Thermal Comfort in Hot, Humid Weather in a Dome-Shaped Building

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Abstract

This study considers natural ventilation in various climates where a hot, humid season exists. Effort was made to reduce the reliance on commonly used mechanical systems and incorporate natural ventilation to achieve higher levels of comfort and IEQ. Simulations were performed using Computational Fluid Dynamics (CFD) modeling software, with natural ventilation and a solar chimney, as well as combined natural and mechanical ventilation, in a building with a domed roof. The total amount of solar radiation on a hemispherical dome surface was calculated using equations. The average solar radiation per unit of roof surface area was then calculated. Next, the temperature on the dome surface and heat transfer were simulated. The impact of the air velocity on human comfort was examined using different combinations of windows and skylights. The results indicated that because of a high elevation of the skylight, the velocity in the room increased, exceeding the comfort zone.

Keywords*:* natural ventilation, thermal comfort, hot weather, dome

Introduction

More than 10% of the building energy consumption is reported to be for ventilation (U.S. EIA, 2022). With the trend of global warming, the energy usage of ventilation as well as cooling can be expected to increase. Studies have shown the impact of poor prevalent mechanical ventilation systems on human health and/or comfort could be adverse, considering sick building syndrome or stress resulting from indoor pollutants, VOCs, office work-related stressors, humidification, and odors associated with moisture and bioaerosol exposure (Ibrahim et al. 2022; Nag, 2018). Moreover, the issues related to overcooling have drawn attention (Chong, 2014; Sekhar, 2015). It is important to enhance energy savings while maintaining indoor air quality, especially in hot, humid weather, when it is more critical.

Proper design of overall building configuration, temperature distribution, and airflow are important to achieve thermal comfort and save energy and resources. To meet thermal comfort without spending excessive energy, this research explored the potential of natural ventilation in a hot, humid environment in a building with a dome roof. It examined thermal comfort under various combinations of air inlets and outlets, while changing temperature, relative humidity and air velocity. The study uses a CFD software program to simulate these indoor conditions.

Thermal Comfort

There are predictions that the frequency and duration of intensified, humid heat events are expected to increase in the coming years. We often experience excessive temperatures both in the summer and the winter in urban buildings. According to Sekhar (2015), "The findings suggest that overcooled buildings are not a consequence of occupant preference but more like an outcome of the HVAC system design and operation".

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Ming-Tse et al suggest that thermal comfort may be achieved at higher temperatures by adding airflow around the body. Proper design of the overall building configuration, considering temperature distribution, humidity, and airflow, would help achieve thermal comfort and save energy and resources.

Temperature Range

A study in China indicates that “the neutral temperatures in naturally ventilated and air-conditioned buildings were 28.3ºC and 27.7ºC, respectively” (Yang and Zhang, 2008). It suggests a temperature of not lower than 26°C for a conditioned space with natural ventilation, and an increase in the air velocity to achieve greater comfort.

According to Caetano et al., “Based on the Predictive-Mean-Vote (PMV)-Model, the thermal comfort zone is defined to be between 22.5°C to 25.5°C operative temperature when relative humidity is above 65% and 23.0°C to 26.0°C operative temperature when relative humidity is above 35%”.

The acceptable thermal comfort range in Malaysia was reported to fall within 23.4°C – 31.5°C for a natural, ventilated space in a field study by Abdul Rahman & Kannan, as quoted in research by Ahmad and Abdul Rahman (2017).

Humidity

A study about humidity in hot, humid climates indicated “the impact of humidity on human responses was not significant when the relative humidity was below 70% and was significant and increased with an increase in air temperature when the relative humidity was above 70%.” (Jin et al., 2017). “The upper limit for people in hot, humid climates who engaged in sedentary activity and dressed in summer clothing (0.57 clo) was determined to be 30.3 °C in ET* for the 90% acceptable range and 32.3 °C in ET* for the 80% acceptable range.” ET* is the new effective temperature.

For simulation in this study, temperature was set at 30°C and relative humidity was set at 70%. A simulation for 35°C and 80% humidity was explored as well.

Air Velocity

According to Zhou et al. (2023), “For a long time, the air speed in a typical indoor office environment was restricted to a level below 0.2 m/s, with the highest acceptable air temperature controlled at 26°C.” Per ASHRAE 55-2010, the same research quotes, “Under the upper air speed limits of 0.8 m/s and 1.2 m/s, the maximum operative temperatures would be extended to around 30.5°C and 31.0°C, respectively”.

Evaporative heat loss decreases when humidity rises due to a reduced water vapor pressure gradient between the ambient air and the skin’s surface. According to Sobolewski et al. (1990), “Despite access to drinking water, a hot and humid environment causes more serious problems to living organisms than a dry environment." They continue that, "In these circumstances, any chance of physical activity is only possible in conditions of intense air flow."

