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Air velocity and turbulence distribution in a slot-ventilated room

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Abstract
Air velocity and turbulence intensity are very important features of draught comfort in rooms. There are several slot-ventilated spaces like classrooms, offices, etc. Several researchers have investigated room airflow characteristics in ventilated spaces - also in slot-ventilated rooms. However, most of the investigations had not considered the effect of some important inlet parameters on room's draught comfort. These inlet parameters are slot Reynolds-number (Re_0), air diffuser's aspect ratio (AR), and diffuser's offset ratio (OR).
In this paper a slot-ventilated room is investigated on a full-scale model applying measurement investigation method. The three most important inlet parameters were changed during the measurements: Re_0, AR and OR. Air velocity and temperature were measured and then the turbulence intensity of the airflow was calculated because these quantities effect draught comfort in rooms. The investigations were conducted in isothermal and steady-state conditions using omni-directional probes. The measurement points were fixed at relevant areas of the occupied zone in four heights: ankle level, knee level and head level of sitting and standing person. The measured data were evaluated with statistical methods and tests, including measurement uncertainty calculation. Draught Rate (DR) number which describes the draught comfort was also investigated in the room. Results can help designing draught comfort in slot-ventilated spaces.

Keywords - air velocity; turbulence intensity; slot-ventilated room; draught comfort

1. Introduction and theoretical background

People spend most of their life in closed spaces so it is important to provide acceptable air microclimate parameters. Air velocity, turbulence intensity and air temperature – like the most important microclimate parameters – effect the draught comfort in rooms [1]. There are several types of ventilated rooms in various buildings. One of the most widely used is the slot-ventilated type room e.g. offices, classrooms, hotel rooms, etc. In these ventilated spaces the most common air diffuser is a simple slot which is usually located next to a wall surface as shown in Fig. 1. The main advantage of such slot diffuser placement is that supply air is injected outside of the occupied zone of the room. As a result, draught risk can be decreased in the space [2], [3].

On Fig. 1 it can be seen that supply air flows out from the slot diffuser and a negatively pressurized recirculation zone appears between the supplied air jet and the wall. Then the Coanda-effect appears and the injected air jet bends towards the wall and adheres to the surface at the attachment point. After this, the injected air jet flows along the wall surface and then ventilates the room. The vertical distance between air inlet and the attachment point is the attachment distance (y_a) which can influence room airflow [4], [5]. It should be mentioned that in many cases, the throw of slot is horizontal and not vertical, however, the vertical air inlet is often used in cellular offices.

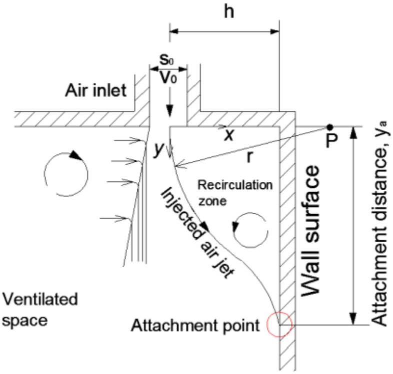

Fig. 1 Sketch of the injected air jet into the room

Fig. 2 shows a simple sketch of a slot ventilated room.

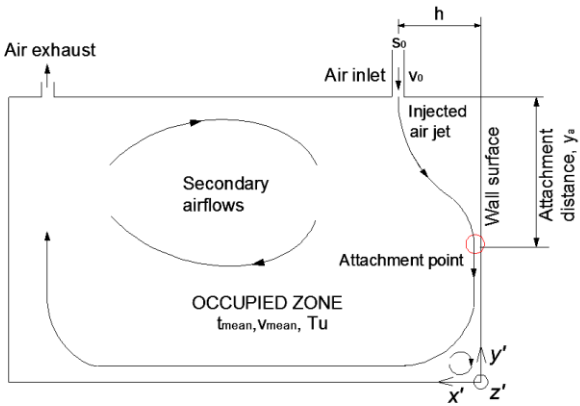

Fig. 2 Sketch of the slot-ventilated room

Nominal length of the slot air diffuser is L_0 (perpendicular to plane x-y) and the nominal width is s_0. Aspect ratio (AR) of the diffuser can be defined as:

