CODEN STJSAO ISSN 0562-1887
ZX470/1409 UDK 772.962:628.87:697.9:725

Implementation of Thermography for Determination of Air Jet Geometry in HVAC Systems

Srećko ŠVAIĆ, Ivanka BORAS* and *Nenad FERDELJI

Fakultet strojarstva i brodogradnje, Sveučilište u Zagrebu (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb),
Ivana Lučića 5, HR - 10000 Zagreb,
Republic of Croatia

ivanka.boras@fsb.hr

Subject review

A properly designed room air diffusion scheme ensures that when conditioned air is supplied into a room, it causes no discomfort to the occupants. To confirm the design characteristic of an air diffusion arrangement a measurement of different parameters of air movement pattern like jet geometry, air temperature and velocity or humidity must be done. IR thermography can be successfully applied for quick determination of the air jet geometry, not only for new and existing systems, but also in the design phase of air inlets and outlets. The paper presents the possibilities for the determination of jet geometry, radius and spread by means of IR thermography.

Keywords
Air movement patterns
HVAC systems
IR thermography

Ključne riječi
IC termografija
KGHV sustavi (sustavi za grijanje, hlađenje i ventilaciju)
Načini strujanja zraka

Received (primljeno): 2009-03-15
Accepted (prihvaćeno): 2009-08-31

Primjena IC termografije za određivanje geometrije istrujnog mlaza u KGHV sustavima

Pregledni članak

Ispravno projektiran sustav za distribuciju zraka u prostoriji osigurava stanje ugode osobama koji u njoj borave. Da bi se potvrdili parametri koji karakteriziraju tu distribuciju, potrebno je izvršiti određena mjerenja poput geometrije mlaza, temperature, brzine i vlažnosti zraka koji se ubacuje u prostor. IC termografija se može uspješno primijeniti ne samo za brzo određivanje mlaza kod novih i postojećih sustava već i kod konstruiranja usisnih i odsisnih elemenata. Radom su prikazane mogućnosti određivanja geometrije mlaza kao što su domet i širina upotrebom IC termografije.

1. Introduction

A properly designed room air diffusion scheme ensures that conditioned air supplied into a room causes no discomfort to the occupants. With conventional diffusion arrangements, primary air is supplied over the occupied zone where it entrains and mixes with room secondary air. This process results in decay of the initial temperature and velocity difference between the supply and room air, so that when the supply jet reaches the occupied zone the velocity and temperature are close to room conditions. To obtain the designed parameters, air outlets and inlets must be properly selected and balanced and the predicted air movement patterns achieved. For evaluation of the air movement patterns, IR thermography can be applied as a method for quick determination of air jet geometry. The method was investigated in the Laboratory for Applied Thermodynamic of the Faculty for Mechanical Engineering and Naval Architecture, University of Zagreb, and some of results are presented in this paper.

2. Air jet, terms and definitions

Air supplied into rooms thorough various types of outlets is distributed by turbulent air jets. It is important to understand some of the basic terms while air jets are the primary factor affecting room air motion.

If the air jet is not obstructed by walls or other obstructions it is called *free jet*.

There are jets whose air motion is attached to the surface when they are called *attached air jets*.

Based on placement and flow characteristics a jet can be a *confined jet*. This is the case when a jet air movement pattern is influenced by reverse flow created by the same jet.

If the temperature of the supplied air is equal to the ambient air temperature, the jet is called an *isothermal jet*. When there is a temperature difference of supplied and ambient air, the jet is called *non-isothermal jet*.

Another classification depending on air jet diffuser type can be found in [1]

Symbols/Oznake

A_0 - effective area of stream at discharge, m^2
- efektivna površina mlaza kod istrujavanja

A_c - core area of stream at discharge, m^2
- ukupna površina mlaza kod istrujavanja

Ar - Archimedes number
- Arhimedov broj

C_d - discharge coefficient
- koeficijent istrujavanja

H_0 - width of jet at outlet or at vena contracta, m
- širina mlaza kod istrujavanja ili na najmanjem presjeku

D_0 - effective or equivalent diameter of stream at discharge
- efektivni ili ekvivalentni promjer mlaza kod istrujavanja

