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DECREASING OF VOLUME FLOW-RATE MEASUREMENT ERROR{PRIVATE } IN MODIFIED AVERAGING IMPACT TUBES

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Abstract: The criteria for classification of averaging impact tubes are introduced (the art of measuring of reference pressure, the construction of the primary device, the number of ports and their displacement, the way of taking of total pressure).
and some technical solutions are presented. Mathematical model of averaging impact tube is introduced and the correction factor is derivated. This factor takes into account the fact, that the output signal from differential pressure transducer is proportional to the average of dynamic pressures (velocities in second power) but the flow-rate is proportional to the average of velocities. Author introduced proposal of independent pressures measurement and calculating velocities in front of these ports in purpose of estimating of velocity distribution and than calculating flow-rate analytically.

Keywords: Flow measurement, Velocity measurement, Mathematical modelling of flowmeters, Insertion meter, Averaging impact tube.

1 INTRODUCTION

Averaging impact tubes (known as Annubar, Delta-Tube, Beta Probe) enable the measurement of volume flow-rate or mass flow-rate on the base of the averaged dynamic pressures. These dynamic pressures are sensed in some places along the sensor. Averaging impact tubes are sampling flowmeters because they enable to take information about the flow profile only from some points in the flow area [1]. They are also insertion flowmeters [2, 3] and they give permanent pressure drop but much smaller than orifices.

Their advantages are: low permanent pressure loss, capability of inserting the probe with velocity sensor into the operating conduit, relatively low cost. The disadvantages of averaging impact tubes are: low rangeability, low accuracy and essential influence of ambient conditions (pollution, pressure, temperature and composition of gases).

The flow-rate is calculated on the base of the difference of pressures averaged in the upstream site of tube and the pressure taken from reversed port or averaged outlet pressures or static pressure taken by the pipe wall. Taking pressure from reversed port of the tube is more convenient [4, 5, 6, 7] than taking static pressure from pressure port in the wall of the conduit [3, 8, 9, 10].

The popularity of these flowmeters is confirmed by many producers: Auxitrol LTD, Brandt Industries Inc., Dietrich Standard Corporation, Honeywell-Austria Gesellshaft M.B.H., Industrial Measurement Devices LTD, Meriam Instruments, Mid West Instruments, Tekflo Limited, Validyne Engineering Corporation. Other suppliers are given in [3, 11, 12]. Good describes [13] trends in flow measurement and introduces the averaging impact tubes as offering 50% cost saving and 95% lower permanent pressure loss in comparison to the orifice plate. In 1983 author installed Annubar

(Dietrich Standard Corporation) with the hot-tapping technology in the pipe with the rough water and with diameter of 1,2 m. On the same pipe the segmental orifice and ultrasonic flowmeter were installed. During the exploitation the ports were clogging and it inspired author to make some considerations with the problem of using averaging impact tubes and their metrological properties [14, 15, 16, 17].

The problems connected with averaging dynamic pressures in the tube and with changing of resistances of ports inspired author to propose the construction with independent measurement of each dynamic pressure [18].

2 CLASSIFICATION OF AVERAGING IMPACT TUBES

Analysis of literature [2, 3, 4, 5, 12, 19, 20, 21, 22, 23] enabled to formulate the criteria for classification of averaging impact tubes:

1. The art of measuring of reference pressure,
2. The construction of the primary device,
3. The number of ports and their displacement,
4. The way of taking of total pressure.

2.1 Art of the reference pressure measurement

In Fig. 2 three possibilities of the reference pressure measurement used in averaging impact tubes are introduced.

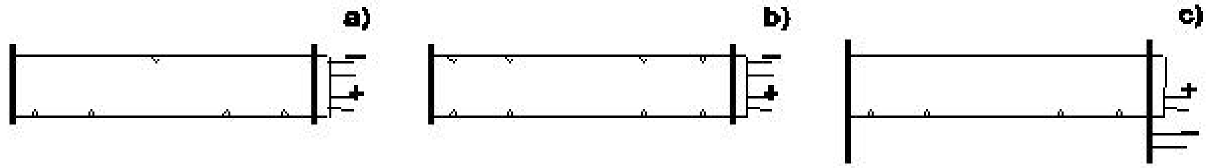

Figure 1. Reference pressure measurements.

