PRESSURE LOSSES IN A CONDUIT WITH A VENTURI TUBE

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UDC 621.643.2

We present the experimental relationships for the coefficient of kinetic flow energy and static pressure as a function of conduit length following a Venturi tube. A formula is proposed for the determination of the coefficient of the hydraulic resistance of the Venturi tube as a function of its structural parameters, as well as a function of the length of the straight segment of the conduit behind the Venturi tube.

In practical applications, extensive use is made of Venturi tubes to measure the flow rate of liquids and gases. Their characteristics as flow meters have been rather fully studied [1-3], but there is little information as to the hydraulic losses which result from the installation of Venturi tubes.

In this connection, we used an installation made up of a KSÉ-5 air compressor, and a receiver from which the air is passed through a measuring diaphragm into a straight line cylindrical conduit segment with a diameter of 53 mm, in which Venturi tubes of various constrictions were set up. The lengths of the conduit segment ahead of and behind the Venturi tubes were more than 45 d, which is sufficient to stabilize the velocity profile. The basic characteristic of Venturi tubes is the constriction ratio

$$n = \frac{F_0}{F_t}.$$

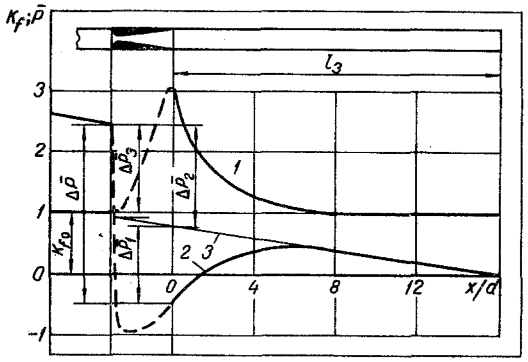

Fig. 1

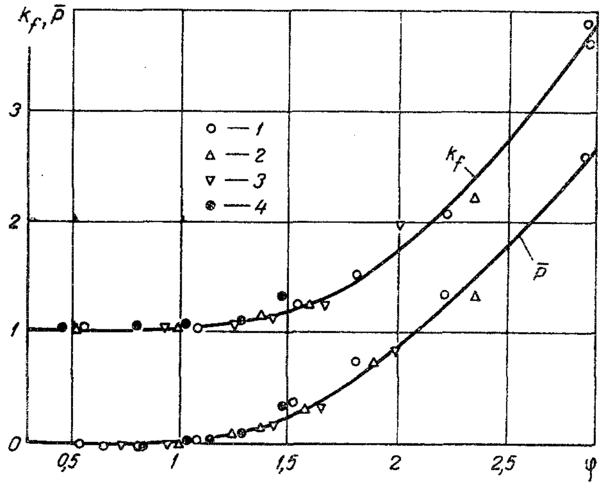

Fig. 2

Fig. 1. Change in the coefficient of kinetic energy (1) and in the coefficient of static pressure (2) along the conduit behind the Venturi tube.

Fig. 2. Coefficient of kinetic energy and coefficient of static pressure in the conduit behind the Venturi tube (with various constriction ratios) as functions of the dimensionless distance: 1) n = 6.15; 2) 3.6; 3) 2.95; 4) 2.05.

Machine Building Institute, Lugansk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 16, No. 4, pp. 731-736, April, 1969. Original article submitted June 24, 1968.

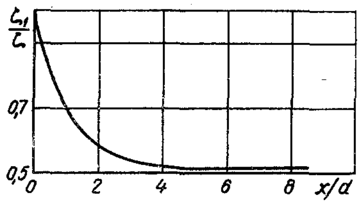

Fig. 3. Ratio ζ_1/ζ as a function of the length of the straight-line segment of the conduit behind the Venturi tube.

The inlet portion of the Venturi tube has a radius of 8 mm; this is followed by a cylinder segment 2 mm in length, and a diffuser with a divergence angle of 6°. At six cross sections of the conduit, following the Venturi tube at distances of x = 0.094d, 0.85d, 1.6d, 2.36d, 4.4d, 11.5d, respectively, and in the section directly in front of the Venturi tube we measured the profiles of the total and static flow pressures along the diameter of the lateral cross section of the conduit. The measurements were carried out with Γ-shaped total- and static-pressure nozzles which were mounted on a positioning device, designed by the Central Aerohydrodynamics Institute. The average velocities of the air flow in the conduit varied from 10 to 40 m/sec, which enabled us to neglect the change in density over the length of the conduit and across it.

