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Flow Field Measurements in a Large Controlled Ventilated Room

Di Tommaso R.M., Faruoli M., Ferrara N. Nino E.

School of Engineering University of Basilicata
Via dell'Ateneo Lucano, 10. 85100 Potenza Italy

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Abstract - *A large-scale test room, which represents a Test Control Room facilities in scale 1:1, has been recently developed in order to evaluate the internal flow filed induced by the ventilation system. Due to its crucial relevance in numerous technical applications, rooms ventilation efficiency has been subject of several scientific investigations considering also the restricted requirements that such devices should satisfy in terms of microbiology, particulate concentration and pathogen diffusion (Covid-19). Such a large-scale test room with an internal dimension of 6x6x3 m (corresponding to an internal volume of 108 m3) has been equipped with four inlets and twelve exhaust terminal grids, parts of the ventilation system entirely customary designed. In order to assess effects of different air flow rates, induced by the ventilation system, on the internal flow distribution, a relevant number of three dimensional velocity measurements has been performed, under isothermal conditions, by using a fiber optic Laser Doppler Velocimetry. Consistently with the survived literature, two different inlet flow rates have been considered, in particular 15 and 30 Air Change per Hour (ACH) respectively corresponding to 0.45 and 0.90 m3/s. The whole campaign of measurements has been performed totally in 690 points for a total of 4140 single velocity components acquired.*

Key Words: Room Ventilations, Laser Döppler Velocimetry; Internal Flow Field.

1.INTRODUCTION

An environment maintained at a high level of cleanliness is a general requirement for the microelectronics, biological and chemical industry; particular clean environments are also required for operating rooms to avoid infections (COVID-19) and bacteria propagation during surgeries. Whole flow field airflow patterns and velocity distribution are fundamental information to understand the performance of ventilation systems for cleanliness and for occupants comfort. Obviously, the air distribution in the entire environment is strongly affected by ventilation terminals typologies, their position in the walls, and flow rates set. Those data are commonly provided in manufacture's product catalogs; these data are used to evaluate the position and orientation of the terminals in the room, unfortunately they are not suitable to understand in detail the flow distribution in terms of velocity profile, turbulence and vorticity in the exit region. In the open literature are available works, numerical and experimental, which describe the flow distribution in the exit region of diffusers and terminals and often the consequent flow pattern in the rooms in which they are installed. A complete work that could be seen as the state of the art in the ventilation is represented by the ASHRAE Report 2000 [1]. The report shows results carried out numerically and experimentally for different types of diffusers, in particular in order to evaluate the velocity distribution in the exit region of the diffusers a hot sphere anemometer system as a measuring technique was chosen. As in the mentioned work the literature shows that hot-wire anemometer system and hot sphere anemometer system were widely used to measure the flow distribution in ventilated environments. Thermal anemometers measure the flow velocity by sensing the heat transfer changes from an electrically heated sensing element. In the case of a high-temperature sensing head and low-velocity flow, a significant amount of free convection is generated, which creates measurement errors. Zhang [2] evaluated this error for flow velocity less than 0.25 m/s and determined that the uncertainty is 25% of the mean velocities of the measured airflow. Therefore hot-wire techniques provide velocity measurements at a single point in space over time, in this case, the flow's fluctuations are completely missed and only the velocity magnitude is measured, but thermal sensors are still widely adopted (Han and Li [3]). The flow field structure investigated using thermal sensor are often integrated with flow visualizations techniques (Carpenter et al [4], Nielsen [5], Timmons [6], Murakami and Kato [7], Zhang et al. [8]) by using either smoke or soap bubbles to visualize airflow patterns, are also suitable to characterize the flow but only in a qualitative way. A more sophisticated alternative that allows to measurement of the flow distribution with high spatial resolution is represented by the Particle Image Velocimetry (PIV) technique as widely described by Zhao et al. [9], Angioletti et al. [10] and Cao et al. [11]. PIV has the advantage of measuring a complete velocity field at each instant in time even with low-velocity values. Unfortunately, the actual resolution of the CCD and laser density adopted in the PIV techniques, allowed the flow field measurements only in plane with a few dozen of centimetres in size, so for reconstruct a section of a real scale room several measurements need to be performed.

