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Full-scale experimental study of ceiling turbulent air jets in mechanically ventilated rooms

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ABSTRACT

Experimental investigation of ceiling circular grille air jets was conducted in a full-scale entirely controlled test room (6.2 x 3.1 x 2.5 m). Our case study is based on a realistic ventilation system configuration: it introduces a plenum box, two air exhausts, as well as a vertical wall near the air inlet. Analyses were initially concentrated at the air inlet region since it is the zone having strong gradients.

Deviations concerning the trajectory of the actual jet were observed with respect to the theoretical jet. These results are particularly interesting because, based on the academic configuration of the circular turbulent air jet, which is very well documented in the literature; our configuration introduces architecture elements which will necessarily have an impact on the jet. Therefore, it is this deviation from the theoretical model which will become discriminating as to the capacity of a CFD numerical model to simulate airflows in buildings. These results obtained allow for further cases studies under non-isothermal and moisture conditions and also in the presence of condensation in order to provide new useful data concerning airflow and hygrothermal fields in mechanically ventilated rooms.

KEYWORDS

HVAC, mixing ventilation, turbulent jet, room interaction, full-scale experimentation

1 INTRODUCTION

Understanding room air distribution is essential to the buildings ventilation systems design and occupants' thermal comfort and indoor air quality controls. Indoor thermal comfort prediction requires the determination of the airflow and hygrothermal fields within ventilated rooms. In addition, it is clear that air distribution in occupied zones is one of the determining factors that directly affect indoor air quality. For instance, too low air change rate trap all pollutants, contaminants harming the occupants' health while a very high airflow can cause a feeling of discomfort.

Indoor air distribution investigation involves two common methods: numerical simulation and full-scale measurements. By using Computational Fluid Dynamics (CFD) model, numerical simulation is most convenient and efficient for predicting airflow and hygrothermal transfer in ventilated rooms (*Chen, 2009*). However, this method is limited by the lack of relevant experimental data, especially from full-scale measurements. In fact, experiments in full-scale rooms can provide valuable data concerning room airflows characteristics, including the turbulent flow characteristics.

Numerous theoretical studies based on full-scale experiments have been conducted since the 1940s on the behavior and characteristics of circular turbulent air jets (*Corrsin, 1946*), (*Abramovich, 1963*), (*Rajaratnam, 1976*), (*Chen and Rodi, 1980*). In HVAC applications, several studies were conducted in order to improve the knowledge of vertical jet development and room air distribution (*Tuve, 1953*), (*Koestel, 1954*), (*Shepelev, 1961*) and (*Grimitlyn,*

1970). A summary and review of research mentioned above can be found in the study of Li (*Li and al., 1993*). They confirmed that it is possible to predict indoor air velocity and temperature based on the characteristics of diffuser air jets. They also suggested further research to examine the effects of room geometry on the jet development. Indeed, while turbulent free air jet theory has been widely studied by many researchers, few studied a realistic vertical air jet having interaction with the room.

Consequently, the main objective of the present experimental research is to get improved knowledge of the mean and turbulent characteristics of a nearly-free circular vertical air jet. This configuration is particularly interesting since it is based on an academic configuration of the circular turbulent air jet, which is very well documented in the literature; our configuration introduces architecture elements which will necessarily have an impact on the jet. Therefore, it is this deviation from the theoretical model which will become discriminating when evaluating the capacity of a CFD numerical model to predict airflows and coupled transfers in buildings.

The article will be organized as follows: firstly, the experimental set-up will be described. Then, the second part provides a description of the theoretical model of a turbulent free vertical jet from the literature. The last part is devoted to presenting the tested configuration as well as the experimental results of the studied jet.

