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Influence of a Plenum Box Design on Uniformity of the Radial Air Jet Issuing From a Vortex Diffuser

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Preliminary note

Uniformity of the radial air jet issuing from the ceiling vortex diffuser with side entry plenum box was investigated experimentally. Two different cases of diffuser plenum box design were used: plenum box with perforated plate and plenum box without perforated plate. Air jet velocities were measured under isothermal conditions circumferentially around a diffuser. It was found that the jets in both cases were radially asymmetric. A simple method of quantifying radial asymmetry of the jet was proposed and used to compare two cases. Analysis showed that the jet issuing from the diffuser with plenum box that has a perforated plate is somewhat more symmetric.

Keywords
Air jet asymmetry
Perforated plate
Plenum box
Vartex diffuser

Ključne riječi
Asimetričnost zračnog mlaza
Perforirani lim
Priljučna kutija
Vrtložni difuzor

Utjecaj konstrukcije priključne kutije vrtložnog difuzora na uniformnost radijalnog zračnog mlaza

Prethodno priopćenje

Mjerenjem brzine zraka istraživana je asimetrija istrujavanja zračnog mlaza iz vrtložnog difuzora s priključnom kutijom i horizontalnim priključkom. Mjerenja su vršena dvjema različitim konstrukcijama priključne kutije: priključna kutija sa perforiranim limom za umirenje i priključna kutija bez lima za umirenje. Brzine mlaza su mjerene u uvjetima izotermnog istrujavanja, kružno oko difuzora. Istraživanje je pokazalo da su mlazovi u oba slučaja bili radijalno asimetrični. Jednostavna metoda za kvantificiranje radijalne asimetrije mlaza je predložena i upotrebljena za usporedbu dvaju slučajeva. Analiza je pokazala da je mlaz koji istrujava iz difuzora s priključnom kutijom sa perforiranim limom za umirenje nešto simetričniji.

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1. Introduction

Designers of ventilating and air-conditioning systems usually select air supply diffusers using the jet throw data, given by the diffuser manufacturers. Diffuser manufacturers give jet throw data that treats jet outflow from the diffuser as uniform. Uniformity of the air jet depends, among other factors, on diffuser plenum box design. In most cases ceiling air diffusers are installed with diffuser face flat with the ceiling and diffuser plenum box above the suspended ceiling. Plenum boxes are designed with the top or side (vertical or horizontal) air supply entry. This means that plenum box with the top (vertical) entry provides better conditions for symmetrical jet outflow because, the direction of the air flow coming into the plenum box is in line with direction of the outflow from the diffuser face. Although a plenum box by the top entry provides more uniform jet, selection of the plenum box is usually determined with the availability of space above the suspended ceiling. As a plenum box with the top entry requires more height above the suspended ceiling, and space is often limited, the side (horizontal) entry is more commonly applied. Diffuser manufacturers usually install perforated plate in the plenum box. The purpose of this plate is to distribute the air flowing into the plenum box more evenly over the area of the diffuser face and therefore improve the uniformity of the issuing jet.

The objectives for this research were to investigate and quantify uniformity of the radial air jet that is issuing from the vortex ceiling diffuser in two cases when: 1) a diffuser face is connected to the side entry plenum box with a perforated plate, 2) a diffuser face is connected to the side entry plenum box without a perforated plate. Air jet velocities were measured circumferentially around a vortex ceiling diffuser in isothermal conditions.

Technical information on influence of the diffuser connecting conditions on uniformity of the air jet in literature is limited because scientists usually install diffusers in such a way as to produce uniform radial jet.

Symbols/Oznake

r	- the distance from the center of the diffuser, cm - udaljenost od centra difuzora
STD	- the standard deviation of velocity, m/s - standardna devijacija brzine
v	- velocity, m/s - brzina
v_{av}	- the arithmetic mean of all velocities recorded at one radial distance, m/s - aritmetička srednja vrijednost svih brzina izmjerenjih na jednoj radijalnoj udaljenosti
$\left(\sum_{n} v\right)_{\max,r}$	- the maximum sum of *n* adjacent velocities that are recorded at *n* adjacent points at radial distance *r* - maksimalna suma *n* susjednih brzina izmjerenih na *n* susjednih lokacija na radijalnoj udaljenosti *r*
$\left(\sum_{n} v\right)_{\min,r}$	- minimum sum of *n* adjacent velocities that are recorded at *n* adjacent points at radial distance *r* - minimalna suma *n* susjednih brzina izmjerenih na *n* susjednih lokacija na radijalnoj udaljenosti *r*

Literature search identified one experimental study, a Hongze Ren, Bin Zhao, Xianting Li and others [1], where square diffuser was connected to a side entry plenum box and air jet velocities were measured in four directions from the center of the diffuser. It was concluded that jet characteristic were asymmetric and that the influence of the asymmetric diffuser jet on indoor air distribution was distinct.