Also, Laser Döppler Velocimety (LDV) has been widely adopted, for example by Hurnik et al. [12] Angioletti et al. [9] for measuring the flow distribution inside ventilated environments under different mixing conditions and wall temperature distribution. Posner et al. [10] performed both PIV and LDV measurements and CFD simulations in a model room (scale 1:10), but again the considered flow rates were not suitable for a real scale room. PIV technique (Angioletti et al. [11]) was also used to perform measurements of the flow field in terms of instantaneous velocity distribution, turbulence intensity and vorticity distribution in the exit region of terminals commonly used in clean rooms. Still, an interaction between the air supply terminal and the rooms was not considered. In the present work, flow field investigations have been performed in a Test Control Room (TCR), to investigate the effect of the terminals described in [11] in a test room with real dimensions.

2. EXPERIMENTAL SET-UP

A Test Control Room (TCR), represented in a three-dimensional view in Fig. 1, with inner dimensions of 6x6x3 m. The TCR is realized by modular cave elements (with dimensions of 1x2 m and an internal cavity of 0.08 m). Inside each element, a copper pipe serpentine has been placed to ensure and control the temperature of each module utilizing water circulation inside the serpentine. The circulating, inside the serpentine, water temperature is controlled by a refrigerant/heating system. With this solution, it is possible to control the temperature of each surface of the room including the floor and ceiling, The same system have been adopted for control the inlet air temperature. In this specific work a constant and uniform temperature have been adopted for the internal walls of the TCR and for the inlet air. The overall temperature has been set at 20 °C and measured by means of K type thermocouples that ensures a measurements precision of ±0.5 °C.

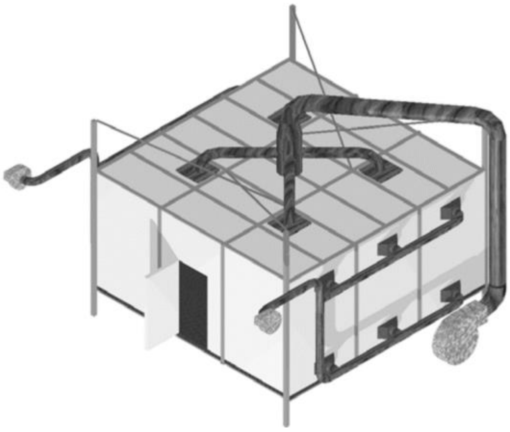

Fig -1. The Test Control Room (TCR)

The adopted ventilation system can supply flow rates up to 1.1 m^3/s (more than 37 ACH) and by employing inverters it is possible to regulate the rotation speed of the fans, and so, the supply (and exhaust) air flow rates. The investigated flow rates were 0.45 and 0.9 m^3/s corresponding respectively to 15 and 30 ACH (Air Change per Hour). The separate control on both inlet and outlet flow is suitable to obtain a positive gauge pressure inside the test room (usually 50 Pa), compared with external atmospheric pressure. Different air supply devices can be mounted in four square frames of 0.70x0.70 m. In the present work, the typology of diffuser adopted (fig. 2) was the same investigated in [11] and the typical velocity distribution obtained have been reported in fig. 3 and 4. The employed Laser Doppler Velocimetry (LDV) technique system, depicted in fig. 5 and working in backscattering, is based on a CW Argon:Ion laser, air-cooled, with a multiline maximum power of 250 mW, a TSI PDM1000-1P and a TSI FSA3500P were provided, respectively, to split and to acquire/analyze the signal, focused at the measurement point by a TSI FBL1 beam generator, linked utilizing two couplers optical fiber.

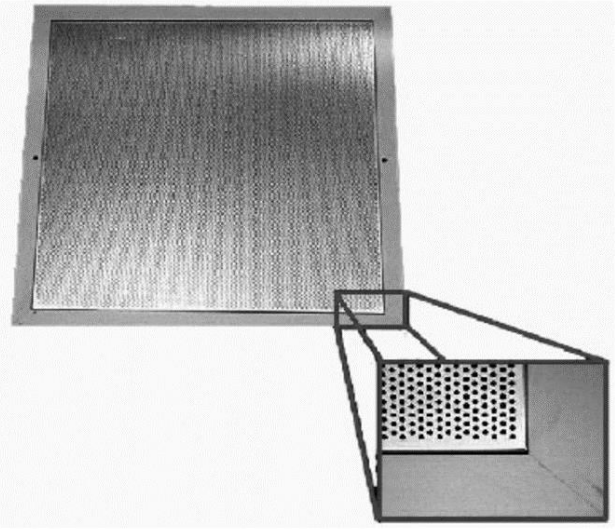

Fig -2. Whole and particular view of inlet grid

The transmitting/receiving optics were mounted on a three-axis positioning system, driven by CC-optical encoders motors and an host PC. The positioning system allows a precision in measurement point allocation of 0.5 mm. The working fluid (air) was seeded using a glycerin smoke generator to get particles with a diameter of about 0.5 μm, able to follow the flow's fluctuations. The seeding was generated directly in the TCR, saturating the inlet air then, repeating the operation when the seeding density became too low. During the LDV, measurements the seeding generator was kept off to eliminate the interferences between the flow produced by the seeding generator and the flow field induced by the ventilation flow inside the TCR.

