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Turbulence intensity and air velocity characteristics in a slot ventilated space

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RESEARCH ARTICLE

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Abstract

The determination of turbulence intensity and air velocity distribution in the ventilated spaces is very important from the point of view of discomfort caused by draught. In most cases, in slot ventilated spaces tangential air distribution system is applied. There are several references investigating the discomfort caused by draught in ventilated spaces. However, most of these studies do not consider the exact type of the air distribution system. Another relevant question is how average 40 [%] turbulence intensity given in standard EN 13779 for designing depends on the tangential air distribution.

In this paper the turbulence intensity and air velocity distribution were experimentally investigated in case of applying tangential air distribution system. Results showed that turbulence intensity and air velocity distribution depend on the air distribution system. Furthermore, average 40 [%] turbulence intensity given in the standard is not always relevant.

Keywords

turbulence intensity · air velocity · draught · tangential air distribution · slot ventilated

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1 Introduction and theoretical background

As we know, primary air introduced to the ventilated space makes indoor air move in a sensible and characteristic way. As a result, the primary airflow induces secondary flows in the ventilated space. These primary- and secondary flows make an air distribution system (ADS) [16]. In HVAC practice tangential air distribution systems using slot diffuser(s) are frequently used not only in comfort places but also in industrial spaces [17]. At this ADS supply air is usually injected at the edge of the occupied zone, generally along the wall, window, and floor or ceiling surface. This tangential air introduction makes higher air velocity injection possible into the ventilated spaces under 3 [m] height, so there may be draught [16].

Draught can be defined as a local discomfort factor, which can cause local overcooling of human body or zones of human body by airflow. This problem can be seen in residential buildings, on vehicles (e.g. cars, trains, airplanes, and so on). Consequently, draught is well known as one of the most disturbing discomfort factors in ventilated spaces. As a result, people usually require higher indoor air temperature, so the percentage of people dissatisfied with draft decreases, but the building's energy consumption (and also operation costs) increase [1,2,3].

In the previous studies, local comfort was associated with thermal comfort [4,2]. The earliest study about draught comfort was written by Houghten et al. in 1938, in which draught comfort was investigated with the help of subjects in case of nearly laminar airflow [5,6]. They found that the higher the air temperature in the occupied zone, the less the percentage of the dissatisfied. Later, Fanger et al. found that it is necessary to have low draught rate values in order to achieve pleasant comfort in the ventilated space [2,3]. Consequently, a mathematical model was created in order to calculate the percentage of thedissatisfied with the draft. At the beginning, this model was a function of average air velocity ($\overline{v}$) and temperature ($\overline{t}$) [2]. Besides, later they have discovered that velocity fluctuation (v_{RMS}) also can influence draught comfort [7].

$$\mathrm{DR}\left(Draught\ Rate\right) = \left(34 - \bar{t}\right) \cdot \left(\bar{v} - 0.05\right)^{0.62} \cdot \left(0.37 \cdot Tu \cdot \bar{v} + 3.14\right)\left[\%\right]$$

It should be considered that boundary conditions for these formula are:
$20 < \bar{t}$ [°C] < 26; $0{,}05 < \bar{v}$ [m/s] $< 0{,}5$ and $0 <$ Tu [%] < 70.

The ratio between average air velocity and velocity fluctuation is called as turbulence intensity [3,7].

$$\mathrm{Tu} = v_{RMS} / \bar{v} \cdot 100\left[\%\right]$$

As it is known, velocity as a function of time can be written as the sum of the average air velocity and velocity fluctuation, which depends on time [18]:

$$v\left(\tau\right) = \bar{v} + v_{RMS}$$

The average air velocity is written:

$$\bar{v} = 1/T \cdot \int_0^T v\left(\tau\right) \cdot d\tau \left[\frac{m}{s}\right]$$

The velocity fluctuation is:

$$v_{RMS} = \sqrt{1/T \cdot \int_0^T \left(v - \bar{v}\right)^2 \cdot d\tau} \left[\frac{m}{s}\right]$$

The calculation of draught rate is very important from the point of view of designing ventilation systems; therefore the calculation of DR and turbulence intensity appears in recommendation [CR 1752] and standards [ISO 7726], [EN 13779]. According to CR 1752 there are three designing category for occupied zones considering draught comfort. The most adequate is category “A” with DR = 15 [%], it is followed by category “B” with 20 [%] draught rate and finally category “C” with DR = 25 [%], which is the most unfavorable class.

