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EXPERIMENTAL INVESTIGATION OF THE FLOW THROUGH A NON-RETURN DIAPHRAGM VALVE

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Abstract: The non-return diaphragm valve consists of a perforated plate and a rubber diaphragm with a central hole both inserted between a two part wide-angle diverging and converging body. The pressure distribution along the valve axis and flow visualization demonstrated the mechanism and the main source of the energy dissipation. It was found that the diameter of the central hole in a diaphragm and the shape of the unperforated central part of the plate play the crucial role in the process of the pressure losses at low flow rates. At high flow rates the pressure losses are dominated by the hydraulic resistance of the short diffuser and the perforated plate. The measured pressure loss coefficient versus Reynolds number shows the simple exponential dependence: $K = \text{const.}Re^{-1.3}$.

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INTRODUCTION

Non-return valves play a very important role in the operation of many hydraulic systems. The non-return diaphragm valve under investigation is shown in Fig. 1 and consists of a two-part wide-angle diverging-converging body, a perforated plate and an elastic diaphragm. A central part of the plate (called torpedo) is nonperforated and protrudes downstream creating a plug in the diaphragm at the closed position. As the pressure difference across the diaphragm rises the diaphragm is deflected and stretched downstream, initially forming a ring-shaped gap between the diaphragm and the torpedo. When the flow is reversed the pressure difference becomes negative and presses the diaphragm onto the perforated plate, thereby closing the valve tightly.

The flow in the valve is complex and highly turbulent. It is made up of a large separation bubble in the diverging (diffuser) part of the valve body, a jet impingement region in front of the perforated plate, flow through a perforated plate, a recirculation region between the diaphragm and the diverging part of the valve body, and a jet flow issued from the hole of the deflected diaphragm.

This valve offers significant advantages such as:

* droptight closure,
** silent operation,
*** can be installed vertically or horizontally,

but at the expense of relatively high pressure losses. The possibility of the suppression of the pressure losses was the main motivation for these experiments.

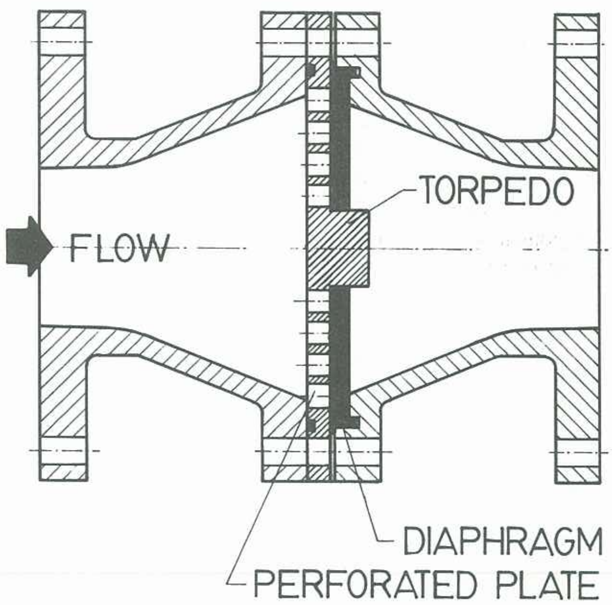

Fig. 1. Non-return diaphragm valve.

EXPERIMENTAL SETUP

A general arrangement of the experimental set-up for the flow visualization and measurements of the pressure losses of the valve for the 80 mm pipe is shown in Fig. 2. The experimental rig consists of a hydraulically smooth 90/79.6 mm in diameter PVC pipe, a valve model and an orifice plate flow meter.

__Valve model__. A valve model was made with transparent perspex. Its external surfaces are perpendicular to form a rectangular parallelepiped. The two parts of the perspex valve body, accommodating a perforated plate and a rubber diaphragm, were clamped between two flanges glued to the pipe ends. In Fig. 3 the side view of the valve model with a stretched diaphragm is shown.

