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Određivanje brzine strujanja vazduha u pravougaonom zatvorenom cevovodu korišćenjem metoda polja brzina

Determination of Air Flow Rate in a Rectangular Closed Conduit by Principle of Velocity-Area Method

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Rezime **-** U tehničkoj praksi često je potrebno meriti ili kontrolisati protok fluida u cevovodima i kanalima. Metoda polja brzina zahteva merenja u određenim tačkama u odgovarajućem poprečnom preseku zatvorenih cevi. Istovremeno izmerene lokalne srednje brzine meračima integrišu se u mernom preseku kako bi se izračunao protok. U ovom radu, tri pristupa ove metode primenjuju se na pravougaonom zatvorenom cevovodu za određivanje protoka vazduha pomoću tehnika integracije koje se koriste za izračunavanje protoka pretpostavljajući raspodele brzina koje se blisko približavaju poznatim zakonima, posebno u blizini granica čvrstih tela. U tu svrhu, merači brzine su bili 7 Pitoovih cevi postavljenih vertikalno u unapred definisanim mernim tačkama koje pokrivaju visinu cevovoda, i pomerale su se horizontalno duž širine cevi. Položaj Pitotovih cevi duž preseka cevovoda praćen je i kontrolisan mernim pretvaračem pomeranja. Pritisak se meri digitalnim senzorima. Prva tehnika za određivanje protoka vazduha zasniva se na fiksnim mernim tačkama po preseku cevi u kojima se određuju prosečne vrednosti lokalne brzine, druga je polukontinualno merenje profila brzine primenom interpolacije između prosečne lokalne brzine u fiksnoj tački i izmerene brzine pri kretanju između dva položaja, a treća se zasniva na kontinuiranom pomeranju Pitotovih cevi bez zaustavljanja. Rezultati se izračunavaju i predstavljaju pomoću različitih vrsta softvera. Kod poslednje tehnike, upoređivani su rezultati dobijeni primenom različitih brzina kretanja Pitotovih cevi kako bi se ispitao njihov uticaj na profil brzine.

Ključne reči - eksperimentalna merenja, protok, kanal, profil brzine

Abstract **-** In the technical practice, it is often necessary to measure or control the fluid flow rate in pipelines and channels. The velocity-area method requires a number of meters located at specified points in a suitable cross-section of closed conduits. Simultaneous measurements of local mean velocity with the meters are integrated over the gauging section to provide the discharge. In this paper, three approaches of this method are applied on a rectangular closed conduit to determine the air flow rate with integration techniques used to compute the discharge assume velocity distributions that closely approximate known laws, especially in the neighborhood of solid boundaries. For this purpose, meters for velocity were 7 Pitot tubes placed vertically in predefined measurement points covering the conduit height, and moved horizontally along the conduit width. The position of the Pitot tubes along the conduit width was monitored and controlled by a linear displacement transducer. Pressure is measured using digital sensors.

The first technique for determination of air flow rate is on basis of fixed (stopping) measuring points across the conduit width as averaged values of local velocity, the second one is semi continual measurement of velocity profile by applying interpolation between the average local velocity on fixed (stopping) points and measured velocity in the movement between two positions, and the third is by continuously moving the Pitot tubes without stopping. The results of the three techniques are calculated and presented using different types of software. Considering the last technique, comparison of results is made applying different movement speeds of the Pitot tubes in order to examine their influence on the velocity profile.

Index Terms - experimental measurements, flow, channel, velocity profile

I INTRODUCTION

Many practical engineering problems are associated with the need for an accurate fluid flow measurement. Determining the volume flow of a fluid passing through a conduit is often needed. One of the most common methods to measure the volume fluid flow rate in a pipe or a channel is the velocity-area method based on a velocity field exploration.

Velocity can be measured by several different principles such as pressure difference, rotating mechanical devices, hot wires, laser doppler anemometer (LDA) etc. Experimental investigations often employ calculation of local velocity by means of pressure difference measurements using Pitot tubes.

