Journal of Engineering Science and Technology
Vol. 19, No. 1 (2024) 207 - 225

SIMULATION OF DESIGN BY USING CFD FOR THE VENTILATION SYSTEM OF A PORTABLE CLEANROOM CHAMBER

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Abstract

The air washer is a hybrid appliance combining air purifier and a humidifier. Air washer removes symptom-triggering allergens and pollutants from the air while adding therapeutic moisture. This industry-academia collaborative project designs a ventilation system for a portable air chamber that effectively draws in the clean air from an air washer, circulates fresh air and exhaust stale air through the outlet vent. Two ventilation system were developed based on impinging jet and underfloor air distribution technologies. The design models underwent computational fluid dynamics simulations to determine the optimal design. The key elements used to assess the effectiveness of the chamber design were human comfort level, including airflow velocity, skin temperature acceptability and chamber temperature and pressure differentials. The ANSYS results revealed that the impinging jet system has better overall performance than underfloor air distribution system. The impinging jet system achieved an air velocity of 1.25 m/s, a mean human skin temperature of 30 °C, a temperature stratification of 2 °C/m. The chamber temperature is 20.5 °C and chamber differential pressure within the range of 2 Pa to 3.75 Pa. The proposed impinging jet design has fulfilled both the design and performance requirements, making it an effective ventilation chamber. The portable air cleanrooms, in general, are relatively compact and portable enclosures designed to provide a controlled environment with a low level of airborne particles and other contaminants. The proposed systems can be used in various industries such as pharmaceuticals, electronics, biotechnology, and more.

Keywords: Air flow, Air washer, Computational fluid dynamics, Impinging jet, Thermal comfort.

1. Introduction

The awareness of the importance of a healthy indoor climate is growing all the time. Nearly everyone knows that poor air is bad for our health with detrimental effect displayed in those who expose to it over long hours of time. The World Health Organization (WHO) has reported that indoor air is 2 to 5 times more polluted than the outdoor air and in average, a person spends over 90% of their time indoors which is in accordance with the United States Environmental Protection Agency [1].

Two most important factors that determine an indoor air climate are the air quality and relative humidity. Indoor air quality is measured with the Air Quality Index (AQI) that indicate the amount of pollutant and contaminant within an enclosure. An AQI value of ≤50 represents good air quality, while an AQI value over 300 represents hazardous air quality [2]. For air humidity, a relative humidity of 40% - 60% is regarded as a pleasant level which generally recommended by the ASHRAE Handbook [3].

All indoor parameters related to Indoor Air Quality (IAQ), including thermal comfort are greatly influenced by ventilation because ventilation can remove indoor contaminants and provide the occupants with fresh air, contributing to controlling and improving IAQ [4, 5]. In some circumstances, ventilation can be used to adjust the indoor air temperature and relative humidity via the introduced fresh air, resulting in less operation of mechanical systems and corresponding lower energy consumption [6].

To improve indoor air quality, one of the effective ways is to use an air purifier or air washer with good air flow system. Good air flow would effectively remove stagnant and stale air to improve the indoor air quality. Malaysia though is placed at the lower end of the moderate spectrum, there are months throughout the year, the country experiences rapid spikes in pollution.

This research is an industry collaborated project. The company focuses on manufacturing, research, technological innovation, and production processes to provide customized air filtration and air related products and services. An air washer is a hybrid appliance, a combination of an air purifier and a humidifier. Like a conventional air purifier, an air washer removes symptom-triggering allergens and pollutants from the air. Similar to conventional humidifiers, air washers add therapeutic moisture to the air. However, the current design of appliances has portability, effectiveness, and adaptability constraints for different range of applications.

This research aims to fill the gaps by investigates the design and specification for a fresh air ventilated chamber unit that fulfils specified requirements and standard. The chamber needs to maintain a constant airflow with optimal ventilation for user' thermal comfort, ensuring a satisfying and enjoyable experiential feel within the chamber. The chamber design will be integrated with the company's air washer product, specially designed and built for the company's use as a kiosk. In a broader perspective, the research output represents a novel approach to maintaining controlled environments in a flexible and adaptable manner, with key elements including mobility, portability, compact, modularity, scalability, and compatibility with various applications.

2. Preliminary Study

This section discusses the published information and knowledge on subjects related to the research scope. In this context, various approaches and types of air ventilation and air distribution technologies were studied and investigated. Previous research on ventilation systems in chambers to achieve human thermal comfort were reviewed.

2.1. Air washer

An air washer is a 2 in 1 hybrid unit, consist of an air purifier and a humidifier. It is as though the conventional type of air purifier and humidifier; an air washer usually removes household allergens from the air and as well able to provide moisture to the air. As dirty air is pulled into the air washer, pollutants like dirt, dust, dander and pollen stick to the wet disc stacks and are trapped in the unit's reservoir. Only crisp clean air is released; thus, airwasher is capable to sooth the dry air environment, removes contaminants and ease allergies. There are water-based and filter-based types of air washer which applies different humidification technology. Water-base air washer is based on direct evaporative cooling technology which uses water evaporation for air cooling and involves the application of heat and mass transfer process in the air washer system, this type of air washer is ideal for larger rooms since they use internal fans to push the clean air to all direction [7].

2.2. Ventilation and air distribution

To achieve a better AQI and energy efficiency, both design and working concepts of ventilation and air distribution system are important. Ventilation is the process of taking the outdoor air into a space and distributes the air within it such as a room. The purpose is to provide and achieve good and healthy air quality for breathing by reducing and removing pollutants from the space. Ventilation systems can be easily categorised into the natural or mechanical ventilation system. Natural ventilation is the process of air movement in and out of the room or building, it is very much depending on outdoor condition of wind and temperature which may vary and hard to control. As for mechanical ventilation system, the circulation of air uses fans and ducts, and it is normally done by installing fans directly in air ducts to supply or remove air from a space. There are three basic categories of mechanical ventilation namely exhausted-only ventilation, supply-only ventilation, and balanced ventilation [8]. Balanced ventilation is the combination of supply-only and exhausted-only systems as it uses fans to introduces air both into and out of the spaces [9]. This system has the advantages of supply-only and exhausted-only systems such as reduced dust and contaminants without the limitation of moisture problems.