The art as in Fig. 1a is introduced in [2, 4, 5, 7, 22, 24, 25]. It gives the greatest pressure difference, but when the port from outlet side will be clogged, the measuring error can be great. Second art shown in Fig. 1b gives averaging of four or more [3, 22, 24, 26, 27, 28] velocities and gives about two times greater dynamic pressure than the art showed in the Fig. 1c [3, 8, 9, 10, 19,]. The third art demand proper making of the static pressure port and it is described in [3].

2.2 Construction of the primary device

The technical solutions of averaging impact tubes are introduced in Fig. 2: a) half tube (covering only radius of the pipe) for axisymmetrical velocity distribution (authors proposition in [17]); cheeper than full tube and easier for installation in the measuring point, where is not enough place near the conduit, b) full tube (covering full diameter) for normal use, when some distortions of velocity profile can be averaged, c) crossed types (for distorted velocity distribution) [12, 19], d) multiple crossed types (for very distorted velocity distribution - authors proposition in [17]).

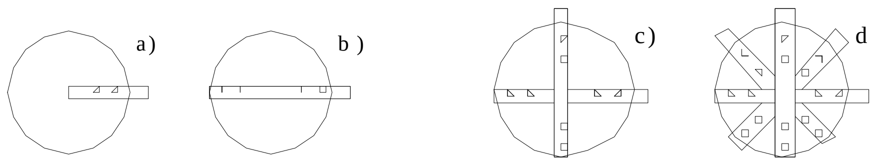

Figure 2. The technical solutions of averaging impact tubes: a) half tube, b) full tube, c) crossed type, d) multiple crossed type.

In Fig. 3 are introduced some cross-sections of sensors which gives more stable work or certain independence on the direction of flowing fluid [20, 23, 29].

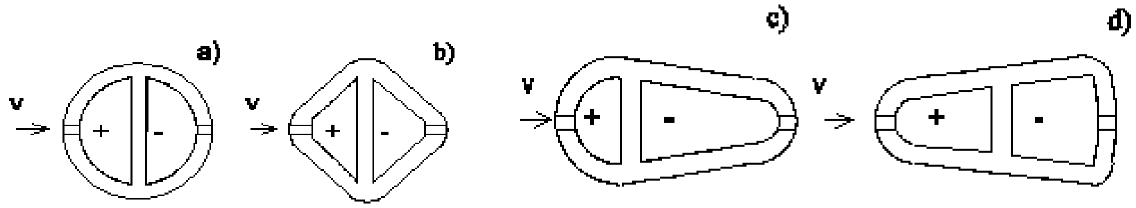

Figure 3. Cross-section shapes of tubes: a) round, b) diamond, c) plane, d) with increasing width.

The shape introduced in Fig. 3a called Annubar or Accutube [2, 20, 23, 28] is used in sensors produced by Validine Engineering Corporation, the diamond shape is presented in [22] and produced by Dietrich Standard Corporation and Honeywell-Austria Gesellshaft M.B.H. In [12, 20] is proposed shape simillar to introduced in Fig.3d [12, 20, 29], which enables to achieve constant tube factor for Reynolds number $Re_D = 6.10^4$ to 7.10^5 [20].

2.3 Number of ports and their location

The number of ports (holes) from upstream side of averaging impact tube is usually four [2, 4, 5, 22, 25, 26, 28], eventually six [3, 10, 24, 27], and very rare - more [9, 19, 21, 23, 24]. There are five locations for one point velocity measurement for volume flow-rate calculation [30]: 1) a centerline position [1, 2] - in the axis of the pipe, 2) a critical position [1, 2, 12] - in the point in which the velocity is equal to the average velocity in the pipe cross section area, 3) an equal surface position - in the point which is on the circle dividing the surface of the pipe for two parts with the same surfaces, 4) an equal volume flow-rate position [31] - in the point which is on the circle dividing the surface of the pipe for two parts in which the volume flow-rates are the same, 5) an optimum position (author's proposition [30]) - in the point in which the error is minimal for chosen Reynolds number span. A centerline position (tube with one port) is proposed in Tekprobes PR2/25 and PR2/13 [25]. Other four positions can be used in location of ports in averaging impact tubes. The critical position was proposed by author in [16], because introduced in literature equal surface position didn't give the velocity equal to the average velocity in the ring. The equal surface position is proposed in [3, 32, 33]. For averaging impact tubes is possible to locate ports with art number 2), 3), 4) and 5) and also in the places according to the numerical integration of profiles [31, 34, 35] (Chebyshev or other method).