International standards such as [1] offer different methods of flow rate computation among which:

- Graphical integration of the velocity area which includes plotting velocity profile on a graph and evaluating the area under the curve bounded by the measuring points closest to the wall;

- Numerical integration of the velocity area by which the velocity profile is presented by an algebraic curve and the integration is performed analytically;
- Arithmetical methods which assume that the velocity distribution follows a particular law and the mean velocity in the conduit is given by a linear combination of the individual measured velocities.

In this paper, flow rate of air flowing in a rectangular closed conduit is determined using the velocity-area method which includes:

- Division of the conduit cross-section into elementary surfaces,
- Measurement of velocity in each elementary surface, and
- Calculating total flow rate as a sum of all the flow rates through the elementary surfaces.

Figure 1. Experimental system for measurement of velocity: rectangular conduit with measuring sections and equipment

To achieve high accuracy of determining the flow rate, 49 measuring points were used. Based on this method, three techniques of velocity determination were proposed and compared:

- Measuring the velocity by stopping at fixed points across the conduit width and calculating averaged local velocities;
- Interpolation between the measured velocities by stopping at the fixed points and obtaining an algebraic curve – polynomial function, and
- Mathematically representing the velocity profile in the measurement cross-section without stopping at points.

II METHODOLOGY

The methodology of determining volume flow rate of air flowing in the conduit under steady state conditions is based on calculating local velocities from measured differential pressures and therefore computing the flow rate by velocity integration.

The subject of analysis in this paper was a horizontal closed conduit (Figure.1) in the Laboratory for fluid mechanics and hydraulic machines at the Faculty of Mechanical Engineering-Skopje. The conduit has a rectangular cross-section of 280 mm height and 150 mm width. The conduit length is $10D_h$ = 2 m in order to establish a developed velocity profile. Air flow is provided by a centrifugal fan. Two measuring sections are set at 1200 mm and 1600 mm, respectively, from the beginning of the conduit and normal to the conduit axis. Seven Pitot tubes are placed vertically in predefined fixed measurement points covering the conduit height, at each measuring section, and connected to digital sensors for measuring and data acquisition of total pressure. Moving horizontally along the conduit width, their location is monitored and controlled by a linear displacement transducer. Static pressure is measured and monitored using digital sensor.

CALCULATION MODEL

a) Local velocity

Since the total pressure p_t is sum of the static pressure p_{st} and dynamic pressure p_d of the air:

$$p_t = p_{st} + p_d = p_{st} + \rho \frac{v^2}{2}$$

the local velocity v of the air, averaged over a small region around the Pitot tube nose, can be calculated as:

$$v = \sqrt{\frac{2(p_t - p_{st})}{\rho}}$$

considering compressible flow at low Mach number $M<0,2$ when air compressibility is not influential.

The air density ρ is determined according to the ideal gas law:

$$\rho = \frac{p_{atm} + p_{st}}{R \cdot T}$$

where the atmospheric pressure is p_{atm} = 101325 *Pa* and the gas constant for air is R = 287 *J/kgK*. The temperature is being measured with resistance thermometer.

b) Air flow rate

Three techniques of flow field data monitoring, acquisition and processing are considered for the air flow rate evaluation in a rectangular closed conduit using the velocity-area method.

The first technique considers moving the 7 Pitot tubes along the conduit width while stopping and shortly staying at 7 positions. The arrangement of the measuring points across the conduit width is determined according to the standard [1]. In one operating mode, total pressure with 7 Pitot tubes and digital sensors, and static pressure with one probe, are being measured. For every measured set of values (total pressure, static pressure, temperature), local velocity of air is calculated using the afore-described calculation model.

Separating the zone of the corresponding measuring point, average value of the indirectly measured velocity is calculated as:

$$\overline{v} = \frac{v_1 + v_2 + ... + v_n}{n} = \frac{\sum_{i=1}^{n} v_i}{n}$$

Having 7 Pitot tubes positioned vertically and stopping at 7 (9) points along the conduit width, the air velocity is calculated in 49 (63) measuring points to permit more precise velocity profile determination. Pitot tubes are mounted on a stationary rake in order to explore simultaneously the whole measuring cross-section. The position of the measuring points in the cross-section is shown on Figure 2.