To deal with the air distribution within the space, this involves inlet and outlet processes of the air into the area. The system involves in different components such as air handlers, ductwork, ventilating, and air-conditioning and buildings. An effective air distribution system is able provide air quality to the user with minimum energy use. Air supply system is one of the important systems to be considered. An air supply system that results in upward displacement flow is said to provide better performance than conventional air supply systems. Besides, the supply air velocity of the air distribution system must be appropriate so that fresh air can be delivered upon user with better thermal comfort [10].

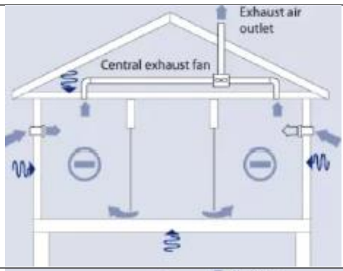
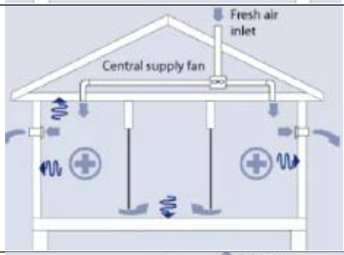
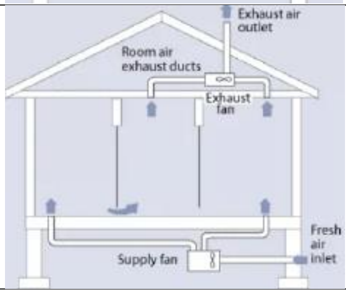
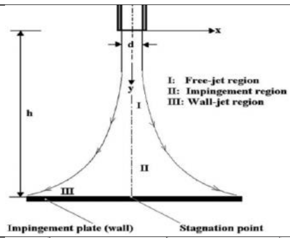
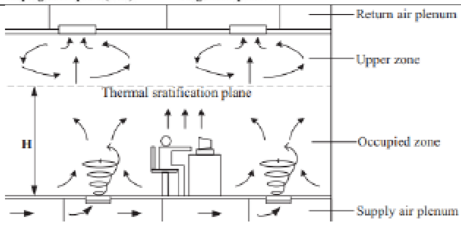
A displacement ventilation (DV) system can improve air quality by supplying fresh air direct to the occupied zone with lower energy consumption. DV system supplies low-velocity ventilation air with near laminar flow condition horizontally at floor level to create a pool of fresh air. This low velocity supply air cause very minimal induction and mixing of room air. Mixing ventilation (MV) is a type of mechanical ventilation based on design of air supply diffusers and exhaust vents. This system supply air in the way that the entire room space is fully mixed. The air is supplied with high velocity that generate a high and intense turbulence to promote good mixing in the area by entrainment, which reduces air velocity and uniform the air distribution in the space. A hybrid air supply system combines the characteristic of both mixing ventilation and displacement ventilation to overcome the drawbacks of the displacement ventilation system. One of the types of hybrid air distribution system is known as impinging jet (IJ) system. The working principle of IJ system is based on supplying jet of air with high momentum directly downwards onto the floor and as the air jet impinges onto the floor, it spread over a large area causing the air to travel long distances. The IJ distribution system has advantage of both the mixing and displacement ventilation system in terms of air distribution and energy efficiency and able to produce similar flow field with momentum range in between the MV and DV systems [11]. IJ system produces a clean air with a wider horizontal spread over area in the lower part of ventilated zone and exhibits higher air-exchange effectiveness. In the meanwhile, an underfloor air distribution (UFAD) system delivers the conditioned air into the space through supply diffuser at near floor level and expelled via exhaust at ceiling level. This creates the buoyancy effects for air circulation within the space and maintain the stratification level. Table 1 summarises the different approaches to ventilation and the configuration of the air distribution.

Ye et al. [12] investigated the improved of energy efficiency by splitting the exhaust unit and return vent into two single units in impinging jet ventilations (IJV) system. Navier Stokes equation with RNG k-epsilon turbulence model is applied to predict the airflow in a test chamber with dimension of 5.16m x 2.43m x 3.65m. Various height of return outlet in the IJV room were simulated for its temperature difference, draught comfort, air change efficiency, contaminant removal efficiency and energy saving. The return outlet height ranging from 1.2 to 1.5 gives the best overall ventilation performance.

Staveckis and Borodinecs [13] researched on impinging jet ventilation (IJV) to study the thermal comfort and indoor air quality in office building. The work was conducted experimentally with a climate chamber. Simulation is carried out for the distribution of air quality and air-temperature. The chamber area of 11.56 m^2 is modelled with occupant, computer device and lamps. Air duct of IJV is attached to the wall and supplied by fan with constant height of air supply throughout the experiment. From the simulated result, a higher ventilation effectiveness performance makes IJ a better system as compared to mixing ventilation as IJ achieves a lower temperature difference between supply air and indoor air. As for thermal comfort and indoor air quality, the optimal supply airflow velocity is between 1.7 m/s to 2.3 m/s. A review was done on the performance test of a ventilation fan unit by using the real-time airflow rate and measuring and monitoring airflow at inlet and outlet. Singh et al. [14] suggested that fan performance could be further improved by improvising duct and fan filter cleaning.

Also, the most efficient and economical way could be installing proper diffuser to improve fan performance to distribute the air flow evenly in the desired direction.

Table 1. Types of mechanical ventilation and the air distribution configuration.