3 MATHEMATICAL MODEL

The aim of mathematical model derivation is to calculate enough accurate characteristic of averaging impact tube to enable simulation of errors in expected practical conditions.

3.1 Flow-rate calculation

The impact pressure (dynamic pressure) can be calculated from Bernoulli equation [36]:

$$p_d = r\, v^2 / 2 \tag{1}$$

where v is the fluid velocity, ρ - fluid density.
The impact pressure is the difference between total pressure p and static pressure p_S:

$$p_d = p - p_s \tag{2}$$

The true relationship between the dynamic pressure in the hole in impact tube and the velocity in front of this hole is expressed by [21]:

$$v = k_c\, k_t \sqrt{2\, p_d / r} \tag{3}$$

where k_c is the correction factor taking into account the fluid compressibility, k_t - tube factor.

The factor k_c in the practice is 1 for liquids and also 1 for gases having velocity under 10 m/s. The value of k_t is 1   0,0025 [21], about 1 [5]. The scheme of the averaging impact tube is shoved in Fig. 4.

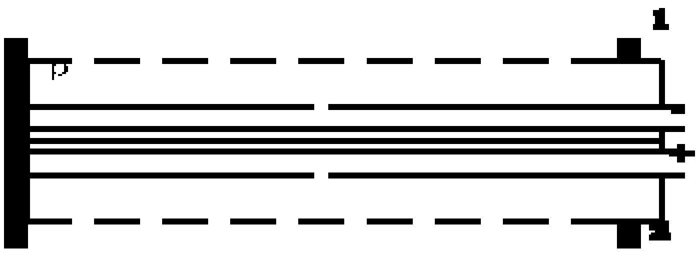

Figure 4. The scheme of averaging impact tube: v_{n1}, ..., v_{nm} are inlet fluid velocities, p_{ni}, p_{oj} - impact pressures, 1 - pipe wall, 2 - the averaging impact tube, D - pipe inside diameter, d - impact tube outside diameter, m and k are numbers of ports on upstream and downstream tube side.

Assuming that k_c = 1 for upstream side and downstream side:

$$p_{dn} = k_{tn}\, r\, v^2 / 2 \tag{4}$$

$$p_{do} = k_{to}\, r\, v^2 / 2 \tag{5}$$

The pressure difference (p_{do} has minus value):

$$Dp = p_{dn} - p_{do} \tag{6}$$

The volume flow-rate can be calculated from:

$$q_v = \sum_{i=1}^{m} v_i A_i \tag{7}$$

where A_i is the part of cross-section area of the pipe in which average velocity is v_i, and usually $A_i = A/m$, where $A = \pi D^2/4$.

3.2 Dynamic pressure averaging in the impact tube

In Fig. 5 is introduced the model of the averaging impact tube.