Standards for ventilation systems offer only recommended turbulence intensity values considering the necessary category to calculate draught rate; but the effect of the applied air distribution system is not considered. Based on this, in case of applying mixing ventilation this recommended turbulence intensity value is 40 [%], while in case of applying displacement air distribution it is only 20 [%].

Studies investigating draught comfort include experiments in offices, residential buildings, schools [8,9,10]; further investigations were conducted in laboratories [3–6], numerical simulations [11,12] and application of thermal manikin [13,14]. T. Magyar and R. Goda also made a mathematical model of a tangential air distribution system, in which they give methods to investigate it [15]. In these studies, average air velocity, velocity fluctuations, air temperature and turbulence intensity were measured. Based on these studies we could find that the turbulence intensity distribution in the ventilated space has not been investigated in case of applying tangential air distribution system.

2 General aims and investigation method

All of the investigations were conducted in case of applying *vertical air inlet, isothermal condition and stationary state*. Based on the above mentioned previous results, our general aims and investigation methods are the followings:

1) Average air velocity, velocity fluctuation, temperature and turbulence intensity measurements in the occupied zone of a test room in the Ventilation Laboratory of BUTE.
2) Investigation of draught comfort in the occupied zone of the test room by determining velocity- and DR distributions.
3) Investigation of the effect of tangential air distribution on velocity- and DR distributions.
4) Determining the differences between average 40 [%] turbulence intensity given in the standard and measured average turbulence intensities.

3 Experimental methods

The measurement investigations were conducted in a test room in the Ventilation Laboratory of BUTE. Basic area of the test room is 3x3 [m] and the interior height is 3 [m]. The supply air was circulated by a CRAC (*C*omputer *R*oom *A*ir *C*onditioning). In the ventilation system an air-filter was used in order to filter the supply air. The airflow rate to the room was measured and controlled by a flow control valve by measuring the measured pressure difference at the orifice plate (Δp) in Pascal. The airflow rate can be calculated by using the measured pressure difference at the orifice plate and position (K) of the flow control valve [19]:

$$\dot{\mathrm{V}}_0 = 3.6 \cdot \mathrm{K}\sqrt{\Delta \mathrm{p}} \left[\frac{\mathrm{m}^3}{\mathrm{h}}\right]$$

Air velocity, temperature and turbulence intensity measurements were carried out according to standards EN ISO 5167-1:2003, EN 24006:2002 and ISO 7726. These quantities in the occupied zone were measured by using an omni-directional hot sphere anemometer.

In the occupied zone the measurements were conducted at four relevant heights in accordance with standard ISO 7726. These are the followings: y = 0.1; 0.6; 1.1 and 1.7 [m]. In these measurement heights 116 points were took up at each series of measurement. Altogether seven series of measurements were taken up. The applied range of airflow rate to the room (V_0) went from 60 to 140 [m³/h].

The position of the measurement points can be seen in Fig. 1 seen from above, while Fig. 2 contains these points from front-view.

4 Results and discussion

4.1 Air velocity distribution

The distribution of the velocity fluctuation in the occupied zone is a very important thing from the point of view of

