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A flow control device for incompressible fluids

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ABSTRACT

This paper introduces a constant flow method for incompressible fluids using a mechanical choked orifice plate (MCOP), even when changes in differential pressure occur between the upstream and downstream. The MCOP is constructed by inserting a float-spring blockage into an ordinary orifice plate to imitate the function of a critical cavitating flow in a cavitating Venturi. A model MCOP is established and verified by numerical simulation, and a prototype MCOP is designed and tested by experiments. The results show that the numerical simulation is a good guide for the MCOP design. The designed MCOP can keep a constant flow with an error in the flow control of $\pm 4\%$ within the range of the differential pressure between the upstream and downstream of 6–70 kPa. Because the constant flow is obtained without fluid vapourization, the pressure loss is greatly reduced and the noise and erosion are avoided. Additionally, due to the action of the float-spring blockage being based on the differential pressure between upstream and downstream, it is simultaneously insensitive to both upstream and downstream pressure fluctuations. The design idea and the conclusions can be used as a reference in the design of a constant flow control device for incompressible fluids.

1. Introduction

In the fields of petroleum [1,2], aerospace [3,4] and refrigeration engineering [5,6], the critical flow phenomenon is being widely used to control or measure the flow rate. Critical flow occurs when the mass flow rate maintains a constant value that is independent of the pressure drop applied across a flow control device [7]. In such a case, the flow is also said to be choked [8]. Critical flow provides a constant mass flow rate for a specified fluid, which is unaffected by fluctuations, surges or changes in the downstream pressure [9]. Based on this behaviour, a flow can be accurately controlled and measured [10–12].

The critical flow phenomenon can occur in both compressible and incompressible fluids [3–6]. For a compressible fluid, it is commonly acknowledged that the flow becomes choked simply by accelerating the fluid to the local sonic velocity at the throat section of nozzles, because in this case, downstream pressure waves cannot travel upstream. Presently, research on the critical flow of compressible fluids is extremely mature, and many technology standards have been established [10]. However, a wide range of application and further mechanism studies regarding these sonic nozzles are still in progress [13,14].

The sonic velocity of an incompressible fluid is significantly greater than that of a compressible fluid [15]. Before the accelerating incompressible fluid reaches its sonic velocity in a nozzle, evaporation will have already begun and vapour bubbles will appear adjacent to the throat section of the nozzle or further downstream [16]. Although the mass of the vapour bubbles is extremely small, their total volume is large, forming a bubbly cloud area and impeding fluid flow due to the additional resistance created in the nozzle. As the downstream pressure decreases, cavitation intensity increases immediately, which causes the area of the bubbly cloud to further increase. As a result, there is an increased resistance to the flow at this location in the nozzle, which ensures that the flow rate remains unchanged. Conversely, if the downstream pressure increases, cavitation intensity decreases, which results in a decrease in the area of the bubbly cloud. This lowers the resistance to the flow at this location in the nozzle thereby ensuring a constant flow rate. Thus, these vapour bubbles effectively prevent the upstream transmission of any pressure fluctuation and make the flow through the Venturi orifice become "choked". According to the definition of critical flow, this type of flow can also be called as the critical flow, or specifically referred to as critical cavitating flow [17]; the nozzle is called as a cavitating Venturi nozzle [3,4].

However, as soon as the bubbles form, they rapidly collapse in the diffusion region of the nozzle and inevitably give rise to undesirable effects to most fluid machinery because of their erosive nature [18]. Furthermore, because of the extremely low vapour pressure of an ordinary liquid, a large pressure drop is necessary to cause choked liquid flow, particularly for a high-pressure fluid, which will cause an extremely large pressure loss [7]. Finally, although the cavitating Venturi nozzle can block the influence of

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the downstream pressure disturbance on the flow rate, it does nothing to shield off upstream pressure disturbances, which directly affect the constant flow rate and the accuracy of the flow control and measurements. These shortcomings greatly limit the application of the liquid critical flow.

There are many other flow control devices for incompressible fluid, such as active control systems [3], which generally consist of a remote-controlled valve, a flowmeter, and a control unit (or a computer). During operation, the flow rate is continuously monitored by the computer with the flowmeter and adjusted with the remote-controlled valve if the level is not within the acceptable range. Active control systems are expensive and heavy. In contrast, the cavitating Venturi nozzle, which is lighter and less expensive than the active control systems, is more attractive for flow control. Unfortunately, as discussed above, critical flow achieved based on the cavitation method is difficult to accept in both general science and engineering applications. However, although the behaviour of vapour bubbles is extremely complex, the net effect is the creation of additional “resistance” that can automatically adjust the flow rate. Therefore, if other approaches could be used to replace the functions of the vapour bubbles, the aforementioned problems would be solved.