Solar Radiation on Dome

In earlier research, the total amount of solar radiation on a hemispherical dome surface was assumed to be equal to the sum of the radiation shone on two surfaces S_1 and S_2 (Figure 1) (Taheri, 1990):

$$I_{tD} = S_1 I_{DN} \sin h + S_2 I_{DN} = \pi\, r^2 I_{DN}\ (\sin h + 1)$$

The average solar radiation per unit of roof surface area was expressed as

$$I_{uD} = I_{tD} / S = \pi\, r^2 I_{DN}\ (sin\ h + 1)/2(2\pi r^2) = I_{DN}\ (\sin h{+}1)\ /(4\ I_{tD})$$

is the total normal radiation on the roof surface, I_{DN} is the normal solar radiation, and I_{uD} is the normal solar radiation per unit area of the roof.

The temperature on the dome surface and the heat transfer were then calculated. A hybrid simulation based on this calculation was performed and airflow within a model showed turbulence within the model.

In this study, a CFD model was used to explore the airflow and velocity in a similar building, producing similar results for patterns of airflow.

Natural Ventilation

The airflow in natural ventilation may be obtained from the equations below (Taheri et al., 1987).

γ (T) = 1.293 $*$ 273.16 / T = 353.20 / T
p (z) = (10332.3 - $\gamma * z$) g
$\Delta p = \gamma * 273.16 * z\ (1/T_i - 1/T_o)$
v : $\sqrt{[2g * \Delta p/(\xi\gamma)]}$
γ is the density of air at 30°C (303.16°K), 1.164 kg/m^3. The density at 0°C is 1.293 (kg/m^3).

z is the height from the top opening to the center of the low opening.

ξ is pressure loss coefficient, which is 1.

v is the air velocity at the opening [m/s].

g is the gravity acceleration constant, 9.8 m/s^2.

Δp is the pressure loss Kg/m^2.

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T_o is the outdoor temperature in Kelvin.

T_i is the indoor temperature in Kelvin.

Air velocity at the openings was calculated for natural ventilation in two cases of cross-ventilation and stack ventilation and generally agreed with the results of the CFD simulations.

Simulation

For this study, as the location of a building with a hot, humid summer, Washington, DC, is selected. A psychrometric chart for Washington DC is indicated in Graph 1.

Simulation Settings

The simulations are under ambient temperature of 30°C and 70% relative humidity.

Our goal is to obtain a velocity of between 0.2 and 0.8 m/s at the seating-area level. The initial velocity at the perimeter inlets was assumed to be 0.1 m/s. The second set of simulations use 2.5 m/s, as the wind or mechanical ventilation-induced scenario. The building is circular with a dome roof. The overall height is 50 meters and the wall height is 25 meters. The simulations are performed for three cases of:

(A) Four openings at a low level with the bottom of the opening 2 m above floor finish.

(B) Four openings at a low level and a 2-m diameter skylight,

(C) Four openings at a low level and four openings at a high level.

Simulation Results

The net radiative heat flux is shown on the first model for cross ventilation (case A) at 8 a.m. (Figure 2).

The velocity in the room with four air inlets at a low height and a skylight opening indicates a combination of cross ventilation with a stack effect. The opening at the top is circular with a 2-meter diameter. In this simulation, with an initial velocity of 2.5 m/s, a high air velocity was observed at the seating area in the middle of the room, at the height of about 1.5 meters (about 1 m/s at 10 a.m. and 1.8 m/s at 2 p.m.). This is beyond the comfort level we would like to achieve, which is between 0.2 to 0.8 for indoors. The humidity level, on the other hand, was not alleviated (Figure 4), conceivably because the outside humid air was brought inside at a higher speed compared to the scenarios with an initial velocity of 0.1 m/s. The velocity in the middle of the room seating area fluctuates between 0.05 and 0.6 m/s (Figure 3). Considering that according to the psychrometric chart (Graph 1), a relative humidity of 70% and a

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temperature of 30°C is close to the comfort zone, it may be assumed that a mild breeze could help provide comfort.

In case C, with four high and four low openings, with an induced initial velocity of 2.5 m/s, the air velocity in the middle of the room at the seating area ranges between 0~2.7 m/s. With initial velocity of 0.1 m/s, the seating area velocity remains under 0.4 m/s and reaches as low as 0.1 m/s.

In the case of 2.5 m/s initial velocity, a wider range of humidity is observed. The increase of humidity at the lower outlet opening may be attributed to the concentration of air accumulating to exit the space. In the case of eight openings, the lower row of outlets has a higher humidity caused by the higher weight of air due to gravity.

Increase in Temperature and Humidity

A scenario of 35°C and 80% relative humidity was simulated. With an increased velocity of 2.5 m/s, this scenario may fall in the comfort zone for the outdoor environment; however, for indoor sedentary activities, the combination is not assumed to be acceptable. The 0.1 m/s does not provide comfort under this thermal condition.

Case C, with two rows of openings, did not provide an optimal environment for either the 0.1 or 2.5 initial velocities.