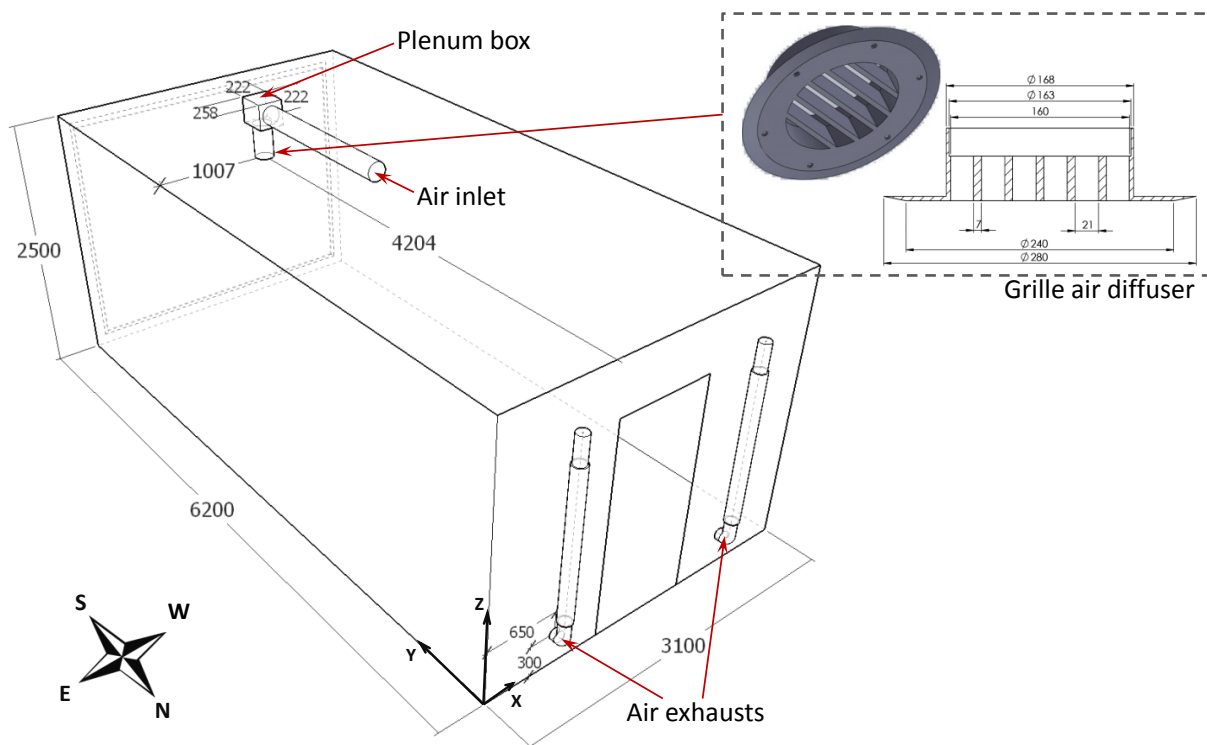


Figure 1: Scheme of MINIBAT test room with flow configuration

2 EXPERIMENTAL FACILITY AND MEASUREMENT APPARATUS

2.1 MINIBAT test room

Experimental investigation was conducted in a full-scale entirely controlled test cell entitled "MINIBAT". It is located at the CETHIL laboratory – INSA de Lyon, France. It consists of three distinct parts: a test room, a thermal buffer zone and a climatic chamber.

The test room, with dimensions $L \times W \times H = 6.20 \times 3.10 \times 2.50$ m, is the place where the experimentation is carried out (c.f. Figure 1). Five of its façade are surrounded by the thermal

buffer zone that allows maintaining a stable temperature. The South façade is in contact with the climatic chamber through a glazing wall. The climatic chamber acts like a weather generator which is capable of simulating outdoor temperature and solar conditions.

Air temperature inside thermal buffer zone is entirely regulated thanks to controlled mechanical ventilation operating in closed loop. Air distribution inside the thermal buffer zone is ensured by means of air ducts network, which allows a regular and homogeneous air mixing.

The climate chamber is also temperature controlled. The temperature range allowed by the system goes from -10 °C to 40 °C. There is also an artificial sunlight system in the climatic chamber. This system was not used for this study; therefore they will not be described in the present paper.

