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Microclimate Thermal Control for Open-Air Areas

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ABSTRACT

Thermal comfort in openair situations is a difficult industrial task. In literature there were insufficient studies on how to control the external microclimate in a region, and there are many activities outside the house in open areas that require temperature control, such as the stadiums in hot humid countries, and tourism, and recreational areas in humid and hot climates. Openair conditioning requires huge amount of energy, that negatively affects the global warming of the earth. To reduce energy consumption microclimate control is proposed. Isolation of the controlled area is performed to reduce the amount of air-conditioned load. In this project the air conditioning of an external open area will be studied. Wind tunnel with two air flows at different temperatures, relative humilities, angle of attach and velocities will be constructed. The two flows will be allowed to intersect to gather at different conditions (different wind speeds ranging from 1 to 7 m/s, as well as a jet flow about 1 m/s and angles 60 to 90 degrees) to construct an isolation Dom for the targeted outside open area. An open area with the use of cross flow that stops the local wind speed in the targeted area and allows to keep the conditioned air for a long time in the open space. This method allows to save huge energy used continuously for the air-conditioning purpose.

Keywords: open space conditioning, open area air-conditioning, outdoor thermal comfort, cross flow, jet flow, jet velocity ratio, comfortable zone, jet interaction.

INTRODUCTION

Openair regions air conditioning is a hard task requiring huge amount of energy to be performed. Many activities worldwide require to be held in open air regions, which raises a major problem of how to air condition an open area with minimum amount of energy. This problem has been approached with microclimate control for the selected openair region. To separate the required region air jet can be used. Literature related to openair thermal comfort was searched. There were insufficient studies on how to control the microclimate of an openair region. The air conditioning of an external openair region will be studied. Wind tunnel with two air flows, angles of attack and velocities will be constructed. The two flows will be allowed to intersect together at different conditions to construct an isolation Dome for the targeted outside region. A secondary Jet flow will intersect the local wind at the boundaries of the targeted area, this allows to keep the conditioned air for a long time within the selected region. This method allows to save huge energy used continuously for the air conditioning purpose.

Air jet in cross flow (JCF) have many applications in aircraft engines anti-icing, fuel air mixing, food processing, drying whether in textile industry or paper production (Wang et al., 2019). Many researchers have studied experimentally the round jet in cross flow (Cambonie and Aider, 2014). Through their analysis; instantaneous transverse and longitudinal vortices of the jet in the cross flow were characterized for 0.15 < R < 2.2. they observed a new transition at very low velocity ratio (LVR) (R < 0.3). Whereas, when R > 1.25, the classic topology was recovered. Schematic of the investigations done is shown in Figure 1.

Flow instabilities through the interaction of primary flow intersected with three round secondary jets was performed (Kristo and Kimber, 2021). A secondary temperature and flow control system supplies independent control for each of the three jet lines into the test section, with a return line found sufficiently far downstream of the test section Figure 2. The stability of JCF under LVR low Reynolds numbers was also investigated by Klotz et al. (2019).

The stability of the JCF was also investigated by (Chauvat et al., 2020). Simulations were performed to locate the critical velocity ratio (CVR) as a function of Re, with constant boundary-layer thickness. Steady regime at LVR were observed at all Re numbers. Increasing velocity ratio hairpin vortices were observed. Fully nonlinear simulations were performed in order to locate the stability region of the flow in the parameter space. Andreopoulos and Rodi (1984) reports on measurements in the flow generated by a jet issuing from a circular outlet in a wall into a cross-stream along this wall. For the jet-to-crossflow velocity ratios *R* of 0.5, 1 and 2, the mean and fluctuating velocity components.