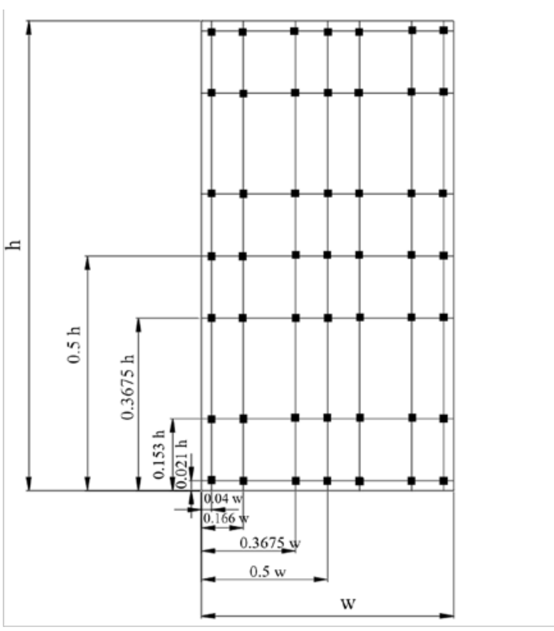


Figure 2. Measuring points in the conduit cross-section

Discretizing the conduit cross-section, the air flow is computed as a sum of the elementary flow rates Q_{ij} which are products of the averaged local velocity v_{ij} and the elementary surface S_{ij} around the corresponding measuring point, i.e.:

$$Q = \sum Q_{ij} = \sum (v_{ij} S_{ij}) = \sum (v_{ij} \cdot \frac{w_i + w_{i+1}}{2} \cdot \frac{h_j + h_{j+1}}{2})$$

where $i, j = 1,2,...7$ are the numbers of the measuring point along the width w and height h, respectively.

The second technique is based on the same measurement procedure with stopping points along the conduit width as in the first case. Interpolating the data from Excel to obtain polynomial equations, the flow rate is calculated. A 6th order or lower order polynomial equation which most accurately describes the indirectly measured values of air velocity along the measuring lines is obtained in Microsoft Excel by the least-squares method:

$$v = C_6 w^6 + C_5 w^5 + C_4 w^4 + C_3 w^3 + C_2 w^2 + C_1 w + C_0$$

The extracted coefficients of the polynomial are used to calculate the air velocity in a numerous arbitrarily chosen points across the conduit width. Applying a discretization scheme as in the first case, the total flow rate of air in the rectangular conduit is evaluated. In addition, the polynomial equations are used in MATLAB within the previously described computing procedure to obtain the air flow rate. Grid of points in which the velocity v is evaluated is represented by the coordinates of width w and height h. A 3D surface is interpolated at the specified grid coordinates. The volume flow rate is computed by applying a function for numerical integration with trapezoidal method, which integrates the inserted numeric data. Since the velocity $v = f(w, h)$, the flow rate in MATLAB is evaluated as:

$$Q = \iint v(w,h) dw dh$$

The third technique is obtaining air flow rate with the application of the graphical software GAMBIT. The total flow rate was calculated as the volume bounded between the curves obtained with interpolation applied on the given coordinates (velocity field) derived from the polynomial functions.

c) Average velocity of the conduit

After calculating the air flow rate, the average velocity of the conduit is evaluated as:

$$v_{ave} = \frac{Q}{A} = \frac{Q}{w \cdot h}$$

Having the velocity profile for the cross-section, the location of the average velocity can be defined by width and height.

III RESULTS

a) Sampling time of total pressure

In one operating mode, total pressure with 7 Pitot tubes and digital sensors, and static pressure with one probe, are being measured during 5 minutes and data acquisition is conducted with sampling time of 0,2 s, while staying at each point for 20 s. Local velocity of air is calculated for every measured set of values (total pressure, static pressure, temperature).

The choice of the sampling time is based on pressure measurements at 1200 mm length of the conduit when the Pitot tubes are fixed at the center.

Figure 3 shows the time averaged values of total pressure measured with the central probe using different sampling time of

0.01 s, 0.05 s, 0.1 s and 0.2 s. Moving average trend line is used to smooth the pressure fluctuations.