2.2 Cell envelope

The envelope of the thermal buffer zone consists of 20 cm thick cellular concrete, covered by 10 cm of extruded polystyrene. The insulating layer has been added in order to reduce the air temperature fluctuation observed in previous studies carried out at MINIBAT (± 1.5 °C according to (Hohota, 2003), (Kuznik, 2005), ± 1.3 °C according to (Gavan, 2009)). Thus, a fluctuation of ± 0.6 °C around the setpoint temperature has been recorded.

The opaque vertical walls separating the test room and the thermal buffer zone are made of 5 cm thick agglomerated wood panels covered on their internal faces by 13 mm thick plasterboard. The floor is made of 20 cm thick cellular concrete. The ceiling consists of 2.5 cm thick plywood plate, covered with 4.5 cm thick of glass wool. The South façade comprises a 1.2 cm thick high-resistance laminated glazing.

2.3 Measurement apparatus – Boundary conditions and indoor air measurements

There are sensors which are devoted to the measurement of the boundary conditions around the test cell (wall temperatures and ventilation characteristics). Other sensors are devoted to the measurement of the indoor temperature and velocity fields.

In order to precisely check the boundary conditions of wall temperature on the different test cases, a network of 180 Pt100 probes was implemented on both external and internal sides of 6 walls of the test room. Each wall surface has 36 measurement points, except the North wall and the South (glazing) wall which have 18 measurement points.

Air supply parameters are regulated in temperature and humidity by using Pt100 probes and SHT75 probes. The measurements are recorded at 5 locations: 3 points inside the air handling unit (AHU): air inlet, cooling coil and air supply; 2 other points are located inside Minibat test room which are air inlet and air exhausts. Besides, airflow rate are regulated thanks to a propeller flow meter with an accuracy of ± 0.5 m³/h.

We have designed and programmed a mobile robot (c.f. Figure 2) equipped with various sensors, in order to determine indoor air velocity, temperature and humidity fields.

The robot chassis is made of aluminum alloy whose dimensions are 0.4 x 0.3 x 0.12 m (L x W x H). The main masts (1) and (3) are made of carbon fiber. The robot is equipped with 4 Mecanum wheels; each of these wheels has its own geared motor and its own rotary encoder. This configuration makes it possible to independently control the movement of each wheel.

The four motors are driven by a microcontroller, which is controlled by a mini PC (2). The exact position of the robot inside the room can be determined thanks to a Lidar (laser detection and ranging) system (4).