K, K' - constants
- konstante

R_{fa} - ratio of free area to core area
- omjer slobodne površine i ukupne površine

m - Mixing factor
- Faktor miješanja

T_0 - room air temperature, K
- sobna temperatura

ΔT_0 - temperature difference of ambient and supply air, K
- temperaturna razlika dobavnog zraka i zraka unutar prostorije

v_0 - average initial velocity at discharge, m/s
- prosječna početna brzina kod istrujavanja

v_x - centerline velocity at distance x from the outlet, m/s
- brzina strujanja na osi mlaza na udaljenosti x od istrujnog otvora

v_y - vertical velocity at distance x from the outlet, m/s
- poprečna brzina strujanja na osi mlaza na udaljenosti x od istrujnog otvora

y - distance from the centerline at x, m
- udaljenost od osi mlaza na mjestu x

Y - drop or rise of an air jet at x, m
- pad ili uspon mlaza na mjestu x

x - distance from outlet to measurement of centerline velocity, m
- udaljenost na osi mlaza od istrujnog otvora do mjesta mjerenja brzine

x_0 - fictional jet core length, m
- zamišljena duljina jezgre mlaza

Air jet geometry:

Some basic terms concerning air jet geometry:

Throw or radius of diffusion is the forward travel of a jet to the point where the maximum velocity has decayed to a nominated terminal velocity.

Drop or rise is the distance between the jet centerline and supply outlet centerline at nominated throw.

Entrainment or induction is the movement of room air into the jet caused by the airstream discharged from the outlet – *secondary air motion*

Envelope is a jet area within the boundary of a nominated air velocity.

Expansion or spread is normal divergence of a jet as it leaves an outlet and entrains the surrounding air.

Drop is the vertical distance that the lower edge of a horizontally projected stream drops between the outlet and the end of its throw.

Outlet velocity is the average velocity of air emerging from the outlet, measured in the plane of the opening.

Terminal velocity is the maximum air stream velocity at the end of the throw

3. Standard air movement patterns

In HVAC systems, the main idea is to create a relatively uniform air velocity, temperature, humidity and air quality conditions in the occupied zone.

An occupied zone is defined as the space of up to 1.8 m from the floor and as close as 150 mm from any room surface.

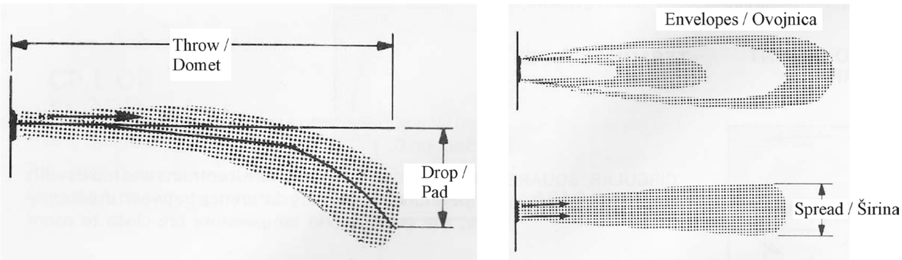


Figure 1. Air jet throw, drop, envelopes and spread
Slika 1. Domet, pad, širina i ovojnica mlaza

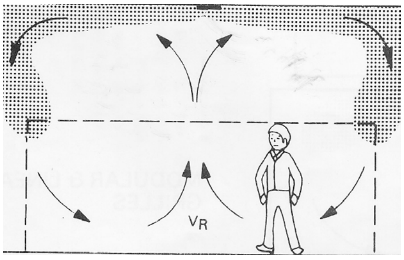


Figure 2. Occupied zone

Slika 2. Zona boravka

Depending on the type of ventilation, air diffusion systems in the room can be classified as mixing, displacement and local systems. [1]

1. In mixing systems, conditioned air is normally discharged from air outlets at velocities much grater than those acceptable in the occupied zone. Conditioned air temperature may be above, below or equal to the air temperature in the occupied zone. The diffuser jets mix with the ambient room air by entrainment, which reduces the air velocity and equalizes the air temperature. The occupied zone is ventilated either by the decayed air jet directly or by the reverse flow created by the jets.
2. In displacement ventilation, conditioned air with a temperature slightly lower than the desired room air temperature in the occupied zone is supplied from air outlets at low air velocities. The outlets are located at or near the floor level and the supply air is introduced directly to the occupied zone. Returns through which the warm room air is exhausted from the room are located at or close to the ceiling. The supply air spreads over the floor and then rises as it is heated by the heat sources in the occupied zone. Heat sources (e.g. person, computer) in the occupied zone create upward convective flows in the form of thermal plumes. In contrast to mixing ventilation, displacement ventilation is designed to minimize mixing of air within the occupied zone. The objective of the displacement ventilation is to create conditions close to supply air conditions in the occupied zone. This type of ventilation was originally used in industrial buildings as an effective method for removing contaminants in the occupied zone. It is now also used for ventilating and cooling office buildings but local discomfort due to draft and vertical temperature gradient may be critical.
3. Localized ventilation systems supply conditioned air to localized areas close to the building occupants. In comparison to conventional ceiling based air diffusion, localized ventilation systems generally have a large number of supply diffusers directly in the occupied zone of the building. Air is typically returned at or close to the ceiling level so that localized systems benefit from the same overall upward movement of air in the room as displacement ventilation systems. In cooling applications, this allows more efficient removal of heat and contaminant sources from the room. Localized ventilation systems differ from displacement ventilation systems in that they generally use higher supply volumes, which enable higher cooling loads to be met and they supply air at higher velocities through smaller diffusers. Because air is delivered directly into the occupied zone, supply air temperatures are usually higher than those maintained for conventional ceiling-based systems in order to avoid local draft discomfort for the occupants.