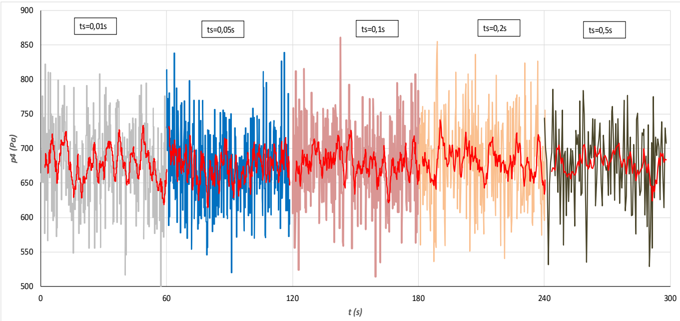


Figure 3. Time averaged total pressure measured using different sampling time

This test was done in order to show that the sampling time does not affect the calculated average local velocity because of the presence of pulsations in the fluid flow. Based on the measurement results, it was concluded that:

- The duration time of the sampling process does not have an influence on the calculated average local velocity and consequently all measurements are continued with sampling time of 0.2 s;
- The sampling time of 0.01 s, 0.05 s, 0.1 s and 0.2 s give similar trend of the moving average unlike 0.5 s which indicated that most favorable conduction of the measurements is with sampling time of 0.2 s as precise enough and least data consuming.

b) Technique for velocity profile measurement

The velocity profile in cross-section of the duct was defined with following techniques:

A. Technique 1 - velocity profile by average local velocity in some stop points of the cross section area

This technique understands measuring the local velocity in some predefined position (defined as percent of length and width) in the cross section (previously shown in Figure 2) with the probe for velocity measurement, and velocity profile development based on that data. This approach for measurement was applied by stopping the stationary array of 7 Pitot tubes positioned vertically at 7 (9) points along the conduit width and calculating the local velocity as average value of the total pressure measured. Using the first technique along with the velocity-area method for calculating the air flow rate, the averaged values of the velocity, at the predefined points across the conduit width were calculated for different test conditions. Figure 4 present the horizontal velocity profile along the duct width, presented by averaged local velocities. The results are given for measurements at the first section at 1200 mm conduit length.

Taking into account that the vertical velocity profile is measured at the same time, the net of measuring points in the cross section can be defined by the position of the probes used for calculation of air flow rate.

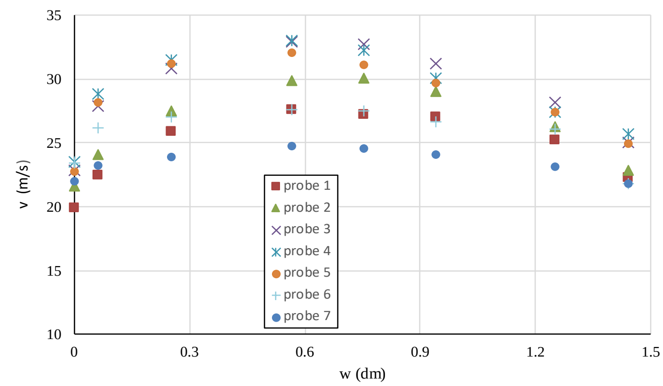


Figure 4. Horizontal velocity profile presented by averaged velocities in fixed stopping points along the conduit width

B. Technique 2 - velocity profile by semi continual measurement of local velocity –stopping in some point of the cross section area

This technique consists in continuous monitoring and data acquisition of the velocity profile with the measuring device. During the monitoring and data acquisition, the stationary rake of Pitot tubes is stopped at predefined points. The technique includes all the measurement points, i.e. the velocities are measured both in the stopping points as well as in the passage between two consecutive stopping points.

The graph given in Figure 5 shows the measured velocity distribution in the conduit cross-sectional area when using the semi continual measurement of velocity. The averaged local velocities determined by the first approach are given with dominant symbols.