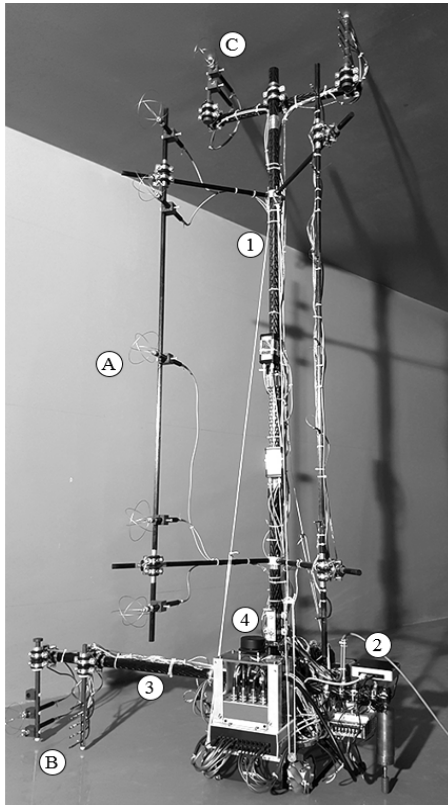


Figure 2: Mobile robot with sensors equipped

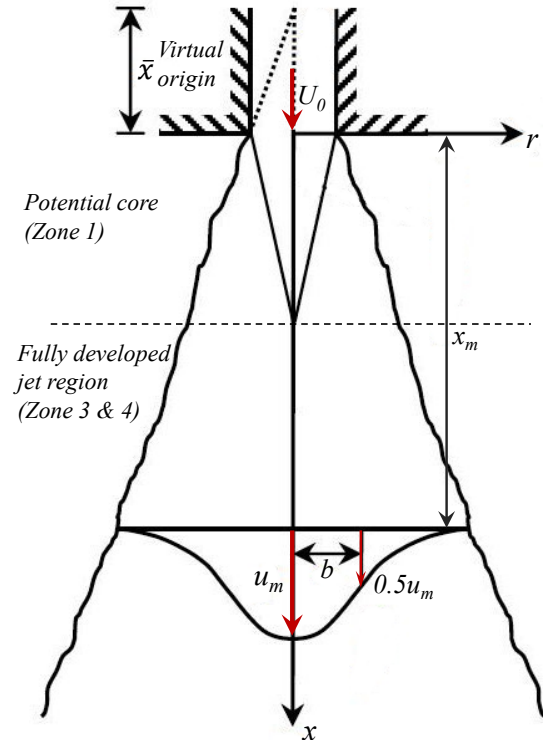


Figure 3: Scheme of theoretical free air jet

Air temperature measurements on the robot is achieved using thermocouples with a diameter of $25 \mu\text{m}$, which allows a very fast-response and a high accuracy ($\pm 0.06 \text{ }^\circ\text{C}$ in mean value). Air relative humidity measurements are done using SHT75 probes with an absolute accuracy of $\pm 1.8 \text{ \%RH}$. Air velocity measurements are carried out using thermoelectric anemometers with an accuracy of $\pm 1.5\%$ of the measured value.

The sensors are implemented along three vertical profiles. There are two profiles located near the ground (B) and near the ceiling (C). Each of these profiles contains 5 temperature and humidity probes, and 2 anemometers. They capture high gradients, which make it possible to distinguish the different types of boundary conditions at the walls. There is a central profile with vertical amplitude of 1.5 m (A). The main purpose of this profile is to measure air jet characteristics. It includes 7 measurements of air temperature and humidity, and 5 measurements of air velocity.

Compared to the mobile arm on rail system used previously by (Hohota, 2003) and (Kuznik, 2005), there are two main advantages of using the mobile robot system: air flow disturbances reduction and free access to the entire volume of the test room. In addition, it is important to mention that the total heat gain (due to the microcontroller, mini PC, Lidar and data acquisition center) is of order of 10 W, thus air flow characteristics disturbance is minimal.

2.4 Experimental protocol

For each measurement campaign, three days are required in order to obtain steady state within the test room. During this stage, air change rate, air temperature and humidity setpoints are fixed depending on the configuration tested. Once the steady state reached, the mobile robot is used to examine the area of interest ($1 \times 1 \text{ m}$ around the air inlet with a mesh of 10 cm).

For each robot position, air velocity and temperature are measured with an acquisition frequency of 10 Hz (100 ms between each measure). Recorded values are averaged over 2000 samples, i.e. 200 s in order to reduce fluctuations.

3 THEORETICAL FREE JET MODEL

3.1 Air jet theory

According to ASHRAE Handbook Fundamentals (*ASHRAE, 2013*), an air jet that is not affected and obstructed by neighbouring elements such as ceiling, walls, other surfaces, is considered a free jet. The theory is based on a jet with a homogeneous velocity equal to U_0 across the duct outlet. The development of an air jet can be divided into four zones (c.f. Figure 3):

- Zone 1: the potential core zone where centerline velocity u_m is equal to outlet velocity U_0 ;
- Zone 2: the transition zone, which have a negligible length for a circular jet, according to (*Kuznik, 2005*);
- Zone 3: the zone of fully developed jet, characterized by heat and mass transfers and by turbulence as well as the similarity of the velocity profiles;
- Zone 4: the terminal zone where residual velocity decreases rapidly, often assume to subside below 0.25 m/s.

3.2 Centreline velocity decay in zone 3

From a technical point of view, zone 3 is the most important area since, in most cases, it is the part of the jet that enters the occupied region. Therefore, it influences occupants' thermal comfort and indoor air quality. We are mainly interested in this area which allows describing heat and mass transfers with the room ambience.