Mechanical Ventilation	Advantages	Disadvantages	
Type: Exhaust Only	Inexpensive, simple to instal. Allow install of filtration system.	Easily draw pollutants into space. May depressurise the ventilated space. Rely air inlet on random leakage.	
Type: Supply Only	Inexpensive, simple to instal. Better flowrate than exhaust type. Allow install of filters, function in hot and mixed climate	Easily cause moisture problem. Increase heating and cooling cost.	
Type: Balanced	Function well in all climates by equally drawing and expelling air. Pressure inside the space stay constant	Relatively expensive than the exhaust-only and supply-only system. No removal of moisture from incoming air. Increase heating and cooling cost	
Air Distribution Characteristic			
Impinging Jet	Breathing zone: up to 1.2 m from floor. Air supply: > 0. 25 m/s. Location of supply: lower part of the room		
Underfloor Air Distribution	Breathing zone: up to 2 m from floor Air supply: 0.15 m/s - 0. 25 m/s Location of supply: floor level		

2.3. Fan design

Fan is one of the main components of the ventilation system to provide fresh air. To achieve a high efficiency ventilation system, fans used needs to be of appropriate type and size according to length, type and design of duct system to provide airflow to sufficiently capture contaminants and remove them systematically. Fans that are commonly found in the markets are axial fan and centrifugal fan. Axial fans draw air and exhaust parallel through the fan while centrifugal fans draw air into the fan on the face and exhaust it at a 90-degree angle. The ventilation fan which supplies fresh air must be always higher than the exhaust air quantity to always keep the room under positive pressure. The exhaust fan device selected must correspond to the exact calculated values of exhaust air volume while the fresh air supply fan device chosen must be 1.1 times. For the application in this study, the AC centrifugal fan single intake type of size 120mm is used, measured values are speed, n = 2515 rpm, power consumption, P_e = 73W, air flow and q_v = 205 m^3/h.

2.4. Fluid dynamics

For a functional enclosed chamber design equipped with suitable components for an effective ventilation system, fluid dynamics is engaged, and a preliminary analysis of feasible design inputs is performed to determine the specifications. With a low air flow velocities and small pressure variations conditions, air can be considered as an incompressible fluid in practical engineering applications. Assuming a uniform velocity profile throughout the flow, given the Continuity Equation Eq. (1), with Q and A are the air flow rate and flow area, respectively.

$$Q = A_1 v_1 = A_2 v_2 \tag{1}$$

Air change rate (ACH) is a measure of air volume needed per hour to be added or removed to the ventilated area during ventilation. When ACH is served as the input [15], it is required to be calculated so that the ventilation requirement is known which depends on the size of ventilated area. The ACH equation is given by Eq. (2) with V and Q being the volume of the ventilation space (m^3) and flow rate of exhaust or supply (m^3/hr) respectively.

$$ACH = Q/V \tag{2}$$

3. Methodology

The research activities will begin with design requirement specifications, preliminary analysis and system model design, followed by computational fluid dynamics (CFD) modelling and analysis through ANSYS.

3.1. Design inputs and requirements

To establish the basis and boundary conditions for the ventilated chamber design, some of the physical and performance characteristics were determined. The design inputs and requirements are set and summarised in Table 2.

- Air washer type - powerful to work with indoor space up to 600 square feet for living room, family room and other open rooms.
- Size of chamber - occupy 1 to 2 adults at a time.

- Chamber structure - dynamic, flexible and modular structure with light weight material considering that the chamber needs to be portable, easy to assemble and disassemble, and moving from one place to another.

Cheng et al. [16] have revealed the key elements that determined human comfort is affected by physical body condition and environmental factors. Proper maintain of human comfort is one of the key elements to be investigated in order to provide the desired comfortability. The physical factors are but not limited to airflow velocity comfort and skin temperature acceptability whereas for the environmental factors, they are but not limited room temperature and room pressure.

Table 2. Inputs and design requirements.

	Requirement
Air washer	3-gallon capacity for 600ft^2 (room space with standard 8ft ceilings)
Air washer dimension	0.450 m (W) × 0.300 m (H) × 0.330 m (D)
Air washer flowrate	0.071 m^3/s
Chamber dimension	1.5m × 1.5m × 2.5m
No of occupant in room	For one to two adults
Ventilation fan	Centrifugal fan type for air inlet and air exhaust
Inlet fan (2 units)	Rated flowrate 0.043 m^3/s
Exhaust fan	Rated flowrate 0.058 m^3/s (as to maintain positive air pressure)
Chamber Material	Aluminium alloy

The Airflow velocity, also known as average speed of the air to which the body is exposed. In a typical indoor situation, the maximum allowable air velocity by ASHRAE-55 standard is in range of 0.8 m/s - 1.2 m/s. However, Candido mentioned that the maximum acceptable indoor air velocity is from 0.5 m/s to 2.5 m/s. In addition, Taweekun and Tantiwichien [17] proposed that air velocity of 0.2 m/s - 0.4 m/s could provide comfortability and optimal airflow velocity of 1.5 m/s is suggested to bring good body thermal comfort.

The skin temperature acceptability is one unavoidable element to determine human thermal comfort. The factors include mean skin temperature and surrounding air temperature around a person. The best thermal comfort for mean skin temperature is at around 30°C - 33°C. However, the individual differences such as gender and physically differences could also contribution to the factor of thermal comfort [18]. For surrounding air temperature around a person, it has high linkage with the thermal stratification because thermal discomfort may occur when the air temperature at the head level is higher than of ankle level. ASHRAE- 55 imposed a limit of 3°C/m between the head and feet of a seat occupant. Sappenen et al. [19] shows that the influence of gender can be negligible when the vertical temperature gradient is within 5°C/m. For the environmental aspects, the factors that contributes to the indoor air quality and thermal comfort of the occupant include but not limited to are the room temperature and room pressure. Study had revealed that the productivity of human decreases as the temperature increase from 24°C onwards and the optimum temperature is within 20 °C-22 °C [20], another study had revealed that for a normal operated positive air pressure ventilated room, the range of 2 Pa to 10 Pa of differential pressure is adequate [20, 21].