The location, type and size of the air terminal device will determine the manner in which the supply jet and resultant room air motion behave. The change in supply air temperature from cooling to heating will also modify the jet trajectory and movement pattern. Depending on the air terminal device location and type of outlet jet, according to [1] there are five groups of outlet:

- **Group A**. *Outlets mounted in or near the ceiling that discharge air horizontally*

The primary air envelopes show a horizontal, two-jet pattern for the high sidewall and 360 degree diffusion pattern for the ceiling outlet.

During cooling, the total air drops into the occupied zone at a distance from the outlet that depends on air quantity, supply velocity, temperature differential between supply and room air, deflection setting, Coanda effect and type of loading within space.

During heating, warm supply air introduced at the ceiling can cause stratification in the space if there is insufficient induction of room air at the outlet. Selecting diffusers properly, limiting the room supply temperature differential and maintaining air supply rates at a level high enough to ensure air mixing by induction provide adequate air diffusion and minimize stratification.

- **Group B**. *Outlets mounted in or near the floor that discharge air vertically in a non spreading jet.*

Because these outlets have no deflecting vanes, the primary air is discharged in a single vertical jet. When the total air strikes the ceiling, it fans out in all directions from the point of contact and, during cooling, follows the ceiling for some distance before dropping towards the occupied zone.

During heating, the total air flow follows the ceiling across the room, then descends partway down the exterior wall.

A comparison of Figures 3a and 3b for heating shows that the stagnant region is smaller for Group B outlets because the air entrained in the immediate vicinity of the outlet is taken mainly from the stagnant region, which is the coolest air in the room. This results in greater temperature equalization and less buoyancy in the total air than would occur with Group A outlets.

- **Group C.** *Outlets mounted in or near the floor that discharge air vertically in a spreading jet.*

Although Group C outlets are related to Group B outlets, they are characterized by wide-spreading jets and diffusing action. This difference causes the stagnant zone formed to be larger during cooling and smaller during heating.

Diffusion of the primary air usually causes the total air to fold back on the primary and total air during cooling, instead of following the ceiling. This diffusing action of the outlets makes it more difficult to project the cool air but it also provides a greater area for induction of room air. This action is beneficial during heating because the induced air comes from the lower regions of the room.

- **Group D.** *Outlets mounted in or near the floor that discharge air horizontally*

During cooling, because the air is discharged horizontally across the floor, the total air remains near the floor and a large stagnant zone forms in the entire upper region of the room.

During heating, the total air rises towards the ceiling because of the buoyancy effect of warm air. The temperature variations are uniform, except in the total air region.

- **Group E.** *Outlets mounted in or near the ceiling that project primary air vertically.*

During cooling, the total air mores towards to and follows the floor, producing a stagnant region near the ceiling.

During heating, the total airflow reaches the floor and folds back towards the ceiling. If projected air does not reach the floor, a stagnant zone results.

4. Air jet theory and characteristic

Here some basic terms concerning air jet theory of both isothermal and non-isothermal jets will be introduced. [1]

4.1. *Isothermal circular free jet*

For many conditions of jet discharge, it is possible to analyze jet performance which means to determine:

1. Angle of divergence
2. Velocity patterns along the jet axis
3. The velocity profile at any cross section in the zone of maximum engineering importance
4. The entrainment ratios in the same zone

- Angle of divergence

The angle of divergence is well defined near the outlet face, but the boundary contours are billowy and easily affected by external influences.