Proposed by (*Li et al., 1993*) and (*Goodfellow, 2001*), the centreline velocity decay is given by the following equation:

$$\frac{u_m}{U_o} = \frac{K_1 \sqrt{A_0}}{x + \bar{x}} \quad (1)$$

In this equation, U_0 is the averaged initial velocity at the diffuser outlet of effective area A_0 . u_m is the centreline velocity at distance x_m (c.f. Figure 3). This formula includes two empirical constants: \bar{x} is the virtual origin of the jet and K_1 represents the centreline velocity decay coefficient. These two parameters, which are interdependent according to (*Zou, 2002*), depend mainly upon the type of jets, the type of outlets and the jet initial velocity.

According to Tuve's experimental study (*Tuve, 1953*), K_1 varies between 5.7 and 7 for a horizontal circular jet. Recently, Malmström's study (*Malmström, 1992*) concluded that K_1 depends on the jet initial velocity rather than Reynolds numbers Re_0 : it varies between 3 and 6 for $U_0 < 5$ m/s and remains equal to 6 for $U_0 > 5$ m/s. For an ascending vertical circular jet, (*ASHRAE, 2013*) suggests a value of 4.7.

As for the virtual origin, some researchers (*(Rajaratnam, 1976)*, (*Goodfellow, 2001*)) set $\bar{x} = 0$ since the length of the fully developed jet zone is usually preponderant. According to Zou's study (*Zou, 2001*), for $U_0 < 5$ m/s, the virtual origin varies between 0 and 4 times the diffuser outlet diameter. In our present study, since the length of the jet is limited by the height of the cell (2.5 m), taking into account the virtual origin allows a correction of the jet behaviour.

3.3 Jet boundaries

According to (*Rajaratnam, 1976*), the boundary (or expansion) of the jet can be obtained using this equation:

$$b = K_2 (x + \bar{x}) \quad (2)$$

where b is the radial distance at which $u(r = b) = 0.5u_m$; K_2 represents jet expansion coefficient.

K_2 also depends on the type and initial velocity of the jet. It has been evaluated by various researchers in the literature: 0.097 according to (Abramovich, 1963), 0.151 according to (Tollmien, 1926), 0.1 according to (Rajaratnam, 1976).

3.4 Velocity profiles in the cross-section of a jet

(Rajaratnam, 1976) and (Goodfellow, 2001) demonstrated that, in the fully developed jet region, transverse velocity distribution at different heights of the jet were found to have a similar shape. These profiles could be approximated by the following Gauss error-function:

$$\frac{u}{u_m} = \exp\left(-\ln 2 \cdot \left(\frac{r}{b}\right)^2\right) \quad (3)$$

where u is the jet velocity corresponding to the radial distance r .

4 EXPERIMENTAL RESULTS

4.1 Flow configuration

The air in the test room is ventilated using a closed-loop air handling unit. As illustrated in Figure 1, the ceiling supply air diffuser is located 1.0 m from the East wall and 4.2 m from the North wall. Its diameter is 16 cm and it is equipped with grilles with an effective area/total area ratio of 76% (c.f. Figure 1).

The two air exhausts, which are circular with a diameter of 10 cm, are located in the North wall. They are distanced by 0.3 m from the floor and 0.65 m from the adjacent vertical walls (East and West). This disposition allows us to promote homogeneous air distribution within the test room.

Based on theoretical configuration of a totally free circular vertical jet, which is very well documented in the literature (Goodfellow, 2001), our configuration approaches realistic cases in buildings. Indeed, due to limited dimensions of a room, supply air inlet should be located near a vertical wall. Considering the available space above suspended ceiling, a plenum box must be used before the air inlet. These architecture elements will necessarily have an impact on the jet behaviour and performance, as will be described in next sections.