We may conclude that with lower temperature and humidity levels, it is possible to obtain comfort in this building with natural ventilation only. However, with humidity of 80 and temperature of 35°C, dehumidification and/or cooling may be needed.

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Conclusion

Thermal comfort seems to be achievable in a hot, humid summer in a climate similar to Washington, DC, by natural ventilation in a circular building with a 33-meter radius with a dome roof and an overall height of 50 meters according to the simulations performed using a CFD software.

Generally, a higher level of air velocity may be achieved in the seating area by inducing a wind or mechanical air flow of 2.5 m/s. However, as the velocity in this zone surpasses the 0.2 to 0.8 m/s optimum velocity for seated individuals, a lower initial velocity is desirable. Simulations with a skylight indicate a higher level of turbulence and air velocity. For this study which represents a large hall, it can be concluded that an opening in the roof to achieve stack ventilation is not necessary. The cross ventilation between the four low openings, as well as the case of four low openings and four high openings, produce a more uniform indoor thermal environment and are easier to predict and control. At a higher temperature of 35°C and 80% relative humidity, natural ventilation alone was not adequate and dehumidification and/or cooling may be needed to obtain thermal comfort.

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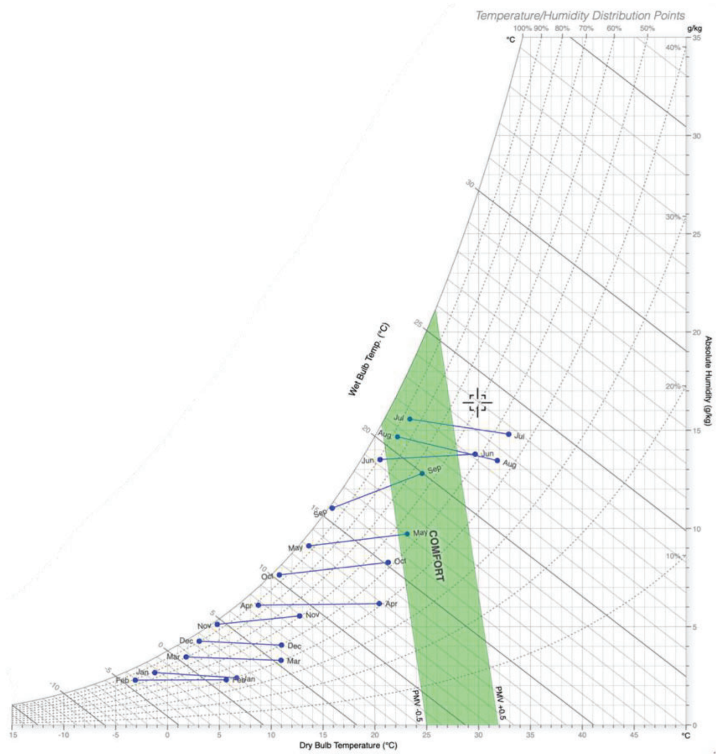

Graph 1. Thermal comfort in hot and humid summers in Washington D.C..(Marsh, A.D. 2018)

<u>In the summer seasons, the temperature and relative humidity ranges between;</u>

23°C to 35°C and 45% RH to 90% RH
Mean radiant temperature: 20°C
Air velocity: 0.70 m/s
Metabolic activity: 1.2 met (seated and light activity)

The comfort temperature and relative humidity according to the psychrometric graph:
June between 28°C-30°C and 55% RH
July between 30°C-34°C and 50%-60% RH
August between 29°C-33°C and 50% RH

Psychrometric Chart

ASHRAE 55-2017
Dry Bulb: 29.90 °C
Rel Humidity: 60.68%
Sensation: Slightly Warm
SET: 28.48 °C
PMV: +0.89
PPD: 7.1%

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Figures

Fig. 1. Solar Radiation on Dome

"Total amount of solar radiation on a hemispherical dome surface was assumed equal to the sum of radiation shone on two surfaces S_1 and S_2" (Taheri, 1990).