An experimental study of vortex diffusers by Shakerin and Miller [2] found that the surface attached isothermal jets issuing from the vortex diffusers are rotational at the outlet but decay into straight radial flow within three diffuser diameters. Also that maximum velocity at a given radial position of 75cm from the center of the diffuser, occurs within 2 cm of the surface. An experimental study by Chen and Srebric [3] found that the distance at which vortex jet loses its tangential component depends on the airflow rate and diffuser geometry. Diffuser connecting conditions in those studies [2-3] were performed in such a way as to produce a uniform radial jet.

2. Experimental setup

An experimental apparatus is shown in Figure 1. The test room, 10 m long, 9 m wide, and 4 m high was built in a large production hall. The airflow loop consists of an supply air fan, mass flow transducer, 12 m plastic air duct, 7m aluminium flexible duct, the diffuser, and exhaust air fan. The diffuser was a installed with diffuser face flat with the ceiling in the center of the room, and a plenum box with horizontal entry above the ceiling. The plenum box air supply entry was oriented towards the north and connected with 7 m flexible duct and flexible duct to plastic round duct. Air was sucked from the production hall, introduced into the test room, and extracted from the room through the exhaust grille diffuser that was installed in the lower corner of the south wall. Air velocity, mass flow, temperature and pressure in the test room were measured in this study. The hot-sphere anemometers with omnidirectional sensors were used for air velocity and air temperature measurements. Hot-sphere omnidirectional sensors fulfill requirements for air velocity measurements in ventilated spaces from EN 13182, [4]. This device has two sensors, heated and unheated. Heated measures air velocity and unheated measures air temperature. Four hot sphere anemometers were attached to movable telescopic poles that enable sensors to be placed at the height from 10 cm above the floor to the ceiling height of 4m. The large production hall was air conditioned at constant temperature. There were no internal heat sources in the test room and the room walls were well insulated. This ensured isothermal flow conditions.

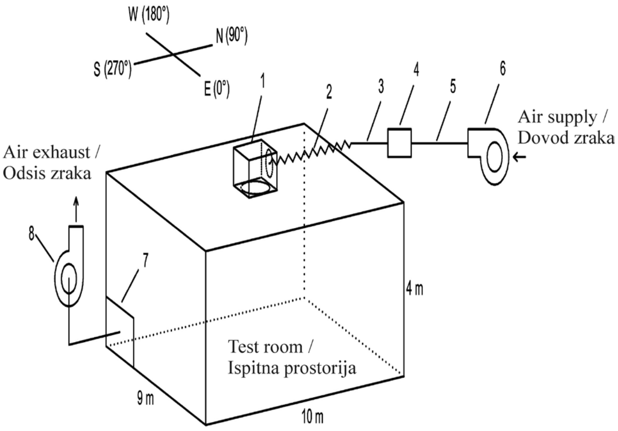


Figure 1. Test apparatus: (1) Diffuser with diffuser face and horizontal entry plenum box, (2) 7m round flexible duct, (3) 2m round plastic duct, (4) Mass flow meter, (5) 12m plastic duct, (6) Supply air fan, (7) Exhaust grille diffuser, (8) Exhaust air fan.

Slika 1. Mjerna linija: (1) Difuzor sa istrujnom pločom i priključnom kutijom sa horizontalnim priključkom, (2) 7m okrugli fleksibilni kanal, (3) 2m okrugli plastični kanal, (4) količinski protokomjer, (5) 12m plastični kanal, (6) tlačni ventilator, (7) odsisna rešetka, (8) odsisni ventilator.

Figure 2 a) shows face of the tested vortex diffuser. Diffuser has 36 identical, radially fixed vanes. This shape forces the air to rotate around vertical axis as the air flows horizontally out of the diffuser. Figure 2 b) shows a diffuser face fixed to the plenum box with a horizontal entry and perforated plate, and Figure 2 c) a diffuser with plenum box without a perforated plate. The perforated plate installed in the plenum box should ensure equal air distribution and improve uniformity of the jet. These two different designs of plenum box were used in this research with the same diffuser face. Plenum boxes were the same except that one did not have a perforated plate.