Table 2: Test cell walls temperature (°C)

	Ceiling	Floor	S	N	E	W
Mean value	28.0	27.8	28.3	27.7	27.8	27.8
SDEV	0.2	0.3	0.2	0.1	0.3	0.3

Table 1: Air supply parameters

	Flow rate (m ³ /h)	U ₀ (m/s)	Re ₀ (-)	T ₀ (°C)
Value	150.1	2.1	21538	28.0
SDEV	2.3	-	-	0.1

4.2 Jet behaviour and characteristics

In the present paper, the case of an isothermal jet is analyzed. The boundary conditions and air supply parameters are summarized in Tables 1 and 2. Investigations were carried out following 11 measurement planes around the air inlet with a mesh size of 10 cm, thus a total of 121 measurement positions.

K_1 and \bar{x} are based on the linear regression of the function $U_0/u_m = f(x/\sqrt{A_0})$. K_2 is determined using equation (2) for 5 height positions of the jet. In our jet configuration ($U_0 = 2.1$ m/s ; $Re_0 = 21538$), K_1 -value is equal to 4.4; quite similar to the value recommended by ASHRAE (ASHRAE, 2013). The length of virtual origin can be neglected ($\bar{x} = -0.004$ m). K_2 -value is found to be equal to 0.15.

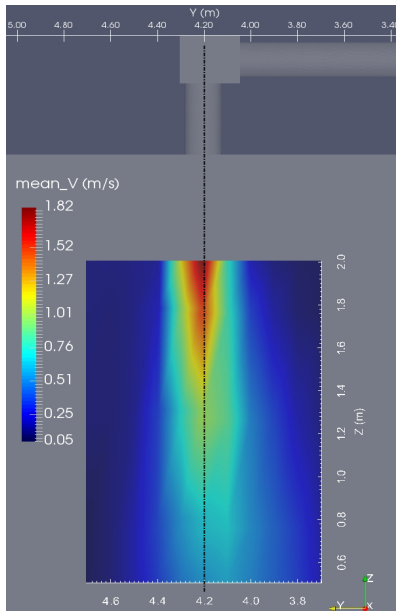


Figure 4: Jet behaviour following plane $x = 1.0$ m

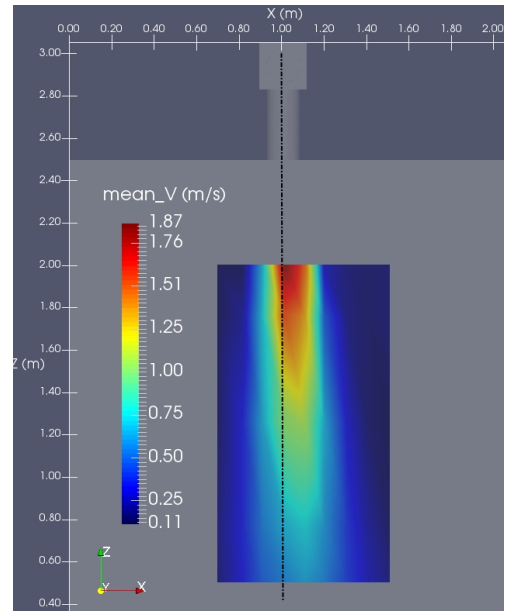


Figure 5: Jet behaviour following plane $y = 4.2$ m

Figure 4 and Figure 5 show an airflow visualization followings 2 section planes $x = 1.0$ m and $y = 4.2$ m. As a reminder, the point $(x = 1.0; y = 4.2$ m) corresponds to the centre of the diffuser in MINIBAT coordination (c.f. Figure 1). As can be seen in 2 figures, the jet trajectory was deviated in both direction x and y . In y -direction, the jet is deviated to the air exhaust side; we can confirm that the plenum box presence and the air exhausts aspiration could be the origin of this jet deviation. In x -direction, the jet is deviated to the West wall side (i.e. the opposite direction of the near wall (East wall)). Thus, a near wall situated 1 meter from an air inlet could have a significantly impact on the jet behaviour.

