Energy and comfort in spaces equipped with ascendant airflow

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Abstract. This article presents a numerical study on an impinging jet ventilation system applied in a virtual office with the aim of improving indoor air quality (IAQ) and thermal comfort conditions for its occupants. The study was carried out for winter conditions, also evaluating the thermal energy consumption obtained in the acclimatized space by the proposed ventilation system. The numerical model used is based on the coupling of two numerical models, the Computational Fluid Dynamics to simulate the heat and mass turbulent flow, and the Human Thermal Modelling to evaluate the human and clothing thermal response. A third numerical model, the Building Thermal Modelling, was used to provide some input data required for the two aforementioned models. The evaluation of the thermal comfort is done by the Predicted Percentage of Dissatisfied (PPD) people index. The evaluation of the IAQ is done by the dioxide carbon (CO_2) concentration in the breathing zone of occupants. The evaluation of the impinging jet ventilation system is done by the Air Distribution Index (ADI). This study was done in a virtual chamber occupied by four virtual manikins seated around a table. The impinging jet ventilation system has an inlet system based on four ducts located in the corners of the chamber, whose air terminal devices are 0.25 m from the floor, and an outlet system, whose air terminal device is located close to the ceiling central area. This numerical study considered different values of the airflow rate for the impinging jet ventilation system. When the airflow rate increases, the level of IAQ, the level of thermal comfort and the ADI improve. Moreover, results obtained for PPD and CO_2 show values within acceptable limits accordingly to the international standards.

Keywords. ADI, Indoor Air Quality, Thermal Comfort; Virtual Thermal Manikin.
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1. Introduction

In this study it is applied a ventilation system based on impinging jets with downward supply (near the floor) and upward exhaust (ceiling). The principle of operation of this ventilation system is described in the study of Ye et al. [1]. This kind of ventilation system has the advantages of mixing and displacement ventilation systems in the occupied area [2], and lower energy consumption than mixed ventilation systems [1]. The ventilation performance of impinging jet ventilation systems was assessed, e.g., in works of Karimipanah et al. [3], Ye et al. [4] and Chen et al. [5]. Factors as the shape of the air supply device, the discharge height, the supply airflow rate, the supply air temperature and the thermal load in space influence the performance of these systems [6]. Staveckis and Borodinecs [7] concluded that impinging jet ventilation systems can improve the thermal comfort and Indoor Air Quality (IAQ) in indoor occupied spaces due higher ventilation effectiveness.

Therefore, in order to assess the performance of these types of ventilation systems, it is important to use methodologies for assessing thermal comfort and IAQ.

In order to evaluate the thermal comfort in occupied spaces provided by Heating, Ventilation and Air Conditioning (HVAC) systems, Fanger developed through experimental tests two comfort indexes, PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfied) [8]. These indexes were adopted by the international standard ISO 7730 to define three acceptable thermal comfort categories [9].

The carbon dioxide (CO_2) concentration can be used as reference to evaluate the IAQ level in occupied spaces [10,11]. The international standard ASHRAE 62.1 [12] defines a concentration of CO_2 released in the occupant breathing process of 1800 mg/m^3 as the acceptable limit for IAQ in occupied spaces. The CO_2 concentration depends on the airflow rate used by the ventilation system [13,14].

In this work the numerical models used, developed by the authors over the years, are based on the Building Thermal Response [15], and a coupling between two numerical models, namely, a numerical model that simulates the turbulent flow of heat and mass using Computer Fluid Dynamics [16], and a numerical model that simulates the thermal response of the human body and respective clothing, named Human Thermal Response [17]. Results obtained by the Building Thermal Response are used as input data in the coupling numerical models.

The Air Distribution Index (ADI) is used to evaluate the HVAC system performance [18]. The thermal comfort level, IAQ level, effectiveness for heat removal and effectiveness for contaminant removal are parameters considering by ADI. The ADI depends of the thermal comfort number and the air quality number. The thermal comfort number depends of the coefficient between the effectiveness for heat removal and the PPD due the thermal comfort level. The air quality number depends of the coefficient between the effectiveness for contaminant removal and the Percentage of Dissatisfied people due to IAQ level. The application of ADI is shown, e.g., in the works of Almesri et al. [19] and Conceição and Awbi [20].