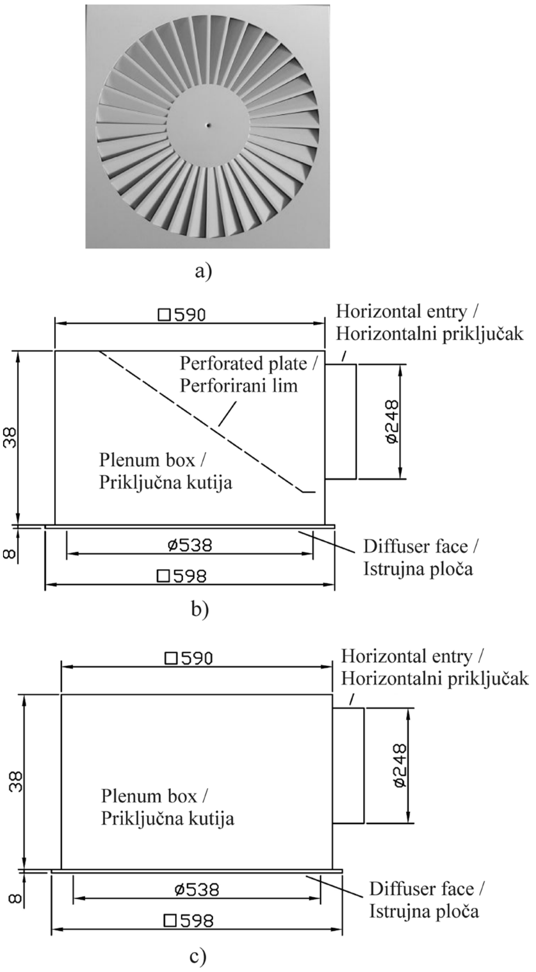


Figure 2. a) Diffuser face, b) diffuser with plenum box with perforated plate, c) diffuser with plenum box without perforated plate.

Slika 2. a) Istrujna ploča difuzora, b) difuzor s priključnom kutijom sa perforiranom limom, c) difuzor s priključnom kutijom bez peforiranog lima.

3. Experimental method

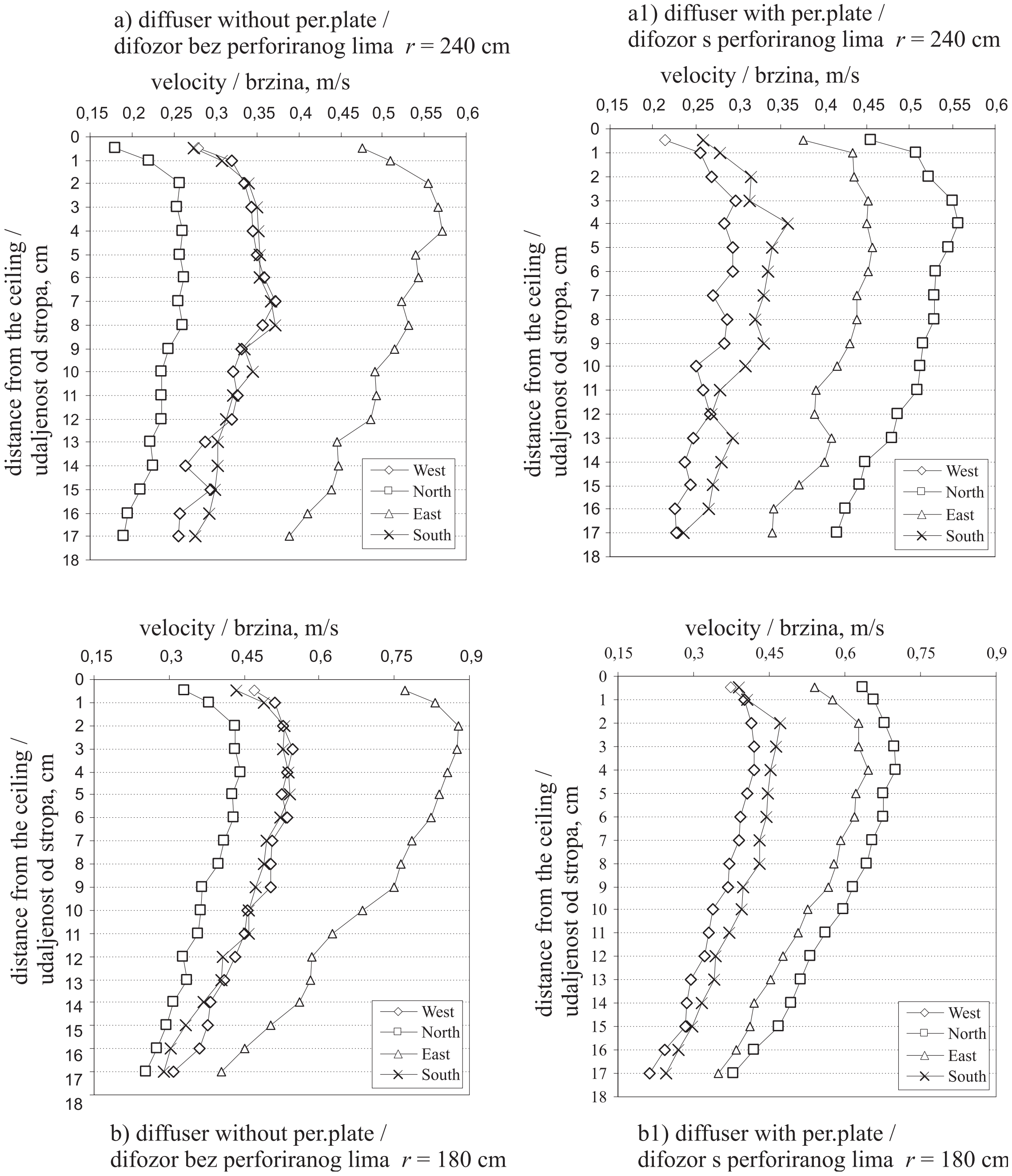
Velocity and temperature in the air jet were measured with three hot-sphere anemometers and fourth anemometer measured room temperature and velocity at the centre of the exhaust grille diffuser to ensure that the jet was isothermal. Measurements started after isothermal conditions were achieved and were performed under isothermal conditions at all time. Isothermal conditions are said to exist when supply and exhaust temperatures do not differ from each other by more than 2K prior to and at any time during the test, ISO 5219 [5]. Atmospheric pressure and room air temperature that were measured in the test room were needed to calculate air volume flow rate from air mass flow rate at normal condition, measured by mass flow instrument. Velocity, temperature and flow rate were measured for 5min with 10Hz sampling frequency and then averaged, for each measurement point. Some of the runs were repeated to investigate the repeatability in the data. To ensure that the jet is attached to the ceiling and to investigate uniformity of the jet, velocity profiles were measured from 0,5cm to 17cm below the ceiling. Also, jet velocities were measured circumferentially around the diffuser over 360 degrees to investigate radial asymmetry of a vortex jet. All measurements were performed at a volume flow rate of 600 m^3/h.