Bidan and Nikitopoulos (2013) performed an experimental study searching the description and the behavior of vortical structure dynamics

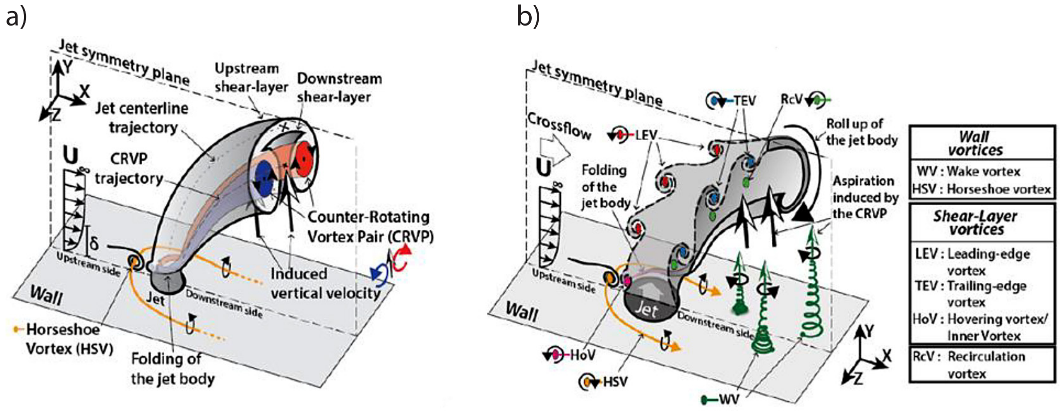


Figure 1. (a) Classical time-averaged topology of the high-velocity-ratio round JICF; (b) Instantaneous topology of the high-velocity-ratio round JICF (Cambonie and Aider, 2014)

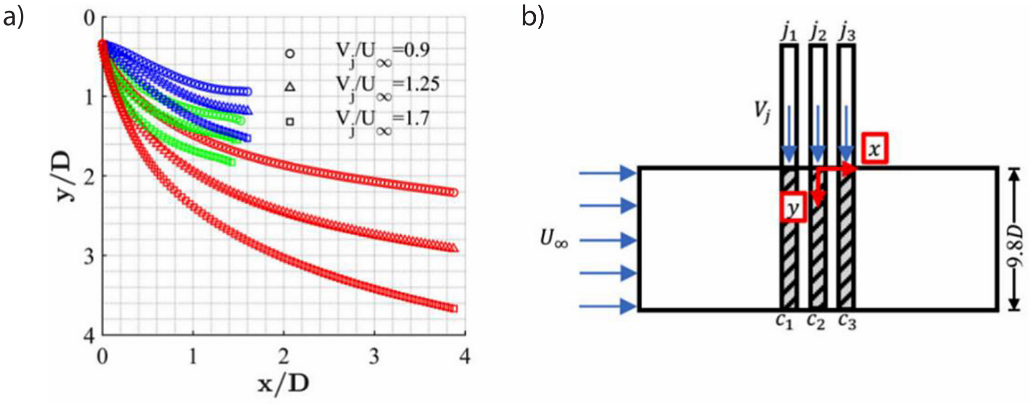


Figure 2. (a) Collapsed streamline trajectories for each jet, (b) Schematic of the experimental test section x-y plane (Kristo and Kimber, 2021)

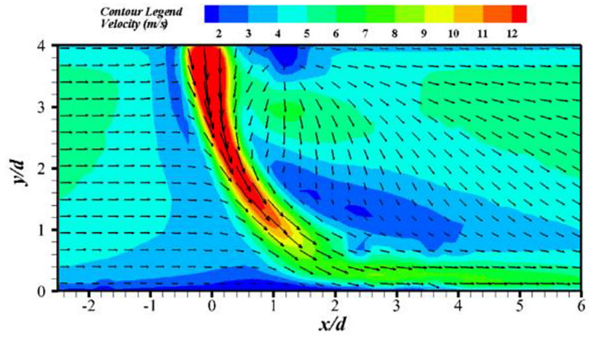
involved in steady and pulsed transverse jets at low blowing ratios. Ingestion mechanisms were observed in experiments and in simulations. Broadwell and Breidenthal (1984) studied the incompressible flow generated by a JCF, they compared the results with those in a reacting water-jet experiment. Noting the importance of JCF in fuel injection and combustion, Mörtberg et al. (2007) analyzed the flow dynamics and flame thermal signatures of a fuel jet injected into a cross-flow of normal temperature and very high-temperature combustion air. Ahmed et al. (2007). Considered a coal-fired power station boiler, in their work they emphasized that ignition and the combustion is highly controlled by burner aerodynamics. An experimental and numerical study of the rectangular slot-burners has been conducted to improve jet development in the boiler.