The objective of this numerical work is to present the influence of an impingement jet ventilation system on the IAQ and thermal comfort levels of the occupants of a space with dimensions similar to a small office. This virtual office is occupied by four occupants seated on chairs around one table. The impingement jet ventilation system is constituted by an inlet system located in the four corners of the office and one outlet system located at the central area of the chamber close to the ceiling. The study, carried out in steady state regime, was done for five different air inlet velocities considering external winter conditions.

2. Methodology

The numerical simulation was carried out for a virtual chamber (Fig. 1), with the dimensions 2.7×2.45×2.4 m^3. The virtual chamber, simulating a small office, is occupied by four people sitting in chairs around a table, and is equipped with an inlet and outlet airflow systems, based on impinging jet ventilation. Each occupant, represented by a virtual manikin, is 1.70 m tall and 70 kg in weight.

The impinging jet ventilation consists of:

- An exhaust system equipped with an exhaust fan, installed 1.8 m from the floor, connected to the central ceiling area;

- An inlet system, based on four vertical ducts, of 0.125 m diameter, located in the walls corners. Each duct is equipped with a fan. The inlet airflow, with downward airflow, is located 0.25 m from the floor.

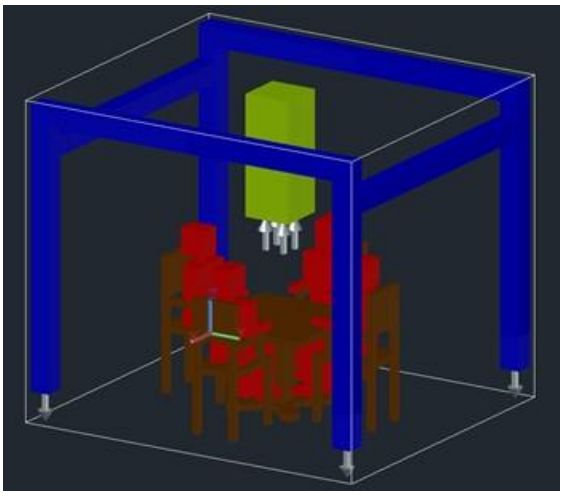

Fig. 1 – Scheme of the virtual chamber used in the numerical simulation. The inlet system is represented in blue and the outlet system in green. Arrows indicate the direction of airflow.

The numerical simulation was done considering winter conditions. The external inlet air temperature is 0°C. The inlet CO_2 concentration is 500 mg/m^3. The inlet turbulent intensity is 2.5%.

It was considered that the occupants have an activity level of 1.2 met [9], and are considered to be dressed at a clothing insulation level of 1.0 clo [9], a typical value for winter conditions.

This numerical simulation was done for five different Cases characterized by the inlet air velocities and inlet air temperatures present in Tab. 1.

Tab. 1 – Cases considered in the numerical simulation.

Case	Air inlet velocity (m/s)	Air inlet temperature (°C)
A	0.43	13.0
B	0.86	16.5
C	1.29	17.7
D	1.72	18.3
E	2.15	18.6

The air introduced into the virtual office comes from outside and is heated by the HVAC system in order to reach a temperature that guarantees thermal comfort conditions for the occupants. The inlet air velocity is varied to ensure that the air quality in the occupants' breathing zone is acceptable.

The occupants' thermal comfort level is evaluated by the PPD index, which in turn depends on the PMV index [8]. The PMV index depends on four indoor environmental parameters, air temperature, relative air humidity, air velocity and Mean Radiant Temperature, and two personal parameters, clothing and occupant activity [8,9].

The assessment of the IAQ is done through the concentration of CO_2 released in the breathing zone of the occupants [12].

The performance of the ventilation system is measured using the ADI index. The ADI depends on the thermal comfort number and the air quality number [18]. The thermal comfort number depends of the coefficient between the effectiveness for heat removal and the PPD due the thermal comfort level [18]. The air quality number depends of the coefficient between the effectiveness for contaminant removal and the Percentage of Dissatisfied people due to IAQ level [18].

3. Results and discussion

This section presents the results obtained from PPD (Fig. 2), CO_2 concentration (Fig. 3), effectiveness for heat removal and effectiveness for contaminant removal (Fig. 4), thermal comfort number and air quality number (Fig. 5), and ADI (Fig. 6) for the five Cases defined in Table 1. The values of the results presented refer to the average of the values obtained in each occupant.