The above findings summarise the following conditions that contribute to a good thermal comfort level for humans in an enclosed area. These factors need to be studied and evaluated to determine the design of the chamber unit.

- Airflow velocity within the range of 0.2 m/s to 2.5 m/s, and 1.5 m/s (optimal)
- Human skin temperature around 30°C - 33°C
- Thermal stratification of 3°C/m between the head and feet of a seated occupant
- Chamber room temperature 20°C - 22°C
- Positive air pressure in the chamber and differential pressure within range of 2 Pa to 10 Pa

3.2. Engineering designs

Two approaches of air ventilation system from literature concepts were used to generate the chamber designs, there are the impinging jet (IJ) system and the underfloor air distribution (UFAD) system.

3.2.1. Impinging jet (IJ) system

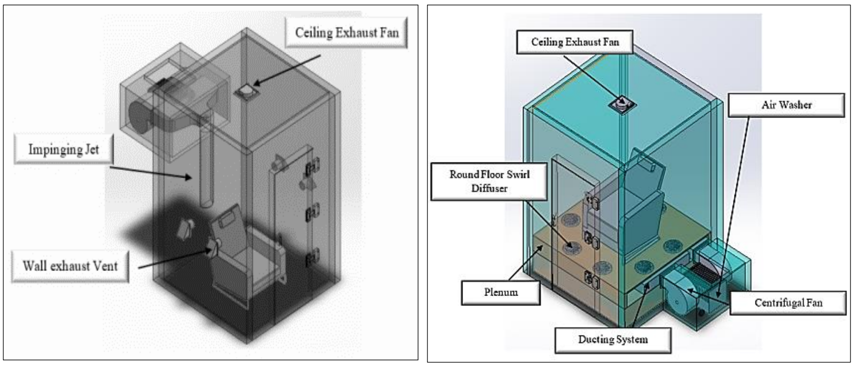
For a hybrid distribution method [22], the semi-elliptic shaped impinging jet device manufactured by Air Queen is used. From the product specification, the area of impinging jet A_{jet} is given as 0.01319 m^2. The velocity of the semi-elliptic shaped impinging jet, as defined by Staveckis and Borodinecs [13] will be v_{jet} = 5 m/s. From equation $Q_{jet} = A_{jet}\, v_{jet}$, the flow rate of the impinging jet is 0.066 m^3/s. Then, the 3D model for the chamber was generated and Fig. 1(a) shows its isometric view. The design has an impinging jet, a ceiling exhaust fan and wall exhaust vents. The impinging jet outlet is located at 0.6m above the floor level, there are two centrifugal fans which are used to draw in the fresh air from the air washer into the air duct and supply directly to the chamber. The ceiling exhaust fan expels the stale warm air that rises to the ceiling because of air movement in the room. To improve more uniform air distribution, exhaust vents are designed on both sides of the wall. Thus, the fresh air can be continuous flow to the enclosed chamber for user's comfort. The chamber is equipped with a chair for the user to relax and enjoy the fresh air from the air washer.

3.2.2. Underfloor air distribution (UFAD) system

The conceptual idea inspired from the configuration layout review [23] of underfloor air distribution system. Preliminary analysis is done to obtain the design parameters for the volume of chamber, air change rate and number of air diffuser.

- Volume of chamber, $V_{chamber}$ = 1.5 m × 1.5 m × 2.5 m = 5.625m^3
- Given $Q_{exhaust}$ = 210 m^3 / hr (0.058 m^3/s ×3600), the air change rate, ACH = $Q_{exhaust}$ / $V_{chamber}$ = 37.33 ≈ 37/hr

From the product spec of floor diffuser by Swirl Floor Diffuser, System Air 2021, Q_{diffuser} is 30 m^3/hr, or 0.010208 kg/s. Hence, the number of air diffuser required is, $Q_{\text{supply}}/Q_{\text{diffuser}}$ = 210/30 = 7. Thus, the total mass flow rate will be 0.071456 kg/s. The 3D model for the UFAD ventilated chamber unit was developed as shown in Fig. 1(b). For this design, the fresh air is drawn from air washer through the plenum and directly supply to the enclosed chamber. There are seven floor swirl diffusers installed on the floor and each of them are equally space to ensure the occupant experience the fresh air from all direction. The floor swirl diffusers are designed to be at least 0.6m away from the occupant to reduce the draft. In the design, two centrifugal fans are used to supply the fresh air to the ducts underneath the floor by taking in the fresh air from both side of the air washer. The ducts then deliver the fresh air to the round swirl floor diffuser. The user can always experience continuous surge of fresh air directly from the ground and stale air can escape directly through the ceiling exhaust fan.



(a) IJ system. **(b) UFAD system.**

Fig. 1. Isometric view of IJ and UFAD systems.

3.3. Computational fluid dynamics (CFD) modelling

The application of CFD is used to determine airflow in terms of its direction, temperature, and turbulence levels in a ventilation model. The computational domain is governed by the conservation laws of mass, momentum and energy which the mathematical models involve are the continuity equation, Navier-Stroke equations and energy equation [24].

