AN EXPERIMENTAL INVESTIGATION OF INTERACTING SWIRLING MULTIPLE JETS

by

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This article deals with the experimental investigation of multiple interacting jets, which may be interested in many engineering applications such as design of a ventilation supply device. The main objective of this study is to achieve the best configuration for use in ventilation applications. To achieve this, several parameters have been considered and discussed such as the imbalance in temperature and diffuser orifices position with relative imbalance in flow rate between central and peripheral jets. Flow rate has been adjusted at Reynolds numbers, ranging from 10^4 to $3\cdot10^4$. The present study is carried out under uniform heat flux condition for each diffuser, and air is used as a working fluid. Experiences concerning the fusion of several jets show that the resulting jet is clearly more homogenized under the influence of the central swirling jet. Highlights of such an investigation show that, if the relative position of the central jet is higher, the radial spreading of the resultant jet is more important when all jets are in the same plane. This spreading is also improved compared to the case where the relative position of the peripheral jets is higher, thereby allowing to process a large volume of air. In addition, it becomes attractive to operate, especially when we aim premises homogenization.

Key words: *experimental investigation, swirling jets, flow interaction, ventilation, multiple jets*

Introduction

Multiple swirling jets have been one of the most active areas of research in heat transfer for many years. They represent a handful of basic flows that, although of great practical importance, allow the fundamental study of complex dynamical processes and their interactions. Free and confined jets are extensively investigated in industrial applications for their large utility in ventilation. Several industrial applications generate turbulent jets inside a confined environment. The majority of achieved works have been oriented substantially towards the combustion in the burner or in engines to improve the homogenization of the mixture used [1-4]. The main purpose of this study is to examine different blowing configurations of multiple swirling jets with different dispositions. To optimize the best configuration that can be used in ventilation applications, several parameters will be discussed, such as the imbalance (difference) in temperature and the diffuser orifices position with a relative imbalance

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in the flow rate between the central and peripheral jets. According to Syred and Beer [5], the swirl has been frequently used for the stabilization of high intensity combustion. This can be summed up as follows: the swirling jet reduces combustion length by producing higher rates of entrainment of the ambient fluid and a rapid mixing close to the exit orifices and on the boundaries of recirculation zones, improved flame stability through the formation of recirculation zones, and aerodynamic blockage of the flow can reduce the impact of the flame on the burner while ensuring a minimum of maintenance and an extended service life of the unit. Several previous studies have dealt with the multiple swirling jets with compressible or incompressible fluids under various geometric or dynamic conditions. These are briefly discussed hereinafter. Experimental and computational results on the mixing of single, double and opposed rows of jets with an isothermal or variable temperature mainstream in a confined subsonic cross flow have been gathered by Holdeman [6]. He found that, in momentum-flux ratio variations, the orifice size and spacing have a significant effect on the flow distribution and that similar distributions can be obtained regardless of the orifice diameter when the orifice spacing is inversely proportional to the square-root of the momentum-flux ratio. Soheyl and Gadala [7] studied the boiling heat transfer on a moving hot plate caused by multiple impinging water jets from several rows. To determine temperature and heat flow values, the authors developed a reverse thermal conduction code to analyse thermocouple readings that were implemented inside the plate. They examined effects of nozzle offset, plate velocity, and jet line spacing. They found that: the nozzle offset affects the uniformity of heat transfers over the entire the plate width, the jet line spacing can affect the heat transfer between two adjacent rows, and the plate velocity is important only in the hot entry and in the impingement zone. Nuntadusit *et al.* [8] examined the flow and heat transfer characteristics of multiple-swirling impinging jets (M-SIJ) with 3 × 3 in-line arrangement on impinged surfaces. The multiple-conventional impinging jets (M-CIJ) were also tested for comparison. The experimental results showed that M-SIJ offer a higher heat transfer rate on impinged surfaces than the M-CIJ in all jet-to-jet distances, S/D. Oyakawa *et al.* [9] experimentally investigated four jets impinging a target plate while varying both the nozzle-to-nozzle spacing and the nozzle-to-target plate separation distance. They concluded that, at a small X/D, the spent flow after the jet impinged may spread toward a cross-shaped direction. This typical model becomes weak as X/D increases up to eight where flow and the heat transfer can behave similar to those of a single jet. Chaudhari *et al.* [10] conducted experiments on different configurations with a central orifice surrounded by multiple satellite orifices. In their study, the Reynolds number is in the range of 1000-2600, while the normalized axial distance varied in the range of 1-30. They found that the maximum heat transfer coefficient with multiple orifice synthetic jet is about 12 times greater than natural heat transfer coefficient and up to 30% more than that of a conventional single orifice jet. The experimental results of three rectangular jets have been reported by Mostafa *et al.* [11]. Their measurements were performed using a hot wire anemometer of an x-type probe. They found a strong mutual entrainment and a turbulent transport between the three jets start at the exit plane. On the other hand, they observed a rapid merging at $x/r < 10$ due to a strong interaction between the different streams. Likewise, they noted that this region is characterized by a rapid increase in streamwise mean velocity and shear stress. A rapid decrease in turbulent kinetic energy along the axis also typifies this region. On the other hand, the normalized mean velocity has shown a self-preservation at $x/r >= 10$. According to Braikia *et al.* [12], optimizing parameters such as diffuser geometry, initial velocity, swirl number, gap between jets, blown jets number, and the central jet can significantly improve the quality of the cooling air mixture. Moawad *et al.* [13] achieved a study of multiple jets efficiency for the chemical mixing in an open channel. More explicitly, they considered two jet arrangements whose ratio of the velocity of the jets to that of the cross-flow varies from 8 to 16. The first arrangement is a combination of co-flow and cross-flow jets, while the second is cross-flow jets that discharge into the ambient flow. These authors concluded that the results of the standard deviation and the dilution were independent of the spacing and the number of ports, and showed that turbulent jets could be a successful alternative to mechanical methods for achieving a suitable chemical mixing. Yin *et al.* [14] experimentally examined twin jets flow generated by two identical parallel axisymmetric nozzles. They found that the twin jets attract each other. In addition, they noted that the mixing process of twin jets varies with the gaps between the two nozzles. It should be pointed out that one of their salient findings is that the twin jets spread linearly downstream and grow with a spacing between the two nozzles. Ozmen [15] has experimentally studied the flow structure characteristics of a confined impinging twin jet for Reynolds numbers up to 5.104 with various nozzle-to-plate spacings and jet-to-jet spacings. He examined the effects of Reynolds number, nozzle-to-plate spacing and jet-to-jet spacing on the flow structure. He concluded that there exists a relationship between sub-atmospheric regions and peaks in heat transfer coefficients for low spacings of the impinging jets. Through this literature review, it appears that the multiple swirling jets undeniably have advantages in terms of mixing power. However, it seems that all research conducted on such kind of flow are somewhat remote from our present study. Thereby, the relevance assessment of integrating multiple swirling jets in the air-cooling and ventilation of living spaces and transport requires a prior study and an analysis of multiple swirling over its entire length. This is why it is necessary to choose a system composed of blowing jets that are more efficient in terms of mixing and propagation. This, is the main motivation of this work.