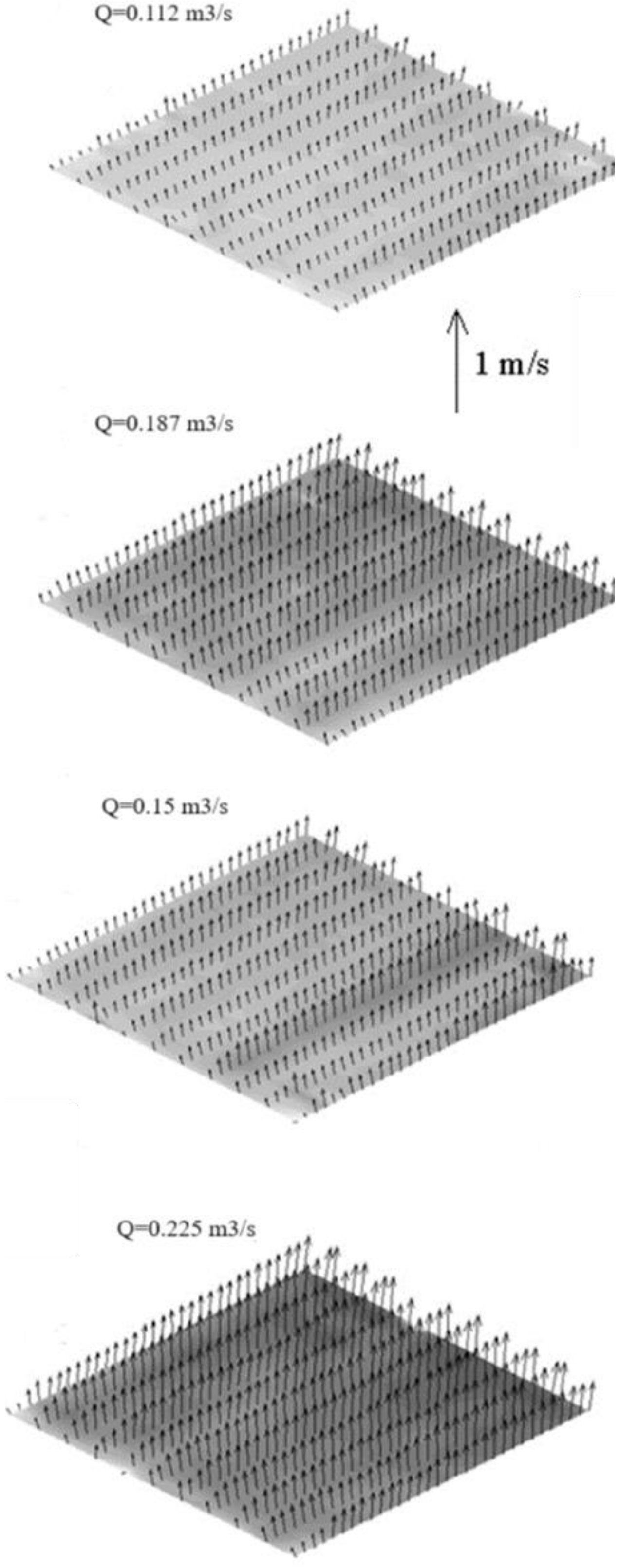

Fig -3: Velocity distribution at the inlet ventilation terminal at four flow rates as reported by [11].Name of the figure

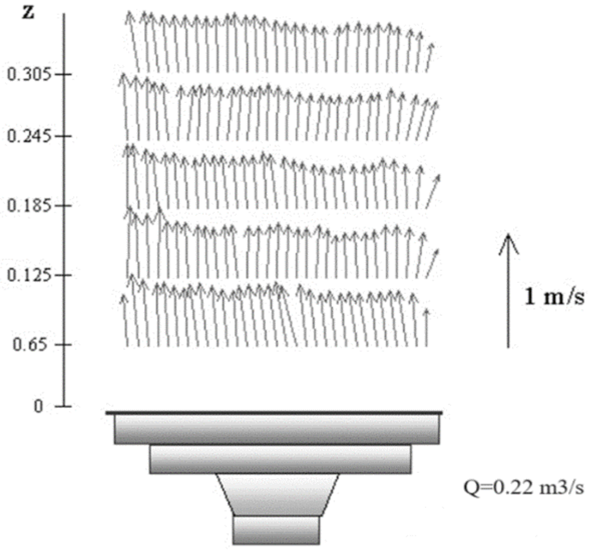

Fig -4: Velocity distributions above the inlet ventilation terminal with a flow rate of 810 m3/h as reported by [11]