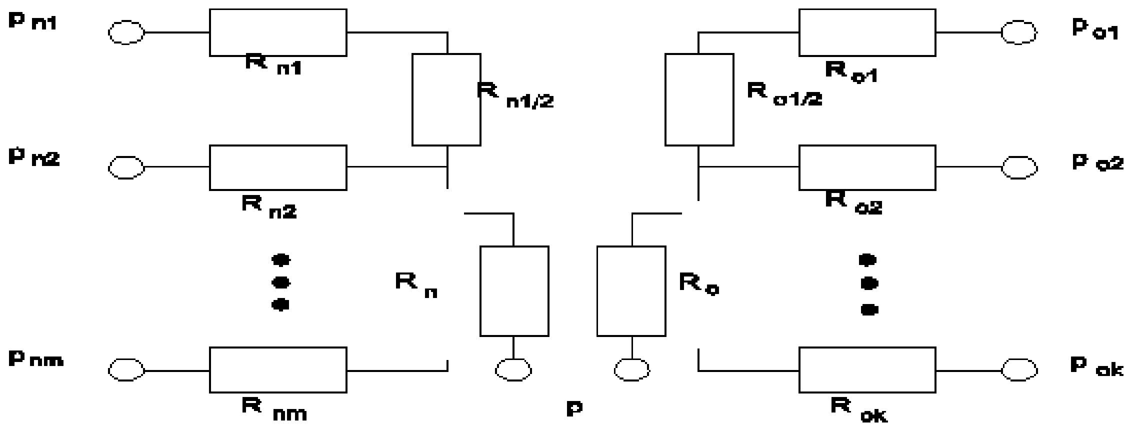

Figure 5. Model of averaging impact tube: R_i - resistances of holes, $R_{i,i+1}$ - resistances in the tube between holes, p_i - total pressure in front of the hole, q_i - flows through holes, $q_{i,i+1}$ - flows in the tube, Δp - output pressure.

Resistances of flow in the tube $R_{ni/i+1}$, $R_{oj/j+1}$ are much smaller than resistances of holes R_{ni} and R_{oj}, measurement of Δp is without flow, and therefore the sum of flows through holes is zero:

$$\sum_{i=1}^{m} \frac{p_{ni} - p_{ns}}{R_i} = 0 \tag{8}$$

where: p_{ns} - average total pressure in the averaging impact tube from upstream direction.

From (8):

$$p_{ns} = \sum_{i=1}^{m} a_i p_{ni} \tag{9}$$

where:

$$a_i = 1 \Big/ \left(R_i \sum_{i=1}^{m} \frac{1}{R_i} \right) \tag{10}$$

The same equation as (8) can be written for downstream direction:

$$\sum_{j=1}^{k} \frac{p_{oj} - p_{os}}{R_j} = 0 \tag{11}$$

From (11):

$$p_{os} = \sum_{j=1}^{k} a_j \, p_{oj} \tag{12}$$

where:

$$a_j = 1 / \left(R_j \sum_{j=1}^{k} \frac{1}{R_j} \right) \tag{13}$$

When the pressures p_{ni} are equal, the average pressure p_{ns} is the same as p_n:

$$p_{ns} = p_n \sum_{i=1}^{m} a_i \tag{14}$$

When the pressures p_{oi} are equal, the average pressure p_{os} is the same as p_o:

$$p_{os} = p_o \sum_{j=1}^{k} a_j \tag{15}$$

where a_i and a_j - coefficients depending on the construction of the tube, and on the base on (14) and (15):

$$\sum_{i=1}^{m} a_i = 1 \tag{16}$$

$$\sum_{j=1}^{k} a_j = 1 \tag{17}$$

For circular cross-section of the tube the pressure difference Δp is almoust two times greater than dynamic pressure (for this situation k_t 1):

$$\Delta p = p_{ns} - p_{os} = 2 \, p_{dns} \tag{18}$$

and the averaged velocity can be calculated from:

$$p_{dns} = \rho \, v'^{\,2} / 2 \tag{19}$$

3.3 Correction factor

The correction factor takes into account the fact, that output signal is proportional to square root of the sum of second power velocity values, but the flow rate is proportional to the average velocity values.

The calculated velocity v' usually is not equal to the averaged velocity in the whole cross-section of the pipe and from (18) and (19) we receive:

$$v' = \sqrt{(p_{ns} - p_{os}) / \rho} \tag{20}$$

The averaged velocity for critical position of ports (holes in tube) in the rings (and for surfaces of rings equal each other) can be calculated from formula:

$$v = 0{,}5 \left(\frac{1}{m} \sum_{i=1}^{m} v_{ni} + \frac{1}{k} \sum_{j=1}^{k} v_{oj} \right) \tag{21}$$

The measured velocity v' must be multiplied by the correction coefficient k_p, in purpose to obtain average velocity in the flow area:

$$v = v' \; k_p \qquad (22)$$

On the base of (2), (4) and for (9) the averaged total pressure can be calculated from:

$$p_{ns} = \frac{k_{tn}\,\rho}{2}\sum_{i=1}^{m} a_i\, v_{ni}^{\;2} + p_s \qquad (23)$$