Barata and Durao (2004), studied the JCF vortices for Reynolds numbers between 60,000 and 105,000 based on the jet exit conditions. They concluded that the crossflow acceleration over the ground vortex was found to be connected directly with the jet exit velocity.

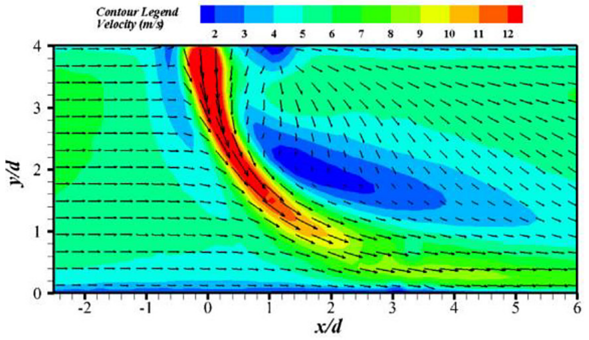
Wang et al. (2014) studied water jets injected into a Ma = 2.1 crossflow. Kalifa et al. (2014) concentrated on flow generation by the interaction of JCF for different velocity ratios. Wang et al. (2019) investigated the fluid flow and heat transfer behaviors of JCF, the velocity of the jet is kept at 12 m/s and that of the crossflow is varied between 5 m/s and 8 m/s (Fig. 3).

As observed from the literature JCF was mostly attached for the fuel air mixing, flame propagation and ignition. Consideration of jet flow in air conditioning is found for space air diffusion (Kareeva, 2020; Fan, 2019), the distribution of air within a space under different conditions (Chen et al. 2020). The interaction of a JCF for air conditioning purposes has been reviewed by Mahesh (2013). Entrainment in the transverse jet is larger than that in a regular jet. The jet interaction in vehicle air conditioning has a great concern (Ostermann et al. 2019).

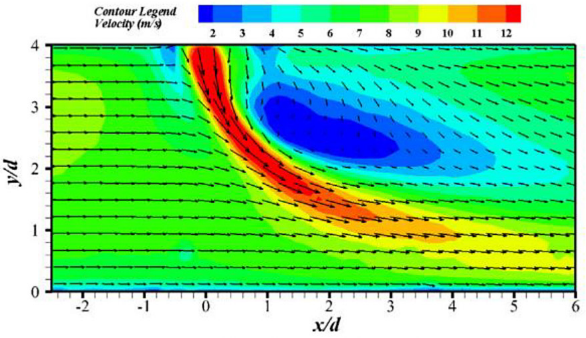
Song et al. (2023) applied the air curtain (AC) as an airflow barrier indoors, they concluded that the combination of a 60° diffuser air supply angle and 2 m/s AC velocity can reduce the convective load from the adjacent space by more than 50%. Ruiz et al. (2023) performed a systematic evaluation of the AC separation efficiency under moderate environmental temperature ($5\ ^\circ C \leq \Delta T \leq 25\ ^\circ C$) and pressure ($1\ Pa \leq \Delta P \leq 8\ Pa$) difference conditions. Results show a strong



(a) U_j=12 m/s, U_c=5 m/s, R=2.4



(b) U_j=12 m/s, U_c=6 m/s, R=2.0



(c) U_j=12 m/s, U_c=8 m/s, R=1.5

Figure 3. Velocity contours of the jet impingement in cross-flow at the middle x-y plane. Velocity vectors are plotted to show the flow direction (d = 20 mm) (Wang et al., 2019)

dependency of AC performance on environmental parameters and indicate there is an optimal separation efficiency. Amin et al. (2011) targeted the important variables that affect the penetration of outside air into the system. Khayrullina et al. (2020) presented a numerical study on momentum flux ratio to prevent AC breakthrough in case of cross-jet pressure gradients. They reported that a maximum separation efficiency is achieved at lower momentum flux ratios for inclined jets and jets with smaller height-to-width ratios. Gaspar et al. (2009) modelled the air flow and heat transfer for a refrigerated cabinet to evaluate the discharge air velocity on the recirculated air curtain.