For this study, the simulation was conducted by using the ANSYS Fluid Flow (FLUENT), the computational domain of 1.5m x 1.5m x 2.5m is created with the components of air inlet, air outlet, chair and human model all comes into one and form the whole domain. For meshing process, the mesh shape used are the combination of tetrahedral and hexahedral and for good mesh quality, finer mesh density is placed at the air inlet (20mm), the air outlet (30mm) and the chamber body (30mm) locations because these are the important areas to be investigated and mesh control is needed. The set-up conditions are then defined for the energy, turbulence model, fluid type and boundary conditions as shown in Table 3. The pressure-based steady state solver type is applied in this case which flow parameters do not change over time. The domain is set to have the presence of gravitational force. Energy equation is turned on so that the temperature can be set at the desired value. For the viscous model, the realizable k-epsilon with standard wall functions are applied as it provides a higher degree of solution accuracy for indoor simulation. For the human model to be close-in realistic situation, the radiation model is switch to the discrete ordinates so that the heat radiated from human body can be achieved. At here, surrounding temperature is set at $20°C$ according to the ASHRAE standard, thermoregulation models releasing a heat flux of $60 W/m^2$ is used for thermal comfort studies, turbulence intensity and turbulence viscosity ratio of the air is defined to be 5% and 10% respectively and all wall surfaces are treated as adiabatic and non-slip conditions as mentioned by Heidari et al. [25]. At the solution set up, the SIMPLEC method for the steady-state pressure-based algorithm is applied besides speed up the convergence rate as stated [26].

Table 3. CFD settings.

Solver			
Type		Pressure-Based	
Velocity Information		Absolute	
Time		Steady	
Gravitational Acceleration			
Gravity		-9.81 (Y-axis)	
Energy Equation			
Energy		On	
Radiation Model			
Radiation		Discrete Ordinates (DO)	
Viscous Model			
Model		Reliazable k-epsilon (2 equations)	
Near Wall Treatment		Standard Wall Functions	
Material			
Fluid		Air	
Solid		Human and Polycarbonate	
Boundary Conditions of Impinging Jet Ventilation Design		**Boundary Conditions of Underfloor Air Distribution Design**	
Inlet	5 m/s	Inlet	0.07145 kg/s
Outlet	Pressure Outlet	Outlet	Pressure Outlet
Wall	Stationary and non-slip condition	Wall	Stationary and non-slip condition

4. Results and Discussion

The 3D models of the two ventilated chamber designs for the IJ and UFAD systems are subjected to CFD analysis in ANSYS environment. Simulation is performed for the 4 key criteria listed below which include both the physical and environmental factors. Results obtained were analysed to evaluate the ventilation effect and the comfort level of the occupant in the chamber.

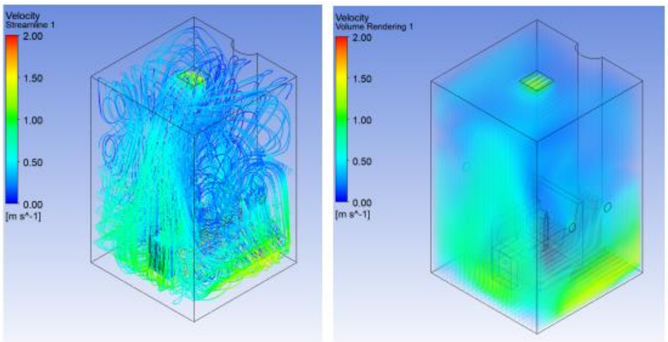
- Air distribution profile and airflow velocity (or average air velocity)
- Mean human skin temperature and thermal stratification
- Chamber temperature
- Chamber differential pressure

4.1. Air distribution profile and airflow velocity

Simulated results for both IJ and UFAD system for their air distribution profile and airflow velocity were analysed and discussed below.

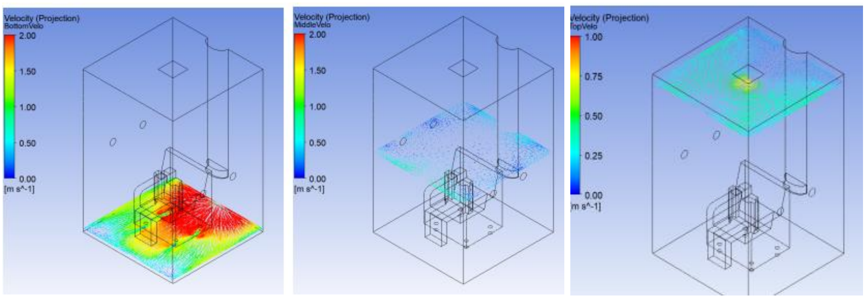
4.1.1. IJ system

Post CFD simulated plots in Fig. 2 showed that the air displaces and mixes in the chamber as it widens in spatial span from bottom to top part of the chamber. The air moves downwards after exit from the nozzle and hit the floor surface, it then turns, spread radially outwards and reaching to the corner of chamber. The air velocity is around 1.5 m/s at the lower floor area and velocity of 1.5 m/s again seen at the top near the exit exhaust. The air that enveloped the occupant at the bottom to middle has velocity around 1 m/s to 1.5 m/s. To further investigate, the air velocity vectors were simulated (Fig. 3) at three sectional planes which are located at the bottom, middle and top plane along the height of the chamber. At the bottom plane, the impinging jet spreads widely at high speed immediately as it leaves the exit nozzle. The air velocity decreases as the air displacing around the areas and moving up, which air velocity drops to around 0.5 m/s at the middle plane. At the top plane, it shows a higher velocity of air at around 0.75 m/s and at exit exhaust, velocity value is 1.5 m/s. The air flow and distribution pattern are sufficient to allow good mixing and displacement in the chamber without exhausting air at high rates than it supplies.



(a) Velocity streamline. **(b) Velocity render.**

Fig. 2. Air distribution and air velocity for IJ system.



(a) Bottom. **(b) Middle.** **(c) Top.**

Fig. 3. Air Velocity at different plane in the chamber (IJ).