On the base of (2), (5) and for (12) the averaged total pressure can be calculated from:

$$p_{os} = \frac{k_{to}\,\rho}{2}\sum_{j=1}^{k} a_j\, v_{oj}^{\;2} + p_s \qquad (24)$$

From (20), (21), (22), (23) and (24) the correction factor k_p can be calculated:

$$k_p = \frac{\frac{1}{m}\sum_{i=1}^{m} v_{ni} + \frac{1}{k}\sum_{j=1}^{k} v_{jo}}{\sqrt{2}\sqrt{k_n \sum_{i=1}^{n} a_i\, v_{ni}^2 + k_o \sum_{j=1}^{k} b_j\, v_{jo}^{\;2}}} \qquad (25)$$

For reference pressure measured as static pressure in the port in the pipe wall the measured pressure will be dynamic pressure in upstream direction:

$$\Delta p = p_{ns} - p_s = p_{dns} = \rho\, v'^{\,2} / 2 \qquad (26)$$

Therefore calculated velocity will be as follows:

$$v' = \sqrt{2\, p_{dns} / \rho} \qquad (27)$$

The average velocity for this situation:

$$v = \frac{1}{m}\sum_{i=1}^{m} v_{ni} \qquad (28)$$

The correction coefficient can be calculated from (220, (23), (26), (27), and (28):

$$k_p = \frac{1}{m}\sum_{i=1}^{m} v_{ni} \Big/ \sqrt{k_{tn}\sum_{i=1}^{m} a_i\, v_{ni}^{\;2}} \qquad (29)$$

4 NEW CONSTRUCTION OF AVERAGING IMPACT TUBE

When values of resistances R_i are not equal, the average pressure in the tube will not be the arithmetical average of pressures p_{dni} and p_{doj} (this is the result of equation (13)).

4.1 Construction with the same inner tube resistances

Resistances $R_{i/i+1}$ and $R_{j/j+1}$ influence for pressures averaging. Authors' experiences with the Annubar installed in the pipe of 1,2 m diameter with raw water in the water supply station in Kobiernice near Bielsko-Bia a shoved, that the holes were plugging and the error was great. The flow-rate was almost constant and as comparison were used: existing segmental orifice and installed by author one-path ultrasonic flowmeter UF 211 (Ultraflux - France).

In [15, 37] are some results of error calculation made on analysis of mathematical model of the averaging impact tube, and it is visible, that the error can be significant.

Author proposed [37] small improvement of construction of averaging impact tube - the tubules leading out average pressure are as long as the averaging impact tube (Fig. 4) and it assures the same resistances in the tube. Introduced constructions in handbooks [7 p.197, 22 p.11-28] are only examples of tubes with non symmetrical resistances.

4.2 Direct measurement of dynamic pressures in each port

Further works on mathematical modelling of primary devices of flowmeters [38, 39] shoved, that in sampling flowmeters, when the velocity distribution is distorted, the error can be significant. Author proposed more complicated construction of averaging impact tube [18], and it is shown in Fig.6. For such construction is possible to calculate the parameters of assumed velocity shape and integration of flow-rate analytically.