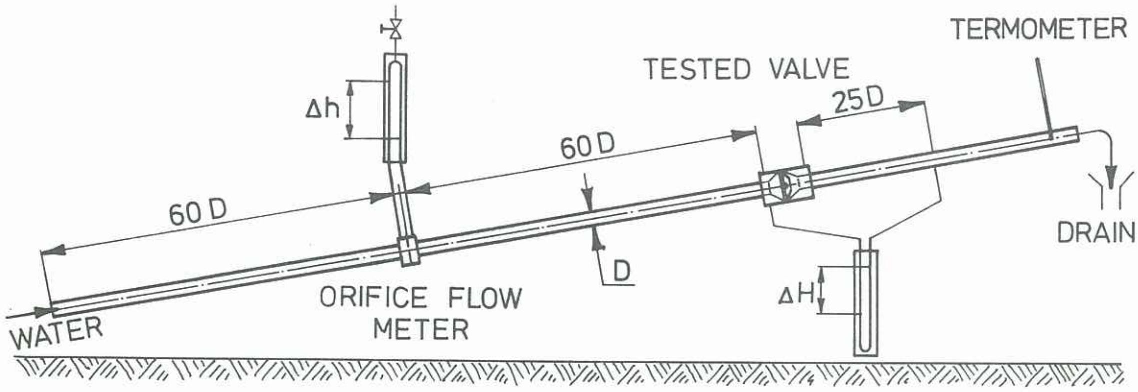

Fig. 2. Experimental water rig.

Perforated plate. A perforated plate of 140 mm in diameter exposed to the flow with a central nonperforated part of about 48 mm in diameter was used. The porosity factor of the perforated part of the plate was 0.42. The diameter of the uniformly (staggered) distributed holes was 12 mm, and the shortest separation between hole axes was 17 mm.

Diaphragm. The two 8 and 12 mm thick rubber diaphragms having a 38 mm diameter central hole were used. A black general purpose EPDM rubber was used to cast the diaphragms. Typical properties of the EPDM rubber are

* density: 1370 kg/m^3
* tensile strength: 6.96 MN/m^2
* elongation at break: 545 %
* hardness (IRHD): 67
* the corresponding Young's modulus (Allen et al., 1966): 6.33 kN/m^2.

Flow visualization. Despite of the flat external perspex walls of the valve model some optical distortion could not be avoided because of the difference of the water and perspex refraction indices. The flow visualization experiments were performed at the maximum flow rate of water:

- Flow rate of water $Q = 16.6$ l/s
- Velocity of water $U_{pipe} = 3.34$ m/s
- Reynolds number $Re_{pipe} = 260\ 000$
- Water head loss $\Delta H = 5.8$ m H_2O
- Temperature of water $T_w = 21.2$ °C

The flow in a valve was highly turbulent and visualization with a dye technique had rather limited application. The flow was traced quite successfully by an upstream introduction of air which appeared in the valve in the form of large number of small bubbles. The buoyancy effect could be neglected at high flow rates. Illumination was provided by a 10 mm wide sheet of intense light, which was produced by a 250 W lamp and using a cylindrical collimating lens joined to the standard optics of a slide projector.

Pressure loss measurement. The downstream static pressure impulse hole was located 25 diameters downstream from the valve. This arrangement was necessary to take into account the valve flow effect on the total pressure losses introduced by the valve.

RESULTS AND DISCUSSION

Diaphragm upstream flow. The oncoming axisymmetric fully developed pipe flow which enters the wide-angle diffuser (42°) and being separated from the wall, and impinges on the perforated plate is shown in Fig. 4. One can see a separation bubble filled with a large-scale turbulent fluid surrounding the impingement region.