Shoshe et al. (2019) investigated an effective thermal and aerosol barrier against high pressure and velocity gradients generated by a typical shopping mall fire. Eight injection velocity, five injection angle and three flow rates of the air curtain, with five pitch ratios of the flow channel were investigated to find the optimum operating condition to ensure maximum sealing of the heat and smoke. As protection from mass and heat exchange AC were used (Frank and Linden, 2014). In their study the momentum flux of the air curtain have been investigated against the other forces from ventilation. Viegas et al. (2020) studied in a full scale the AC to separate a clean area from a contaminated one. They analysed the effect of exhausting part of the contaminant gas on the effectiveness of the AC. Khayrullina et al. (2021) presented a numerical simulations with CFD to investigate the behaviour and separation efficiency of an AC when it first flows along a wall before reaching the opening. From literature the use of air jet to protect a determined openair region from a variable local wind was not studied before (up to the author knowledge). Lucio and Gomes (2023) reported an outdoor human thermal comfort index for the Qatar 2022 FIFA World Cup's. Zhong et al. (2021) considered using a combination of air curtain with roof cooling to prevent the hot outside air infiltration and reduce the cooling system's energy consumption. As a result, recommended to focus on exploring the influence of supply angle to air curtain gates and roof cooling supply slots. The air conditioning systems used in for cooling open area were depending on pumping large amounts of cooled air into the required space (Fig. 4).

Figure 4. A photo shows the Cold air supply nozzles for open area air conditioning in Qatar. (https://time.com/6236839/qatar-world-cup-outdoor-air-conditioning-environment/)

In this paper, as it has been advised by earlier research Zhong et al. (2021), jet in cross flow JCF principle is investigated as air curtain to protect the mass and heat exchange between the protected zone and outside air. The local wind crossing jet is expected to form a Dome around the protected zone. Different flow rates, jet to wind velocity ratios, jet attack angles were investigated to understand the possibility of reducing the huge amount of energy consumed by implementing JCF to protect the occupied zone from local wind infiltration.

EXPERIMENTAL SETUP

To visualize the behaviour of JCF for different velocity ratios (VRs) and Jet angles (JAs) a wind tunnel with primary and secondary air supplies (Figure 5) were constructed (Figure 6).

The experimental device consist of a wind tunnel equipped with:

- Primary flow (local wind):
  - centrifugal fan,
  - flow control valve,
  - air strainer,
  - test section.
- Secondary flow (air jet):
  - Smoke generator,
  - Air strainer tank,
  - Centrifugal fan,
  - Flow controller,
  - Nozzle.
- In addition to:
  - Hot wire anemometer to measure the air velocity,
  - Sensors for measuring temperature and relative humidity,
  - DAQ to collect the data for each experiment.

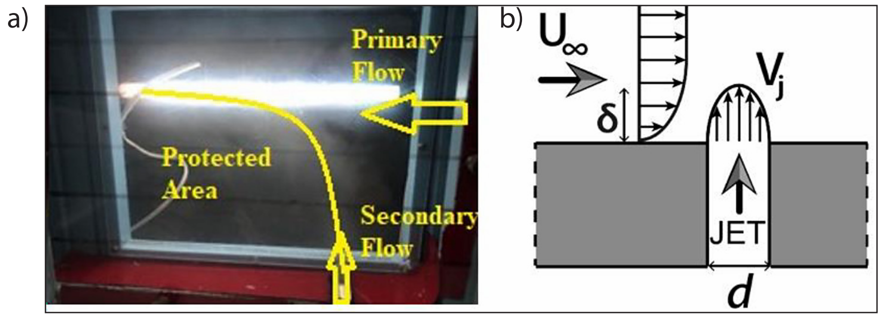


Figure 5. (a) Experimental test section, (b) local wind and Jet flow principle (Cambonie et al., 2013)