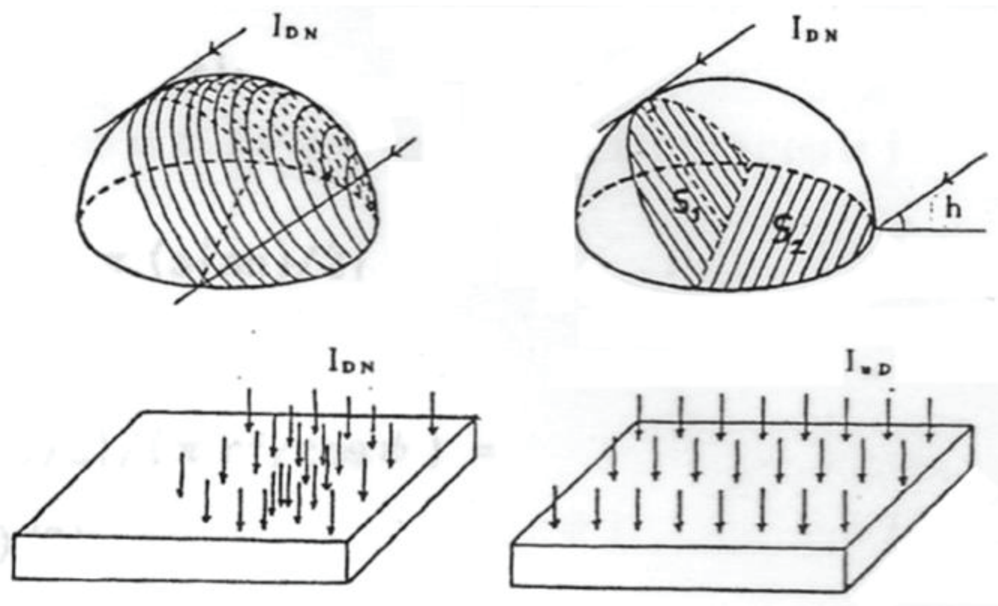

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Fig. 2. Net radiative heat flux (A)
Net radiative heat flux in Case A, cross ventilation, 8 a.m.

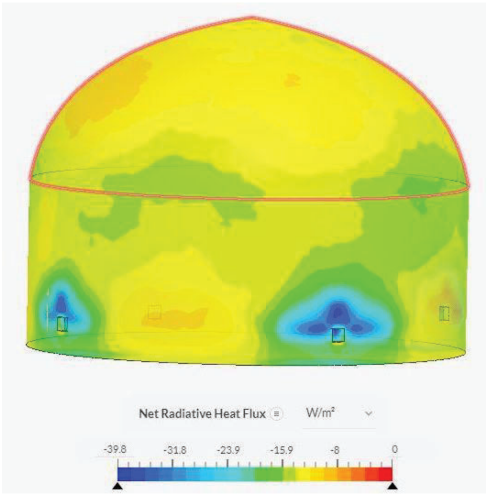

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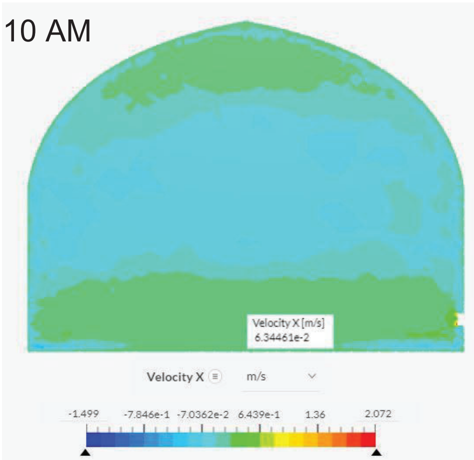
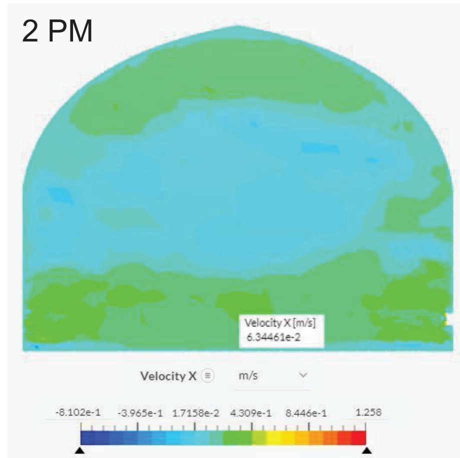
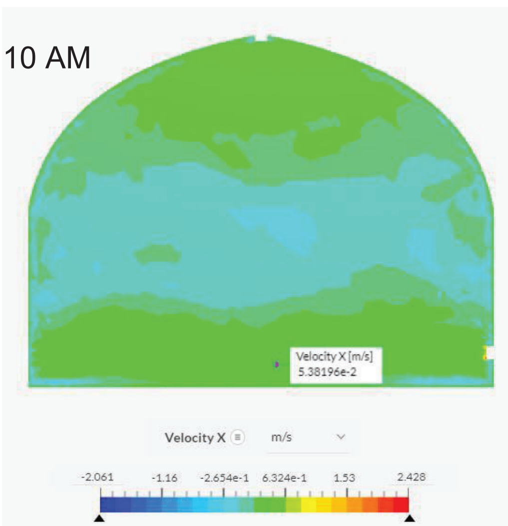
Fig. 3. Air velocity