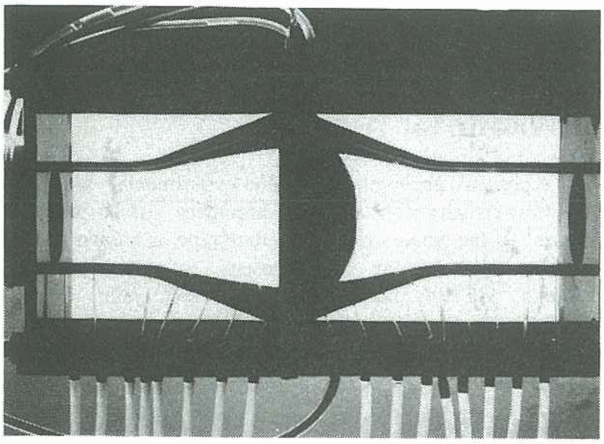

Fig. 3. Model of the valve.

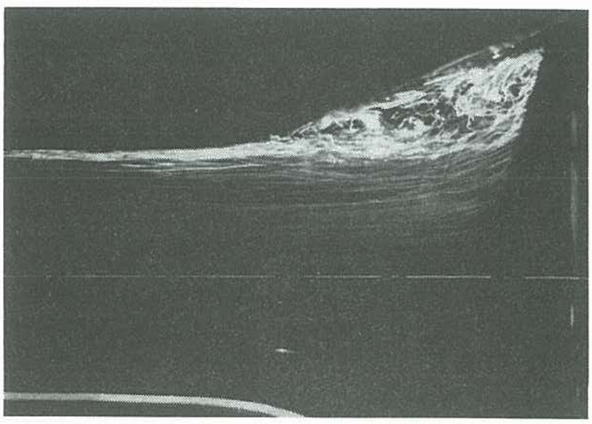

Fig. 4. Separation bubble in a wide-angle diffuser part of the valve.

The flow pattern between the perforated plate and deflected diaphragm was not visualized but it is clear that a multi-jet produced by the perforated plate hits the diaphragm and its kinetic energy is dissipated in a highly turbulent flow. Next, the fluid accelerates radially toward the valve axis and reaches the opening of the deflected diaphragm.

Diaphragm downstream flow. The flow issued from the opening of the deflected diaphragm has the form of an axisymmetric highly turbulent jet (Fig. 5). At low flow rates the deflection of the diaphragm is small and the jet is issued only from a narrow ring-shaped gap between the diaphragm hole edge and the torpedo. At high flow rates the diaphragm is strongly deflected taking a shape of the spherical belly (Fig. 3) being the result of the uniform distribution of the pressure difference along the radius. Directly behind the deflected diaphragm there is a recirculation region terminated downstream with the growing mixing region of the diaphragm jet.

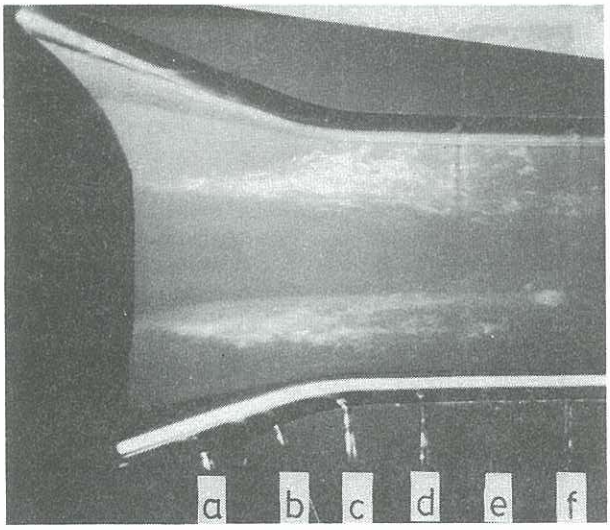

Fig. 5. Flow pattern downstream of the stretched diaphragm.