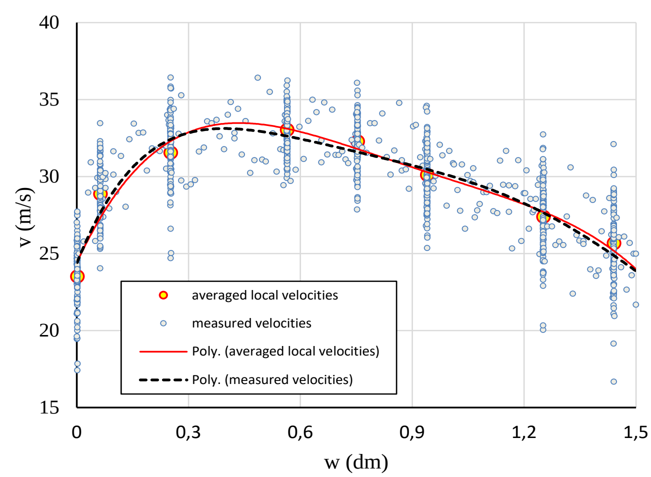


Figure 5. Horizontal velocity profile presented by semi continual measurement of velocities

The comparison of the values of the measured velocities by applying the both techniques i.e. the semi continual method and the method of local averaged velocities measurements shows close agreement in the velocity profile definition. Compared to the first approach for defining the velocity distribution, the second technique considers not only the measurements in the stagnant points, but also measured values between two consecutive points, thus allowing more complete definition of the velocity profile.

C. Technique 3- velocity profile by continual measurement of local velocity (different movement speed)

This technique considers continuous movement of the Pitot tubes along the measuring line without stopping at points, employing different movement speed. The velocity profile measurement by continuous movement of the stationary rake with Pitot tubes is performed for the two measuring sections at 1200 mm and 1600 mm length of the conduit with different constant movement speed given in table 1.

Table 1. Different movement speeds of the Pitot tubes stationary array along the measuring lines at 1200 mm and 1600 mm

Movement speed no.	v_1	v_3	v_5
Meas.sect.	[m/s]	[m/s]	[m/s]
1200 mm	0.03	0.041	0.0535
1600 mm	0.009	0.021	0.044

Figure 6 shows the comparison between the velocity profile measured with continuous movement of the Pitot tubes vertical array (technique 3) and the average local velocities in the stopping points (technique 1). The given results are related to the central probe (no.4) at 1200 mm conduit length.

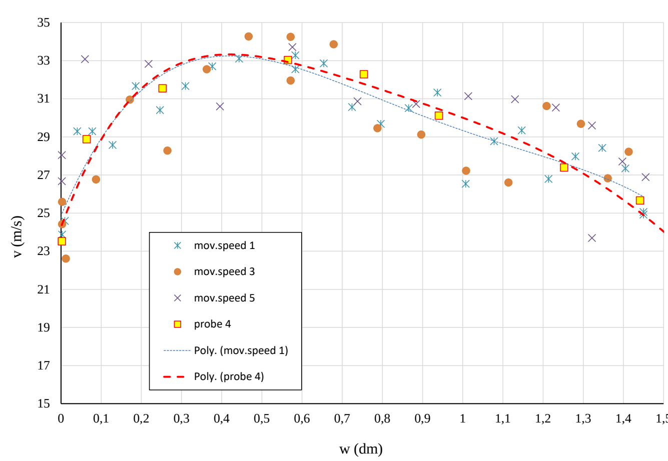


Figure 6. Horizontal velocity profile presented by continual measurement of velocities (1200 mm)

Figure 7 shows the comparison between the velocity profile measured with continuous movement of the Pitot tubes vertical array (technique 3) and the average local velocities in the stopping points (technique 1) for the central probe (no.4) at 1600 mm conduit length.

It can be concluded that there is a close agreement between the velocity distribution results from the measurements with the applied method of continuous movement and the applied method with local averaged velocity measurements. The velocities measured with lower movement speed more closely present the shape of velocity profile in the conduit cross-section.

