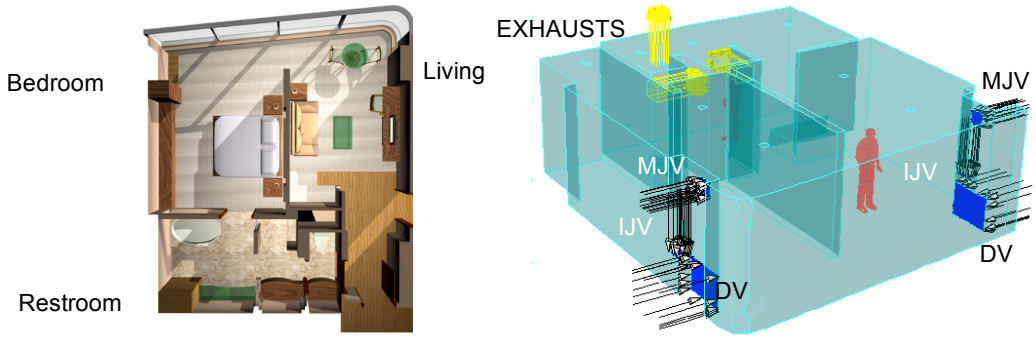

Figure 1: Case study space (left) and CFD representation (right):

VENTILATION REQUIREMENT

The major task of HVAC system is to provide at least the minimum ventilation requirement. Usually, the minimum ventilation requirement must assure thermal comfort, humidity level and IAQ. See **Equation 1** to **Equation 3** respectively (Zhang, 2005). To fulfill these three ventilation needs, the strongest ventilation is always picked. In addition, for the IAQ criterion, a maximum CO_2 concentration of 1000 ppmv is commonly used (more details in ASHRAE62-1999 (ASHRAE, 1999)). The room humidity level can be controlled by the humidity level of the supply air. Since humans can tolerate a wide range of Relative Humidity (RH), the ventilation control is more flexible. On the other hand, thermal environment requires precision. Both supply temperature and flow rate are the key parameters to control room temperature. VAV relies on flow rate variation, while CAV relies on temperature variation. See detailed explanation in ASHRAE (ASHRAE, 2005). Matching the ventilation requirements of thermal, humidity and IAQ simultaneously is ideal but rarely occurs. When the cooling load is too low, ventilation control can be problematic. To assure the IAQ standards are met, cool air has to be continuously supplied. Thus, thermal discomfort is the consequence.

Table 1: Equations of ventilation requirement

Equation 1	Equation 2	Equation 3
$Q = \frac{q}{k(T_a - T_s)}$	$Q = \frac{W_p v_s}{(w_a - w_s)}$	$Q = \frac{M_p}{(C_a - C_s)}$
Q = supplied flow rate (CFM, m^3/sec) q = total cooling load (Btu/h, W) T_a = room temperature (F, C) T_s = supplied temperature (F, C) k = 1.08 in IP system, 1,227 in SI system	Q = supplied flow rate (CFH, m3/s) W_p = total vapor emission rate (lbs/h, kg/s) w_a = room air humidity level (kg of vapor/kg of dry air) w_s = supplied air humidity level (kg of vapor/kg of dry air) v_s = supplied air specific volume (cu.ft/lbs, m3/kg)	Q = supplied flow rate (CFH, m3/s) M_p= total CO2 emission rate (lbs/h, kg/s) C_a= room air CO2 level (lbs/cu.ft, kg/m3) C_s= supplied air CO2 level (lbs/cu.ft, kg/m3) v_c= supplied CO2 specific volume (cu.ft/lbs, m3/kg)

CFD PROTOCOL

CFD is increasingly used in many ventilation studies. The CFD method is sensitive to setup parameters (Zhang, 2005). To systematically record CFD parameters, **Table 1** is recommended in any studies (Yoshie et al., 2005). The RNG *k-ε* model is commonly used for impinging jet studies (Awbi, 2003). The meshing comprises both unstructured tetra and prism layers. The prism layers allow the result near boundary layers to be more accurate (ANSYS, 2005). To optimize the simulation time, steady state with 40 iterations and second order upwind are used. The simulation of humidity and CO_2 concentration require a special setting. The molecular diffusivity of both water vapor and CO_2 must be assigned in these simulations. Water vapor diffusivity of 0.000257 m^2/s at air temperature 20°C is used (Montgomery, 1947). The gases diffusivity depends on the molecule size. Since the CO_2 molecule size is less than 0.001 microns, a CO_2 diffusivity of 5.23E-6 m^2/s is selected (Zhang, 2005).

