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INFLUENCE OF DIAPHRAGM EDGE ROUNDNESS ON THE MEASURED FLOW RATE

ION DOSA[1]

Abstract: *The paper presents the results obtained in the study of influence of the diaphragm edge roundness on the measured flow rate. The possibility to regard the rounded edge diaphragm as a quarter of circle shaped nozzle is also examined.*

Key words: *diaphragm, edge roundness, nozzle, flow rate.*

1. Introduction

In the last period the modern flow metering devices are wide spread.

Such devices as ultrasonic flow meters have multiple advantages among which the most important is that there is no need to shut down the flow or cut the pipe. The ultrasonic flow meters that consist in a pair of sensors that the user attaches to the outside of pipe are easy to install.

There are also disadvantages in using ultrasonic flow meters, such as [1]:

- If there are too few particles, then the reflected signal may not be strong enough to process;
- If there are too many particles, then the measured velocity may measure the fluid velocity at the pipe wall and not represent the average velocity in the pipe. A distorted velocity profile also can adversely affect the measurement.
- Ultrasonic flow meters consist of a pair of sensors that the user attaches to the outside of pipe where the inside diameter and internal condition of the pipe may not be known accurately. In such an installation, the accuracy of the flow rate is questionable, even if the sensors can measure velocity with no error.
- Ultrasonic flow meters have had difficulty measuring in stainless-steel tubing. In these installations, ultrasonic energy can travel in the pipe and create strong return signals from upstream and downstream fittings.

As a result classical methods of measuring flow rates, as constriction devices like diaphragms, nozzles and Venturi tubes are still used especially for measuring compressed air flow rate and natural gas flow rate in low pressure pipelines.

A short review of constriction devices reveals a great variety of them.

In case of diaphragms, as known, the sharpness of edges must be carefully considered, especially the upstream edge, which must be free of scratches, indents and casts.;

In real life, fluids that flow through constricting devices [fig. 1], are usually far from clean [2], [3], small particles and moisture may affect the edges of diaphragms through corrosion.

[1] Dept. of Machines, Installations and Transportation, University of Petroşani.

In order to illustrate the influence of edge roundness of diaphragm on flow rate, a normalized diaphragm is used as base and four diaphragms are built with rounded edges with radius r as follows:0,5 mm, 1,0 mm, 1,5 mm, 2 mm (fig. 2)

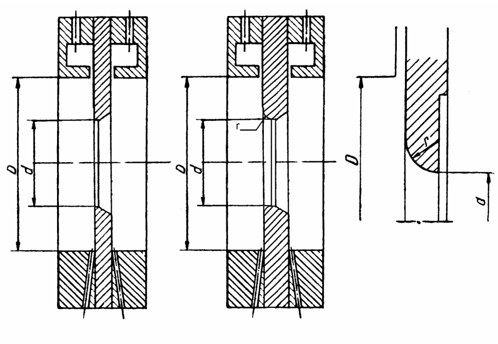

Fig.1. *Diaphragms and nozzle. a-normalized diaphragm, b-diaphragm with round edge, c-quarter of circle shaped nozzle*

Fig. 2. *Diaphragms with round edge*

2. Flow rate calculus using constriction devices

A pipeline is given in which a fluid flows. A constriction device is mounted in the pipeline. In the case we consider the constriction device is a diaphragm.

As known, an amount of the potential energy of the fluid is turned into kinetic energy, the medium velocity of the flow increases in the constricted section, the static pressure in this section drops. As a result the pressure downstream will be smaller that the upstream pressure.

In order to determine the connection between pressure drop and fluid flow, the continuity equation and the Bernoulli equation is used.

The expression of volumetric flow rate of an incompressible fluid can be calculated using [4]:

$$Q_v = \frac{\mu \cdot \tau}{\sqrt{1-\mu^2 \cdot m^2}} S_0 \sqrt{\frac{2}{\rho}(p_1 - p_2)} \frac{m^3}{s} \qquad (1)$$

where: μ is the coefficient of jet narrowing; τ velocity correction coefficient; m span ratio $m = S_0 \cdot S_1^{-1}$; S_0 area of the constriction device; S_1 pipeline area at working temperature; p_1, p_2 upstream and downstream pressure near the constriction device.

As μ and τ can be determined only connected, by definition, the flow rate coefficient is:

$$\alpha = \frac{\mu \cdot \tau}{\sqrt{1-\mu^2 \cdot m^2}} \qquad (2)$$

As a result the expression of volumetric flow rate became:

$$Q_v = \alpha \cdot S_0 \sqrt{\frac{2}{\rho}(p_1 - p_2)} \qquad (3)$$

In case of compressible gases or steam, the changes in specific density must be considered in case of important pressure drops. An adiabatic process can be considered for the gas with no important errors. Using the variation of the specific density for adiabatic processes and substituting in the energy equation the volumetric flow rate for the gas can be established using [4]:

$$Q_v = \alpha \cdot \varepsilon \cdot S_0 \sqrt{\frac{2}{\rho}(p_1 - p_2)} \tag{4}$$

where ε is the expansion coefficient.