Measured angle of divergence for discharge into large open spaces usually range from 20 to 24° with

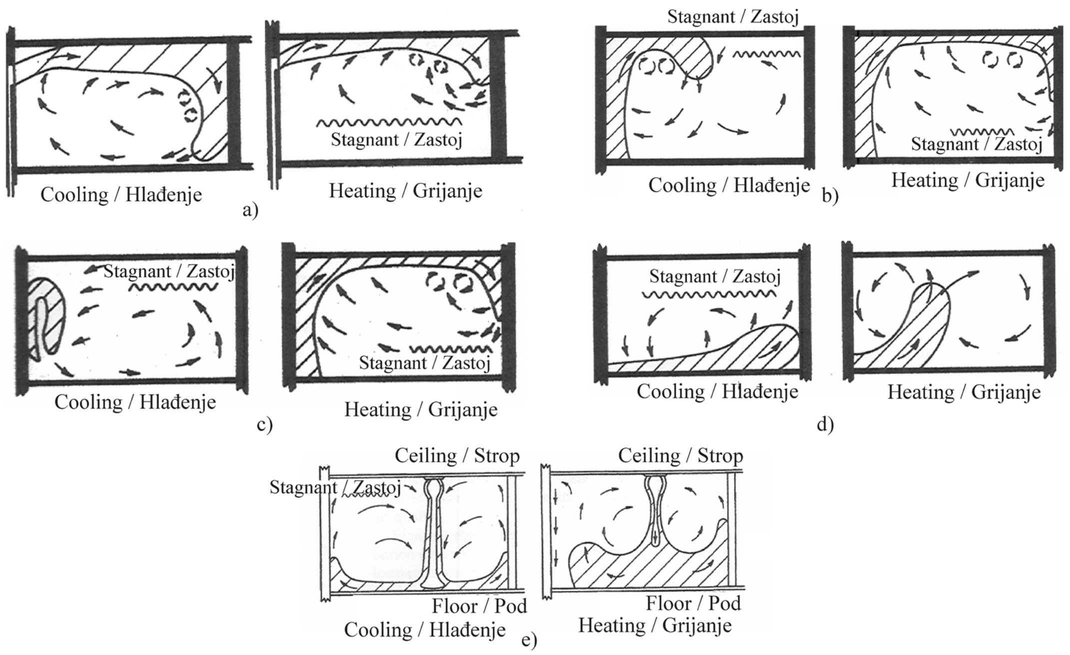


Figure 3. Standard air movement patterns for various outlets: a) group A ,b) group B, c) group C, d) group D, e) group E

Slika 3. Standardni načini strujanja zraka za različite skupine istrujnih otvora: a) skupina A, b) skupina B, c) skupina C, d) skupina D, e) skupina E an average of 22°. Coalescing jets for closely spaced multiple outlet expand at smaller angles, averaging 18°, and jets discharging into relatively small spaces show even smaller angles of expansion. In cases where the outlet area is small compared to the dimensions of the space normal to the jet, the jet may be considered free as long as

$$X \le 1.5\sqrt{A} \ ,$$

where X is a distance from the face outlet and A cross-sectional area of confined space normal to the jet.

- Jet expansion zones

In this chapter some standard terms will be used, which are described below:

v_x =	centerline velocity at distance x from the outlet, m/s
$v_0 = v_c / C_d R_{fa}$ =	average initial velocity at discharge, m/s
C_d =	discharge coefficient (usually between 0.65 and 0.9)
R_{fa} =	ratio of free are to core area
x =	distance from outlet to measurement of centerline velocity, m
y =	distance from the centerline at x, m
Y =	drop or rise of an air jet at x, m
H_0 =	width of jet at outlet or at vena contracta, m
D_0 =	effective or equivalent diameter of stream at discharge, m
$A_0 = A_c C_d R_{fa}$ =	effective area of stream at discharge, m^2
K, K' =	constants

The full length of an air jet, in terms of maximum velocity and temperature differential at the cross section, can be divided into four zones.

1st ZONE – A core zone; a short zone, extending about four diameters or widths from the outlet face, in which the ratio $\frac{v_x}{v_0}$ remains constant and equal to the ratio of the center velocity of the jet at the start of expansion to the average velocity. The ratio varies from approximately 1.0 for rounded entrance nozzles to about 1.2 for straight pipe discharges. It has much higher values for diverging discharge outlets.

2nd ZONE – A transition zone where the jet velocity varies inversely with the square root of the throw. The zone length depends on the type of outlet, initial airflow turbulence and so forth, but is approximately equal to 8 hydraulic diameters.

$$\frac{v_x}{v_0} = \sqrt{\frac{K' H_0}{x}}. \tag{1}$$

3rd ZONE – A zone of fully established turbulent flow that may be 25 to 100 equivalent air outlet diameters long. This zone is of major engineering importance because, in most cases, the diffuser jet enters the occupied area within this zone. Centerline velocities can be determined from: [2]

$$\frac{v_x}{v_0} = \frac{1}{m}\frac{D_0}{x}. \tag{2}$$

Constant m is called a mixing factor and its value depends on the level of outlet air turbulence and on outlet type. Usual values of factor m lie between 0.1 and 0.5.