Experimental set-up and techniques

The device and main design features are depicted in fig. 1 including the nomenclature and location of measurements. The device consists of a frame with a fixed square plexiglass plate. Seven appliances blowing hot air are attached to the plate and directed downwards. Depending on the configuration studied, the bottom part of these devices is used to fix different

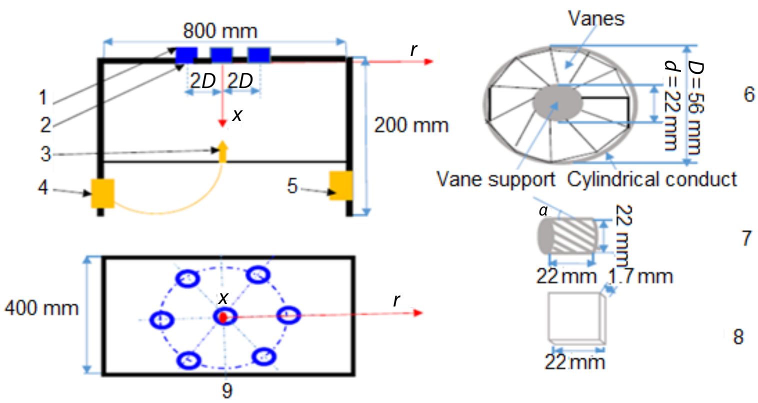


Figure 1. Experimental set-up, test set and cylindrical co-ordinate system;
1 – air blowing devices, 2 – diffuser with inclined vanes,
3 – thermo-anemometer probe, 4 – velocicalc plus air velocity meter 8386,
5 – thermometer, 6 – swirl generator, 7 – vane support, 8 – vane,
9 – diffusers rotation sense

types of diffusers with inclined vanes. The mean temperatures and velocity of the flow are measured by a thermo-anemometer (type Velocicalc Plus Air Velocity Meter 8386, Operation and Service Manual 1980321, Revision H, June 2006 (http://www.tsi.com/uploadedFiles/_Site_Root/Products/Literature/Manuals/1980321J-8384-86-VelociCalc-Plus.pdf), which is a high-precision multifunctional instrument. Note that data can be viewed on the screen, printed or downloaded into a spreadsheet to easily transfer them to a computer for statistical processing. The accuracy is of the order of $\pm 0.015\,\mathrm{m/s}$ for the velocity and $\pm 0.3\,^\circ\mathrm{C}$ for the temperature from the thermal sensor. In addition, we consider that measurements (temperature and speed) are performed a maximum error of about 7%. The latter is supported by rods, which are easily guided vertically and horizontally to sweep the maximum space in axial and radial directions, fig. 1. To achieve the swirling confined jet, one can either use the axial fan impeller for generating swirl turbulent flow or use swirling mechanical systems [16]. The swirl number is defined as the rate between the angular momentum flux, G_θ, to the axial momentum flux, G_x, and a characteristic length scale (here, the diffuser radius seems suitable) [17]. It should be noted that the exact expression of the swirl number depends on the injector geometry and flow profiles. Following Gupta *et al.* [17], for a typical single element injector with a flat vane swirler, the swirl number can be defined:

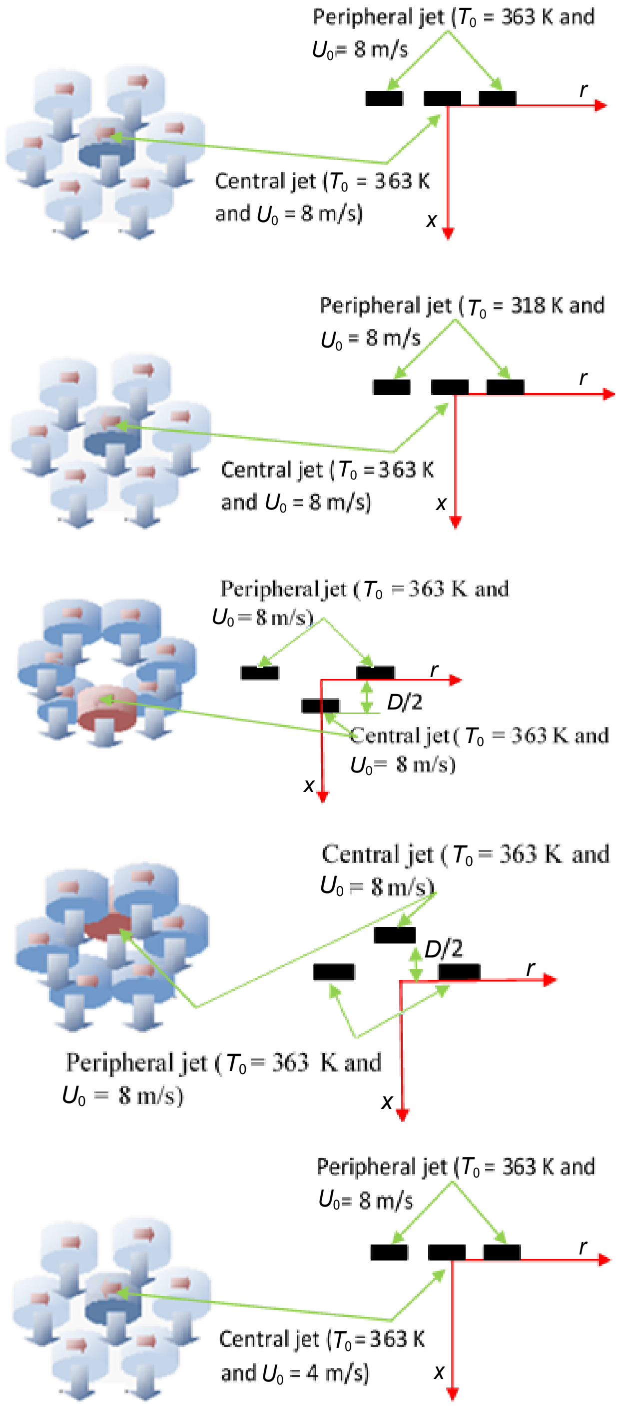
$$S = \frac{G_\theta}{RG_x} = \frac{\int_{R_n}^{R_h} \rho U W r^2 \mathrm{d}r}{R\int_{R_n}^{R_h} \rho U^2 r \mathrm{d}r} \tag{1}$$

Recall that the strict definitions for G_θ and G_x derive from the conservation of momentum and angular momentum and require knowledge of static pressure and turbulent terms. The R is a characteristic length, typically chosen as the diffuser radius, and R_n and R_h are radius of the centre body (vane support) and the inlet duct, respectively. The swirl number used in this study is S =1.3 for α = 60° [4], and the Reynolds number is $\mathrm{Re}_0=U_0D/\nu$, U_0, D, and ν being the air maximum velocity at the origin, the characteristic length scale, and the air kinematic viscosity, respectively. The latter being determined at the maximum temperature, T_0, of the air that blows at the origin.

To carry out the experiments, the following operating conditions have been considered: Q_m = 0.041 kg/s, $\mathrm{Re}_0 = 10^4\text{-}3\cdot 10^4$, r/D = 1 to 10 and $0 \le x/D \le 10$. Note that previous studies are based on similar ranges of Reynolds (see [18-21], to name a few). In addition, the references having addressed topics close to our work are based on similar Reynolds number ranges. It is worth recalling that our main purpose here is both to examine and investigate the evolution of temperature profiles of axial and radial multi-jet swirling for different configurations. This approach allows analysing the influence of key parameters, such as the geometry disposition of the peripheral jets, which are controlled by a central jet. It should be noted that the system studied is actually hexagonal. However, we initially experimented in several directions on the plane of the hexagon including the seven diffusers, and it turned out that the error on T_r and U_r does not exceed 3% from x/D = 5, and becomes almost insignificant beyond this station.