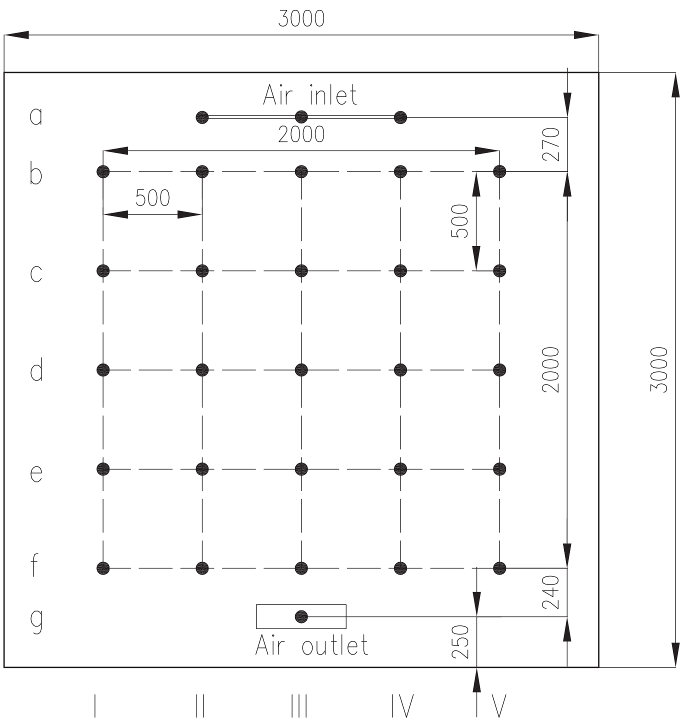

Fig. 1. Position of the measurement points seen from above

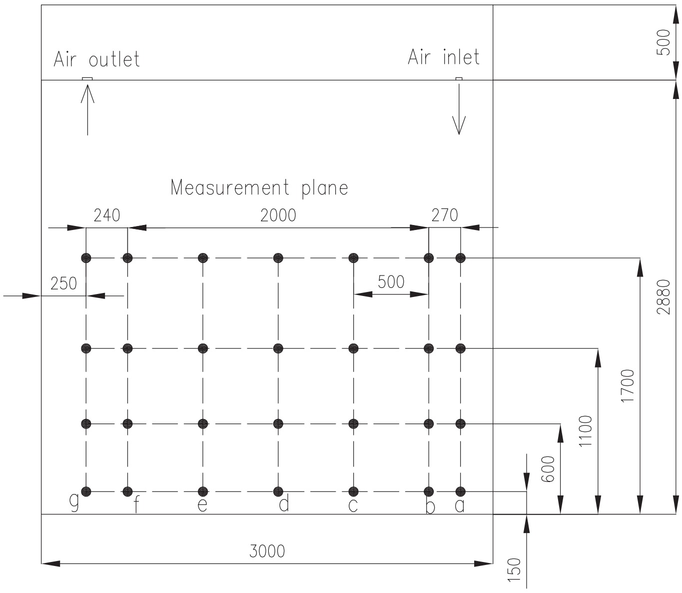

Fig. 2. Position of the measurement points seen from front-view

draught [3]. Fig. 3 shows this distribution near the floor, at y = 0.1 [m] height. It can be seen that at this height the velocity fluctuation distribution is almost constant, however, under the air inlet (position "a") this fluctuation is higher than in the middle of the room. This tendency can be seen next to the wall (see position "d" at measurement plane "I").

Moving away from the floor, there will be a significant difference between velocity fluctuations under the air inlet (position "a") and in the occupied zone (position "b-f"), see Fig. 4. Under the air outlet (position "g") the amount of the fluctuating air velocity starts to decrease due to the presence of the wall.

Similar tendency can be observed at y = 1.1 and y = 1.7 [m].

This tendency can be observed at each series of measurement. Naturally, the higher the amount of airflow rate to the room, the bigger the magnitude of the fluctuating air velocity, but the tendency of changing is the same.

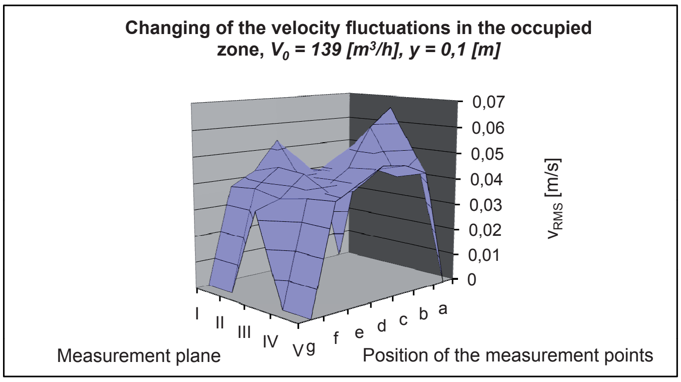

Fig. 3. Velocity fluctuation distribution at y = 0.1 [m]