Table 2: CFD setup parameter

CFD code	ANSYS CFX 5.7 -10.0
Computational method and time integral scheme	Unstructured grid (Tetra + prism layer)
	Steady state (40 iterations)
Turbulent model	RNG k -e
Scheme for advection term	Second Orde r Upwind

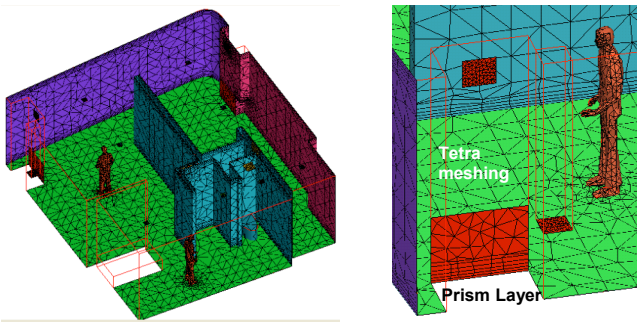

Figure 2 : The case study meshing:

Since simulating transient behaviors is both time and memory consuming, a steady state method is used as a first step in computing the different ventilation scenarios. In steady state, the thermostat routine can not be simulated. The temperature and other parameters are determined by a numerical balance embedded in CFD algorithms. **Equation 1** to **Equation 3** are used as a guideline for the CFD simulation setup. These equations are based on complete mixing theory (homogenous air temperature), while CFD is based on finite volume theory (each point/grid is treated as a control volume, (ANSYS, 2005). Thus, the outcomes from both methods can be different. To replicate the thermostat behavior, at least 3 steady state cases are needed. See **Figure 3**. In order to study the room average temperature, the study planes (described in "ventilation performances" session) of 3 CFD cases must be averaged and plotted. CFD#1 is usually setup to represent direct calculation (**Equation 1**). Both CFD#1 and #2 can be used to predict the CFD#3 parameters (supply temperature or flow rate). CFD#3 represents the actual condition for which temperature needs to be precisely controlled (23.5°C). As a result, the environmental parameters such as stratification discomfort, draft, CO_2, and RH can be obtained.

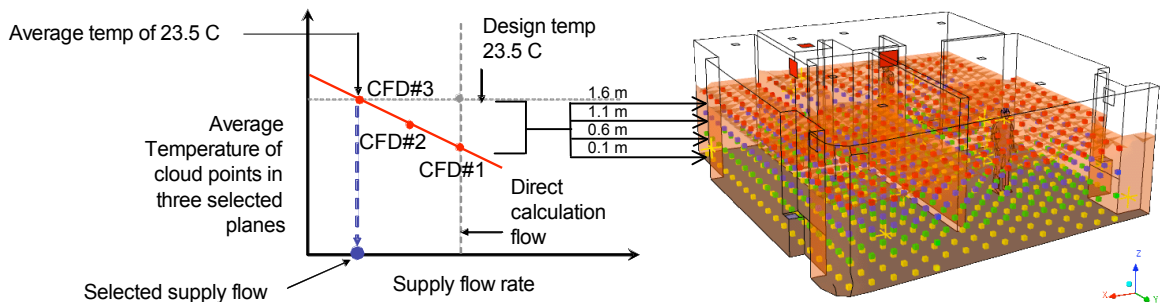

Figure 3 : The temperature control method of steady state simulation:

SCENARIOS SETUP

Eight simulation scenarios are set up for CAV and VAV simulation. The simulation scenarios are based on load variations. High, medium, and low cooling load densities (116, 47, 9 W/m^2) are simulated by both CAV and VAV cases. A peak cooling load (160 W/m^2) is added to VAV, while the heating load (-33 W/m^2) is added to CAV. Overall, at least 96 parametric runs including 3 CFD cases (from **Figure 1**), 8 scenarios (4 CAV and 4 VAV), and 4 ventilation strategies (MJV, DV, IJV#1, and IJV#2) are needed. Load was calculated using **Equation 1** and the energy software, eQUEST (DOE, 2004). For the given supply sizes, the velocity for VAV simulation can be setup with fixed supply temperature of 13°C. See **Table 3**. A supply flow rate of 0.49 m^3/s (11.12 ACH) is used in CAV simulation. To balance the heat removal rate, the CAV supply condition must match the VAV one. Using **Equation 1**, a VAV supply flow rate of 0.44 m^3/sec (at 13°C) is equivalent to a CAV supply temperature of 14.05°C (at a flow rate of 0.49 m^3/s). In **Table 3**, MJV, DV, and IJV supply sizes are shown. Since the supply size of IJV#2 is half of IJV#1, the supply velocity is double. Both IJV nozzles are fixed at a height of 0.75 m from the floor.