Table 1. Values for K' for various standard openings [1]

Tablica 1. Vrijednosti faktora K' za različite standardne istrujne otvore

Type of Outlet / Tip istrujnog otvora	K, v_0 = 2.5 to 5.0 m/s	K, v_0 = 10 to 50 m/s	K', v_0 = 2.5 to 5.0 m/s	K', v_0 = 10 to 50 m/s
Free openings / Slobodni otvori				
Round or square / Kružni ili kvadratni	5.0	6.2	5.7	7.0
Rectangular, large aspect ratio (<40) / Pravokutni, veliki omjer dužina/širina	4.3	5.3	4.9	6.0
Annular slots, axial or radial / Prstenasti otvori, aksijalni ili radijalni	-	-	3.9	4.8
Grilles and grids / Rešetke i mreže				
Free area 40 % or more / Slobodna površina 40 % i više	4.1	5.0	4.7	5.7
Perforated panels / Perforirani poklopci				
Free area 3 to 5 % / Slobodna površina 3 do 5 %	2.7	3.3	3.0	3.7
Free area 10 to 20 % / Slobodna površina 10 do 20 %	3.5	4.3	4.0	4.9

Ratio $x_0 = \dfrac{D_0}{m}$ is called fictional jet core length and the jet has a longer core if the level of turbulence is smaller.

Velocity profile at any cross section can be calculated from:

$$\frac{v_y}{v_x} = e^{-2\left(\frac{y}{mx}\right)^2} = e^{-0.69\left(\frac{y}{ya}\right)^2}, \tag{3}$$

where y_a represents distance where $v_x = 0.5\ v_y$

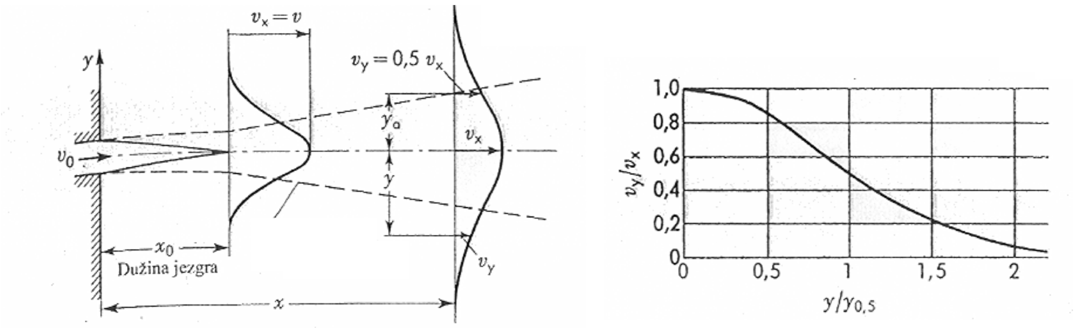
In Figure 4 it can be seen that all profiles at $x > x_0$ are similar and it can be show in the same diagram, in Figure 4.

Gravitational and inertial forces have the same direction and that is when warm air is introduced from the floor or cold air from the ceiling.

These two forces may have opposite direction, when warm air is introduced from the ceiling or cold from the floor. Direction of the air jet in this case will depend on magnitudes of these forces and may become opposite from the introducing direction.

The ratio of these two mentioned forces is called Archimedes number;

$$Ar = \frac{\text{gravitational force}}{\text{inertial force}}.$$



a) b)

Figure 4. a) Profiles of circular free jet, b) Dimension-free profile curve for circular free jet

Slika 4. a) Profili kružnog slobodnog mlaza, b) Bezdimenzijska krivulja profila kružnog slobodnog mlaza

4th ZONE – A zone of diffuser jet degradation where the maximum air velocity and temperature decreases rapidly. The distance to this zone and its length depend on the velocities and turbulence characteristics of ambient air. In just a few diameters or widths, the air velocity drops to the nominated terminal velocity, usually 0.25 m/s.