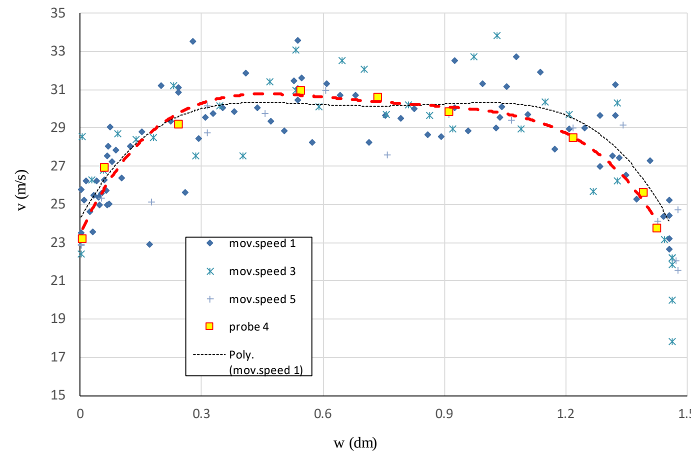


Figure 7. Horizontal velocity profile presented by continual measurement of velocities (1600 mm)

IV Results of Air Flow Rate Calculation

The velocity profiles obtained by the above described techniques can be further used for determining the air flow rate in the closed conduit by the velocity-area method.

A. CALC-Technique 1 - Averaged local velocities along with conduit cross-section discretization

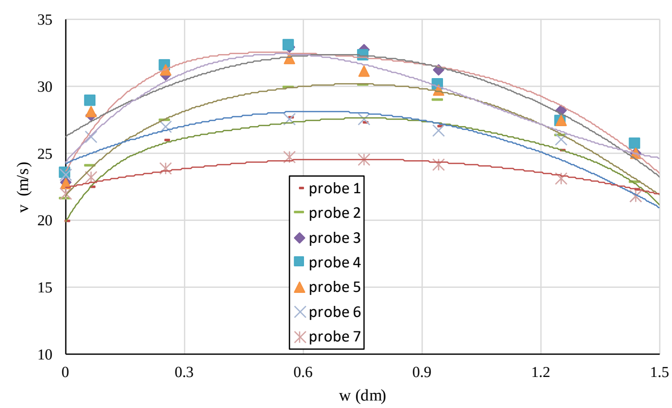


Figure 8. Polynomial functions derived from the measured local velocities at flow regime no.1

The calculation of the flow rate is performed in Excel. Dividing the conduit cross-section in elementary surfaces around the measuring points, and multiplying these areas by the respective local averaged velocities obtained by the first technique, the elementary flow rates were calculated and their sum gives the total air volume flow rate as a result in Excel. In addition, the numeric data is used in MATLAB where grid of points in which the local average velocity *v* is already evaluated is represented by the coordinates of width *w* and height *h*. The numeric data is integrated with trapezoidal method. Applying this method, the flow rate of air at two different flow regimes at 1200 mm of conduit length obtained in both Excel and MATLAB is 1,157 m^3/s and 0,622 m^3/s.

B. *CALC-Technique 2 – Using mathematical functions for describing the velocity field*

Applying interpolation between the values of local averaged velocity measured at the stopping points, a 6^{th} or lower order polynomial is obtained. The equation describes the velocity distribution along the channel width. Figure 8 and 9 shows the function obtained for each probe for the two different flow regimes, respectively.

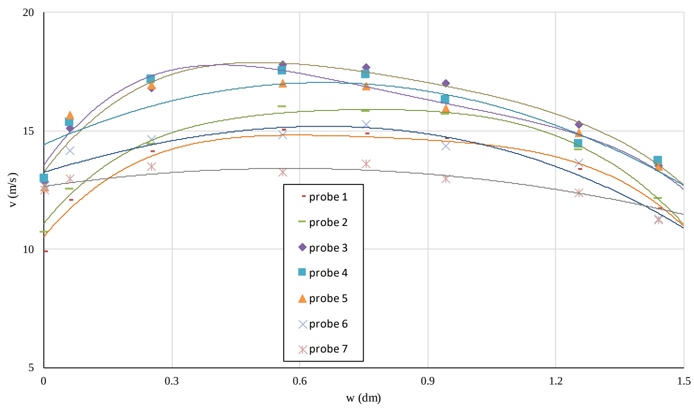
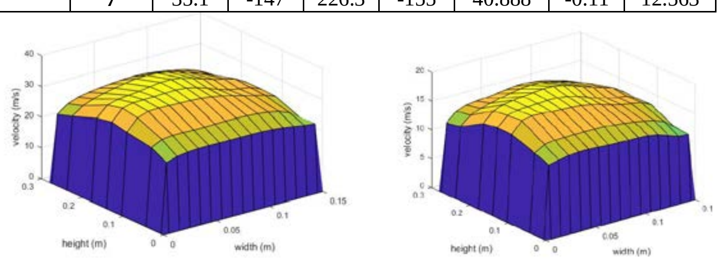