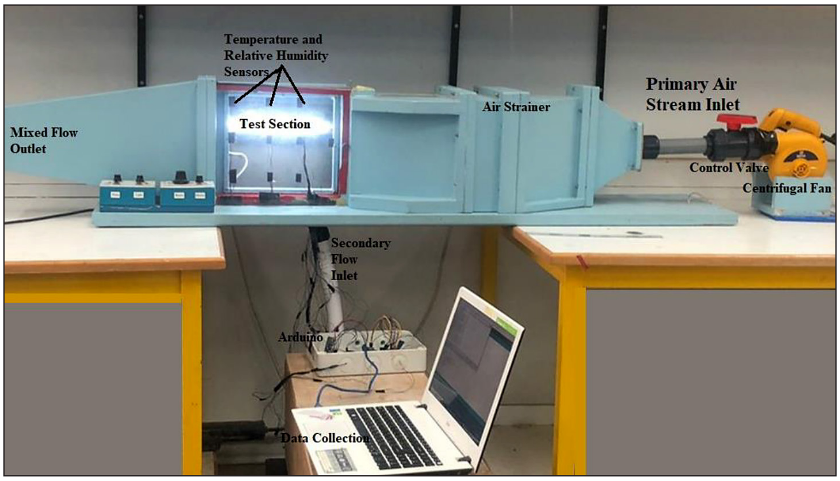


Figure 6. Experimental device used, parts and DAQ system

To analyse the JCF for air conditioning purposed a centrifugal fan is used to blow air representing the local wind (LW) with different flow velocities, from 1 to 7 m/s, the air passes through a strainer to generate uniform laminate air streamlines which enter the test section. The LW at the specific speed is crossed by the jet flow (JF), which has been prepared by a smoke generator to be visualized and pumped through the air nozzle using a centrifugal fan. As the LW is intersected by the JF a dome wise shape is created which represent the protected region.

RESULTS

The experiments have been done to analyse cross flow phenomena of two air streams. The air dome over a specific location and local wind prevention from entering the isolated area were visualized. Different LW velocities between 1 m/s to 7 m/s were tested, JF of 90° and 60° angles were intersected with the LW for a JF of about 1 m/s. The test rig technical specifications are given in Table 1.

Low velocity 1-3 m/s

Three different velocity levels were tested in this study. The low wind speed, the medium wind speed and high wind speed. The results shown in Figure 7 represents the dome created from different low wind speeds (V = 1–3 m/s). As the figures idicate all the low velocities create a dome, this dome has a low velocity inside it. This isolation action performed by the jet flow will reduce highly the air conditioning load inside that rejon. Figure 7a indicates the higher wind speed the lower the dome is. Figure 7b shows the velocity profile from the top to bottom of the test rig. Its clear that the dome area is large, and the high velocity region is limited just at the first 8 cm from the test rig. Figure 8

Table 1. Experiments technical specifications

Test section dimensions (cm)	25×25×5 cm
Primary flow velocities (m/s)	1–7 m/s
Secondary flow velocity (m/s)	3 m/s
Jf attack angles (degrees)	90° and 60°