4. Experimental results and discussion

Figure 3 shows velocity profiles at two radial distances from the center of the diffuser, at four cardinal directions, for the diffuser with and without perforated plate. Velocity profiles show that both jets are not radially uniform. Maximum velocities for the diffuser without perforated plate are at the East and minimum at North, while maximum velocities for the diffuser with perforated plate are on the North and minimum on the West. Maximum velocities are approximately 70 to 100 % percent higher than minimum velocities for both diffusers. Profiles also show that the jet was attached to the ceiling. Based on the measured velocity profiles it cannot be estimated which of the two jets is more radially uniform.

Therefore, to thoroughly investigate radial asymmetry of the radial jet, velocities v were measured circumferentially around the diffuser at 16 locations over 360 degrees at the distances from 1cm to 4cm of the ceiling (depending on the maximum velocity point location). Figure 4 shows polar diagrams with measured jet velocity distribution at the radial distances from r = 25 cm (at diffuser face) to r = 240 cm from the center of the diffuser where velocity v is normalized with average velocity v_{av}. Average velocity v_{av} is arithmetic mean of all velocities recorded at one radial distance r from the center of the diffuser. Plenum box side entry was oriented at 90 degrees (North) in polar diagrams.

The relation between degrees in polar diagrams and cardinal directions is shown in Figure 1. Polar diagrams also show that velocity distribution is not circumferentially uniform over 360 degrees. Maximum velocity at the face of the diffuser (r = 25cm) Figure 4 a), occurs opposite of the plenum box side entry for both diffusers. Due to rotational movement of the vortex jet,



a) diffuser without per.plate / difozor bez perforiranog lima r = 240 cm

a1) diffuser with per.plate / difozor s perforiranog lima r = 240 cm

b) diffuser without per.plate / difozor bez perforiranog lima r = 180 cm

b1) diffuser with per.plate / difozor s perforiranog lima r = 180 cm

Figure 3. Velocity profiles at radial distances r = 180cm and r = 240cm for diffusers with and without perforated plate.

Slika 3. Profili brzina na radijalnim udaljenostima r = 180cm i r = 240cm za difuzore sa i bez lima za umirenje.

with an increase of radial distance maximum velocities rotate for approximately 90 degrees compared to location at diffuser face. On the basis of the observation of shapes of radial velocity distribution for two investigated diffusers, it is not possible to decide which jet is more radially uniform or more asymmetric.

One of the ways to quantify uniformity of the jets is to compare standard deviations STD of velocity recorded at a distance r from the center of the diffuser. In this case STD is a measure of variability of radial velocity distribution. The lowest possible value of STD is zero and that would indicate that the jet is radally symmetric. Higher STD would indicate that the jet is more asymmetric. Figure 5 shows STD of radial velocity distributions for diffuser with and without perforated plate and for radial distances from r = 140 cm to r = 240 cm.

The diffuser without a perforated plate seems to have insignificantly higher standard deviations.