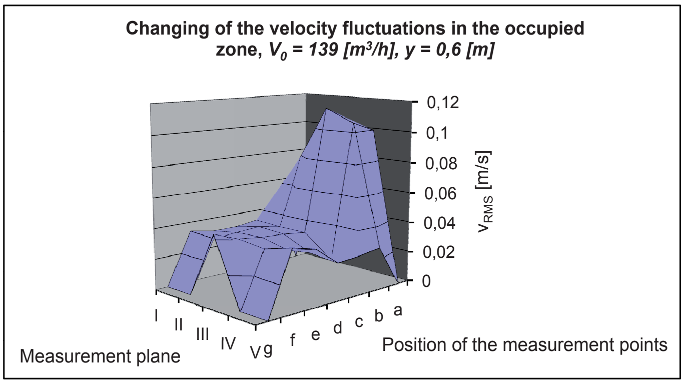

Fig. 4. Velocity fluctuation distribution at y = 0.6 [m]

4.2 DR distribution in the occupied zone

Based on our measurement data, the DR can be calculated at each point in the occupied zone of the investigated test room. It is very important to consider the boundary conditions of the DR formula (see the "Introduction"). At that point, where the measured values are outside this allowable range, the DR cannot be calculated. In Fig. 7-10 the DR distribution can be seen in the whole occupied zone at the relevant heights. At each height the amount of DR is higher under the air inlet (see position "a"), than in the occupied zone. Near the floor (at y = 0.1 [m]) the DR distribution is not constant, in contrast with fluctuating air velocity distribution at the same height. There is a difference between DR values calculated under the air inlet and in the middle of the room. Moving away from the floor (increasing the y height), this different becomes more significantly. The DR value is much higher under the air inlet than in other places in the test room. Moving closer to the air inlet the value of DR is higher. This tendency is also can be seen at each series of measurement.

4.3 Turbulence intensity distribution in the occupied zone

Based on our turbulence intensity results, Fig. 11 shows the turbulence intensity distribution (frequency) at the whole occupied zone on a constant airflow rate. This diagram was made at every series of measurements and results were summarized in Table 1. The most frequent turbulence intensities in the occupied zone are between 25 and 55 [%]. The biggest difference from the 40 [%] turbulence intensity given in standard is ± 15 [%]. The least difference is 0…+5 [%] at 100 [m^3/h].

Table 2 shows the number of measured turbulence intensities. It is clear, that there are more turbulence intensities that are less, than 40 [%], but some turbulence values are higher than 40 [%].

4.4 Measurement error calculation

As far as we know, every measured physical value consists of a so-called measurement error, which may come from the error of the applied measurement method, faulty reading of the measured value, and so on. If a calculated quantity consists of two or more measured values, it is necessary to consider and calculate the absolute measurement error expansions by the following formula:

$$E = \sqrt{\sum_{i=1}^{N} \left(\delta X_i \cdot \frac{\partial C}{\partial X_i} \right)^2}$$

where E is the absolute measurement error, δX_i is the measurement error of the measured quantity i and finally C is the calculated value.

In this case the airflow rate to the room was calculated by two measured quantities: one of them is the measured pressure difference at the orifice plate (Δp), while the other is the position of the flow control valve (K). In the previous formula:

$X_1 = \Delta p$ [Pa], $X_2 = K$ [-].

$$E = \sqrt{\left(\delta \Delta p \cdot \frac{\partial \dot{V}_0}{\partial \Delta p} \right)^2 + \left(\delta K \cdot \frac{\partial \dot{V}_0}{\partial K} \right)^2}$$

The partial derivatives are the followings:

$$\frac{\partial \dot{V}_0}{\partial \Delta p} = 1.8 \cdot \frac{K}{\sqrt{\Delta p}}$$

$$\frac{\partial \dot{V}_0}{\partial K} = 3.6 \cdot \sqrt{\Delta p}$$

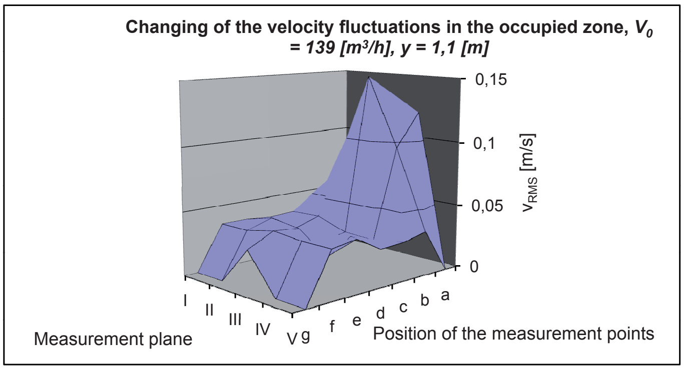

Fig. 5. Velocity fluctuation distribution at y = 1.1 [m]