Figure 9. Polynomial functions derived from the measured local velocities at flow regime no.2

The obtained equations were used in Excel and MATLAB as shown on Figure 10, to evaluate the air flow rate.

Table 2. Coefficients of polynomials for velocity profile

		Coefficients of the 6^{th} order polynomial						
Flow regime	Probe No.	C_6	C_5	C_4	C_3	C_2	C_1	C_0
1	**1**	-38.4	185.8	-354	336.1	-172.8	50.7	19.8
	2	-48.3	231.5	-425	374	-173.64	49.1	21.6
	3	-129	601.7	-1079	930	-405.85	89.5	23.1
	4	-136	635.5	-1143	994.6	-443	97.1	23.8
	5	-73.3	364.9	-712	690.1	-351.6	88.8	22.98
	6	-43.2	203.4	-385	366.5	-181.1	43.1	23.56
	7	11.1	-35.6	26.6	19.66	-36.1	16.65	21.98
2	**1**	-32.9	164.8	-323	309.8	-152.37	38.26	10.17
	2	-40.2	185.3	-330	285.8	-129	33.26	10.879
	3	-53.9	251.9	-453	394.7	-178.23	42.3	12.9
	4	-68.1	312.1	-549	467.8	-205.85	45.56	13.18
	5	-57.6	273.6	-506	460.9	-218.1	49.81	12.996
	6	-26	118.3	-213	193	-92.75	22.65	12.731
	7	35.1	-147	226.3	-155	40.888	-0.11	12.563



a) b)

Figure 10. Graphical representation in MATLAB for flow regime a) no.1 and b) no.2 at 1200 mm section

C. *CALC-Technique 3 – Using graphical software for describing the velocity field*

The third technique of air flow rate determination with velocity-area method employs a graphical software. Creating a net from the polynomials that describe the velocity profile along the cross-section height and width, respectively, a curved 3D surface is created under which the volume i.e. flow rate is evaluated. The approach was implemented in GAMBIT (Figure 11).

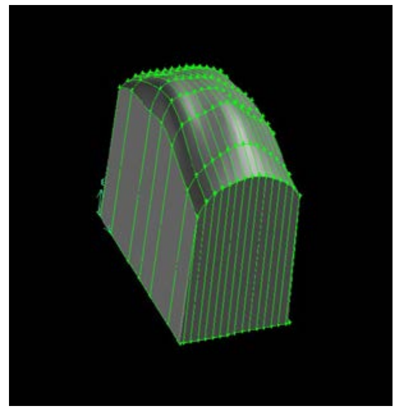


Figure 11. Graphical representation in volume evaluation in GAMBIT for flow regime no.1

Technique no.	Technique 1	Technique 2	Technique 3
Flow reg.no.	Q (m^3/s)	Q (m^3/s)	Q (m^3/s)
1	1.157	1.1	1.12
2	0.622	0.603	0,612

The obtained results for air flow rate, on base of tree techniques for its calculation shows a difference of ± 2,4% refer to average value of measured technique.

The average cross section velocity of the measured regime is given in table 3:

Table 3. Evaluated average velocity pf the cross-section conduit

Flow regime no	v_{ave} (m/s)
1	26,82
2	14,57

V Non-uniformity of Cross Section Fluid Flow Field

The velocity distribution measurement at 1200 mm and 1600 mm conduit length shows different shape of the velocity profile. The velocity profile measured at 1600 mm length than at 1200 mm (Figure 12) is more uniform which indicates the velocity profile development along the conduit.

The flow field uniformity at both measuring sections is given in Figure 13 a) and b).

The results for the uniformity of fluid flow cross section velocity profile shows that at distance of 1600 mm the velocity profile has a core of flow more symmetrical both horizontally and vertically at the intersection.

