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Prediction of non-Newtonian head losses through diaphragm valves at different opening positions

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ABSTRACT

Recent work on fully opened rubber-lined diaphragm valves showed that due to the lack of geometric similarity, dynamic similarity could not be established. The laminar flow loss coefficient constant therefore becomes diameter dependent as is the case of turbulent flow loss coefficients. The purpose of this work was to establish if this is the case for all types of diaphragm valves, by testing diaphragm valves from a different manufacturer. Accurate loss coefficient data is critical for energy efficient hydraulic design. Saunders type straight-through diaphragm valves ranging from 40 mm to 100 mm were tested in the fully open, 75%, 50% and 25% open positions, using a range of Newtonian and non-Newtonian fluids. It was found that the laminar flow loss coefficient constant suggested by Hooper (1981) is sufficient for all valve diameters at Reynolds numbers below 10. However, for transitional and turbulent flow the same loss coefficients cannot be applied for more accurate designs for diaphragm valves from different manufacturers.

A new correlation has therefore been developed to predict the loss coefficients for straight-through Saunders diaphragm valves at various openings from laminar to turbulent flow regimes.

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Keywords: Laminar flow; Diaphragm valves; Head loss; Pressure; Non-Newtonian; Efficient design

1. Introduction

Spellman and Drinan (2001) defined a valve as any device by which the flow may be started, stopped, or regulated by a movable part that opens or obstructs passage. Valves are therefore an important part of any pipeline system. Diaphragm valves offer distinct advantages in applications where absolute sealing is required, and where the line fluid cannot be contaminated by the ingress of atmosphere. Even when slurries are being handled, or solids are present in the liquids, leak-tightness is assured; due to the ability of the diaphragm to engulf particles on closure, and release them downstream when the valve is again opened (Myles K and Associates cc, 2000). There is no need for any gland-packing devices for the stem, as the diaphragm provides total sealing between the medium and atmosphere.

Valve losses may be neglected without serious uncertainty in long pipelines, but in shorter pipelines an accurate knowledge of their effects must be known for correct engineering calculations (Streeter and Wylie, 1985). Miller (1990) classifies loss coefficients for diaphragm valves as class 3, which means that they have not been verified by independent studies. Miller (1990) and Perry (1997) published some loss coefficient data in the turbulent regime at various valve opening positions (for fully, 75%, 50%, and 25%) that is defined as the mass or volumetric flow delivery percentage function of the travel of the hand-wheel of the valve (Hutchison, 1976). Unfortunately, the valve size has not been mentioned and this raised questions regarding its applicability for accurate design purposes. In 2004, ESDU provided a correlation supported by some graphs to compute the loss coefficient at various opening positions for different valve sizes in both laminar and turbulent flow, but correction factors were only available for two types of diaphragm valves. These coefficients were all determined for Newtonian fluids. Pienaar et al. (2004) tested non-Newtonian kaolin slurry through a 40 mm Natco diaphragm valve. They

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Nomenclature

Symbols

α_1	correction factor for partial opening of valve
α_2	correction factor for low Reynolds number
λ_Ω	loss coefficient at fully open position
θ	opening position
$\dot{\gamma}$	shear rate (s^{-1})
%	percentage
ρ	density of the fluid (kg/m^3)
τ	shear stress (Pa)
τ_0	shear stress at the wall (Pa)
τ_y	yield stress (Pa)
Δp_v	total pressure loss in the valve (Pa)
C_v	laminar flow valve loss coefficient constant
D	diameter (m)
DS	downstream
f	fanning friction factor
g	gravitational acceleration (m/s^2)
H_f	friction loss (m)
H_v	valve loss (m)
ID	internal diameter
k_v	loss coefficient of the valve
k'	uncorrected pressure loss coefficient
K_1	k_v for the fitting at Re = 1
K_∞	k_v for a large fitting at Re = ∞
K'	apparent fluid consistency index (Pa s^n)
K_d	constant for loss coefficient in the 3-K method
K_i	constant for loss coefficient in the 3-K method
K_m	constant for loss coefficient in the 3-K method
L	the length of the pipe (m)
m	mass (kg)
n	flow behaviour index
n'	apparent flow behaviour index
p	point pressure (static) (Pa)
PD	positive displacement
Q	volumetric flow rate
Re	Reynolds number for Newtonian fluids
Re_3	modified Reynolds number for yield pseudo-plastic and Bingham plastic fluids
US	upstream
V	mean velocity (m/s)
V_{ann}	average velocity in sheared annulus where shearing of a yield stress fluid takes place in a pipe (m/s)

Subscripts

3	slatter
Ann	annulus
exp	experimental
f	friction
O	pipe wall
v	valve
Ω	fully open position

found that the preliminary results compared well with Hooper (1981) in laminar flow, and the loss coefficient given by Perry (1997) in turbulent flow. In order to move loss coefficients for diaphragm valves to class 2 or 1 (Miller, 1990) from class 3, Fester et al. (2007) have tested a set of Natco diaphragm valves using non-Newtonian fluids. They provided loss coefficient data for 5 different sized valves in both laminar and turbulent flow. However, valves were only tested in the fully open position.

The objective of this study was firstly to experimentally determine the loss coefficients for Saunders diaphragm valves ranging from 40 mm to 100 mm at different opening positions, for a range of Newtonian and non-Newtonian materials, and compare it to that of Natco valves. The second objective was to extend Hooper's correlation for the determination of loss coefficients to account for the valve opening.

1.1. *Definition and determination of the loss coefficient*

The loss coefficient is defined as the non-dimensionalised difference in the overall pressure between the ends of two long straight pipes when there is a valve installed, and when there is no valve (Miller, 1990).

The estimation of the head losses in a pipeline system requires knowledge of the frictional losses in the straight pipes as well as the losses encountered in different fittings such as straight-through diaphragm valves. The head losses in straight pipes can be determined by Eq. (1) (Massey, 1970):

$$H_f = \frac{4fLV^2}{D2g} \tag{1}$$

where H_f is the head loss, f is the fanning friction factor, V is the average velocity, D is the internal pipe diameter and g is the gravitational acceleration.

The head loss in a valve is expressed in terms of the velocity energy head from the energy equation

$$H_v = k_v \frac{V^2}{2g} \tag{2}$$

where H_v is the valve loss and k_v the loss coefficient of the valve.

The loss coefficient of the valve is given by

$$k_v = \frac{\Delta p_v}{1/2 \rho V^2} \tag{3}$$

where Δp_v is the pressure loss in the valve.

In turbulent flow the loss coefficient is independent of the Reynolds number, but in laminar flow a hyperbolic relationship exists between the loss coefficient and the Reynolds number (Edwards et al., 1985):

$$C_v = k_v Re \tag{4}$$

where C_v is a characteristic of a specific valve including its dimensions (Edwards et al., 1985).

In many cases it was shown that a Reynolds number should be used that accounts for the viscous characteristic of the fluids (Edwards et al., 1985; Polizelli et al., 2003; Fester et al., 2007). A Reynolds number (Re_{mod}) that can be used for Newtonian fluids, power-law and Herschel–Bulkley fluids is given by (Chhabra and Richardson, 2008),

$$Re_{mod} = \frac{8\rho V_{ann}^2}{\tau_y + K(8V_{ann}/D_{shear})^n} \tag{5}$$

where Re_{mod} is the Reynolds number modified by Slatter (1996), ρ is the density of the fluid, V_{ann} is the average velocity in annulus, τ_y is the yield stress, K is the fluid consistency index and n is the flow behaviour index.

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