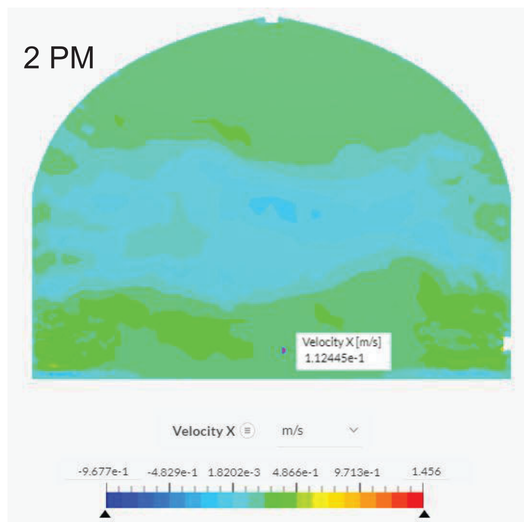
Velocity distribution, Scenario A, (4 openings at low level), Initial velocity 0.1 m/s



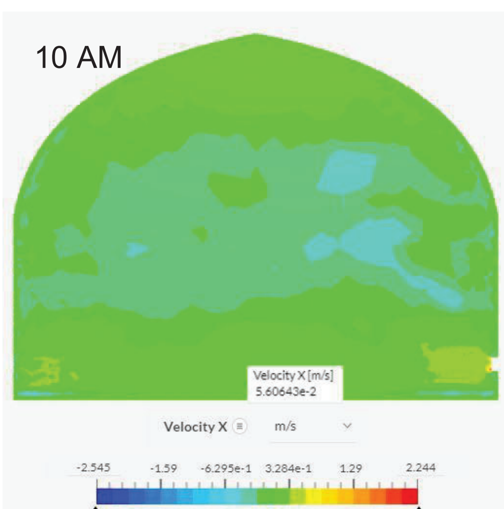


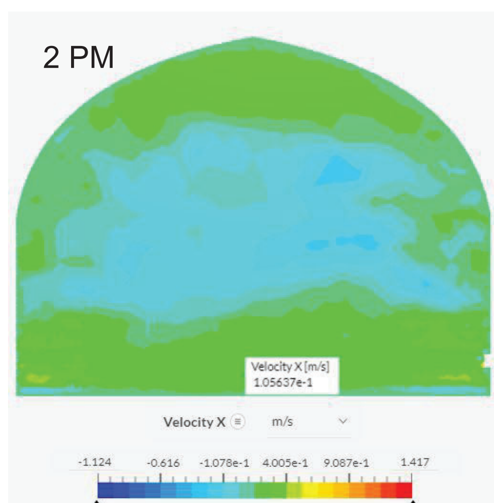
Velocity distribution, Scenario B (4 openings at low level with skylight), Initial velocity 0.1 m/s



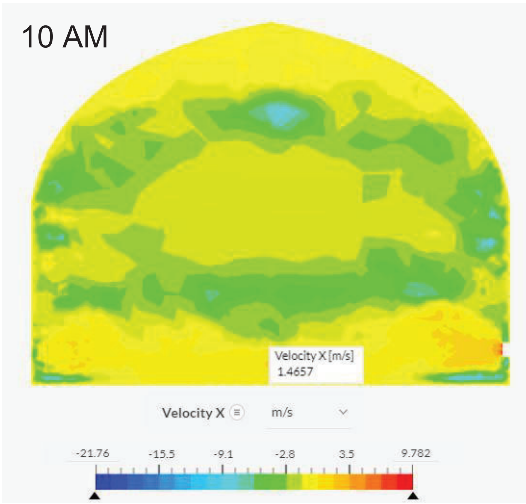


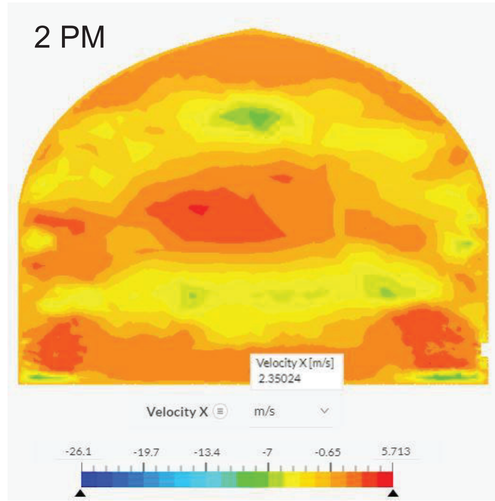
Velocity distribution, Scenario C (4 openings at low and 4 at high level), Initial velocity 0.1 m/s