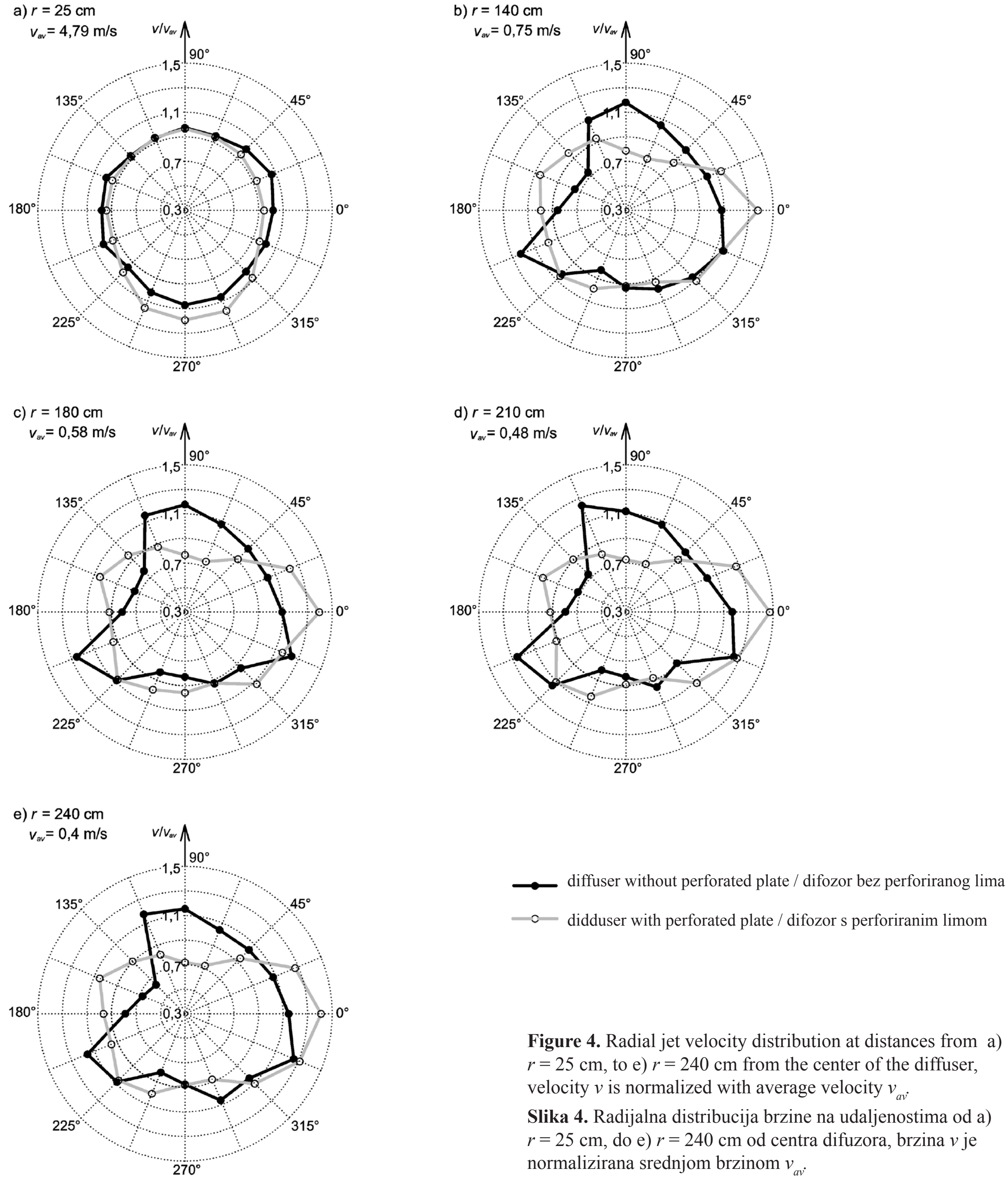


Figure 4. Radial jet velocity distribution at distances from a) $r = 25$ cm, to e) $r = 240$ cm from the center of the diffuser, velocity v is normalized with average velocity v_{av}.

Slika 4. Radijalna distribucija brzine na udaljenostima od a) $r = 25$ cm, do e) $r = 240$ cm od centra difuzora, brzina v je normalizirana srednjom brzinom v_{av}.

This information suggests that those two jets have approximately the same degree of uniformity. However, information from the comparison of STD cannot give good information on which jet is more uniform because it lacks important information about radial velocity distribution. This information contains the location of measured velocities. Higher velocities may be more concentrated on one side of the jet and lower velocities on the other side of the jet of one diffuser, while the other diffuser may have higher and lower velocities of the jet more evenly radially distributed. Therefore the method of quantifying radial uniformity has to take the location of velocities into account. There is no universal method or universal criteria to quantify radial asymmetry i.e. radial uniformity of the shape, in our case radial velocity distribution.