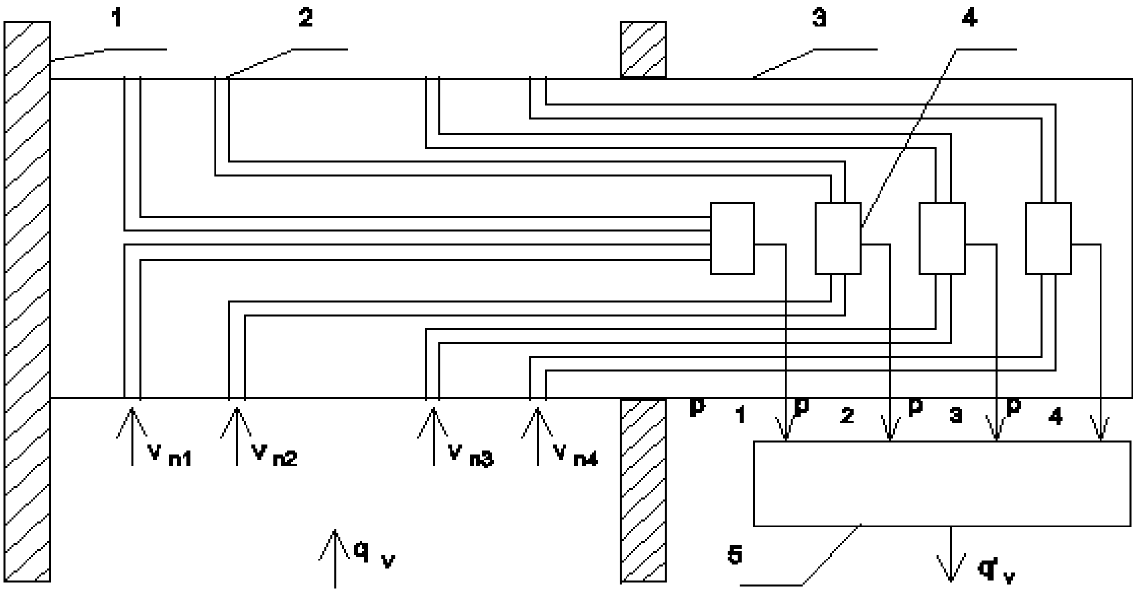

Figure 6. Modified averaging impact tube: 1 - pipe wall, 2 - hole, 3 - primary device of averaging impact tube, 4 - differential pressure sensor, 5 - secondary device of averaging impact tube

4.3 Comparison of traditional and new solution of averaging impact tube

For showing the influence on error some simplifications are assumed: the averaging impact tube
has four holes from upstream side, as the reference pressure is taken the static pressure, the velocity distribution is axisymmetrical therefore only velocities in front of two ports can be taken into account, the resistances of ports (holes) are equal (for two velocities a_i = 0,5), the tube factor k_{tn} = 1 [12]. For these assumptions the formula for k_p on the base of (29) will be:

$$k_p = 0{,}5(v_n1 + v_n2) \,/\, \sqrt{0{,}5(v_n1^2 + v_n2^2)} \qquad (30)$$

The velocity distribution can be described with formula:

$$v = v_o[1 - (r/R)^m] \qquad (31)$$

where v_o is the velocity in the pipe axis, R - pipe inside radius, m - index of the power equal 2 for laminar flow and several to twenty for turbulent flow.

Usually the distances of holes in the tube from the pipe axis are chosen for critical position and for nominal value of flow-rate (in means for nominal value m_n). The average velocity for velocity distribution described with (31) will be:

$$v_s = v_o m / (m+2) \tag{32}$$

During the measurement, when the flow-rate is not nominal, the points of dynamic pressures measurements are not in critical position and the correction factor is also not nominal. The relative error of flow-rate measurement on the base of (26), (29) and (32) can be calculated as the function of m according to equation (33) and some values are presented in table 1.

$$\delta = \frac{0{,}5(m+2)\left[2 - (r_{1n}/R)^{m_n} - (r_{2n}/R)^{m_n}\right]\sqrt{[1-(r_{1n}/R)^m]^2 + [1-(r_{2n}/R)^m]^2}}{m\sqrt{\left[1-(r_{1n}/R)^{m_n}\right]^2 + \left[1-(r_{2n}/R)^{m_n}\right]^2}} - 1 \tag{33}$$

Table 1. Relative error of flow-rate measurement

{PRIVATE **}** m	2	4	6	8	10	12
δ [%]	- 3,85	- 0,37	- 0,05	0	+ 0,29	+ 0,73

The method errors are not so great, but the construction as in the Fig. 6 enables on the base of two velocities (v_1 in the distance of r_1/R and v_2 in the distance of r_2/R) to calculate two parameters (v_o and m) characterizing the model of velocity distribution expressed with equation (31) and than to calculate flow-rate from:

$$q_v = \pi R^2 v_o m / (m+2) \tag{34}$$

This art of flow-rate measurement has no method error as it is in the classic averaging impact tube with averaging of dynamic pressures.

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