An important characteristic of the nonuniformity of velocity distribution through the lateral cross section of the conduit is the coefficient of the kinetic energy of the flow for the given cross section, i.e.,

$$k_f = R^4 \int_0^R w^3 r dr \Big/ 4\left[\int_0^R w r dr\right]^3.$$

Thus, the coefficient k_f shows the extent to which the value of the kinetic energy in this cross section differs from the magnitude of the kinetic energy of the flow, which would be found if the velocities were uniformly distributed.

For the characteristics of the static pressure in the conduit it is convenient to use the concept of the static-pressure coefficient

$$\bar{P} = \frac{P}{\frac{\rho w_{av}^2}{2}}.$$

Processing the experimental data on an electronic computer, we found the quantitative relationships governing the changes in the coefficient of kinetic energy and in the static pressure along the conduit when Venturi tubes were installed in the latter, exhibiting the above-indicated constriction ratios for various flow rates. Figure 1 shows schematically the change in the coefficient k_f (curve 1) and in the coefficient of static pressure $\bar{P}$ (curve 2) along the length of the conduit. For this range of flow rates, the kinetic-energy coefficient k_f and the static-pressure coefficient $\bar{P}$ are independent of the Reynolds number. The sloping line 3 in Fig. 1 shows the pressure losses to overcome the forces of friction to the end of the conduit, according to the Darcy formula

$$\Delta P = \lambda \frac{l_3 - x}{d} \frac{\rho w_{av}^2}{2}.$$

The coefficient k_f falls sharply behind the Venturi tube, over the length of the conduit, whereas $\bar{P}$ increases; the former approaches its value at the inlet to the Venturi tube, whereas the latter approaches the line of the hydraulic gradient.

The quantitative relationship governing the change in the coefficient of the kinetic energy of the flow proved to be similar to that observed in the mixing chamber of an ejector [4], but at the same time there are certain differences. The distribution of the local velocities over the lateral cross section of the conduit are not subject to a universal profile of dimensionless velocity with respect to a dimensionless radius. The change k_f over the length of the conduit can be expressed by an exponential function that is similar in form to the function for the mixing chamber of an ejector [4]:

$$k_f = 1 + 0.02\varphi + 0.04\varphi^4, \tag{1}$$

where for our problem we have

$$\varphi = \frac{R}{a\left(l + x + \frac{b}{n-1} + c\right)}. \tag{2}$$

Here b and c are constants, with b = 202 and c = −34. The experimental data are in good agreement with (1) for a turbulence factor of a = 0.067.

Processing the experimental data and approximating them by the method of least squares, we found k_f as a function of the dimensionless distance φ in the form

$$k_f = k_{f0} + A \exp \frac{B}{\varphi} . \tag{3}$$

In this expression A and B are constants, with A = 54.9 and B = −8.63. For a turbulent flow regime, given an exponential function for velocity distribution [5], we have

$$k_{f0} = \frac{(m+1)^3 (2m+1)^3}{4m^4 (3+m)(3+2m)} .$$

We can draw our conclusions from Fig. 2 with regard to the agreement between (3) and the experimental data.

We were able to approximate the difference between the static pressure determined by the hydraulic gradient (line 3 in Fig. 1) and the actual pressure in the conduit behind the Venturi tube by the following relationship:

$$\Delta P_1 = D \exp \frac{C}{\varphi} \frac{\rho w_{av}^2}{2} . \tag{4}$$

Here D and C are constants, with D = 29.32 and C = −7.03.