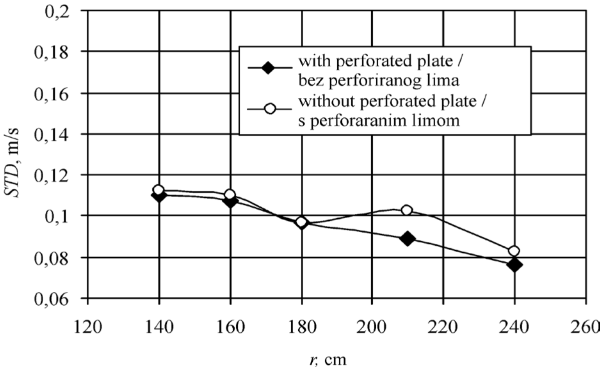


Figure 5. STD - standard deviation of velocities recorded at radial distance *r*.

Slika 5. STD – standardna devijacija brzina izmjerenih na radijalnoj udaljenosti *r*.

To compare jets with respect to their radial asymmetry, our simple method is proposed. The method is based on finding a minimum sum and maximum sum of *n* velocities that are measured at adjacent points at a certain radial distance. We will quantify uniformity of the jet using ratio of maximum and minimum sum of *n* adjacent velocities at radial distance *r*:

$$\left(\sum_{n} v\right)_{\text{max/min,r}} = \frac{\left(\sum_{n} v\right)_{\text{max,r}}}{\left(\sum_{n} v\right)_{\text{min,r}}}, \tag{1}$$

where:

n - number of adjacent velocities (measured at *n* adjacent locations) in radial velocity distribution at radial distance *r*, $1 \leq n < 16$

$\left(\sum_{n} v\right)_{\text{max,r}}$ - maximum sum of *n* adjacent velocities that are recorded at *n* adjacent points at radial distance *r*

$\left(\sum_{n} v\right)_{\text{min,r}}$ - minimum sum of *n* adjacent velocities that are recorded at *n* adjacent points at radial distance *r*

As we measured velocity at 16 locations at each radial distance, there are 16 combinations of *n* adjacent velocities for each *n,* at each radial distance, where $1 \leq n < 16$. For example, there are 16 combinations of $n = 4$ adjacent velocities at the radial distance $r = 140$ cm, shown in Figure 4 b). By summarizing velocities within those 16 combinations we get 16 sums of 4 adjacent velocities. Sum that is the highest is $\left(\sum_{4} v\right)_{\text{max,140}}$ and the lowest is $\left(\sum_{4} v\right)_{\text{min,140}}$. The ratio $\left(\sum_{4} v\right)_{\text{max/min,140}}$ quantifies radial uniformity of the jet. A higher ratio means higher asymmetry i.e. lower uniformity of the jet. The lowest value of this ratio is 1, and it means that the jet is radially symmetric. If the ratio is > 1 it means that the jet is radially asymmetric, and higher ratio indicates higher asymmetry (lower uniformity) of the jet.

This kind of analysis is performed to estimate radial uniformity of the air quantity distribution. It makes sense if we accept the assumption that the purpose of the radial diffuser, among others, is to distribute the air to the room evenly in all directions.

Figure 6 shows ratios of max. and min. sum of *n* adjacent velocities at the distance $r = 140$cm, for diffusers with and without perforated plate, where $n = 4$ to 6. Figure 6 also shows hatched areas where maximum and minimum sum of velocities are located. The ratio of maximum and minimum sum of velocities is also the ratio of volume flow rate of two segments of the jet encompassed by *n* measured adjacent velocities. This is the essence of the method, to compare air volume flow rates of segments of the jet. Ratios of maximum and minimum sums in Figure 6 indicate that the diffuser without perforated plate has more asymmetric jet than the diffuser with perforated a plate. For example, ratio $\left(\sum_{4} v\right)_{\text{max/min,140}}$ for a diffuser with plate is 1,26 and for a diffuser without plate is 1,44 (see Figure 6, b) and b1)). This means that air volume flow rate through the area with maximum sum is in the case of the diffuser with plate 26 % higher than the flow rate through the area with minimum sum, and in the case of diffuser without plate it is 44 % higher. Those numbers indicate a significantly higher rate of asymmetry in the jet of diffuser without plate.

Figure 7 shows ratios of maximum and minimum sum of adjacent velocities for $n = 1$ to 8 at $r = 140$ cm.

Values of *n* higher than 8 would not make sense in our case, because then the areas of maximum and minimum sum of adjacent velocities would overlap (each would encompass area larger than 180°).

Ratios of sums for two cases of diffusers show that diffuser with perforated plate has better uniformity for $n = 1$ to 8. The difference between these two reaches maximum at $n = 5$ (angle of approximately 90°) and disappears at $n = 8$ (angle of approximately 180°). A similar analysis performed for radial distances from $r =$ 160cm to 240cm gives similar results.