In the process of flow rate calculus the main problem consist in determining the flow rate coefficient α and the expansion coefficient ε.

For diaphragm with oblique front pressure socket the expansion coefficient ε can be calculate*d* using [5]:

$$\varepsilon = 1 - \left(0.3707 + 0.3184\beta^4\right) \cdot A \tag{5}$$

And in case of a nozzle [5]:

$$\varepsilon = \sqrt{B \cdot C \cdot D} \tag{6}$$

in which:

- $\beta = \sqrt{m}$ is the diameter ratio;

- $A = \left[1 - \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}\right]^{0.935}$;

- $B = (1 - \delta p)^{\frac{2}{k}}$

- $C = \left(\frac{k}{k-1}\right) \cdot \left(\frac{1 - (1-\delta p)^{\frac{k-1}{k}}}{\delta p}\right)$

- $D = \left(\frac{1-\beta^4}{1-\beta^4 (1-\delta p)^{\frac{2}{k}}}\right)$

- k is the adiabatic coefficient;

- $\delta p = \frac{p_1 - p_2}{p_1}$ relative pressure drop.

The equation of flow rate coefficient α can be calculated using similar formula for diaphragms and nozzles, using [5]:

$$\alpha = \alpha_0 \cdot r_{\mathrm{Re}} \tag{7}$$

and

$$r_{\mathrm{Re}} = (r_0 - 1) \cdot \left[1 - \frac{(\lg(\mathrm{Re}) - 6)^2}{4}\right] + 1 \tag{8}$$

where α_0 is the flow rate coefficient for smooth pipelines in relation with β^4 and Re, r_{Re} rugosity correction, r_0 factor in relation with the reversed relative rugosity $\frac{k_{echiv}}{D}$ and β^2. Values for α_0, r_0 are given in tables [3]. For $\mathrm{Re} \geq 10^6$ $r_{Re} = r_0$, and for $\mathrm{Re} \leq 10^4$ r_{Re}=1;

Relations can be used for diaphragms in the following conditions: 50 mm $\leq D \leq$ 1000 mm, $0{,}22 \leq \beta \leq 0{,}8$, and nozzles for: 50 mm $\leq D \leq$ 500 mm, $0{,}32 \leq \beta \leq 0{,}8$.

3. The experimental unit

The experimental unit consists in a measuring module (fig. 3) on which the diaphragm, manometer, thermometer and the *U*-tube (filled with water) for measuring the pressure drop on the diaphragm is mounted.

The module is connected through flexible houses to an air compressor an on the other end to a faucet. First on the module the diaphragm with the sharp edge is mounted. After that, the air compressor is started, the faucet is partially opened and the pressure drop h [mm], the pressure upstream the diaphragm p_1 [bar], and the compressed air temperature t_1 [ºC] is measured.

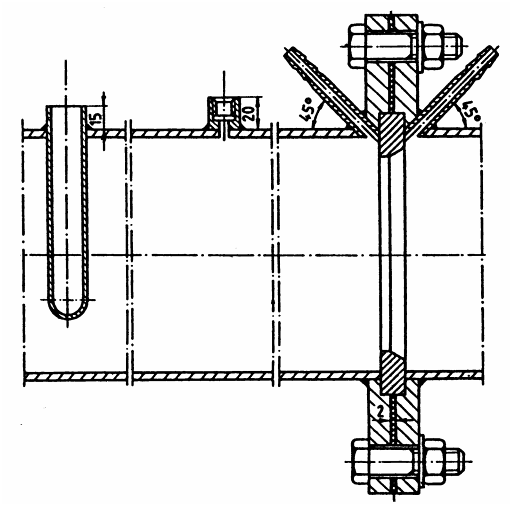

Fig. 3. *The measuring module*

After measuring, the compressor is turned off, the faucet remains in the same position as another diaphragm with rounded edges is mounted (r=0,5 mm).

The measurements are repeated with the new diaphragm, at the same pressure.

When all the modified diaphragms (with rounded edges r=1 mm, 1,5 mm, 2 mm) were mounted, the normalized diaphragm with sharp edge is mounted again, the compressor is turned on and the faucet is opened in another position.

The measurements are carried out again, as above.

Diameter of the module pipeline D=50 mm, the diaphragm diameter d=15,5 mm, and the atmospheric pressure p_0=940 mbar.

4. Results

The measured temperature of the compressed air t_1=20 ºC .

In table 1 the results of measurements are given, and in the last column the calculated volumetric flow rate can be found.