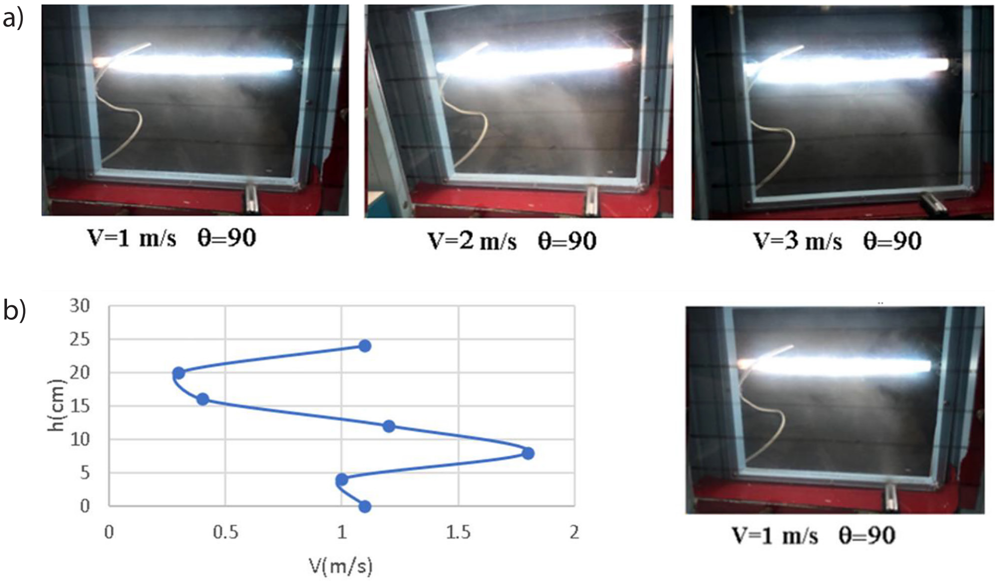


Figure 7. JCF results for low velocity wind (a) the jet flow intersection for velocities 1–3 m/s, (b) the velocity profile in the test reg before the jet directly (V = 1–3 m/s, V_j = 1 m/s)

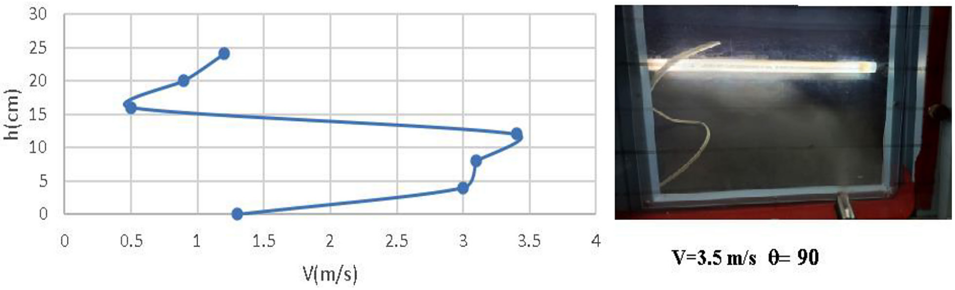


Figure 8. JCF results for low velocity wind, the jet flow intersection for velocities 3.5 m/s

represents the Jet flow cross wind speed of 3.5 m/s, the dome is clear been lowered and high wind speed occupied larger area.

Medium velocity 4–5 m/s

The medium wind flow from 4 to 5 m/s indicates the creation of a highly disordered flow with large vortices. This flow easily can be noticed form Figure 9a. In Figure 9b the measured values of the flow velocities all over the height of the test rig are plotted on the figure. Even though the high speed wind occupies large region, the variation of the velocities due to the creation of vortices is clear on the figure at height 4,8 and 12 cm from the top of the test rig. Lower dome is created at medium wind speeds, this indicates the need to increase the jet velocity to keep the dome area as in low wind speeds.

High velocity 6–7 m/s

Then the high velocity wind is considered, the wind velocities of 6 to 7 m/s are tested on the experimental test rig. Figure 10 shows the behaviour of the Jet in cross flow for high velocities. The dome height is largely reduced and the free wind speed on the top of the dome are much higher than low and medium wind velocities due to continuity. Again if larger dome height is required higher jet velocities must be used. The higher jet velocities do not necessarily mean higher mass flow rates, but it may be a thinner flow. The velocity profile plotted in Figure 10b illustrates the high velocities of the wind and lower dome heights.

Angles 90° and 60°

Figure 11 shows the comparison between the flows of a 2.5 m/s wind speed, 1 m/s jet