In this study, a constant flow method for incompressible fluids with a mechanical choked orifice plate (MCOP) is presented. The MCOP can maintain a constant flow by mechanical action when the differential pressure between the upstream and downstream changes, which resembles the critical cavitating flow in function. Since the constant flow is achieved at a relatively low velocity and pressure drop, large pressure loss, erosion, noise and vibration can be avoided, while simultaneously both downstream and upstream pressure fluctuations can be shielded off, which greatly improves the precision of the flow control.

2. Operating principle of the MCOP

Fig. 1 presents the basic structure of the MCOP, which mainly consists of an ordinary orifice plate, a float, a spring, a guide rod and brackets. As shown in Fig. 1, the float, which is supported by the guide rod, passes through the orifice plate, axially and coaxially. The downstream side of the float connects to a spring whose other end is fixed in a triangle bracket downstream. The guide rod is fixed on both ends by the brackets. When a fluid passes through the annular aperture between the orifice plate and the float (AAOPF), it causes a differential pressure ΔP which pushes the float downstream along the guide rod, immediately the spring is compressed due to the movement of the float. When the forces acting on the float by the fluid and the spring reach equilibrium, the float will remain fixed at a location, and the flow area of the AAOPF is also fixed.

The float has a smooth shape, and the diameter becomes smaller along the flow direction, similar to a cone; however, the float shape is not a cone. Thus, the float-spring blockage in an ordinary orifice plate constitutes additional resistance similar to the vapour bubbles in the cavitating Venturi nozzle. It is able to automatically move to maintain a constant flow rate. For example, when the downstream pressure decreases, the float will automatically move downstream, the spring become compressed, and the flow area of the AAOPF decreased (or the degree of obstruction increased) to prevent a flow rate increase and maintain a constant flow. Vice versa, the device will stop the flow reduction to maintain a constant flow rate when the downstream pressure increases. Thus the float-spring blockage acts as additional resistance that can prevent the influence of downstream pressure disturbances on the flow rate. This function is equivalent to the choked flow at a sonic velocity for compressible fluids and the critical cavitating flow for incompressible fluids. So maybe we can take it as a special type of critical flow produced by mechanical action and call it a mechanical quasi-critical flow.

In addition, the MCOP can also prevent upstream pressure disturbance from affecting the flow rate. For example, when the upstream pressure increases, the differential pressure ΔP will increase to push the float to narrow the flow area of the AAOPF and increase the degree of narrowing; thus, the additional resistance increases, and the flow rate remains constant. By the same reasoning, when the upstream pressure reduces, the flow rate remains unchanged. Fig. 2 shows a 3-dimensional model of the MCOP.

It should be noted that selecting the orifice plate as the fixed throttle for the mechanical quasi-critical flow device, rather than choosing other forms, such as a Venturi nozzle, was primarily based on the following considerations. First, the structure of the orifice plate is simple and easy to manufacture. Second, the pressure distributions are much more uniform, both in the upstream region and in the downstream region of the orifice plate, and the pressure recovery is less; although this results in a larger pressure loss, it can improve the operating differential pressure range of the mechanical quasi-critical flow device. Third, as the float moves into the diverging section of a Venturi nozzle, there will be a severe shock, which would affect the stability of the operation.

3. Design of the float

Experimental studies and theoretical calculations on many 3D float forms have shown that the shape of the float is very significant in the design of an MOCP. If the shape is not correct, the MOCP will not be able to keep a constant flow, i.e., under choking or excessive choking will occur. As shown in Fig. 3, when the float is cone-shaped with the diameter decreasing linearly

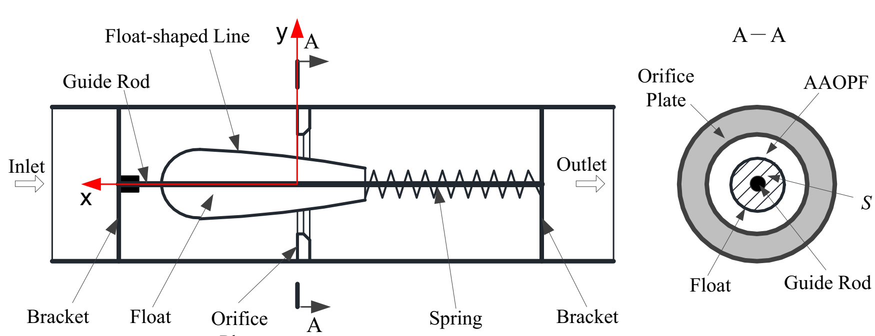

Fig. 1. Basic structure of the MCOP.