Table 3: The CFD scenarios setup and inputs for parametric simulations

	Ventilation Strategies							
	MJV		DV		IJV#1		IJV#2	
	CFD#1	CFD#2	CFD#1	CFD#2	CFD#1	CFD#2	CFD#1	CFD#2
Supply size (m^2)	0.210		1.547		0.186		0.093	
Load (160 W/m^2)								
VAV Flow rate (m^3/s)	0.68	0.5	0.68	0.5	0.68	0.5	0.68	0.5
VAV ACH	15.23	11.12	15.23	11.12	15.23	11.12	15.23	11.12
VAV Supply Speed (m/s)	3.14	2.31	0.44	0.32	3.66	2.69	7.32	5.38
VAV Vapor Conc (kg/m^3)	0.0101							
Load (116 W/m^2)								
VAV Flow rate (m^3/s)	0.44	0.39	0.44	0.39	0.44	0.39	0.44	0.39
VAV ACH	9.7	8.64	9.7	8.64	9.7	8.64	9.7	8.64
VAV Supply Speed (m/s)	2.19	1.84	0.30	0.25	2.47	2.08	4.95	4.15
VAV Vapor Conc (kg/m^3)	0.0101							
CAV Supply Temp (C)	14.05	14.84	14.05	14.84	14.05	14.84	14.05	14.84
CAV Vapor Conc (kg/m^3)	0.0109	0.0114	0.0109	0.0114	0.0109	0.0114	0.0109	0.0114
Load (47 W/m^2)								
VAV Flow rate (m^3/s)	0.20	0.16	0.20	0.16	0.20	0.16	0.20	0.16
VAV ACH	4.48	3.58	4.48	3.58	4.48	3.58	4.48	3.58
VAV Supply Speed (m/s)	0.95	0.76	0.129	0.103	1.08	0.86	2.15	1.72
VAV Vapor Conc (kg/m^3)	0.0101							
CAV Supply Temp (C)	19.18	19.51	19.18	19.51	19.18	19.51	19.18	19.51
CAV Vapor Conc (kg/m^3)	0.0147	0.0150	0.0147	0.0150	0.0147	0.0150	0.0147	0.0150
Load (9 W/m^2)								
VAV Flow rate (m^3/s)	0.04	0.049	0.04	0.049	0.04	0.049	0.04	0.049
VAV ACH	0.9	1.1	0.9	1.1	0.9	1.1	0.9	1.1
VAV Supply Speed (m/s)	0.185	0.227	0.026	0.032	0.215	0.264	0.430	0.528
VAV Vapor Conc (kg/m^3)	0.0101							
CAV Supply Temp (C)	22.653	22.637	22.653	22.637	22.653	22.637	22.653	22.637
CAV Vapor Conc (kg/m^3)	0.01794	0.01792	0.01794	0.01792	0.01794	0.01792	0.01794	0.01792
Load (-33 W/m^2)								
CAV Flow rate (m^3/s)	0.328	0.368	0.328	0.368	0.328	0.368	0.328	0.368
CAV ACH	7.34	8.24	7.34	8.24	7.34	8.24	7.34	8.24
CAV Supply Temp (C)	26.589	26.858	26.589	26.858	26.589	26.858	26.589	26.858
CAV Vapor Conc (kg/m^3)	0.0101							

SIMULATION RESULTS

Only 16 cases of IJV are shown. Since the flow rate variation affects CO_2 level, temperature and CO_2 profiles of VAV are plotted. Also, the supply temperature affects

the RH parameter (no reheat system). Thus, temperature and RH profiles are presented.