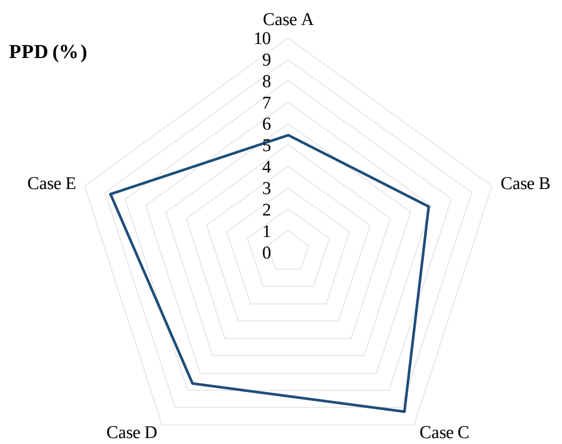

Fig. 2 – Results obtained from PPD for the five Cases simulated.

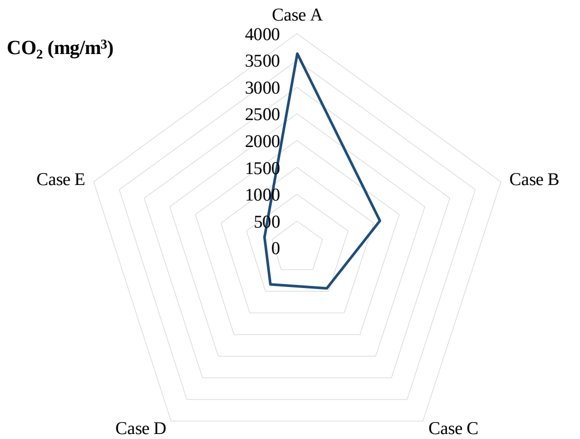

Fig. 3 – Results obtained from CO_2 concentration for the five Cases simulated.

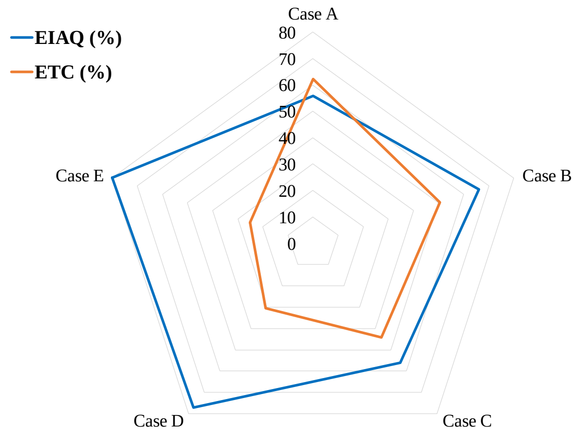

Fig. 4 – Results obtained from effectiveness for heat removal (ETC) and effectiveness for contaminant removal (EIAQ) for the five Cases simulated.

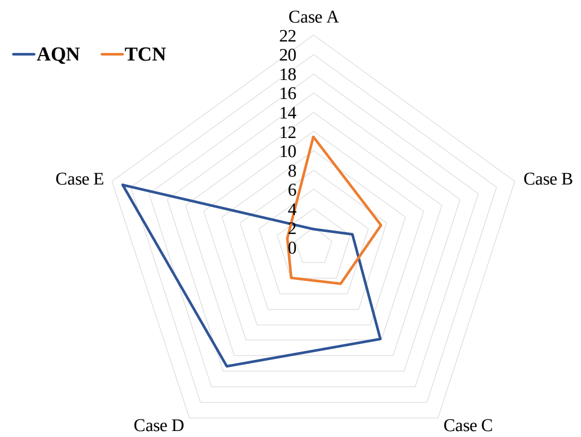

Fig. 5 – Results obtained from thermal comfort number (TCN) and air quality number (AQN) for the five Cases simulated.