In this zone centerline velocity is inversely proportional with squared distance *x*.

$$\frac{v_x}{v_0} \propto \frac{1}{x^2}.$$

4.2. *Non-isothermal circular free jet*

When the temperature of introduced air is different from the room temperature, movement pattern of diffuser jet air is affected by the thermal buoyancy due to air density difference. Behavior of the air jet will depend on magnitude of gravitational and inertial force. There are two distinct cases which can occur; [2]

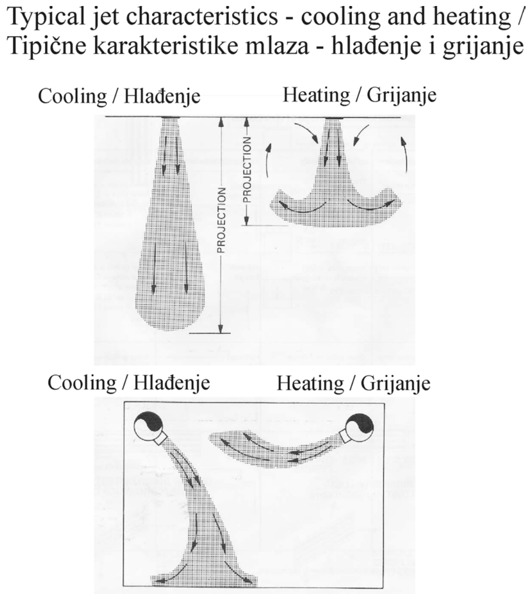


Figure 5. Non-isothermal vertical jet

Slika 5. Neizotermni vertikalni mlaz

Gravitational force depends on temperature difference of introduced and room air. On the other hand, inertial force is proportional to the squared outlet velocity. Thus, for the circular free jet, Archimedes number is defined as follows:

$$Ar = \frac{g \cdot \Delta T_0 \cdot D_0}{T_0 \cdot v_0^2}. \tag{4}$$

Where,

ΔT_0 – temperature difference of ambient and supply air

T_0 – room air temperature

The corresponding formula for calculating the drop or rise of an air jet at distance x from the outlet is:

$$\frac{y}{D_0} = \pm 0.06 \cdot Ar \cdot \left(\frac{x}{D_0} \right)^3. \tag{5}$$

It is important to emphasize that the throw of non-isothermal horizontal jet does not differ much from the throw of isothermal jet.

5. Application of IR thermography for determination of air jet geometry

The method developed at the Laboratory for Applied Thermodynamic tends to visualize the temperature distribution in non-isothermal air jets. A curtain made of a material having a low heat conduction coefficient (paper, textile etc.) is inserted perpendicular to the jet outlet, along its centerline and positioned vertically. The hot or cold air stream passing along the curtain leaves a temperature track on curtain surface having the shape of jet geometry. This temperature field is recorded in a stationary state using the IR thermographic camera, allowing the obtained thermogram to be analyzed later. The experimental rig shown in Figure 6 consist of a synthetic textile curtain placed perpendicular to the outlet grille, plenum with grille in sidewall position, fan with inlet and outlet sections for measurement of air parameters (temperature, velocity, flow) and an air heater. Figure 7 shows the thermograms recorded for three positions of the grille lamellas (horizontal, max. up and max. down position). The air jet had the following parameters; t = 26.7 °C, v = 4.37 m/s, q_v = 0.0772 m³/s.

From the thermograms shown in Figure 7, it can be concluded that the velocity profile is firmly connected with the temperature distribution of an air jet. Therefore, further measurements should be directed to investigate and explore this relationship between air jet temperature and velocity profile.

Figure 6. Experimental rig

Slika 6. Mjerna linija

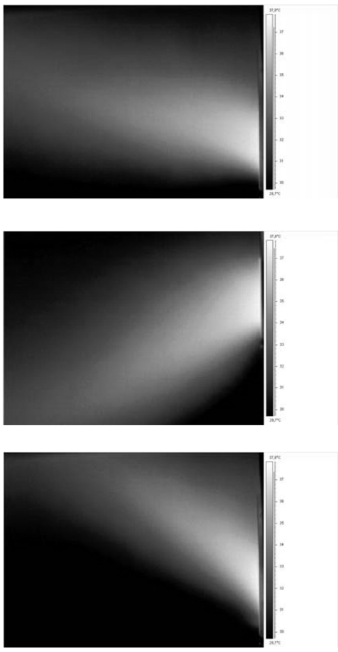


Figure 7. Thermograms obtained for hot air jet from sidewall grille

Slika 7. Termogrami vrućeg zraka iz bočne i strujne rešetke

Figure 8 shows thermogram of an air jet using the same method. An experimental rig used for this measurement was the rig shown in Figure 6 with the exception that in this experiment, instead of a sidewall grille, a circular opening is used as an outlet of hot stream. Hot air exits with temperature of 30 °C, with 0.9 m/s and passes along the curtain as in the previous example.