Thus, if we know the pressure P_3 in the cross section of the conduit at a distance l_3 from the Venturi tube, where its effect is no longer perceived and for which we know the coefficient of hydraulic friction λ, the static pressure in the segment behind the Venturi tube is given by the expression

$$P_x = P_3 + \lambda \frac{l_3 - x}{d} \frac{\rho w_{av}^2}{2} - D \exp \frac{C}{\varphi} \frac{\rho w_{av}^2}{2}$$

or in dimensionless form

$$\bar{P}_x = \bar{P}_3 + \lambda \frac{l_3 - x}{d} - D \exp \frac{C}{\varphi} . \tag{5}$$

Agreement between (4) and the experimental data is demonstrated in Fig. 2.

We know of the Prandtl formula for the determination of losses in a Venturi tube [6]:

$$\Delta P = \zeta \frac{\rho w_{av}^2}{2} (n^2 - 1). \tag{6}$$

The loss factor is assumed to be ζ = 0.15–0.20. Experiment showed that (6) is valid only for the special case in which the Venturi tube is mounted at the end of the conduit, e.g., at the point where the flow discharges into the atmosphere or into a large-volume reservoir, i.e., in these cases in which there are no conditions suitable for the utilization of the kinetic flow energy. In this case, the pressure losses in the Venturi tube represent the difference between the pressures measured at the inlet to and outlet from the Venturi tube. The pressure losses which arise as a consequence of the installation of the Venturi tube in the conduit – with consideration of the restoration of a certain fraction of the kinetic energy in the form of static pressure – are determined by the difference ΔP_2 between the static pressure ahead of the Venturi tube and the pressure in the conduit without a Venturi tube at the cross section corresponding to the outlet from the tube. The static pressure at this section is found from the hydraulic gradient.

The pressure loss in the conduit – a result of the installation of a Venturi tube, considering that the Venturi tube occupies a portion of the original conduit length – will increase by ΔP_3 (see Fig. 1), which is smaller than the difference ΔP_2 by the magnitude of the pressure lost to friction in a conduit segment equal in length to the Venturi tube.

The difference ΔP_2 is smaller than ΔP by ΔP_1, determined from (4), provided that the length of the straightline conduit segment is sufficient for the complete straightening out of the flow. In this case we must carry out the substitution $\varphi = \varphi_0$ in (4). If the straightline segment of the conduit behind the Venturi tube has a length x – which is inadequate for the complete stabilization of the flow velocity profiles – the reduction in the pressure losses in the system will amount to

$$\Delta P_x = \left(D \exp \frac{C}{\varphi_0} - D \exp \frac{C}{\varphi} \right) \frac{\rho w_{av}^2}{2} .$$

The effect of the straightline conduit segment on the magnitude of the losses in the conduit with a Venturi tube can be accounted for, assuming a resistance factor ζ in (6) in the form

$$\zeta_1 = \zeta - \Delta\zeta. \tag{7}$$

Here

$$\Delta\zeta = \frac{D}{n^2 - 1} \exp\frac{C}{\varphi_0}\left(1 - \exp\frac{C_{ax}}{R}\right).$$

Figure 3 shows the curve for the change in the ratio of ζ_1 for the investigated Venturi tubes for the magnitude of ζ, which is the resistance factor recommended in [6].

It should be noted that the function found for a conduit with a Venturi tube are meaningful even for a conduit with a diffuser, since the presence of a constricting inlet portion of a Venturi tube does not alter the coefficient of kinetic energy for the throat section, relative to the value of this coefficient at the inlet to the Venturi tube [3].

NOTATION

P and ΔP	are the static pressure and its difference;
ρ	is the air density;
w and w_{av}	are the local and the average flow velocities;
R, d, and F_0	are the radius, diameter, and area of the lateral conduit cross section;
l, n, and F_t	is the length of the diffuser portion, the constriction ratio, and the area of the throat section of the Venturi tube;
x	is the difference from the section under consideration to the outlet section of the Venturi tube;
l_3	is the distance from the outlet section to the end of the conduit;
k_f and k_{f_0}	are the coefficients of kinetic energy for nonsteady and steady local-velocity profiles, respectively;
φ and φ_0	is the dimensionless distance and its value when x = 0;
a	is the turbulence factor;
λ	is the coefficient of hydraulic conduit friction;
ζ	is the coefficient of Venturi-tube resistance;
1/m	is the exponent in the formula for the exponential distribution of velocities in a turbulent regime.

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