$$AR = L_0/s_0, \text{ m/m.} \quad (1)$$

The horizontal distance between the slot diffuser and the wall surface is h, so the offset ratio (OR) of the diffuser is:

$$OR = h/s_0, \text{ m/m.} \quad (2)$$

Finally inlet (or slot) Reynolds-number can be calculated using air velocity magnitude (v_0), slot width (s_0) and the kinematic viscosity of the air ($\nu_0 = 1.5*10^{-5}$ m^2/s on 20 °C) at inlet:

$$Re_0 = (v_0*s_0)/\nu_0. \quad (3)$$

Re_0 is more scientific, than v_0 at air inlet, because Re_0 contains inlet air temperature and viscosity. The previously defined AR, OR and Re_0 are the most important inlet parameters of room air distribution design. These parameters effect air velocity and temperature distribution in ventilated rooms. Air velocity is a time-dependent quantity which has an average (v_{mean}) and a fluctuating value (v_{RMS}, where RMS stands for Root Mean Square) around the average. Using the average and RMS velocity components, turbulence intensity of the airflow can be calculated [6]:

$$Tu = (v_{RMS}/v_{mean})*100 \text{ \%.} \quad (4)$$

Average air velocity, turbulence intensity and temperature (t_{mean}) are the main features of draught comfort in rooms. The most common and internationally accepted model to predict draught comfort in rooms is Fanger's draught model – or DR model. This model is based on a calculated DR (Draught Rate) number, which is a semi-empirical formula and features draught comfort in the room [6].

$$DR = (34-t_{mean})*(v_{mean}-0.05)^{0.62}*(0.37*Tu*v_{mean}+3.17), \text{ \%.} \quad (5)$$

According to standard CR 1752:2000 [s1] the occupied zone of the ventilated room can be categorized from the aspect of draught comfort. Category A is the best (DR ≤ 15 %) and it is followed by category B (15 < DR ≤ 20 %) and finally category C (20 < DR ≤ 25 %).

Considering the previous statements, it is important to predict air velocity, turbulence intensity and DR in the room to describe draught comfort. In the room space, Ar-number of the jet is a key parameter [18], however, Ar-number is not investigated in the current paper. Several researchers have investigated draught comfort in the past decades. The most accepted and well-known researches for draught comfort in closed spaces come from Fanger et al [1], [6], [7]. They have investigated the main parameters of draught comfort like air velocity, turbulence intensity and air temperature. The investigation were based on experimental methods including measurements in rooms. The exact type of the room – especially the slot-ventilated room – was not considered in these researches. T. Magyar, R. Goda et al. [2], [3], [8], [9], [10] took experimental and numerical investigations on slot-ventilated rooms to describe draught comfort. Cao

[11], Rohdin and Moshfegh [12] used experimental method and numerical simulation to model room airflow. Moureh and Flick [13], [14] also took experimental and numerical researches in slot-ventilated rooms. All of the previously introduced authors investigated room airflow in the occupied zone of the ventilated space. In most of these investigations inlet Reynolds-number was the changing parameter.

Some researchers like Nozaki et al. [4], [15], Nasr and Lai [5], Rathore and Das [16] only investigated injected air jets and their attachment process near the air inlet and did not consider the airflow inside the room. In these researches inlet aspect ratio, offset ratio and Reynolds-number were the changing parameters.

Based on recent literature review it is obvious that:

- most of the researchers investigated air inlet and room airflow separately and did not consider the effect of inlet parameters on room airflow and draught comfort;
- inlet Reynolds-number in previous investigations was mostly out of range of comfort HVAC (Heating, Ventilation, Air Conditioning) systems.

2. Investigation aims

The primary aim of the current investigation is to predict the effect of inlet parameters (OR, AR, Re_0) on a slot-ventilated room's draught comfort. In order to achieve this primary aim it is needed to investigate the maximum values of air velocity and turbulence intensity in the room. These turbulent parameters play important role in designing indoor air comfort and room air distribution. DR number can be calculated by measuring air temperature and qualification of the room's draught comfort can be made according to standard CR 1752:2000 [s1].