Pressure distribution. The axial distribution of the static pressure in the valve shown in Fig. 6 illustrates qualitatively the process of the pressure losses. First the pressure slightly rises in the diffuser part of the valve recovering only 38% of the dynamic pressure. The dramatic pressure drop takes place across the diaphragm where the velocity of water rises to about 6 times the initial velocity. The pressure then slightly decreases to the location where the jet contraction ends and the mixing region of the jet gets in contact with the pipe wall. From this point the pipe wall starts to interact on the jet and during the distance of about 3.5D the fluid recovers of about 30% of its static pressure drop on the diaphragm.

It is clear that the diameter and shape of the diaphragm opening and as well as the jet and pipe interaction play a crucial role in the process of the pressure losses.

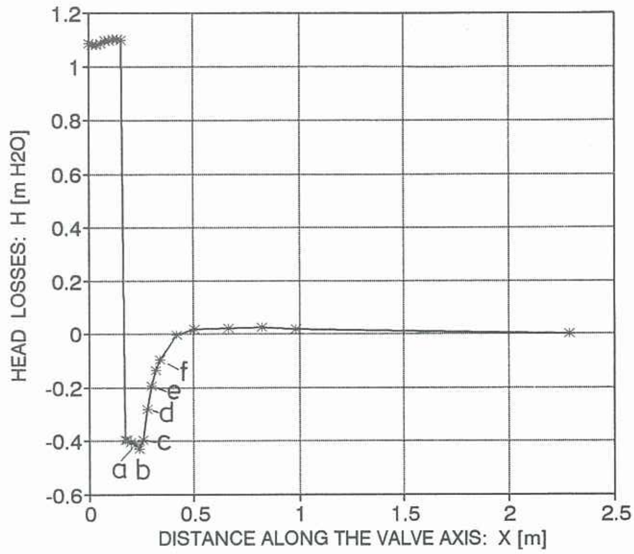

Fig. 6. Pressure distribution along the valve axis (at U=1.11 m/s, Re=83000).

Pressure loss coefficient. The measured pressure loss coefficients for a standard and modified valves are plotted against Reynolds number in Fig. 7. For a comparison the pressure loss coefficient for a perforated plate is also included. The coefficient for a perforated plate only is almost independent of the Reynolds number and is equal to

a) $K<0.6$ for $Re>10^5$ and a flat perforated plate and a short conical diffuser,
b) $K<0.4$ for $Re>3x10^4$ and a short diffuser with curved walls (Idelchik, 1986, p. 204) and a 60° cone at the centre of the plate.

These results are consistent with the correlation formula of Ward-Smith (1980).

One can see that at low Reynolds numbers the main contribution to the total pressure loss coefficient is caused by the diaphragm. At moderate Reynolds numbers, as the diaphragm is more deflected and its opening is strongly stretched, the coefficient decreases linearly (in a logaritmic coordinate system). At higher Reynolds numbers it will tend asymptotically to the value of the coefficient for the perforated plate.

Valve modification. A significant decrease of the pressure loss coefficient was obtained with the number of modifications of the valve:

a) increase of the initial diameter of the diaphragm hole (from 38 to 48.6 mm),
b) rounding of the inlet edge of the diaphragm hole (R=~8 mm),
c) bevelling the end of the torpedo, which was very effective at the low Reynolds numbers,
d) rounding inlets of the holes in the perforated plate (r=2.4 mm),
e) introducing a pressure isogradient (dP/dx=const.) curved-wall diffuser and a cone in front of the perforated plate.