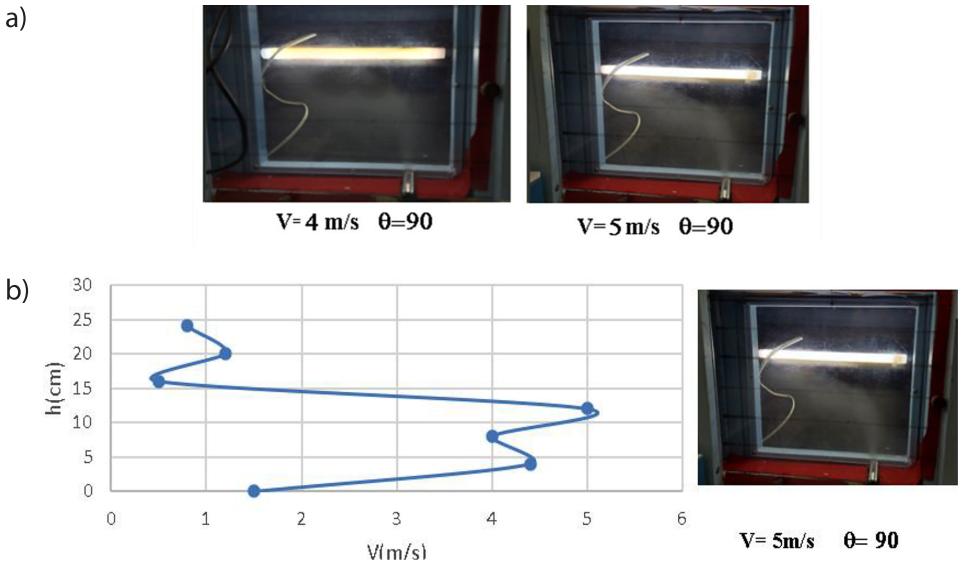


Figure 9. JCF results for medium velocity wind (a) the jet flow intersection for velocities 4 and 5 m/s, (b) the velocity profile in the test reg before the jet directly ($V = 5$ m/s, $V_j = 1$ m/s)

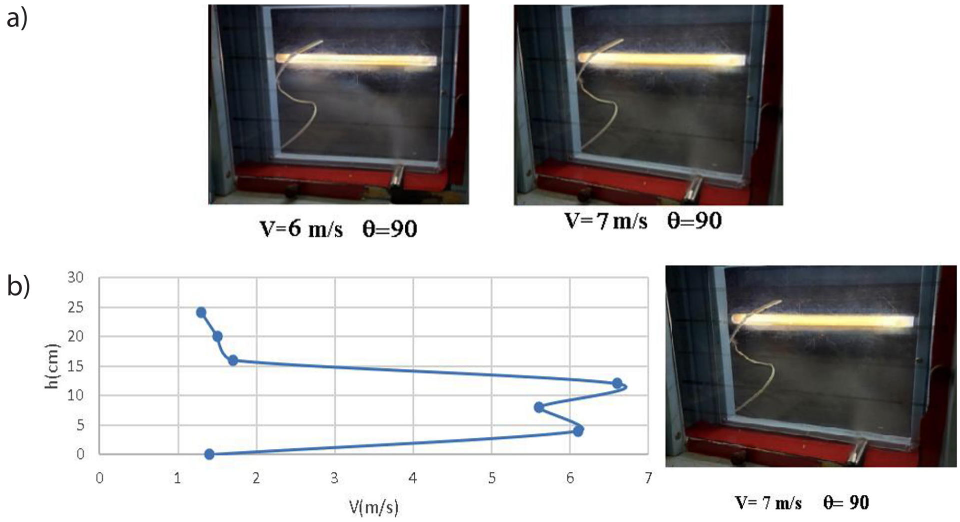


Figure 10. JCF results for high velocity wind (a) the jet flow intersection for velocities 6 and 7 m/s, (b) the velocity profile in the test reg before the jet directly ($V = 6–7$ m/s, $V_j = 1$ m/s)

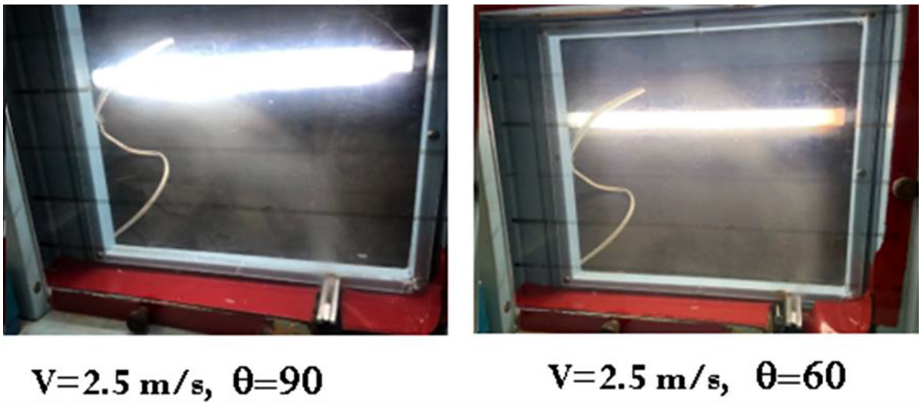


Figure 11. JCF results for different jet angles (90° and 60°) the jet intersecting wind flow ($V = 2.5$ m/s, $V_j = 1$ m/s)