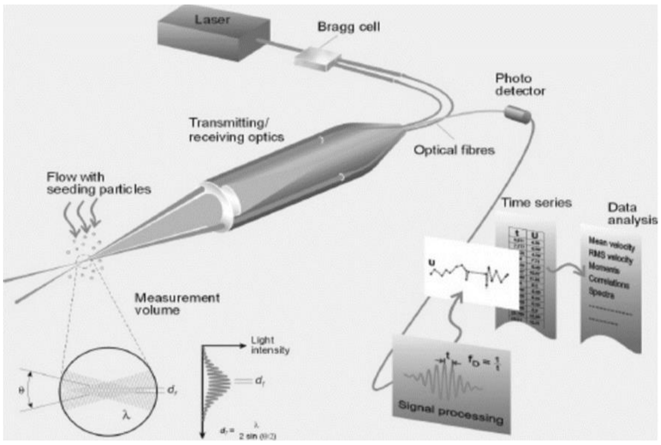

Fig -5: LDV set-up and system component

3. RESULTS AND DISCUSSION

The non-intrusive nature of optical techniques, combined with their insensitivity to fluid properties and flow conditions, make their use suitable for the study of complex flow configurations. For these properties, the LDV technique was chosen to characterize the airflow inside the test room. The set of measurements taken in this campaign was finalized to investigate specific sections of the flow to reconstruct the typical air pattern distribution. Fig. 6 depicts how measuring planes have been chosen inside the investigated volume. In detail each of those plane represents a measuring grid with 138 equispaced sampling points. All measurements were repeated for two different flow rates: 0,45 m^3/s and 0,9 m^3/s (corresponding respectively to 15 and 30 ACH) and for three velocity components. In practice, a total of 4140 velocity measurements have been performed.

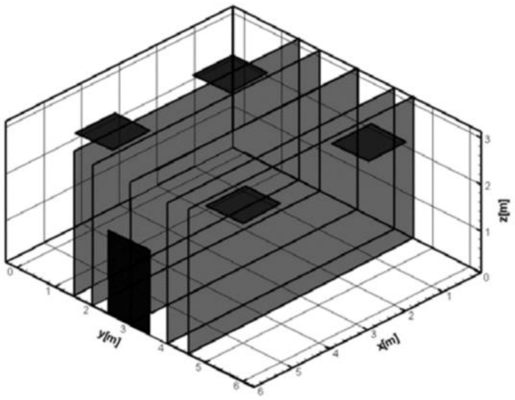

Fig -6: Measuring planes inside the TCR

The discussion on the velocity results obtained, due to the large number of data available, will be carried out with a global vision of the velocity field trend considering the flow pattern inside the room and comparing measurements at 15 ACH (Figures from 7 to 11) with those at 30 ACH (Figures from 12 to 16). Globally, it is evident how the supplied air, exiting from inlet devices mounted even with the ceiling surface and following the velocity distribution at the exit of the inlet terminal visible in Figures 3 and 4, goes almost undisturbed towards the floor. At the level of the floor the main jet impact on it then, the flow, rises in both the central axis and wall region of the room. Part of the flow travels almost directly from intake to outlet after impinging on the floor. Another part of it, keeps enough kinetic energy to be redirected again toward the ceiling and then most likely towards exhaust grids placed on the upper side of the room. The global flow pattern remains, under isothermal conditions, almost the same by changing the flow rate from 15 to 30 ACH. This has also been evaluated by means Air Change Efficiency (ACE) results obtained by using tracer gas technique. In the whole range between the two investigated flow rates, the value of ACE is not changing along with the chosen inlet flow rate and its value is constantly equal to 50%, which testifies a perfect mixing ventilation. By increasing the inlet flow rate, from 15 to 30 ACH, a sensible augmentation in the velocity magnitude distribution is appreciable as well.