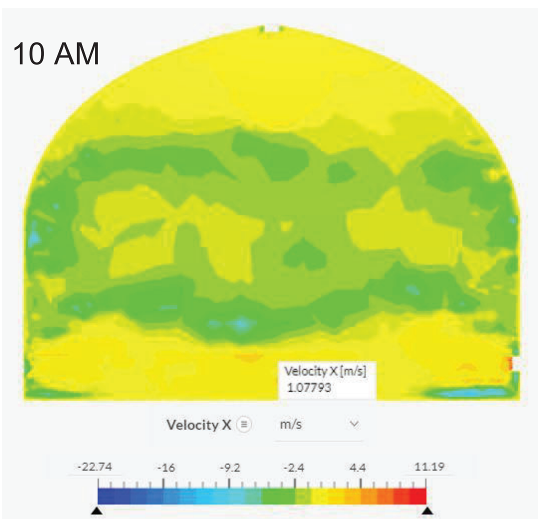


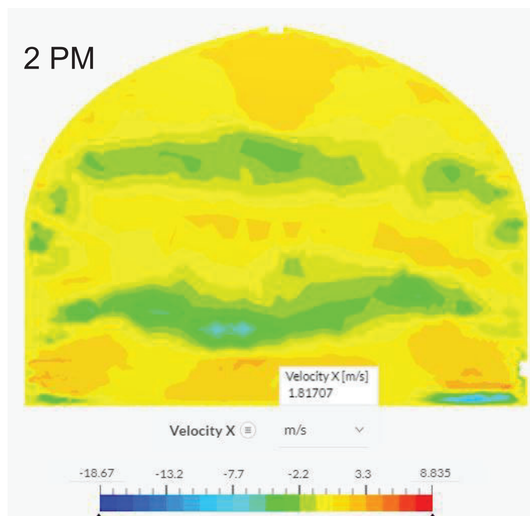
Velocity distribution, Scenario A, (4 openings at low level), Initial velocity 2.5 m/s



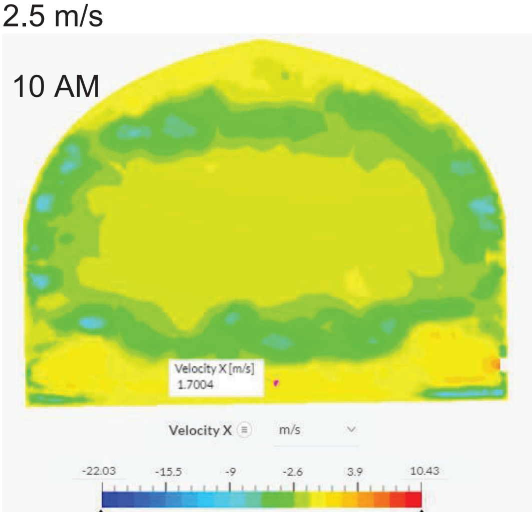


Velocity distribution, Scenario B, (4 openings at low level with a skylight), Initial velocity 2.5 m/s





Velocity distribution, Scenario C (4 openings at low and 4 at high level), Initial velocity 2.5 m/s



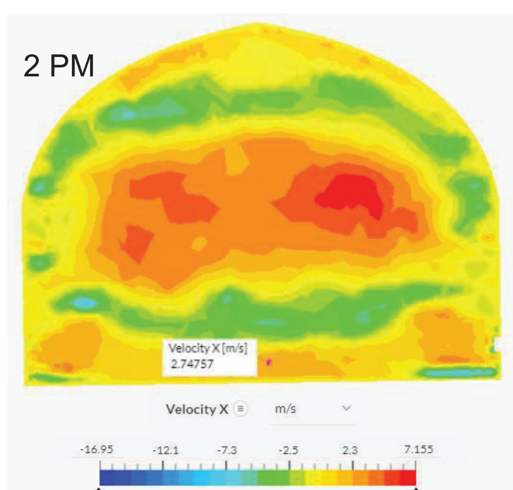


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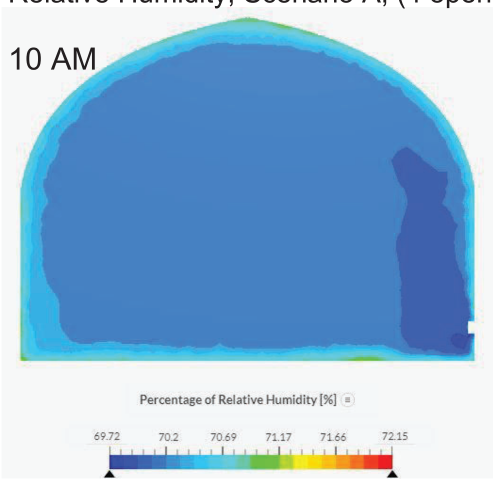
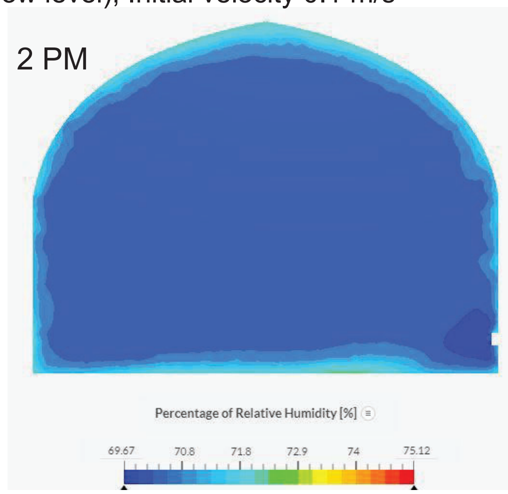
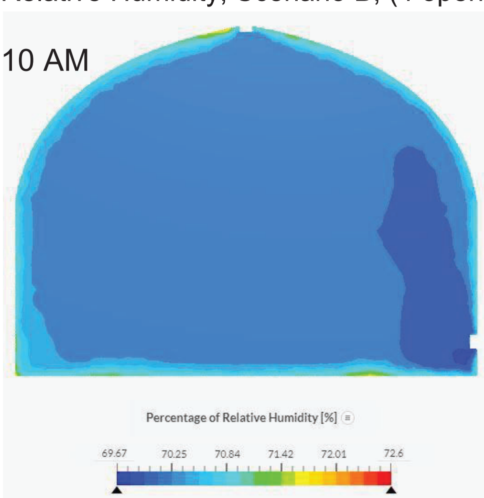
Fig. 4. Relative humidity