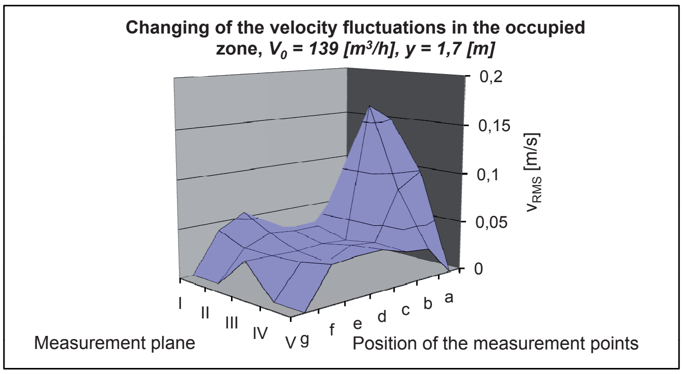

Fig. 6. Velocity fluctuation distribution at y = 1.7 [m]

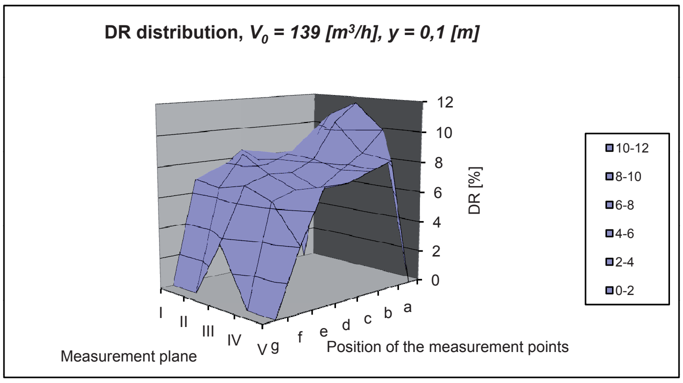

Fig. 7. DR distribution at y = 0.1 [m]

Based on the above:

$$E = \sqrt{\left(\delta \Delta p \cdot 1.8 \cdot \frac{K}{\sqrt{\Delta p}} \right)^2 + \left(\delta K \cdot 3.6 \cdot \sqrt{\Delta p} \right)^2}$$

The measurement errors of the above quantities are given by the manufacturer of the measurement device and flow control valve. These are the followings:

δΔp = 1 [Pa], δK = 0,1 division

These calculated absolute measurement values for the airflow rate are summarized in Table 3.

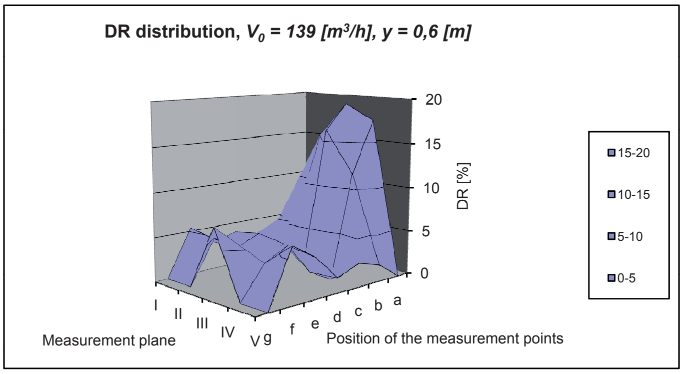

Fig. 8. DR distribution at y = 0.6 [m]

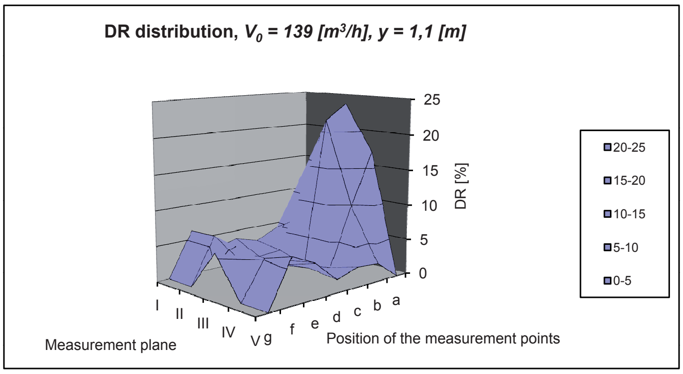

Fig. 9. DR distribution at y = 1.1 [m]