The experiment consists of two separate measurements. In the first part, an air jet stream was recorded with IR thermographic camera in order to compare those results with measured temperatures along the centerline of the air jet, obtained from the second part of the experiment. In the second part, besides the temperature, the velocities along the centerline have been measured. Results of the experiment are also shown in Figure 8.

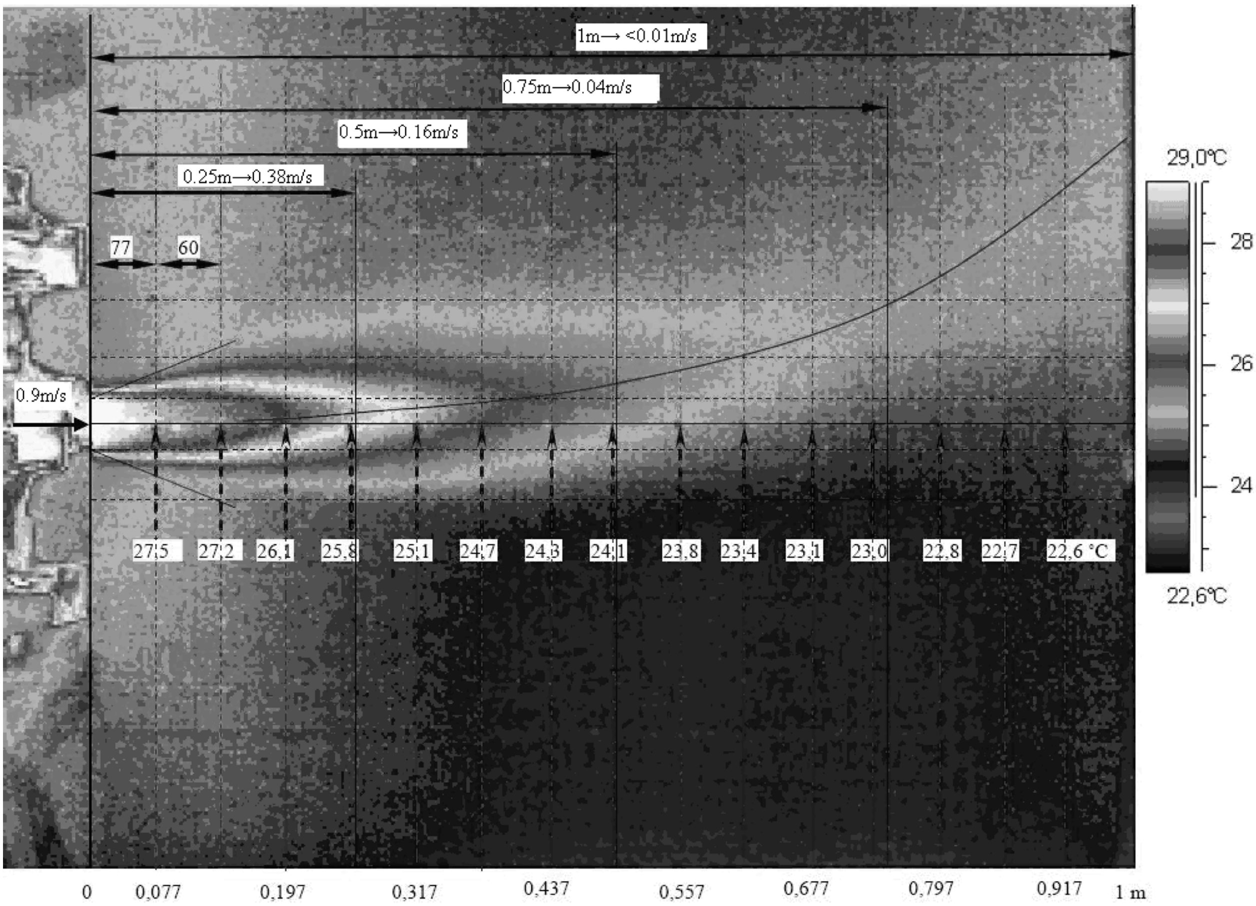


Figure 8. Thermogram of circular free jet

Slika 8. Termogram kružnog slobodnog mlaza

Outgoing velocity of 0.9 m/s and theoretical spread angle of 24° are marked on the left side of the thermogram. Dimensions 77 and 60 are distances in millimeters from the hot air outlet. Those distances can also be seen on the abscise where distance dimensions are in meters. Measured velocities are given above the thermographic image of the jet. Numbers marked with dashed arrows are temperatures along the centerline measured with thermocouples. A blue line along the image represents buoyancy effect calculated using (5).