Although this analysis indicates that a diffuser with a perforated plate has somewhat better radial uniformity, it is difficult to determine if this justifies installation of a perforated plate because of lack of information on

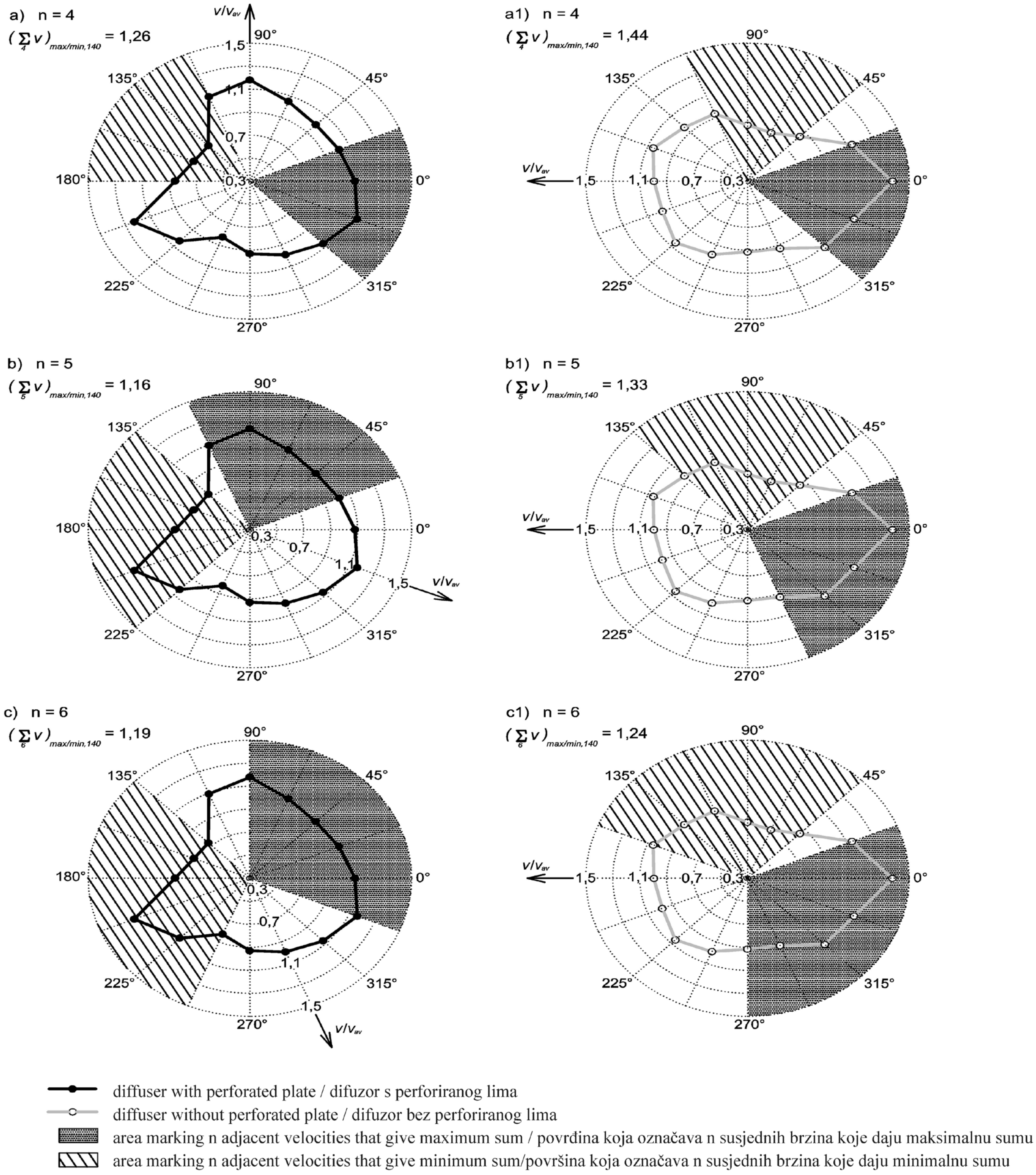


Figure 6. Ratio of max. and min. sum of *n* adjacent velocities at distance *r* = 140 cm, for diffusers with and without perf. plate, (*n* = 4 to 6).

Slika 6. Omjer maksimalne i minimalne sume *n* susjednih brzina na radijalnoj udaljenosti *r* = 140 cm, za difuzore sa i bez lima za umirenje, (*n* = 4 do 6).

influence of asymmetry of the jet on thermal comfort and air quality in the comfort zone of the room.

Due to vortex motion of the air jet issuing from vortex diffuser, there is a high rate of mixing of jet air with air in the room (high rate of entrainment). This itself might be improving uniformity of the jet compared with other radial diffusers with lower rate of entrainment, for example with round diffuser. Therefore, it is possible that installation of a perforated plate in a round diffuser's plenum box, or in some other diffuser with a lower rate of entrainment, has greater effect on improvement of uniformity of the jet than in vortex diffuser.