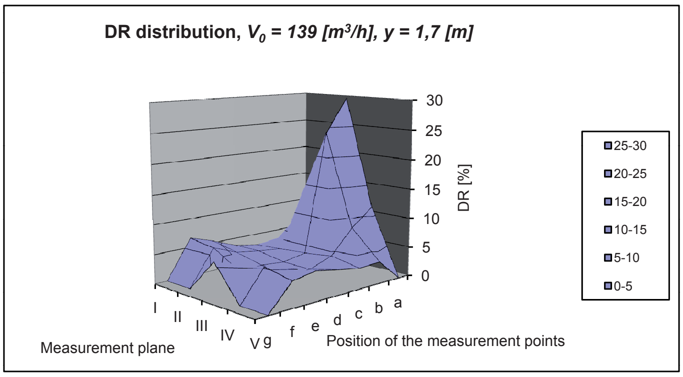

Fig. 10. DR distribution at y = 1.7 [m]

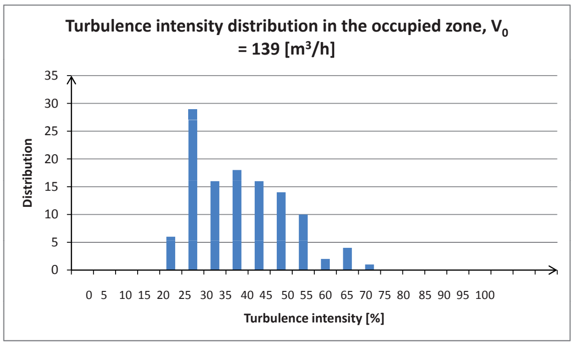

Fig. 11. Turbulence intensity distribution

Tab. 1.

Number of series of measurements	V_0 [m³/h]	Most frequented turbulence intensities in the occupied zone [%]	Difference from the 40 [%] turbulence intensity given in standard
1	139	25…30	-10…-15
2	124	25…30	-10…-15
3	110	50…55	+10…+15
4	100	40…45	0…+5
5	91	25…30	-10…-15
6	79	30…35	-5…-10
7	66	25…30	-10…-15

Tab. 2.

Number of series of measure-ments	V_0 [m³/h]	Number of Tu ≤ 40 [%]	Number of Tu> 40 [%]	Percentage values of turbulence intensities are LESS OR EQUAL to than 40 [%]	Percentage values of turbulence intensities are HIGHER than 40 [%]
1	139	85	31	73	27
2	124	92	24	79	21
3	110	67	49	58	42
4	100	72	44	62	38
5	91	94	22	81	19
6	79	81	35	70	30
7	66	97	19	84	16

Tab. 3.

Series of measurement	Position of the flow control valve, K	Δp [Pa]	V_0 [m³/h]	Measurement error [%]
1	8	23,3	139	3.5
2	5	47.7	124	2.8
3	4	58.6	110	2.9
4	3.5	63.4	100	3.0
5	3	71.6	91	3.1
6	2.5	77.5	79	3.2
7	2	85.3	66	3.3

It can be seen that the maximum relative measurement error for airflow rates is lower, than the 5 [%] value allowed by standard ISO 5167-1.

5 Summary

In this paper a tangential air distribution system was investigated experimentally, considering air velocity-, turbulence intensity- and DR distribution in the occupied zone. Through these distributions the characteristic of the tangential air distribution could be seen.

Results showed that the fluctuating air velocity distribution is almost constant near the floor, but moving away from this surface under the air inlet this velocity value is higher than in the occupied zone. Similar tendency can be seen in case of showing the DR distribution, which also consists of turbulence intensity and air temperature values.

Most frequented turbulence intensities in the occupied zone are between 25 and 55 [%]. The biggest difference from the 40 [%] turbulence intensity given in standard is ± 15 [%]. The least difference is 0…+5 [%] at 100 [m^3/h]. Besides, we could see that there are more turbulence intensities that are less, than 40 [%], but some turbulence values are higher than 40 [%].

Further investigation possibilities may relate to other mixing air distribution systems, including the presented investigation aims in this paper.

The absolute measurement error was calculated to the airflow rate to the room. The results of this calculation showed that the maximum relative measurement error for airflow rates is lower, than 5 [%] allowed by standard ISO 5167-1.

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