Results and discussion

This part of the paper discusses the various experimental studies, which have been performed to optimize the geometry of the diffusers. It is worth recalling that characteristics and



Configuration A
All diffusers are in the same plane and have the same velocity and temperature (U_0 = 8 m/s and T_0 = 363 K).

Configuration B
All diffusers are in the same plane and have the same velocity and temperature (U_0 = 8 m/s and T_0 = 318 K). Note that the temperature of the central jet T_0 = 363 K and the velocity = 8 m/s

Configuration C1
All diffusers have the same velocity and temperature (U_0 = 8 m/s and T_0 = 363 K). Note that the peripheral jets are located above the central jet at a distance of 0.5*D*.

Configuration C2
All diffusers have the same velocity and temperature (U_0 = 8 m/s and T_0 = 363 K). Note that the peripheral jets are located below the central jet with distance 0.5*D*.

Configuration D
All the diffusers are in the same plane and with the same temperature (U_0 = 8 m/s and T_0 = 363 K). Note that the velocity of the central jet is U_0 = 4 m/s.

Figure 2. Schematics of the studied configurations

the structure of multiple swirling jets are influenced by different parameters, such as the control of multi-jets by the central jet and the rotation sense of the central jet with respect to peripheral jets. The optimization of these parameters can achieve a good mixing in premises, even in the combustion chambers. A configuration of the six peripheral jets with a central jet diffusing in the opposite direction and in the same plane presents the best results of thermal homogenization of the treated air volume [4]. It is this configuration that has been chosen and studied experimentally in different situations by examining the axial and radial distribution of temperature and velocity profiles. It should be noted that the central jet rotation direction is opposite (and kept as such for all configurations considered) to that of the six peripheral jets. Figure 2 gathers all these investigated configurations.

Effect of the temperature imbalance between the central jet and peripheral jets

In this case, the impact of the temperature difference over the central jet to peripheral jets on the evolution of temperature profiles, as well as the axial and radial velocities has been studied by measuring the temperatures and velocity at different axial and radial stations. The obtained results are shown in figs. 3 and 4. Dimensionless axial temperature profiles show a sharp decrease for the Configuration (B) compared to Configuration (A), see fig. 3(a). Furthermore, the Configuration (B) exhibits a sharp axial decrease of the temperature and velocity in the blowing source region up to three diameters. Beyond this, the decrease becomes almost linear and less steep tending towards ambient temperature at ten diameters of the blowing origin. This contradicts the result depicted in the Configuration (A) case where the temperature and the axial velocity are at a distance of about two diameters of the diffuser. It is noted that the temperature then decreases linearly to tend towards an ambient temperature.

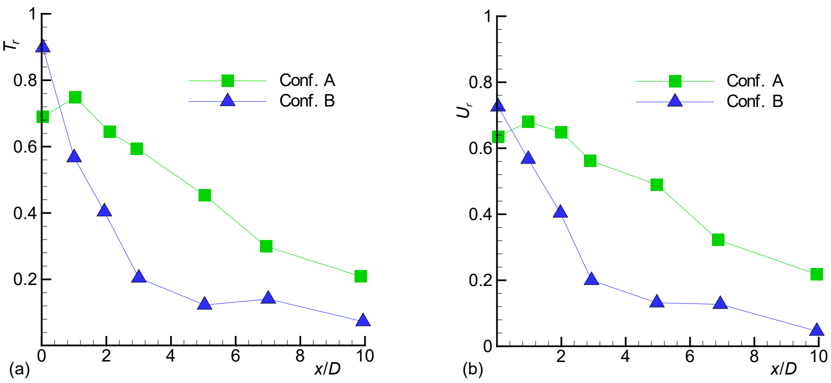


Figure 3. Influence of the central jet temperature compared to the peripheral jets temperature on the evolution of the axial temperature (a) and velocity (b) profiles; (Configurations A and B)

Comparison of radial temperature profiles

The effect of temperature imbalance (difference) between the central and peripheral diffuser, Configurations (A) and (B), on radial velocities distribution and temperature is shown in figs. 4(a) and 4(b). As can be seen, the temperature and velocities begin to stabilize ra-