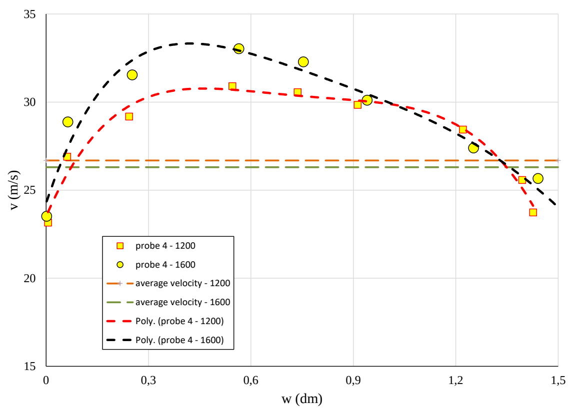
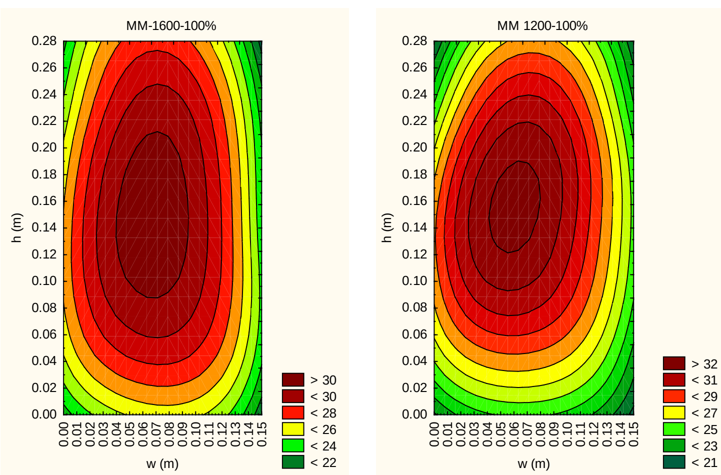


Figure 12. Velocity profile and average velocity at 1200 mm and 1600 mm conduit length



a) 1600 mm b) 1200 mm

Figure 13. Velocity profile development along the conduit

The possibility of measuring the average cross section velocity in the conduit by installing a velocity measuring probe can be predicted through the defined field of uniformity of the velocity profile in the cross section. The intensity of the average cross-section velocity is same in every one cross section along the conduit, the choice of location to position the measurement probe for velocity depend on the velocity profile at cross section. For the distance of 1200 mm it is yellow region in the cross section, but for distance 1600 mm it is the orange region.

The detailed position of location to place the measurement probe for the average cross section velocity of the conduit can be detected in the intersection between the velocity distribution in the cross-section and the calculated average velocity. The location is defined by conduit width and height, which allows using one probe (set at fixed height) and positioning it at the necessary width. This gives the opportunity to use only one probe in fixed position connecting it to digital sensor for the upcoming measurements, without the need of employing the whole stationary array of probes.

VI Conclusion

Fluid flow rate is a parameter in the hydraulic systems whose determination is followed by uncertainty, especially in the case of compressible fluids. In this paper, flow rate determination in a rectangular closed conduit is analyzed by using the velocity-area method which enables the flow rate to be deduced from the measurement of local fluid velocities at a cross-section of the conduit by velocity distribution integration over that cross-section. Different techniques of velocity profile measurement are applied. The results show that the technique with semi-continuous measurement of local velocity is the most accurate since it ensures definition of the average local velocities in predefined stopping points as well as measuring the velocities between two consecutive stopping points. Using algebraic interpolation of the velocity profiles to obtain the law of velocity distribution in the cross-section and applying the velocity-area method, the air flow rate in the rectangular conduit is determined. The flow field non-uniformity is analyzed by the change of the velocity profile along the channel with the aim to define a region where the average velocity in the conduit cross-section would be measured, intending to set only one probe for velocity measurement in the location where the average velocity is expected according to the previous measurements. This way, there would be no need to measure the velocity profile at each experimental test.

The conclusions given in this paper contribute to the approach to flow rate determination as well as control procedure and suggested approaches for velocity profile measurements.

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