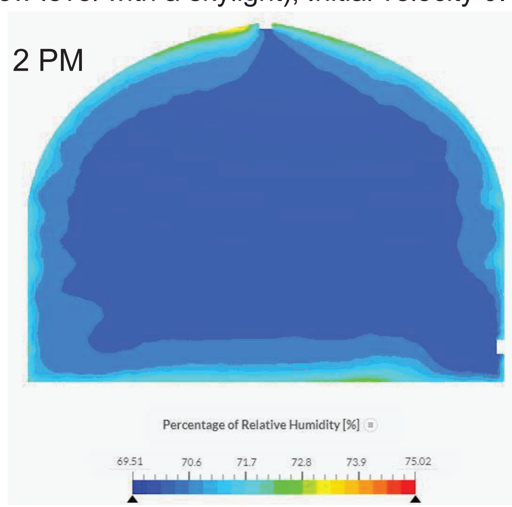
Relative Humidity, Scenario A, (4 openings at low level), Initial velocity 0.1 m/s



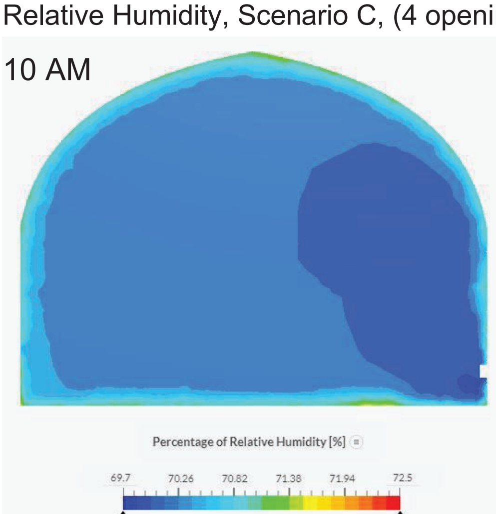


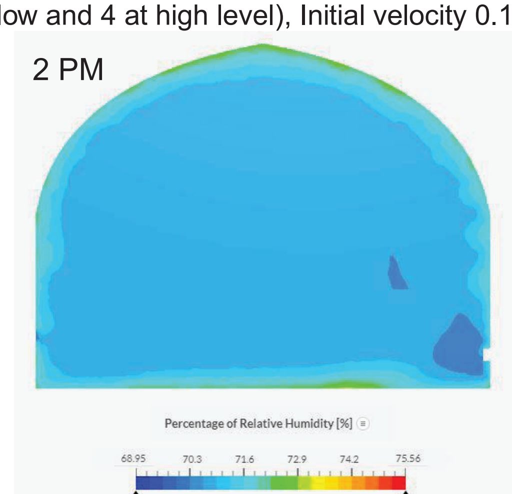
Relative Humidity, Scenario B, (4 openings at low level with a skylight), Initial velocity 0.1 m/s