Each problem in engineering sciences can be solved in three ways: with analytical, experimental and numerical methods. Based on the literature review the analytical solution method is too complicated and requires too much time because of the 3D feature of room airflow. In this article the experimental method was chosen.

3. Experimental method

Air velocity and temperature measurements were taken in a full-scale test room (office-model) in the Ventilation Laboratory of Budapest University of Technology and Economics. The model room was located as a house in house way and thermally insulated against external heat gains. Average air velocity was measured in the air inlet with a hot-wire anemometer and then, inlet Reynolds-number was calculated using equation (3). All of the measurements were done according to relevant standards [s2], [s3], [s4] [s5].

The measurements were took in four relevant heights in the occupied zone of the room according to standard EN ISO 7726 [s4]: ankle level (0.1 m from floor), knee level (0.6 m from floor) and head level of sitting (1.1 m from floor) and standing persons (1.7 m from floor). In each level 29 measurements points were used so the sum of measurement points is 116. Air velocity and temperature were measured by omni-directional hot sphere probes. The sampling frequency of each probe was 3 Hz and the applied sampling time was 200 seconds according to the relevant standards [s4], [s5]. Using the measured data turbulence intensity and DR number could be calculated with equations (4) and (5). Basic area of the test room was 3*3 m and the nominal height was 2.8 m. Main direction of the air injection and exhaust was vertical. Nominal length of the applied slot-diffuser was L_0 = 1000 mm and the width was s_0 = 12 mm.

Main boundary conditions for the measurements were:

- Isothermal air injection;
- Steady-state condition;
- Applied slot-Reynolds-number range was $Re_0 = 1600 \div 3500$;
- Applied aspect ratio range was $AR = 50 \div 85$;
- Applied offset ratio range was $OR = 5 \div 30$.

Measured data were evaluated using mathematical statistical methods [17].

4. Results and discussion

4. 1. Effect of slot-diffuser' aspect ratio (AR)

The maximum value of mean air velocity is an important parameter in designing practice because this peak effects draught comfort. As a result, effect of slot diffusers' aspect ratio (AR) on mean velocity maximum can be seen on Fig. 3. Each measured mean velocity value was averaged at the four measurement heights, then these averaged velocities were investigated as a function of AR. Volume flow rate of supply air to the room was constant during the investigation of ARs' effect. Only the slot diffusers' length was changed, then AR was calculated using equation (1). Inlet Reynolds-number was increased by decreasing the slots' length and AR, according to the continuity equation. Offset ratio of the diffusers was constant.

According to the Abbe-test, the mean velocity maximum values depend on AR significantly at probability level 95 %. On ankle and standing person's head levels the maximum velocity values are decreasing linearly as AR is increasing. Due to the general regression-test the correlation square of the fitted linear lines are above 0.90 which means an acceptable regression fit [17]. At knee level and sitting persons' head levels the maximum velocity values are decreasing in a quadratic way as AR is increasing with also above 0.90 correlation square.

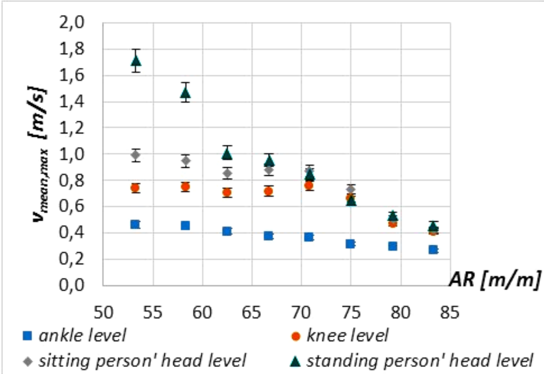

Fig. 3 Effect of AR on mean velocity maximum

Turbulence intensity was found to be independent from slot diffusers' AR at probability level 95 % in the investigated range of AR at the four heights. Turbulence intensity intervals at the four levels are in Table 1. Lowest turbulence intensities are at ankle level according to the airflow characteristic of slot-ventilated rooms. Due to Fig. 2 primary air flows on the floor while in the middle of the room are secondary airflows, induced by the primary airflow. Thus there are higher turbulence intensities above knee level.