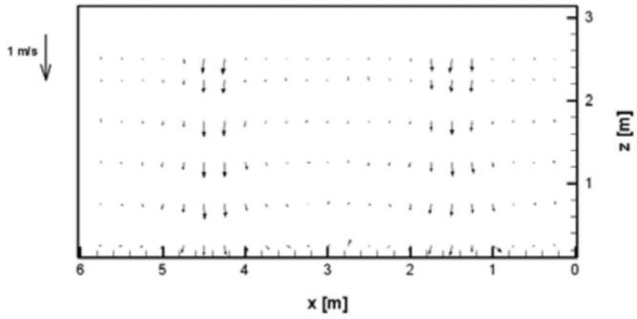

Fig -7: Velocity vectors Vxz – isothermal case –Y=1,5 m – ACH=15

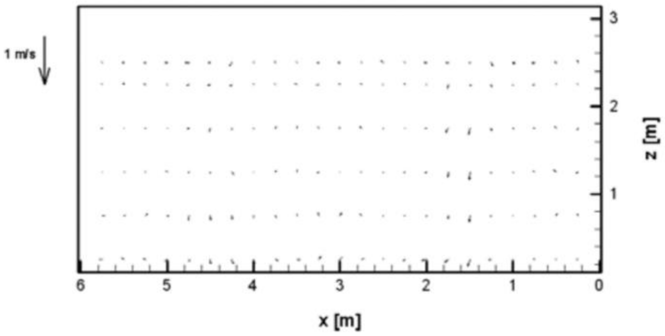

Fig -8: Velocity vectors Vxz – isothermal case –Y=2,0 m – ACH=15

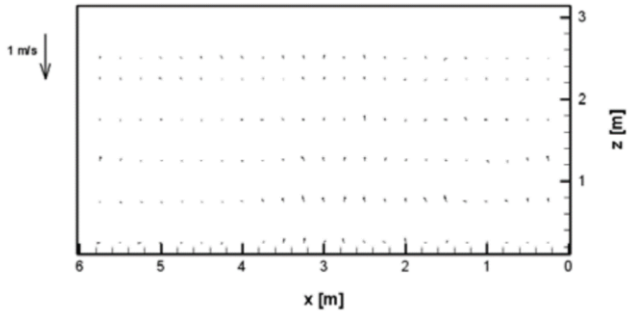

Fig -9: Velocity vectors Vxz – isothermal case –Y=3,0 m – ACH=15

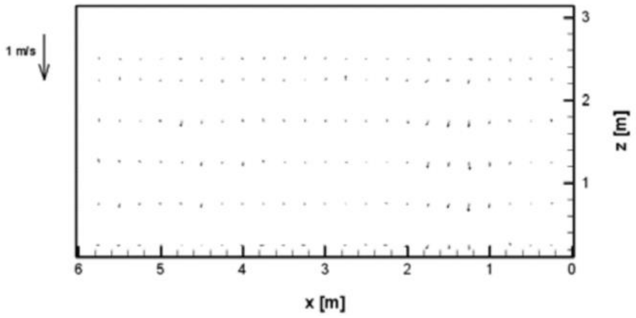

Fig -10: Velocity vectors Vxz – isothermal case –Y=4,0 m – ACH=15

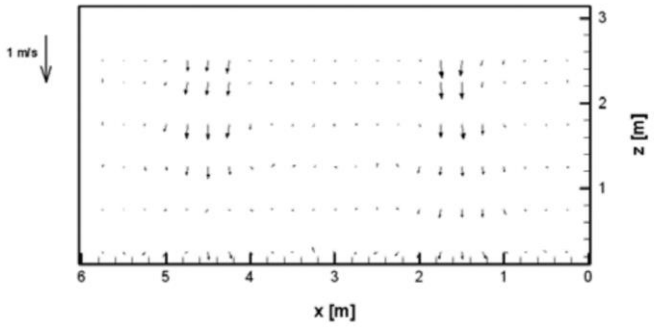

Fig -11: Velocity vectors Vxz – isothermal case –Y=4,5 m – ACH=15

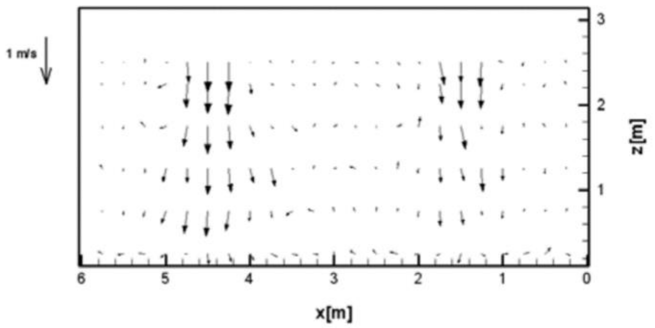

Fig -12: Velocity vectors Vxz – isothermal case –Y=1,5 m – ACH=30

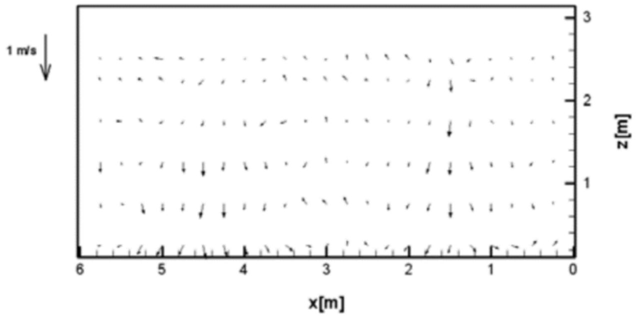

Fig -13: Velocity vectors Vxz – isothermal case –Y=2,0 m – ACH=30

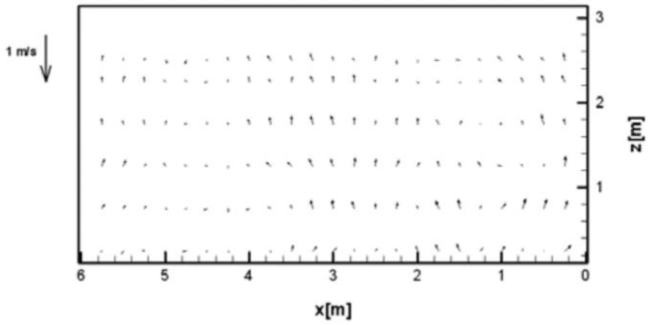

Fig -14: Velocity vectors Vxz – isothermal case –Y=3,0 m – ACH=30

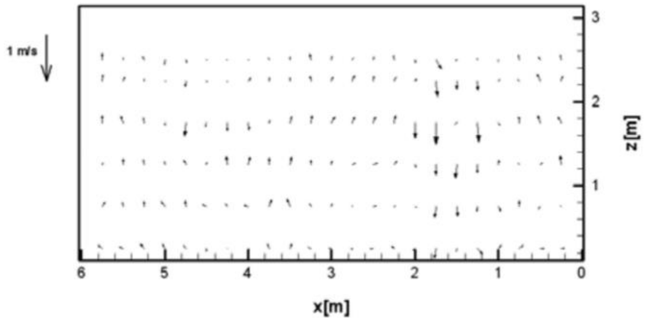

Fig -15: Velocity vectors Vxz – isothermal case –Y=4,0 m – ACH=30

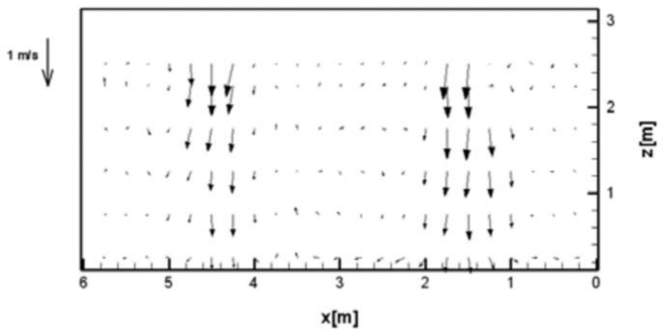

Fig -16: Velocity vectors Vxz – isothermal case –Y=4,5 m – ACH=30

3. CONCLUSIONS

A Laser Doppler Velocimetry technique has been successfully applied to evaluate flow field distribution within a ventilated Test Control Room (TCR). Measurements were performed under isothermal conditions with a supply flow rate corresponding to 15 and 30 ACH's. The paper gives a detailed analysis of the air flow pattern generated by the ventilation system at each specific air flow rate. Velocity vectors distribution has been usefully employed for this purpose. Besides the experimental analysis proposed and displayed in this paper, the set of results obtained could be used to validate CFD codes end eventually, with an integrated experimental-analytical approach, to simulate the whole flow field distribution within specific ventilated enclosures like clean rooms or operating theatres. A natural prosecution of the present work could be a more extensive and complete analysis of the aerodynamic distribution in the entire ventilated environment, or in characteristic parts of it, under specific thermal boundary conditions (i.e. a wall warmer or colder than the others) obtainable with the facilities presented.

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