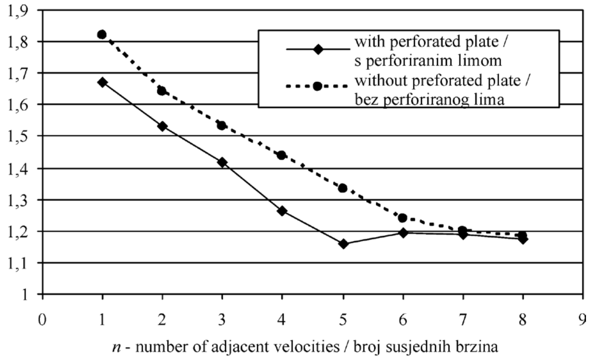


Figure 7. Ratio of max. and min. sum of *n* adjacent velocities at velocity distribution *r* = 140cm (*n* = 1 to 8).

Slika 7. Omjer maksimalne i minimalne sume *n* susjednih brzina na radijalnoj distribuciji *r* = 140cm (*n* = 1 do 8).

An air jet attached to the ceiling issuing from the ceiling diffuser, in most cases reaches a comfort zone after interaction with jets from adjacent diffusers, walls and other obstacles in the room. Therefore, the influence of its asymmetry on thermal comfort and air quality distribution in the comfort zone cannot be estimated without taking into account those and other factors such as air temperature conditions, etc.

5. Measurement uncertainty

In the work of Popiolek, Jorgensen, Melikov and others [6], the important error sources associated with measurements using low velocity thermal anemometers incorporating hot sphere omnidirectional velocity sensor are identified and quantified, and total uncertainty due to all error sources is estimated. The same procedure is used in this work to estimate total uncertainty of mean velocity and standard deviation of velocity. Uncertainties of flow rate and temperature were estimated based on producer data, repeated measurements, and comparisons between measurements obtained from different instruments measuring the same quantity. The following are the accuracy assessment results expressed as absolute expanded uncertainty (95 %) defined in [7] :

- Mean velocity $\hat{U}(v)$ = 0,046 m/s
- Standard deviation of velocity $\hat{U}(v_{RMS})$ = 0,03 m/s
- Temperature $\hat{U}(T)$ = 0,5 °C
- Flow rate $\hat{U}(\dot{V})$ = 30 m^3/h

6. Conclusions

Based on the exposed investigation the following conclusions may be drawn:

1. Both air jets issuing from diffusers with plenum boxes with and without a perforated plate are radially asymmetric.
2. Using standard deviation of radial velocity distribution STD for estimation of radial uniformity of the jet lacks important information about location of measured velocities.
3. A new simple method is proposed for quantification of radial asymmetry of the jet. Analysis of radial jets from two investigated a diffusers with this method indicates that the jet from diffuser without a perforated plate is more asymmetric.
4. Although analysis indicates that a diffuser with a perforated plate has somewhat better radial uniformity, it is difficult to determine if this justifies installation of a perforated plate because of lack of information on the influence of asymmetry of the jet on thermal comfort and air quality in the comfort zone of the room.
5. It may be that installation of a perforated plate in a plenum box of diffuser with a lower rate of entrainment has a greater effect on improvement of uniformity of the jet than in vortex diffuser.

REFERENCES

[1] HONGZE, R.; BIN, Z.; XIANTING, L.; HONGMING, F.; XUDONG, Y.: *Influence of Diffuser Jet Characteristics on Indoor Air Distribution under Actual Connecting conditions*, Journal of Architecturel Engineering 9 (4), 2003, pp 141-144.

[2] SHAKERIN, S.; MILLER, P.L.: *Experimental study of Vortex Diffusers*, ASHRAE Transactions, 102 (2), 1996, pp 340-346.

[3] QINGYAN, C.; SREBRIC, J.: *Simplified Diffuser Boundary Conditions for Numerical Room Airflow Models*, Ashrae RP-1009, 2001.

[4] European Standard EN 13182, *Ventilation for buildings* – Instrumentation requirements for air velocity measurements in ventilated spaces, 2002.

[5] International Standard ISO 5219, *Air distribution and air diffusion* – Laboratory aerodynamic testing and rating of air terminal devices, 1984.

[6] POPIOLEK, Z.; JØRGENSEN, FE.; MELIKOV, AK.; SILVA, MCG.; KIERAT, W.: *Assesment of Uncertainty in Measurements with low Velocity Thermal Anemometers*, International Journal of Ventilation ISSN 1473-3315 6(2), 2007, pp 113-128.

[7] International Organization for Standardization (ISO): Guide to the Expression of Uncertainty in Measurement, 1995.