For precise airflow velocity surrounding the occupant, four sectional planes (Fig. 4) in between the bottom and middle part of the chamber are simulated. These planes provide good reference of information to study the air velocity at the sitting area of occupant in the chamber. The velocity is highest to the floor area (plane 4). The air enveloped the occupant body in the range of 1.0 m/s to 1.5 m/s between plane 2 and 3. This gives a very small difference of air velocity towards the occupant which is adaptable and create a good sensation.

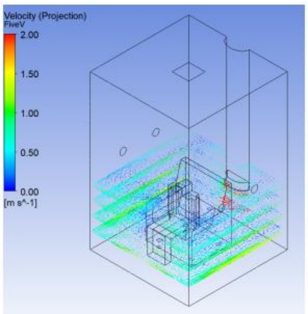
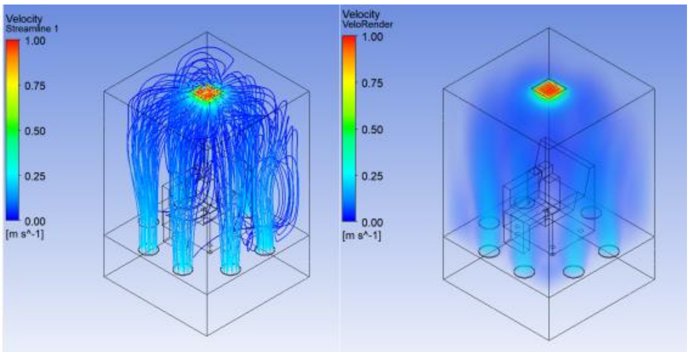


Fig. 4. Air velocity at four planes of the chamber (IJ).

4.1.2. UFAD system

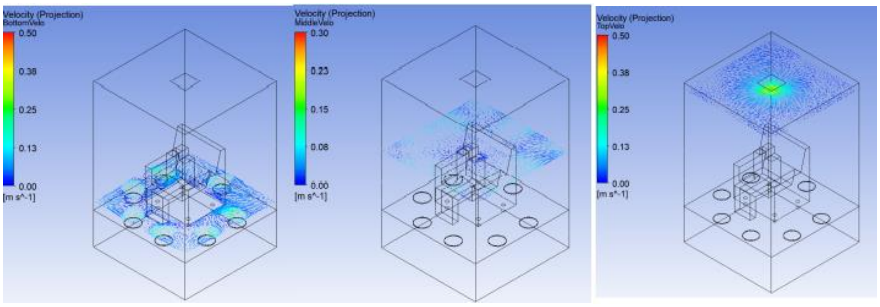
Figure 5 shows the simulation for UFAD model. The air velocity at the inlet of the seven equally spaced air diffuser is about 0.25 m/s and the velocity reach the outlet at about 1 m/s. The flow pattern indicates a surge of air flow supply directly to the occupant from the underfloor plenum in an appropriate manner. There is merely very less volume of air flows at the sides and corners of the chamber in the occupied zone. The velocity at the upper part at the air exhaust is at 1 m/s whereas the lower plenum area is above 0.25 m/s. Figure 6 shows that the inlet air velocity at the bottom plane is at 0.13 m/s - 0.25 m/s. A low air velocity directly heads on to the occupant is considered good to avoid unnecessary draft which might lead to thermal discomfort. This unwanted draft can rapidly carry away heat from the body, decrease in air temperature felt by the body on exposed skin and resulting in variations in perceived temperature across the body, leading to discomfort as different parts of the body experience different thermal conditions.

Subsequently, the air flow decays as it surged through the chamber from bottom to top. As shown at the middle plane where the velocity vector is at around 0.10 m/s. However, this is still sufficient as the flow headed over the occupant. At the top near the ceiling, the stale air is exhaust with a velocity of around 0.25 m/s. Two more planes were simulated in between the bottom and middle part of the chamber to further investigate the air velocity that surrounds the occupants. Figure 7 shows that the air flows that enveloping the occupants is around 0.15 m/s to 0.23 m/s, which is relatively high compared to the middle and at bottom plane. Under this circumstance, it is adequate to provide good thermal sensation to the occupant as the air flows from bottom to top at all direction in the chamber. Additionally, the thermal plume can induce the fresh air from the lower part of the room to the breathing level of the occupant which allow the occupant to take in fresh air at every moment. Table 4 summarised the simulated results and shows that the two systems have met the air velocity requirements (0.2 m/s - 2.5 m/s). As for the average speed of the air to which the body is exposed to, the IJ system show values in range of 0.8 m/s - 1.6 m/s as compared to 0.2 m/s - 0.3 m/s for UFAD. For the average air velocity surrounding the occupant, the data shown that IJ system has an average air flow value of 1.25 m/s which is close to the optimum value of 1.5 m/s, while UFAD system has achieved an average air velocity of 0.21 m/s. Hence, it can be concluded that IJ system is ranked higher in priority order than UFAD system.



(a) Velocity streamline. **(b) Velocity render.**

Fig. 5. Air distribution and air velocity for UFAD system.



(a) Bottom. **(b) Middle.** **(c) Top.**

Fig. 6. Air velocity at different plane in the chamber (UFAD).

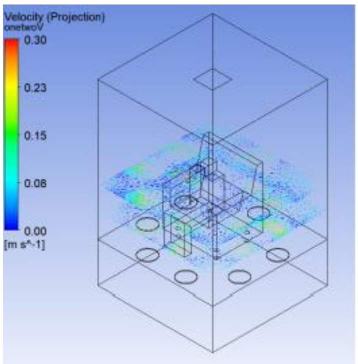


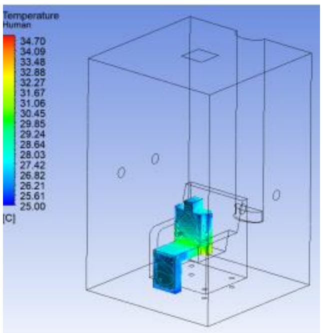
Fig. 7. Air velocity at bottom and middle plane (UFAD).