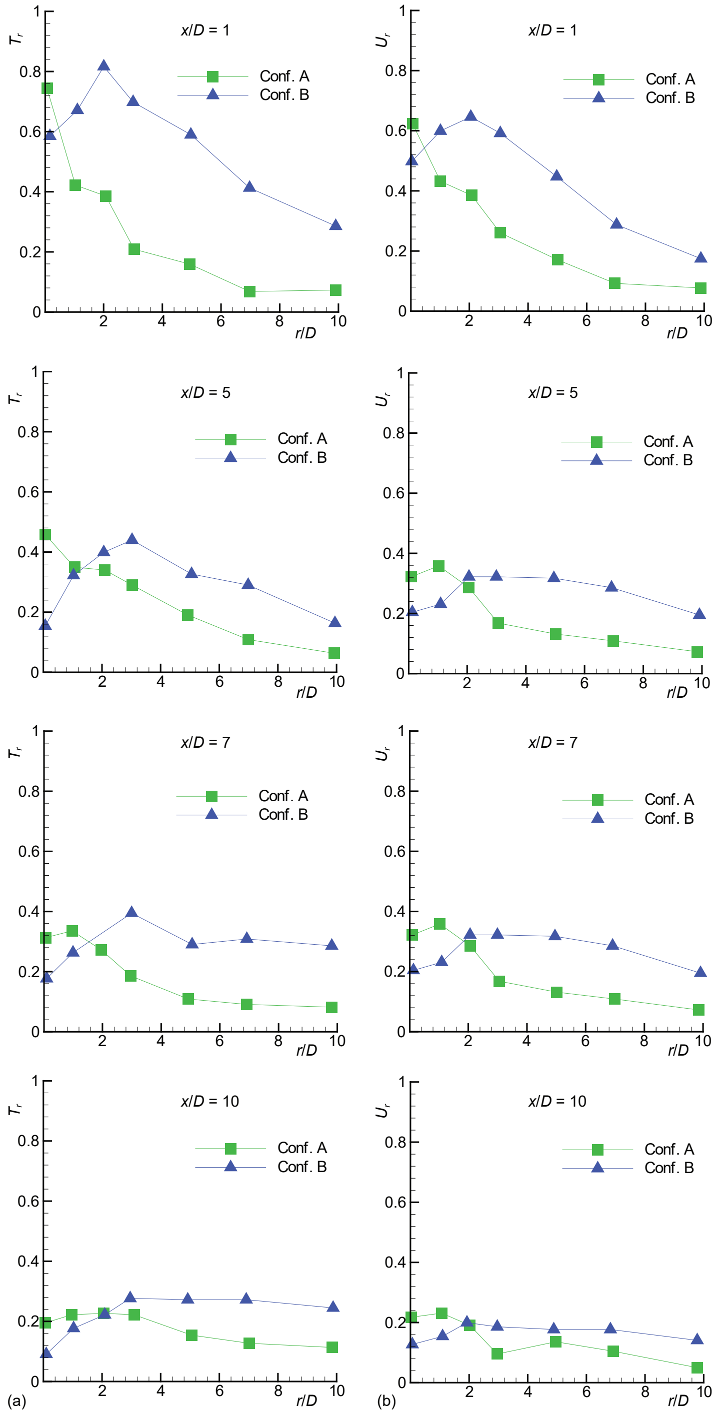


Figure 4. Influence of the central jet temperature variation compared to the peripheral jets temperature on the evolution of the radial temperature (a) and velocity (b) profiles; (Configurations A and B)

dially for the Configuration (B) well before those of the Configuration (A). It is also noted that, for Configuration (B), the thermal homogenization is achieved for a short distance from the blowing diffuser origin. Still for the Configuration (B) (with a central jet hotter than its neighbours), the evolution of the temperature and the axial and radial velocity profiles induce a reverse circulation of the peripheral jets ensuring a maximum temperature stability in the radial direction compared to the Configuration (A) for which all jets have the same temperature. This stability appears very quickly from five diameters while exhibiting a better thermal and dynamic homogenization. In addition, the results show that it is the Configuration (B) which offers a better radial thermal stability associated with significant axial decay. The main conclusion that can be drawn here is that, with a simple system in terms of design (Configuration B), the atmosphere and the temperature of a room can be homogenized suitably while reducing constraints of discomfort induced within a fairly large area. Likewise, for optimal operating temperatures to affect imbalances, the relationship between the central jet temperature and the peripheral jets needs to be further refined and the real impact on system performance must be assessed accordingly.

Effect of imbalance of the blowing orifices position

In the second case, the influence of the relative position of the plane of opening of the central jet with respect to the peripheral jets on the evolution of the profiles of the temperature and the axial and radial velocities has been studied, and highlighted the importance of such a parameter. The comparison of these profiles for the three Configurations A, C1, and C2 is depicted in figs. 5(a), 5(b), 6(a), and 6(b).