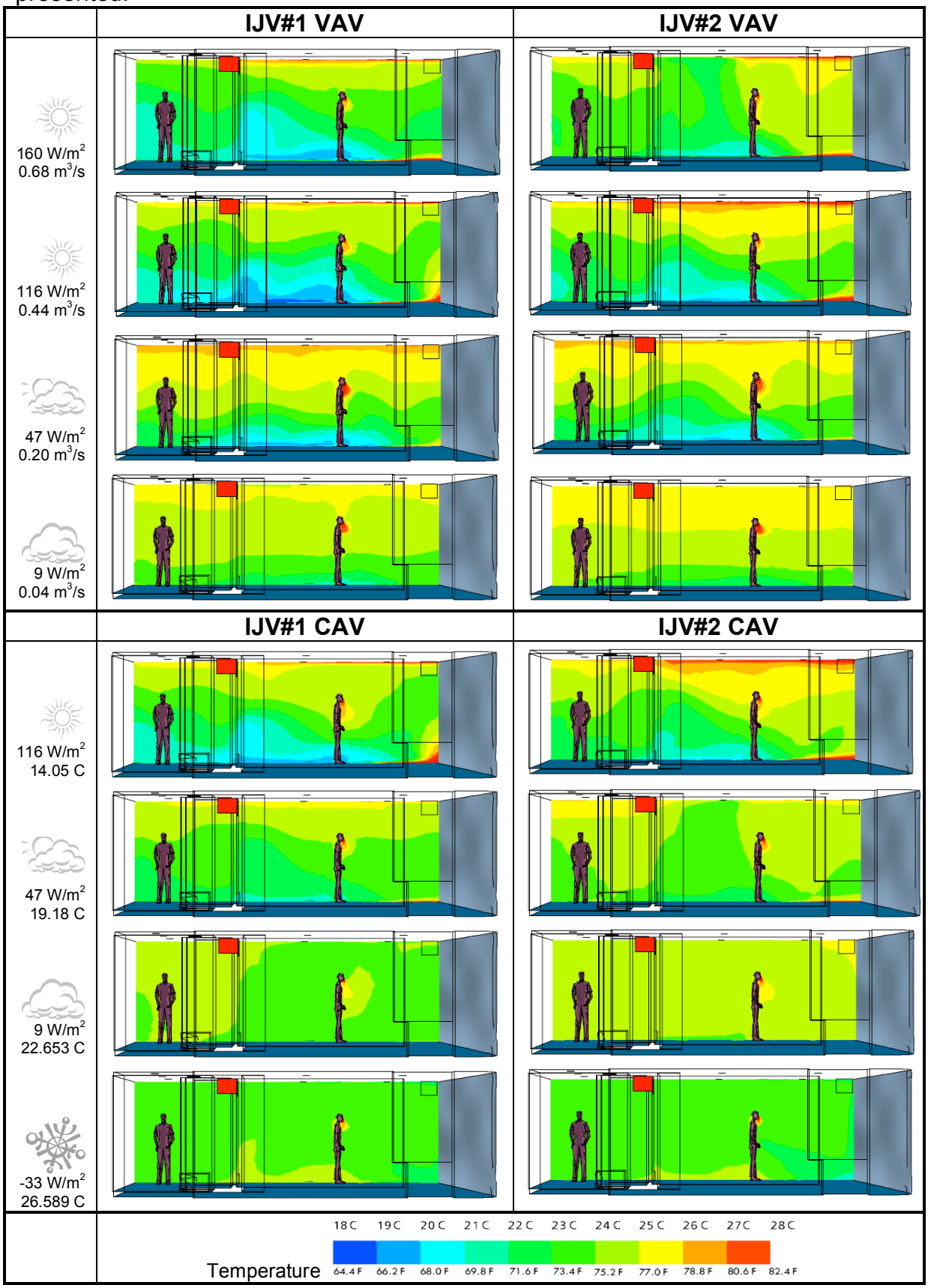

Figure 4 : Temperature profile of IJV using both VAV (top) and CAV (bottom):