Table 1. Average turbulence intensity intervals, AR = 50÷85

Ankle level	Knee level	Head level of sitting person	Head level of standing person
28÷31 %	38÷41 %	37÷40 %	32÷38 %

Note that the average turbulence intensity for designing draught comfort is Tu = 40 % in mixing room ventilation suggested by [s6]. However this suggested average turbulence intensity value is general and do not consider the slot-ventilated room's characteristics.

Similarly to the average turbulence intensity the DR (Draught Rate) number was also found to be independent from the slot diffusers' AR at probability level 95 % based on statistical analysis (Abbe-test, general regression test). The average values of DR goes from 13 to 19 % at the four levels which means acceptable category A and B from the aspect of draught comfort according to standard CR 1752:2000 [s1].

4. 2. Effect of slot-diffuser's offset ratio (OR)

Offset ratio of the slot diffuser was calculated using equation (2) by changing the diffuser's horizontal distance (h) from the wall. Based on the Abbe-test mean velocity maximum values were found to be independent from OR at ankle level at p = 95 % as it can be seen on Fig. 4. Slot

Reynolds-number and air diffuser's aspect ratio were constant during the investigation of OR's effect.

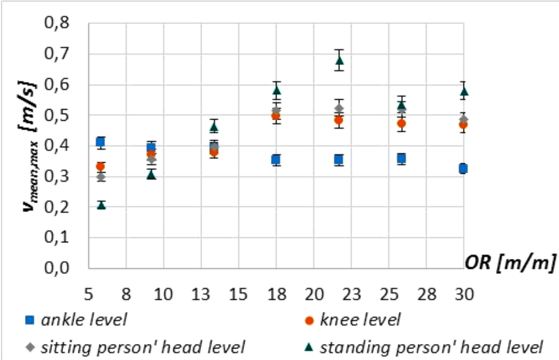

Fig. 4 Effect of OR on mean velocity maximum

At knee, sitting persons' and standing persons' head levels mean velocity maximums are increasing in a quadratic way with over correlation square 0.90. The quadratic change becomes slower at OR=18 and the mean velocity maximum is almost constant between OR=18 and 30. Average air velocity is high in all cases, however, these are maximum values in the vertical air distribution as shown on Fig. 1.

Average turbulence intensity is constant at ankle level at p=95 % (Tu = 27 %). At the other levels the turbulence intensity is increasing as OR becomes higher. Main reason for this increase is that there are bigger recirculation zones between the wall and the injected air jet if the slot diffuser is further away from the wall (OR is higher). It is a well-known fact that in bigger recirculation zones turbulence intensity is also higher [1], [5], [6]. Turbulence intensity intervals at the four levels are in Table 2. This average turbulence intensity range is almost the same when OR and AR is changing.

Table 2. Average turbulence intensity intervals, OR = 5÷30

Ankle level	Knee level	Head level of sitting person	Head level of standing person
27 % constant	33÷41 %	34÷41 %	34÷37 %

Lowest turbulence intensities are at ankle level according to the airflow characteristic of slot-ventilated rooms, however, there are higher turbulence intensities above knee level.

The DR number is significantly increasing as OR is higher due to the bigger recirculation zone and the higher turbulence intensities in this zone. The average DR number for all levels goes from 9 to 17 % which means acceptable draught comfort category A and B according to CR 1752:2000 [s1].

4. 3. Effect of slot Reynolds number (Re_0)

Slot Reynolds-number was calculated using equation (3). Maximum values of mean air velocity as a function of slot Reynolds-number is plotted on Fig. 5. Air diffusers' aspect ratio and offset ratio were constant during the investigation of Re_0's effect.