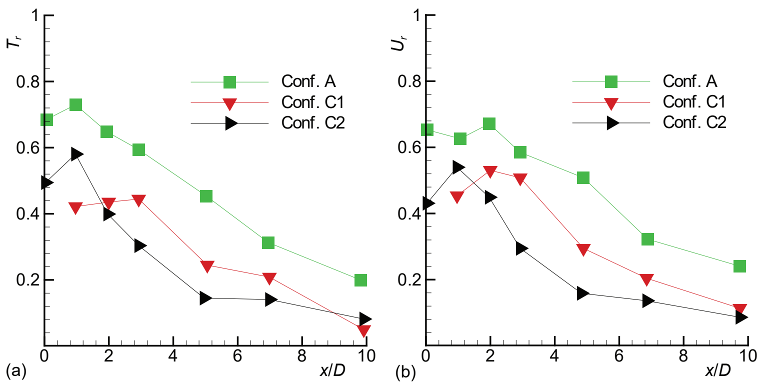


Figure 5. Influence of the central jet position variation compared to the peripheral jets position on the evolution of the axial temperature (a) and velocity profiles (b); (Configurations A, C1, and C2)

Comparison of axial temperature profiles

The effect of the jets relative position for Configurations A, C1, and C2 on the axial distribution of temperature and velocity is shown in figs. 5(a) and 5(b), respectively.

Comparison of radial temperature profiles

For the Configurations A, C1, and C2, the jets relative position effect on the radial distribution of temperature and velocity is shown in figs. 6(a) and 6(b).

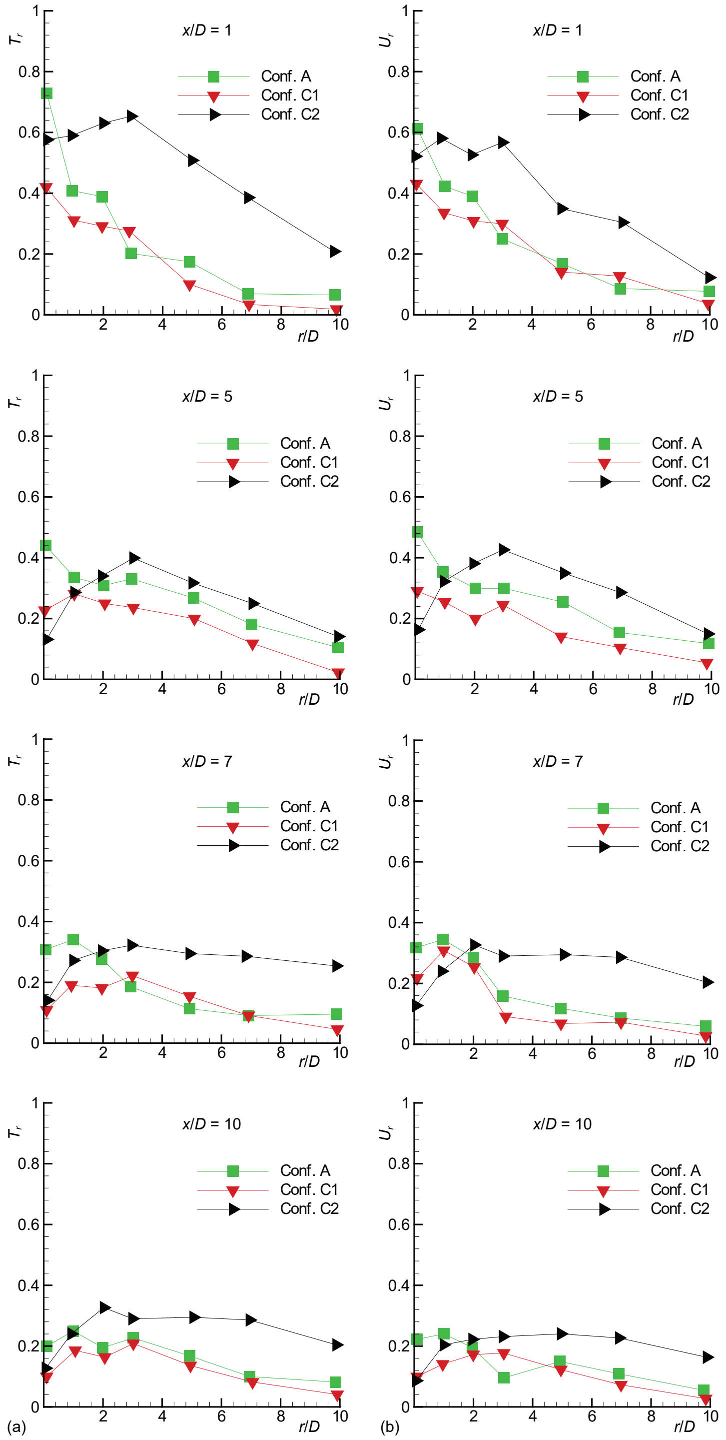


Figure 6. Influence of the central jet position variation regarding the peripheral jets position on the evolution of the radial temperature (a) and velocity (b) profiles; (Configurations A, C1, and C2)

It should be noted that the relative position change of the side jets with respect to the central jet has an influence on the diffusion. Indeed, the results, figs. 5(a), 5(b), 6(a), and 6(b), have shown that the relative position of side jets relative to the central jet can greatly influence the temperature and the jet velocity that results. This effect of the jets relative position on the diffusion has been studied by comparing the distribution and evolution of temperatures and velocity of Configurations A, C1, and C2, respectively.