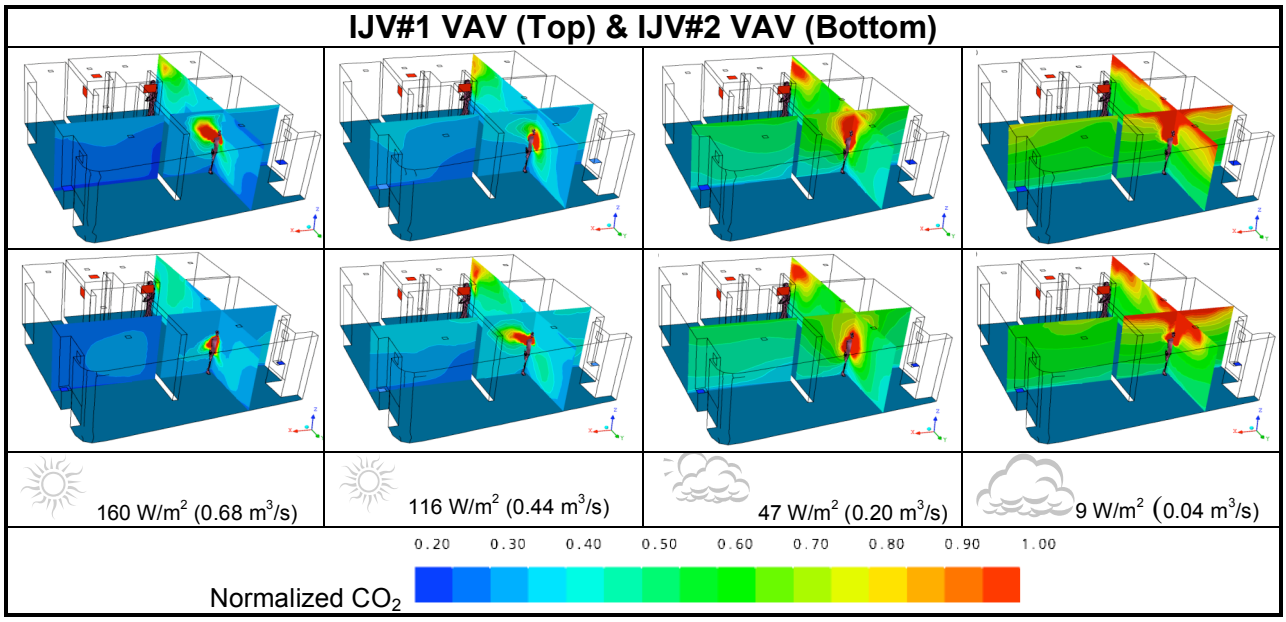

Figure 5 : CO_2 concentration profile of IJV using VAV:

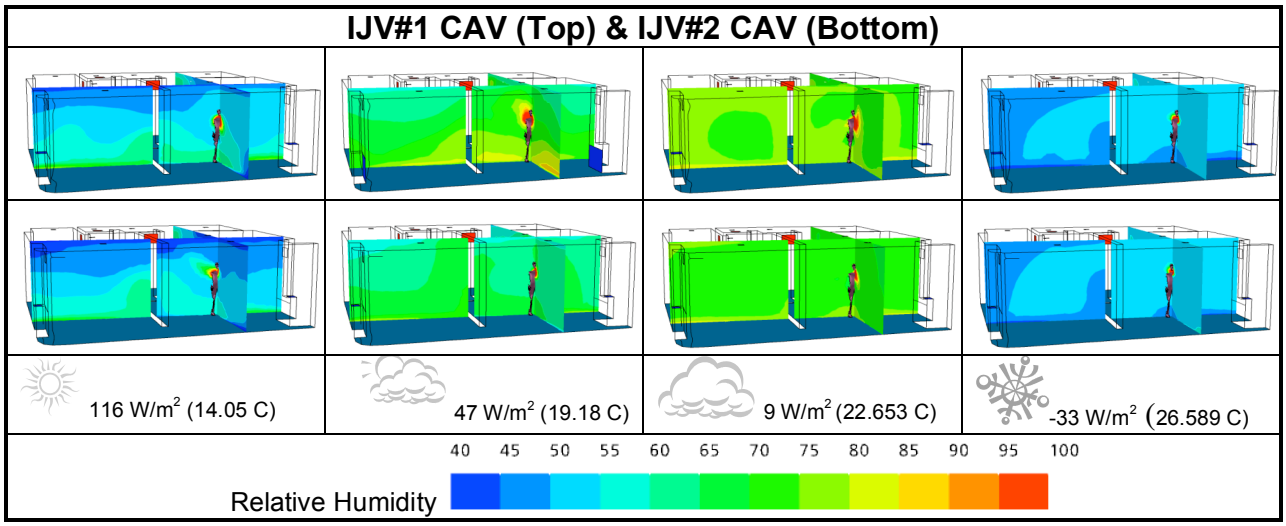

Figure 6 : CAV RH profile of IJV using CAV:

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