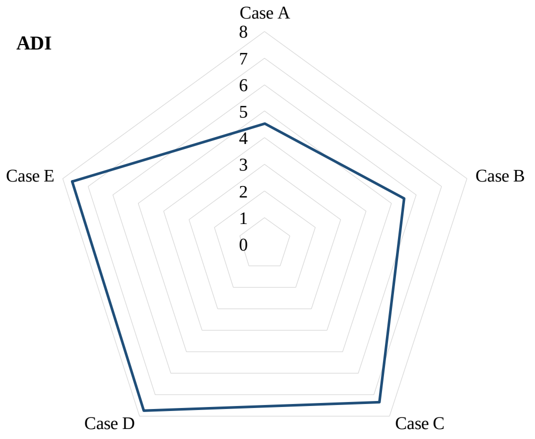

Fig. 6 – Results obtained from ADI for the five Cases simulated.

The results show that when the air velocity increases the PPD value increases. The average increase rate between Cases is about 14.4%. However, for all cases, the PPD values obtained show acceptable levels of thermal comfort according to the ISO 7730 standard [9].

The CO_2 concentration decreases as the air velocity increases. The decrease between Cases is significant. The value of the CO_2 concentration in Case E is around 18% of the value of the CO_2 concentration obtained in Case A. Analysing Case by Case, it appears that the level of air quality in the occupants' breathing zone does not is acceptable according to ASHRAE 62.1 [12] only for the air velocity used in Case A. The air velocities used in Cases C to E allow obtaining CO_2 concentration levels significantly below the acceptable limit of 1800 mg/m^3 recommended by ASHRAE 62.1 [12].

The effectiveness for heat removal decreases with increasing air velocity. The value obtained for the effectiveness for heat removal for Case E is about 40% of the value obtained for Case A, so it can be said that when the air velocity increases, the effectiveness for heat removal worsens.

The effectiveness for contaminant removal increases with increasing air velocity. The value obtained for effectiveness for contaminant removal for Case E is about 143% of the value obtained for Case A, so it can be said that when the air velocity increases, effectiveness for contaminant removal improves.

The thermal comfort number decreases with increasing air velocity. The value obtained for the thermal comfort number for Case E is about 25% of the value obtained for Case A, so it can be concluded that when the air velocity increases, the thermal comfort number gets worse.

The air quality number increases with increasing air velocity. The value obtained for the thermal comfort number for Case E is about 112% of the value obtained for Case A, so it can be concluded that when the air velocity increases, the air quality number improves.

The ADI increases with increasing air velocity. The value obtained from the ADI for Case E is about 168% of the value obtained for Case A, so it can be concluded that when the air velocity increases, the performance of the HVAC system, given by the ADI value, improves.

In general, the results show that IAQ and ADI improve with increasing air velocity, despite the decrease in thermal comfort level, but managing to maintain PPD values within the recommended acceptable values [9].

The values obtained for the heating power for the five Cases are shown in Tab. 2. The heating power was calculated from the integral of the energy over the time required to heat the air transferred from the outside to the interior of the room. The results show that the heating power increases with the increase in air velocity. Note that increasing the inlet air temperature from Case to Case (see Tab. 1) shows that the heating power must increase.

Tab. 2 – Heating power obtained for each of the Cases simulated.

Case	Power (W)
A	546.9
B	1388.2
C	2233.7
D	3079.3
E	3912.2

4. Conclusions

In this paper it was applied an impinging jet ventilation system with downward supply (near the floor) and upward exhaust (next to the ceiling). The performance of this system was evaluated for five different values of air velocity through the average value of the ADI obtained for each of these air velocities. Simultaneously, for each of these air velocities, the level of thermal comfort was evaluated, through the average values of the PPD obtained, and the level of IAQ in the breathing zone of the occupants was evaluated, through the average values of the concentration of CO_2 obtained.

When the air velocity increases, the results obtained allow us to conclude the following:

- As a positive contribution, the decrease in CO_2 concentration, the increase in effectiveness for contaminants removal, in the air quality number and in the ADI;
- From a less significant perspective, the decrease in PPD, effectiveness for heat

removal and thermal comfort number.

However, the thermal comfort level is acceptable, according to ISO 7730 [9], for all simulated air velocities. On the other hand, the IAQ level is acceptable, according to ASHRAE 62.1 [12], for the air velocities used in Cases B to E.

As the air velocity increases, the performance of the ventilation system improves, mainly due to the improvement of IAQ conditions close to the occupants' breathing zone.

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