The findings obtained, see figs. 5(a) and 5(b) showed that the relative position of the highest side jets ($D = +0.5$) and the C2 configuration reduce the axial velocity more rapidly than in the case where such a position is in the same plane (Configuration A). Thereby, it improves the lateral diffusion, resulting in a better homogenization. It should be noted that, from six diameters of the blowing orifice, see figs. 6(a) and 6(b), it can be seen that the radial homogenization and thermal dynamics are almost perfect for the C2 configuration, with a greater spread compared to the two other Configurations A and C1. The rise in the lateral diffusion leads to a better thermal and dynamic homogenization. Note that the central jet acts as a guide for the configuration with imbalance position while piloting the adjacent jets. However, this difference in position induces a decrease of the velocity near the origin of the blowing orifices. Such a configuration should interest industrialists since it contributes to the improvement of thermal comfort in buildings.

Influence of the central jet velocity variation compared to the peripheral jets velocity

Here, we seek to study the influence of the central jet velocity with respect to that of the peripheral jets for Configurations A and D.

Comparison of the axial temperature profiles

The effect of flow rate imbalance (Configurations A and D) on the axial distribution of temperature and velocity is shown in figs. 7(a) and 7(b).

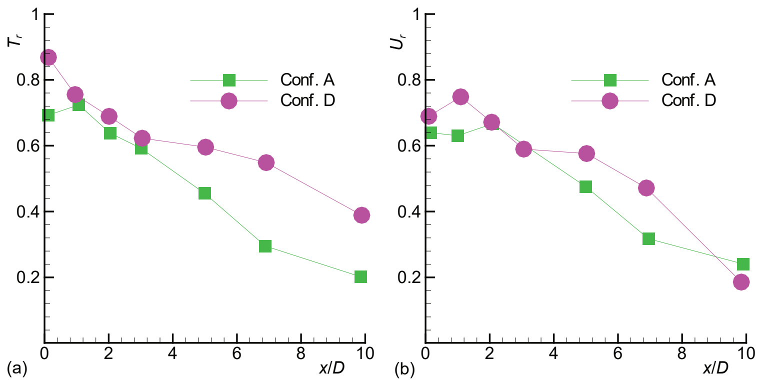


Figure 7. Influence of the central jet velocity variation compared to the peripheral jets velocity on the evolution of the axial temperature (a) and velocity (b) profiles; (Configurations A and D)

Comparison of radial temperature profiles

The effect of flow imbalance (Configurations A and D) on the radial distribution of temperature and velocity is shown in figs. 8(a) and 8(b).