Table 4. Summary data for air velocity.

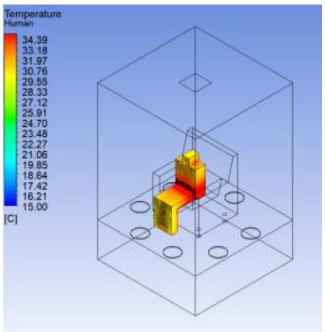
System	Maximum Air Velocity, m/s						Airflow velocity, m/s
	Bottom Plane	Middle Plane	Intermediate Plane				
			1	2	3	4	
IJ	2.00	0.60	0.8	1.2	1.3	1.6	1.25
UFAD	0.24	0.1	0.2	0.3	-	-	0.21

4.2. Mean human skin temperature and temperature stratification

Mean temperature of human skin and temperature stratification are simulated in ANSYS too. Both are important criteria to ensure human comfort in enclosed area. The temperature of human model in IJ shown in Fig. 8(a) has skin temperature of around 30°C, which is the average temperature for the head, chest, waist, shoulder, and feet. In this case, the temperature difference from head and feet is around 29°C to 27°C, a deviation of around 2°C. This small difference in vertical air temperature does not affect the discomfort of the occupant as a high temperature difference from head to feet might cause human thermal discomfort. In this context, thermal comfort is assured. The human body that shows temperature of around 31°C are the waist, hands, and the back part of body. Since the chamber is designed for short duration of stay, a lower chamber temperature within the optimum chamber temperature is said to be tolerant synchronized with the desired air velocity. For the UFAD system, the mean skin temperature of human model shown in Fig. 8(b) is around 32°C. The head and feet temperature are around 31°C, with a small temperature difference that provides thermal comfort. Other parts of the human body such as the waist, hands and the back part of body shows temperature of around 33°C. Table 5 summarised the skin temperature, the mean skin temperature, and the thermal stratification of the chamber occupant for IJ and UFAD system.



(a) IJ system.



(b) UFAD system.

Fig. 8. Temperature of human model.

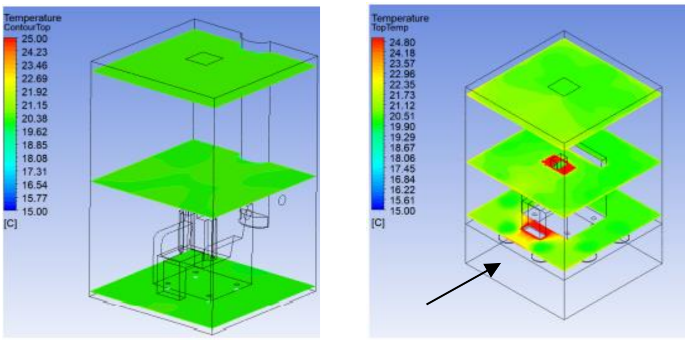
Table 5. Occupant data for the skin temperature and thermal stratification.

System	Skin Temperature, °C					Mean, °C	Thermal stratification, °C/m
	Head	Shoulder	Hand	Lower Body	Leg		
IJ	29	27	33	32	27	30	2
UFAD	32	32	34	33	30	32	2

To evaluate the optimum chamber design in terms of mean skin and thermal stratification, Ji et al. [18] has stated the requirement and acceptable value of for best comfort for mean skin temperature is 30°C - 33°C. ASHRAE-55 imposed a limit of 3°C/m between the head and feet of a seat occupant. Both systems showed equivalent good result. However, individual preferences and other environmental factors should also be considered to determine the optimal comfort level.

4.3. Chamber temperature

The chamber temperature is one of the environmental factors/criteria to determine a good thermal comfort air ventilated chamber. For temperature profile analysis, the chamber of IJ system is stratified into 3 planes which are the bottom, middle and top as shown in Fig. 9(a). The overall temperature is around 20.5°C and slightly lower at the bottom plane as compared to the middle and top planes. In this scenario, the temperature gradient in the chamber is very small and insignificant. The human body thermal flume is the reason for the small increase of temperature at the top plane where the heat is brought by the plume as it buoyant and rise. By locating the ceiling exhaust directly above to the occupant can remove heat more efficiently due to the thermal plume effect. Figure 9(b) shows that the temperature in the UFAD chamber is around 21°C, however it is relatively higher at the front facing of the chamber, indicated by an arrow in Fig. 9(b). At the bottom plane, the temperature is 22°C - 24°C in the occupant's sitting leg position. At the middle plane, it is shown that the temperature of chamber is around 21°C and again it is higher at the front facing area. The similar temperature condition is seen at the top plane, an effect of thermal stratification. In this context, the air in the lower zone is fresh and cool as heat air is trapped at the upper zone. The rise of the temperature at specific region of the chamber might be due to the low velocity of air supply, however, it is cool and comfortable in accordance to literature [20]. The simulated results for both IJ and UFAD system were tabulated in Table 6.



(a) IJ system. **(b) UFAD system.**

Fig. 9. Chamber temperature for IJ system.

Table 6. Chamber temperature for IJ and UFAD systems.