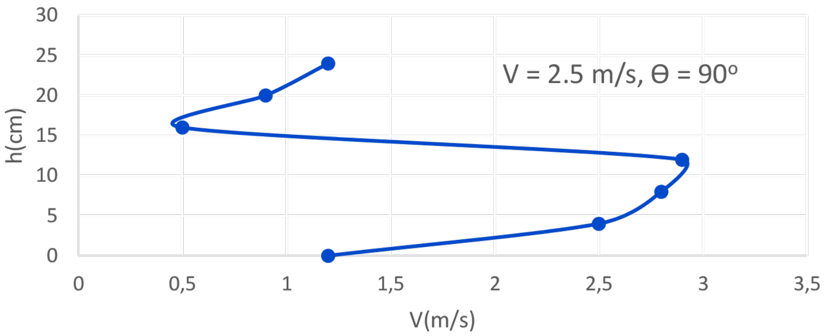


Figure 12. JCF velocity profile for V = 2.5 m/s, V_j = 1 m/s, and ϴ = 90º

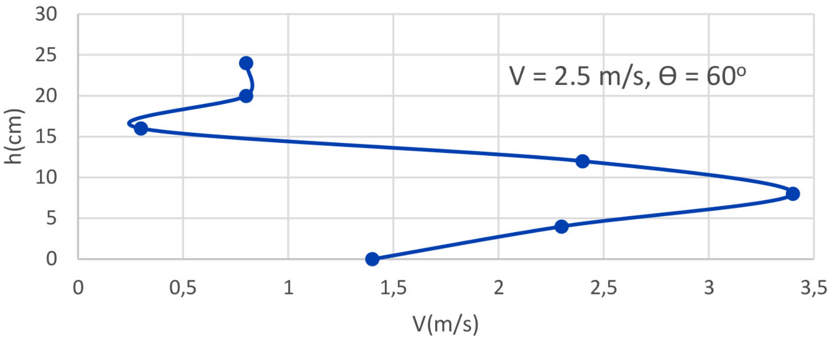


Figure 13. JCF velocity profile for V = 2.5 m/s, V_j = 1 m/s, and ϴ = 60°

speed for two different flow attack angles (90º and 60º). As shown from this figure, the larger dome was created by the 60º jet flow. This emphasize on the importance of the attack angle for dome control.

Figures 12 and 13 present the velocity profiles of both angles and the height of the dome created. Its clear from both figures that the 60 degrees jet attack angle created a larger dome as maximum velocity at ϴ = 60° was at 8 cm and the maximum velocity for ϴ = 90° was at 12 cm.

CONCLUSIONS

The air conditioning of open-air regions represents a challenge. Real air conditioning is not only reducing the high temperatures to lower temperatures, but it is to control and maintain air at a comfortable conditions with minimum energy and minimum impact on environment. This work represents an innovative way to air condition open-air region (required for certain activity) by isolating the required region using a jet flow in the path of wind speed, which allows control and maintain its microclimate at comfortable conditions with minimum energy. For this purpose wind speeds of 1–7 m/s were tested in a preconstructed test rig with a jet flow of 1 m/s, and the dome created by this intersection is analyzed. It has been found that at low velocities domes with large heights are created, this height is reduced as the wind speed increases, which requires the increase of JF to control the dome height. The dome heigh is also affected by the attack angle, 60º created larger dome area than 90º angle. This study clarify that the open-air region can be isolated using JCF and reduce the energy consumed in air conditioning in addition to the reduction of the air conditioning process on global woarming and environment. This study indicate other parameters that may affect the isolated area such as the Jet velocity, thickness and jet temperature, which are currently under a detailed study.

Acknowledgments

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