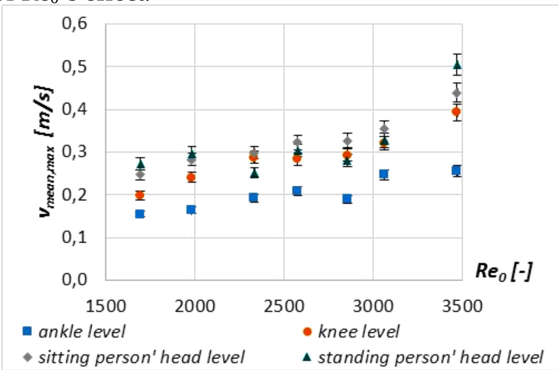

Fig. 5 Effect of Re_0 on mean velocity maximum

It is obvious that maximum values of mean air velocity are increasing linearly as the slot Reynolds-number becomes higher at all levels. Based on the general regression test correlation square of the fitted curves are above 0.90. This increasing tendency is slow in the transitional flow zone below $Re_{0,crit}$ = 2300. Air velocity maximum values are increasing faster above $Re_{0,crit}$ = 2300 in the turbulent zone. Note that in designing practice of slot-ventilated rooms the inlet air velocity is often between 1 and 5 m/s. Consequently the slot Reynolds-number is sometimes in the transitional zone – which also depends on the main size of the slot.

Average values of turbulence intensities were found to be independent from slot Reynolds-number in the investigated range of Re_0. Turbulence intensity intervals at the four heights are in Table 3.

Table 3. Average turbulence intensity intervals, Re_0 = 1600÷3500

Ankle level	Knee level	Head level of sitting person	Head level of standing person
22÷26 %	30÷39 %	34÷44 %	32÷42 %

Lowest turbulence intensities are at ankle level according to the airflow characteristic of slot-ventilated rooms however there are higher turbulence intensities above knee level.

5. Summary

In this article a slot-ventilated office full-scale model room was investigated by applying measurement method. Mean air velocity and mean air temperature were measured in the occupied zone of the room at four relevant heights: ankle, knee and head levels (seated, standing). Turbulence intensity of the airflow was calculated using the measured air velocities. Measured data was evaluated using statistical methods. Three main designing inlet parameters' effect were investigated on room's draught comfort: slot diffusers' aspect ratio (AR), offset ratio (OR) and slot Reynolds-number (Re_0).

Results showed that diffusers' aspect ratio has a significant effect on mean velocity maximum values. At ankle and standing person's head levels the maximum velocity values are decreasing linearly with an increasing AR. At knee height and sitting person's head levels the maximum velocity values are decreasing in a quadratic way as AR is increasing. In this case volume flow rate of the airflow was constant. Turbulence intensity was found to be independent from slot diffusers' AR at probability level 95 % in the investigated range of AR at each level.

Mean velocity maximum values were found to be independent from OR at ankle level at p = 95 %. At knee, sitting person's and standing person's head levels, mean velocity maximums are increasing in a quadratic way as a function of OR. Average turbulence intensity is constant at ankle level at p=95 % (Tu = 27 %). At other heights the turbulence intensity is increasing as OR is higher.

Maximum values of mean air velocity are increasing linearly as the slot Reynolds-number is higher at all levels. Average values of turbulence intensities were found to be independent from slot Reynolds-number in the investigated range of Re_0.

Lowest turbulence intensities are at ankle level according to the airflow characteristic of slot-ventilated rooms. Average turbulence intensity range was almost the same at each level for the three cases: when AR, OR and Re_0 are changing (see Table 1, 2 and 3).

The DR (Draught Rate) number that describes draught comfort in rooms is acceptable in each case and results in draught comfort category A and B.

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Standards

[s1] CR 1752:2000. Ventilation for buildings. Design criteria for the indoor environment.
[s2] EN ISO 5167-1:2003. Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full -Part 1: General principles and requirements.
[s3] EN 24006:2002. Measurement of fluid flow in closed conduits.
[s4] EN ISO 7726. Ergonomics of the thermal environment - Instruments for measuring physical quantities.
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