System	Bottom Plane, °C	Middle Plane, °C	Top Plane, °C	Maximum, °C
IJ	20.5	20.5	20.5	20.5
UFAD	22 - 24	21 - 24	21	2

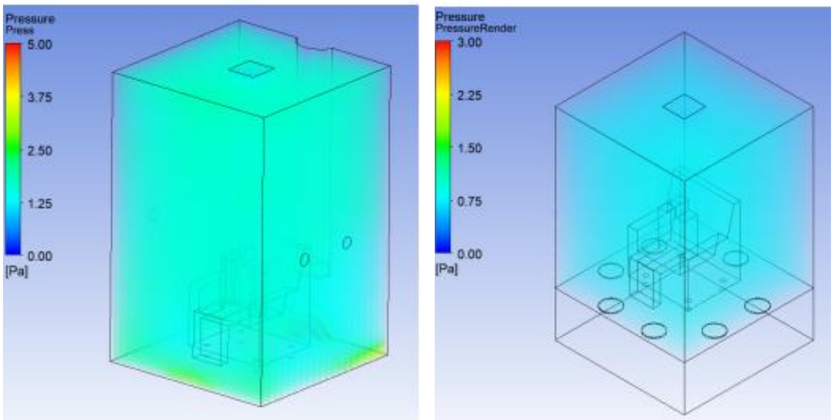
The analysis showed that the IJ system has achieved an acceptable result as the chamber temperature of around 20.5°C in all three planes and it is within the requirement of temperature in range of 20 °C-22 °C [20]. As for UFAD system the maximum temperature of chamber shown is 24°C at the bottom plane around the occupant area which the value has exceeded the recommended range for good comfort and productivity.

4.4. Differential pressure in chamber

Differential pressure is related to assessing thermal comfort. Differential pressure controls movement, distribution and mixing of air to achieve uniform temperature throughout the space, enhancing thermal comfort for occupants. Study had also revealed that for a normal operated positive air pressure ventilated room, the range of 2 Pa to 10 Pa of differential pressure is adequate, therefore, IJ and UFAD designs are subjected to differential pressure analysis.

In Fig. 10(a), the pressure in the IJ system chamber showed a positive differential pressure of about close to 2 Pa throughout the entire chamber, and in some area a higher pressure of 3.75 Pa is shown. This is mainly due to the impinging force exerted on the floor during the supply of fresh air into the chamber. The positive differential pressure can avoid the stale air from being sucked into the chamber from the exhaust and thus ensure good ventilation effect. In the meanwhile,

Figure 10(b) for UFAD system, the differential pressure is considerably low at around 0.75 Pa in the entire chamber. The low differential shows that the chamber is not under negative pressure where stale air is not allowed to re-circulate back into the chamber through the outlet. IJ ventilation system has shown to meet the requirement however for the UFAD system, the low differential pressure value may not be desirable for clean air circulation.



(a) IJ system. **(b) UFAD system.**

Fig. 10. Pressure rendering for IJ system.

Results for all the criteria simulated are summarized in Table 7 to determine the optimum design for its effectiveness for a fresh air ventilated chamber unit. From the analysis of simulated results for parameters of airflow velocity, mean skin temperature, thermal stratification, chamber temperature and the chamber differential pressure, it can be concluded that the impinging jet ventilation system has achieved a better overall result and performance for all the five important performance criteria used to evaluate the effectiveness of the ventilated chamber.

Table 7. Summary of all simulation findings.

Factor	IJ	UFAD	Conclusion
Airflow velocity, m/s	1.25	0.21	Both meeting the condition, however IJ is closer to the optimum velocity of 1.5 m/s.
Skin temperature, °C	30	32	Both meeting the condition
Thermal stratification, °C/m	2	2	Both have equal and good values
Chamber temperature, °C	20.5	21 - 24	Both meeting the condition. However, 24°C was recorded at sitting leg position
Chamber differential pressure, Pa	2 - 3.75	0.75	Both have positive pressure differential. IJ is in the range of requirements thus the ventilation is effective
Air Distribution Profile	In all directions. Adequate distribution for good mixing and displacement.	Surge of air flow directed to the occupant, less air flows at sides and corners occupied zone.	IJ demonstrated more streamline and well coverage in the entire chamber system though both have shown sufficient air flow.

5. Conclusions

Two alternative approaches, the impinging jet and the underfloor air distribution ventilation system were used to design the clean air chamber. The design models for both systems were subjected to fluid flow analysis using ANSYS software. Simulation plots were generated to analyse human comfort level specifically focusing on parameters which include airflow distribution, average air velocity, mean skin temperature and temperature stratification. Additionally, analysis of chamber temperature and chamber differential pressure considered environmental factors that affecting the human thermal comfort.

The obtained results for each of the parameters were studied, analysed and evaluated to determine the optimum design for the chamber. The CFD results showed that the IJ ventilation system has achieved effective ventilation and overall superior performance compared to the UFAD system. The IJ model has successfully fulfilled the design characteristic and performance requirements.

The impinging jet system provides an airflow velocity of 1.25 m/s, a mean skin temperature of 30 °C for the occupant, a temperature stratification of 2 °C/m, a chamber temperature of 20.5 °C and a pressure differential within range of 2 Pa - 3.75 Pa. Moreover, the IJ system ensures adequate air distribution in all directions, allowing for good mixing and displacement of air within the chamber. In conclusion, the IJ design has met the requirements for both design and performance, making it an effective ventilation chamber. It maintains a constant stream of clean, fresh and healthy air, resulting in a comfortable, satisfying and pleasing experience for the occupant.

The design of an effective ventilation chamber has significantly influenced indoor air quality by improving air circulation and fresh air intake, managing moisture, and ensuring a healthier and more comfortable indoor environment. These, in turn, positively impact human health, contributing to a better quality of life and well-being of building occupants by reducing the risk of respiratory illnesses, allergies, fatigue, and stress associated with poor indoor air quality.

For a broader impact, the impinging jet system enhances heat transfer efficiency in heating, ventilation, and air-conditioning applications across various industries such as automotive, aerospace, electronics, and buildings, where effective heat dissipation is crucial for optimal performance. The efficient utilization of resources provided by the impinging jet system contributes to sustainable manufacturing practices, aligning with global efforts towards eco-friendly technologies. In future, a prototype will be developed for experimental performance verification such as on the temperature of each body part and air flow conditions, and to collect feedback from the intended human experiences.

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