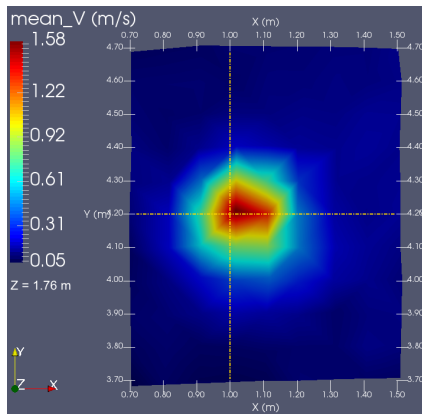


Figure 6: Jet behaviour following plane $z = 1.76$ m

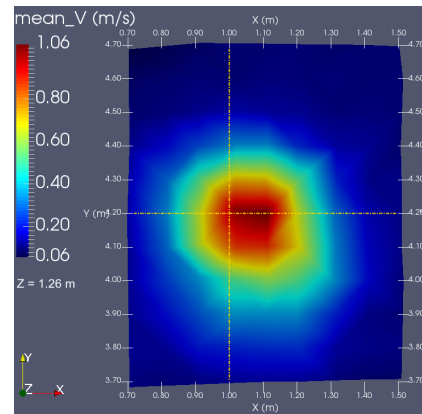


Figure 7: Jet behaviour following plane $z = 1.26$ m

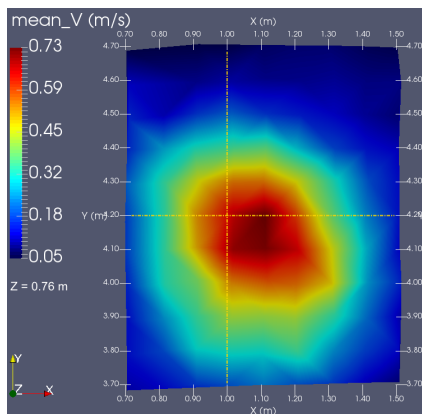


Figure 8: Jet behaviour following plane $z = 0.76$ m

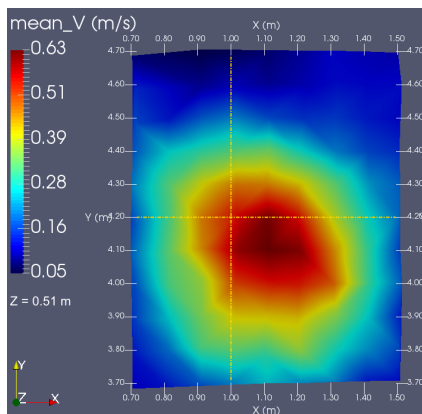


Figure 9: Jet behaviour following plane $z = 0.51$ m

Figure 6 to Figure 9 show air jet velocity isocontours followings 4 section planes $z = 1.76$ m, $z = 1.26$ m, $z = 0.76$ m and $z = 0.51$ m. As can be seen clearly, the studied jet is no longer axisymmetric; instead, it spreads with a deviation to the opposite side of the near wall. Indeed, from the theoretical axe ($x = 1.0$ m), the jet spreads about 10 cm to the left (near wall) and about 30 cm to the right. Besides, a further refine of the examine mesh is necessary in order to obtain more precise isocontours.