Figure 8 shows an almost perfect match of the blue line with temperature trace on the thermogram, confirming the previously mentioned close relationship between temperature and velocity field. Numerical results of experiment are shown in the next figure.

Figure 9 shows first ten points of the air jet centerline temperatures. Blue line represents measured data and the purple line temperatures obtained from IR camera. Both profiles have the same trend, what was expected, but temperature differences refer that there might be also a correlation between these two temperature profiles.

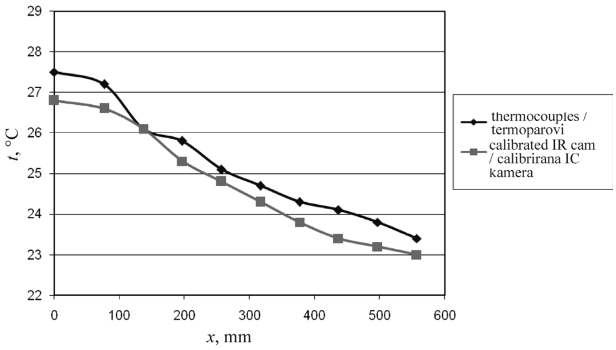


Figure 9. Velocity profile along air jet centerline

Slika 9. Profil brzina duž osi mlaza zraka

In the second part of the experiment, besides temperatures, velocities along the centerline were also measured which will be compared with theoretical velocity profile.

In order to calculate a theoretical velocity profile, according to equation (2), it is necessary to find the mixing factor, *m*. To avoid further measurements, the mixing factor will be calculated from the temperature profile shown in Figure 7. This conjecture can be done based on observed connection between velocity and temperature fields.

From the Figure 8, jet core length is estimated (l = 100 mm) which gives a mixing factor:

$$m = \frac{D_0}{x_0} = \frac{0.05}{0.1} = 0.5.$$

Then from the theoretical velocity profile equation a centerline velocity profile of the jet can be calculated.

In Figure 10, both measured and theoretical velocity profiles are shown.

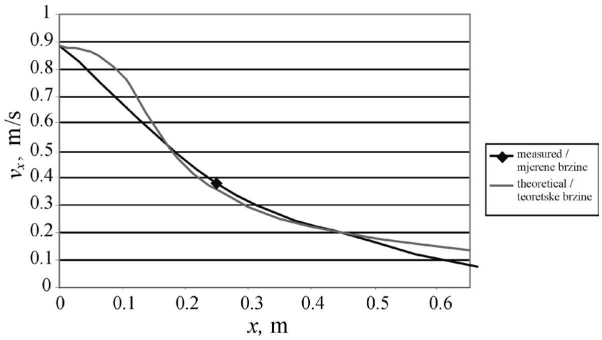


Figure 10. Comparation of measured and calculated velocity profiles

Slika 10. Usporedba mjerenih i teoretskih brzina

It can be seen that measured temperatures mostly match theoretical ones. The only significant difference is in the core zone of the jet. This difference arises from the fact that the first point of measured temperature profile (blue point in the diagram) is outside the core zone.

6. Conclusion

From the results presented, it can be concluded that, using this method, thermography can be successfully applied for determination of air jet geometry in HVAC systems. The method provides relatively easy and cheap measurements whose results can provide better insight and prediction of air movement patterns and thermal phenomenon in HVAC systems. Further research will be directed to quantify parameters such as temperature and flow patterns. The air jet geometry will be studied qualitatively and quantitatively for different terminal types with cold and hot air having different outlet velocities. For this purposes, the experimental rig must be adapted for longer and wider air jets up to the limits of the surrounding area. The primary goal of the method is based on the experimental results, which show that temperature and velocity fields are closely related: If a correlation between these two fields could be found and if this method were be applicable for a wide range of possible air movement patterns, the developing, retrofitting and managing HVAC systems would be significantly improved.

REFERENCES

[1] 1997 ASHRAE Fundamentals Handbook (SI)

[2] RECKNAGEL, SPRENGER, SCHRAMEK: T*aschenbuch für Heizung + Klimatechnik*, Oldenbourg Industrieverlag GmbH, München, 2004.

[3] ANDRASSY, M.; BORAS, I. i ŠVAIĆ, S.: *Osnove termografije s primjenom*, Kigen, Zagreb, 2008.

[4] MALDAGUE, X. P. V.: *Theory and practice of infrared technology for nondestructive testing*, John Wiley & Sons Inc., New York, 2001.