Finally, the pressure loss coefficient for the modified valve can be very precisely approximated with the simple formula:

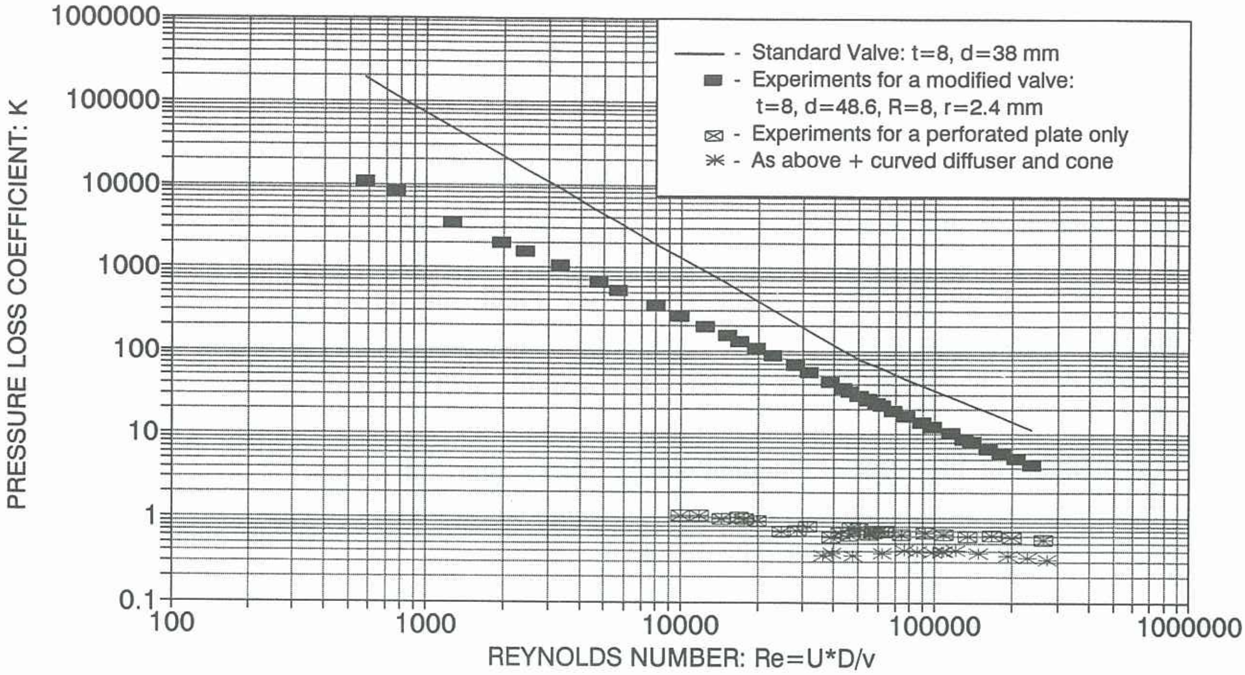

Fig. 7. Pressure loss coefficient for the non-return diaphragm valve (D_{PIPE}=79.6 mm).

$$K = \Delta P/0.5U^2\rho = 4.07\times10^7\ Re^{-1.3} \qquad (1)$$

where: Δ**P** - total pressure losses caused by the valve, ρ - density of the fluid, **Re** is the Reynolds number based on the average velocity in the pipe **U** and the diameter of the pipe or of the inlet to the valve **D**. The pressure loss coefficient for the 12 mm thick diaphragm is only about 25% higher compare to the above experimental data for 8 mm thick diaphragm and this difference decreases at the higher Reynolds numbers.

CONCLUDING REMARKS

1/ The main sources of the pressure losses produced by the diaphragm non-return valve are the
   a) deflected and stretched rubber diaphragm at low flow rates,
   b) short diffuser and perforated plate at the high flow rates.

2/ The dependence of the pressure loss coefficient versus Reynolds number at the low and moderate Reynolds numbers has a linear form in a logaritmic coordinate system ($K = const.Re^{-b}$). At higher Reynolds numbers the total pressure loss coefficient approaches the value of the pressure loss coefficient for the short diffuser and perforated plate system.

3/ The fully theoretical prediction of the pressure losses produced by the non-return diaphragm valve represents a very interesting and challenging problem of the interaction of the highly turbulent fluid flow and the elastic diaphragm structure (Wriggers and Taylor, 1990).

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