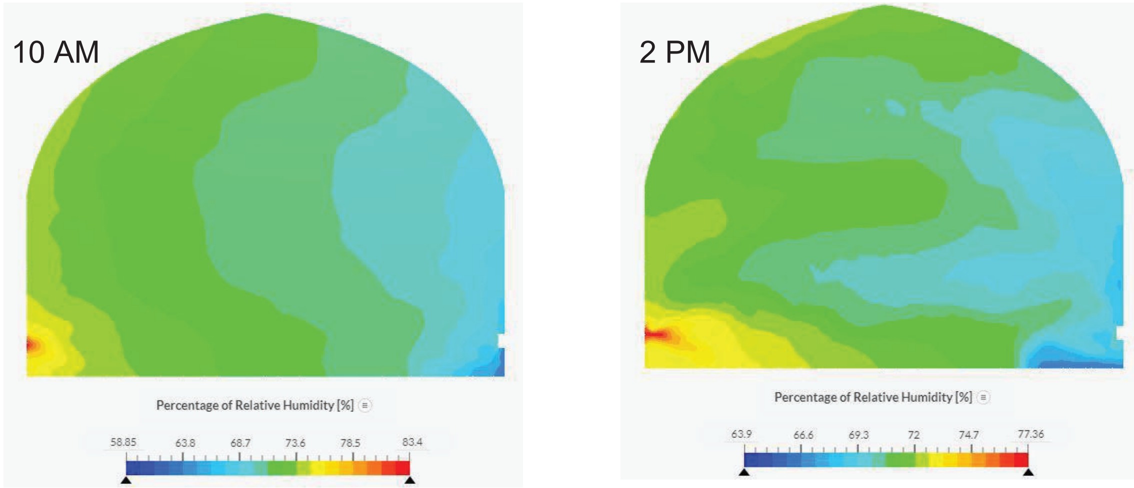


Relative Humidity, Scenario C, (4 openings at low and 4 at high level), Initial velocity 0.1 m/s





Relative Humidity, Scenario A, (4 openings at low level), Initial velocity 2.5 m/s



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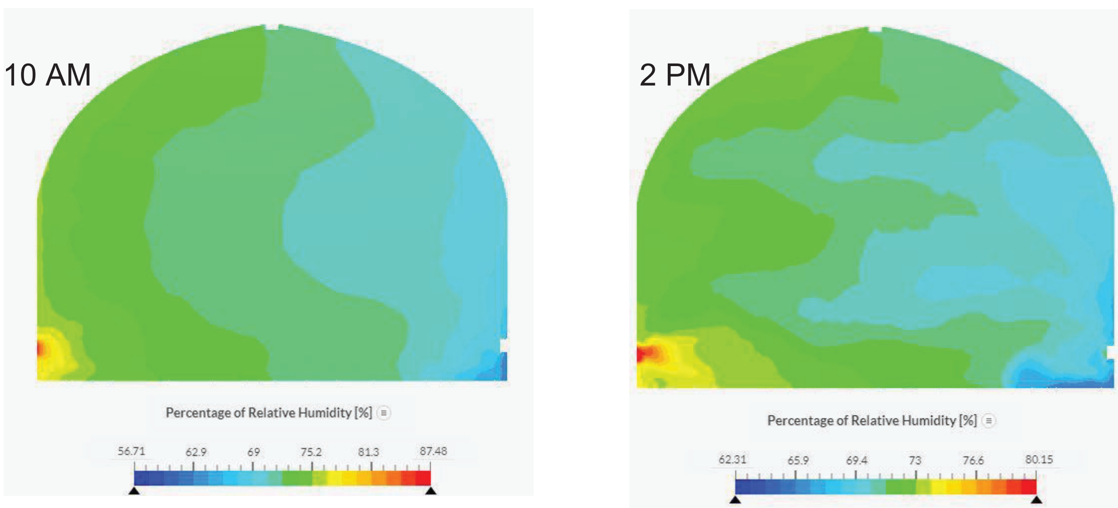
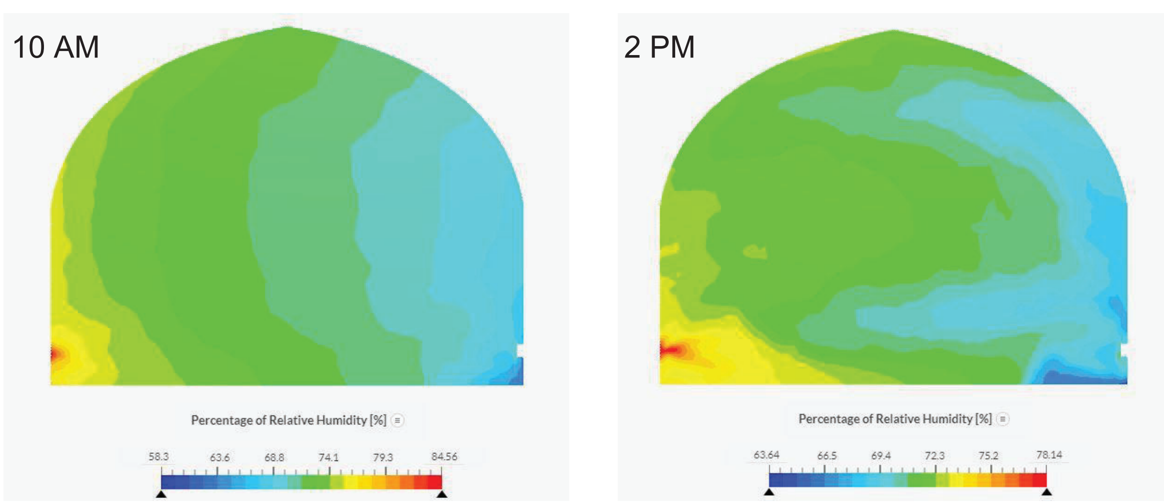


Relative Humidity, Scenario C, (4 openings at low and 4 at high level), Initial velocity 2.5 m/s



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