Primary data for calculus: g = 9,81 m·s^{-2}, the adiabatic coefficient for compressed air k = 1,4, air constant R = 287,14 J·(kg·K)$^{-1}$, water density ρ_{H2O} =1000 kg·m^{-3}, dynamic viscosity of air at 20ºC, η = 18,21·10^{-6} (N·s)·m^{-2}, equivalent rugosity of pipeline k_{ech} = 0,1 mm·

Using data above the span ratio m = 0,0961 and the diameter ratio β = 0,31 were calculated.

Calculated flow rate Table 1

Nr.	p [bar]	h [mm]	Q_v [m^3·s^{-1}]
r=0,0 mm			
1	5,4	50	0,0013
2	3,5	415	0,0045
3	1,7	980	0,0088
r=0,5 mm			
1	5,4	40	0,0012
2	3,5	327	0,004
3	1,7	875	0,0083
r=1,0 mm			
1	5,4	37	0,0011
2	3,5	252	0,0035
3	1,7	640	0,0071
r=1,5 mm			
1	5,4	30	0,001
2	3,5	197	0,0031
3	1,7	538	0,0066
r=2,0 mm			
1	5,4	27	0,00096
2	3,5	174	0,0029
3	1,7	457	0,0063

Values for Reynolds number during calculation were between 10059 and 38595.

In figure 4 data from table 1 is represented, grouping flow rates in connection to the results obtained for the normalized diaphragm with the sharp edge, as it gives the accurate data.

Figure 4 reveals, as expected, that with the increase of the radius of the edge the error in flow rate calculus raises, since the pressure drop is smaller.

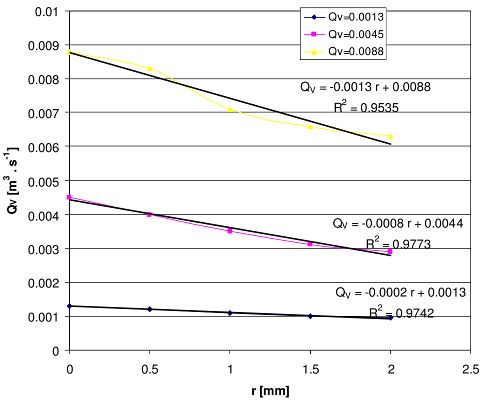

Fig. 4. *Flow rate variation*

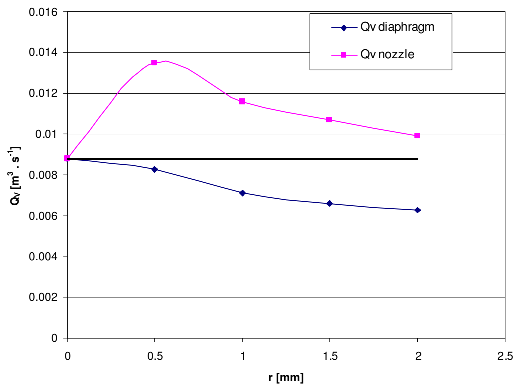

Fig. 5. *Comparison of flow rate for diaphragm and nozzle*

In the same time, for increased flow rates the error is bigger, in connection with Re number which affects the flow rate coefficient.

Analyzing the data above, and observing that the rounded edged diaphragms resembles with quarter of circle shaped nozzles, the idea of calculating the flow rate as if the constricting devices were quarter of circle shaped nozzles occurs.

Calculus are made for the flow rate Q_V = 0,0088 m^3·s^{-1}, considering only the modified diaphragms.

Results can be found in table 2, where the errors were determined considering the accurate flow rate Q_V = 0,0088 m^3·s^{-1}, and values of flow rate calculated for nozzle (third column).

Comparison of flow rates Table 2

r [mm]	Q_v [m^3·s^{-1}] diaphragm	Q_v [m^3·s^{-1}] nozzle	Error [%]
0,0	0,0088	0,0088	0,00
0,5	0,0083	0,0135	53,41
1,0	0,0071	0,0116	31,82
1,5	0,0066	0,0107	21,59
2	0,0063	0,0099	12,50

Since values for Re number during calculus were between 43294 and 59465, the primary flow rate coefficient was considered constant α_0 = 0,9892.

Analyzing figure 5 and table 2 reveals that increasing the value of edge radius the error in calculating flow rate considering nozzles reduces from 53,41% to 12,5%.

The upper graph is approximating the thicker line which represents flow rate Q_V = 0,0088 m^3·s^{-1} = const.

5. Conclusions

Based on results obtained above conclusions are:

- Rounded upstream edge of a diaphragm induces important errors in calculus of flow rate;
- Errors increase proportional with the radius of roundness;
- For increased flow rates the error is bigger, for the same radius, in connection with Re number which affects the flow rate coefficient.

As figure 5 points, for increased radius values, bigger then 2 mm, the diaphragm turns into a nozzle, since the error drops to zero.

As a result, is established that a nozzle must have a radius greater than 2 mm. Otherwise errors can occur in calculating flow rate.

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