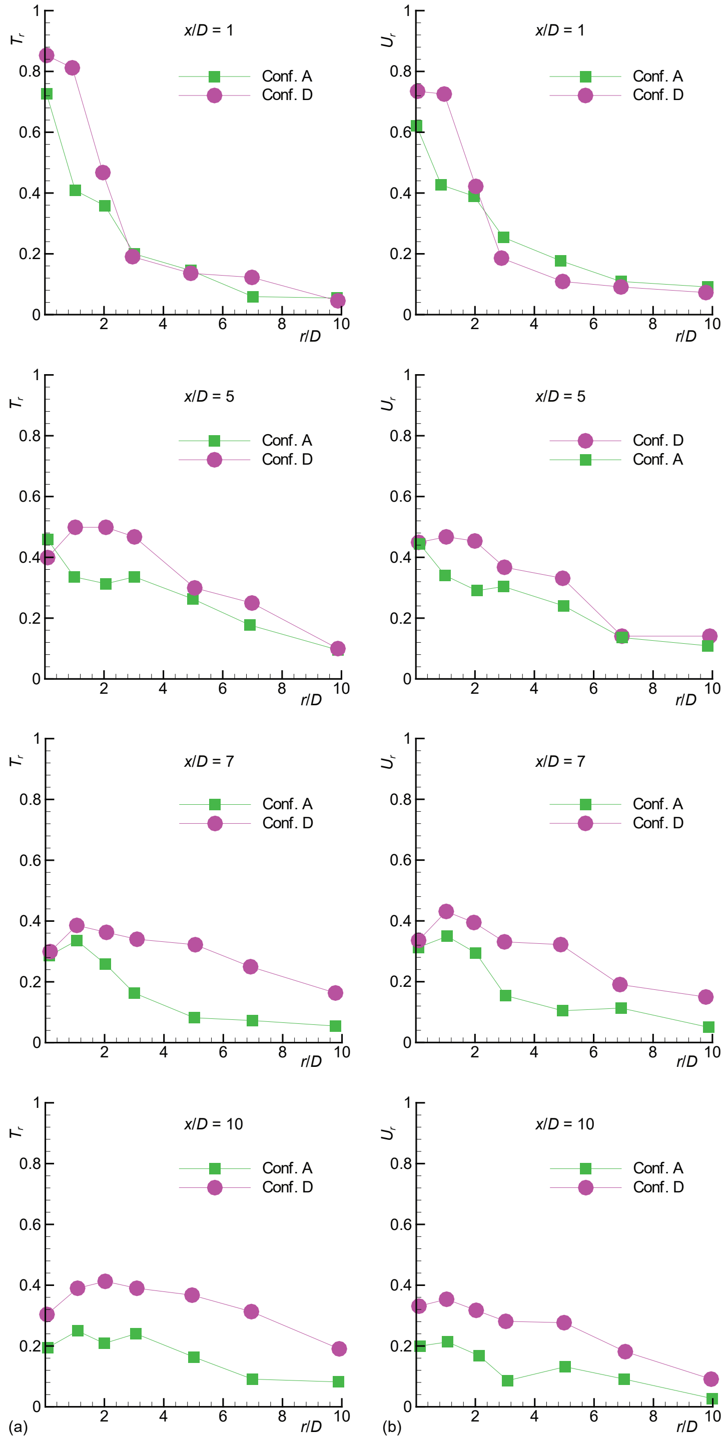


Figure 8. Influence of the central jet velocity variation compared to the peripheral jets velocity on the evolution of the radial temperature (a) and velocity (b) profiles; (Configurations A and D)

The decrease in temperature for Configuration D compared to Configuration A is more sounded due the imbalance of the rate flow between the central jet and peripheral jets, which resulted in a significant radial transfer of energy, thereby, generating an increased transfer of the turbulent mixture. Moreover, in the jet development zone, a decrease of the axial velocity and a thickening of the jet have been observed. Likewise, large shear stresses at the jet boundary also generated turbulence and allowed the entrainment of the ambient fluid, thereby promoting mixing. In addition, it has been observed that the radial temperature profile tends to gradually flatten as one moves further along the axis of the blowing openings. More explicitly, from $x/D = 7$, the homogenization becomes almost perfect for the Configuration (D). To sum up, these developments point out that the relative decrease of the central jet flow leads to a better homogenization by diffusion of the side jets.

Conclusions

This study dealt with the experimental study of different blowing Configurations with multiple swirling jets having different dispositions. In the light of the obtained results, we can state that changing the relative position of side jets relative to the central jet really has an influence on diffusion. It should be emphasized that the highest position ($D = 0.5$) leads to a rapid reduction of the axial velocity than in the case where this position was merged in the same plane. Thereby, the side scatter is more efficient, which leads to a better homogenization. Moreover, the central jet acted as a guide in this configuration with imbalance position, while piloting the adjacent jets. In addition, if the relative position of the central jet is higher, the resultant jet spread seems to be greater compared to Configurations where all jets are in the same plane. The spreading has been shown to be improved over the case where the relative position of the peripheral jets is higher. This allows the processing of a large volume of air. This finding deserves to be operated, especially when we plan to quickly heat or cool a premise. For the Configuration where the position of the jets is placed in the same plane, thermal and dynamic stabilities are greater in all the studied stations. This is therefore significant in cases where one seeks to obtain a better thermal comfort.

It should be pointed out that, when the central jet is warmer (central flow) relative to the circumferential jets, the radial stability is improved, while being associated with significant axial decay.

The relative decrease in the flow rate of the central jet leads to a better homogenization by diffusion of peripheral jets towards the central jet. Finally, it should be pointed out that the experimental measurements made-up are obviously tainted by errors and that they depend on the measuring instruments used. In addition, the approach adopted and the instruments used allow to achieve only the average quantities.

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Nomenclature

D – characteristic length scale, [m]
G_x – axial flux, [kgm^{2}s^{-2}]
G_θ – momentum flux, [kgm^{2}s^{-2}]
Q_m – mass-flow rate, [kgs^{-1}]
Re_0 – Reynolds number, [–]
R_h – inlet duct radius, [m]
R_n – central body radius, [m]
R – diffuser radius, [m]
r – radial co-ordinate, [m]
S – swirl number, [–]
T_0 – maximum temperature of the air blowing at origin, [K]
T_a – ambient temperature [K]

T_r – dimensionless temperature, [$= (T - T_a)/(T_0 - T_a)$]
T – jet temperature, [K]
U_0 – maximum value of the air blowing velocity at origin, [ms^{-1}]
U_r – dimensionless velocity, ($=U/U_0$), [–]
U – axial velocity, [ms^{-1}]
V – radial velocity, [ms^{-1}]
W – tangential velocity, [ms^{-1}]
x – vertical co-ordinate, [m]

Greek symbols

α – swirler vane angle [°]
ρ – air density, [kgm^{-3}]
θ – azimuthal co-ordinate, [–]

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