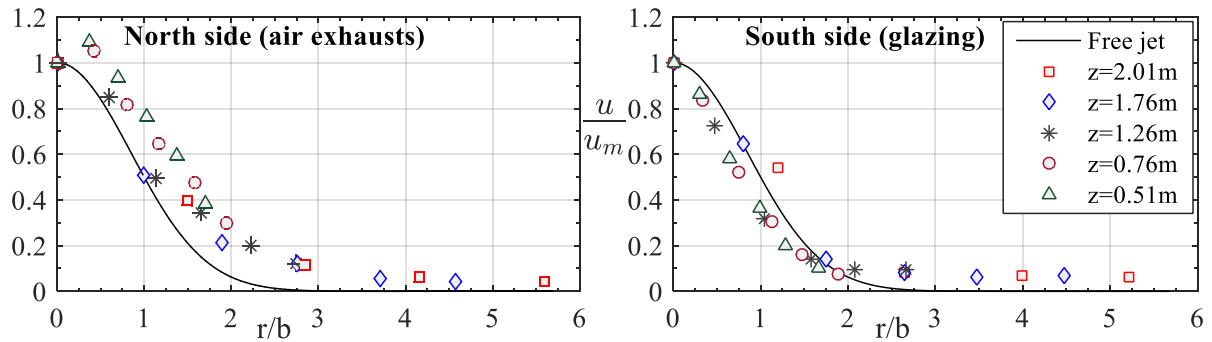


Figure 10: Velocity profiles in the cross-section of the jet following y-direction

Jet velocity profiles in y-direction and on both side of the jet axe are shown on Figure 10. As expected, all velocity profiles according to 5 height positions are similar to each other and to the theoretical profile. Otherwise, u/u_m values of the air exhaust side are all greater than the theoretical curve. Some values of u/u_m is greater than 1 (i.e. $z = 0.76$ m and 0.51 m); it means that centreline velocity of the studied jet is not necessary the maximum velocity, as can be seen in figure below.

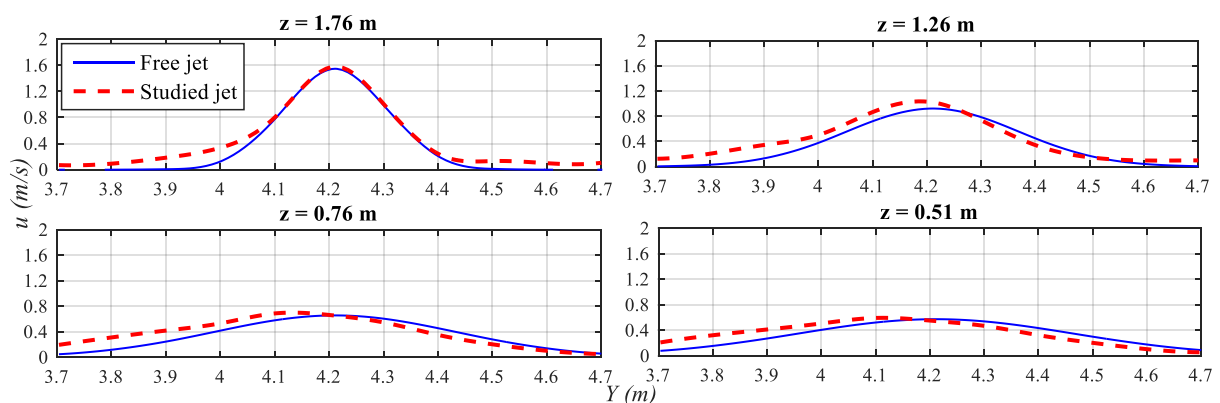


Figure 11: Velocity distribution for 4 height positions of the jet

The velocity distribution according to 4 height positions of the jet is presented in Figure 11. For $z = 1.76$ m, the maximum velocity of the studied jet stay on the free jet theoretical axe. For $z = 1.26$ m, it lightly shifts to the left side (air exhausts side). Moving farther away from the air diffuser, maximum velocity position is completely deviated to the left side, at the order of 10 cm for $z = 0.51$ m.

5 CONCLUSION

The main objective of this research is to get improved knowledge of the mean and turbulent characteristics of a nearly-free circular vertical air jet in a mechanically ventilated room with the presence of a near wall, a plenum box and air exhausts. As expected, experimental results show a deviation with respect to theoretical values. Indeed, the presence of architecture

elements have a significantly impact on the jet behaviour and thus, its real trajectory is deviated compared to a totally free air jet.

Following the present study, it is necessary to refine the experimental measurements by adding additional examine planes with a finer mesh around the air diffuser in order to obtain a higher precision, particularly in the jet region. On the other hand, the results obtained allow for more thorough research under non-isothermal conditions, with the presence of moisture, as well as in condensation condition.

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