The Modeling and Design of Pressure Detection Device in an Automated-cutoff Valve

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Abstract. In order to improve the efficiency of the design of gaseous pressure detection device in an automated-cutoff valve, a model is established according to its deformation characteristics. After the simulation of fluid field which illustrates the dispersed gaseous pressure in the inner cavity and the analysis of displacement produced by a deformed flexible part in the device, the main parameters of the device are designed based on the model. Finally, the data in the corresponding test verifies that the established model is correct and parameters design are effective in the engineering.

1. Introduction

The supply of natural gas which is an essential for daily life is believed to result in danger in case that gaseous pressure is higher than the upper limit (8±15% kPa) or lower than the lower limit (0.8±15% kPa) stipulated by national regulation. It is necessary to assemble automated-cutoff valves, which will cut off the supply of gas when its pressure is beyond the limits, on gas pipe to reduce the occurrence of such accidents.

Gaseous pressure detection device which acts as the indispensable part in an automated-cutoff valve can activate the operation of cutting off the supply of gas for protection purpose automatically when the abnormal gas parameters are detected, e.g. underpressure or overpressure. However, the device which affects the performance of the valve greatly is designed only by experience because of lack of reliable model and parameters design methods.

This paper will present a rational physical model of the device and a workable design method of parameters is discussed subsequently, the effectiveness of which has been validated by tested data.

2. The Modeling of Pressure Detection Device

There are two common methods of the detection of gaseous pressure in engineering. One is by electronic circuits. Wu proposed to detect the photoacoustic voltage electrification caused by the change of gas absorption coefficient, so as to indirectly detect air pressure[1]. Ma studied the air pressure with resonant cylinder pressure sensors which can provide different resonant frequencies with various gas pressure[2]. Zhao designed a micro-differential pressure sensor to detect the change of air pressure by the variable capacitance, the fundamental of which is the gap between the two plates changes with gas pressure[3]. Yang designed a pressure detector based on double-core hollow fiber to detect the pressure...
by using the change of interference spectrum under different pressure\textsuperscript{[4]}. The detected data in electronic way are more precise and convenient to adopted by control system. Thus, the currency in circuits may lead to unpredictable risks in the transportation of natural gas.

It is more acceptable for the second way in such occasion that the detection of gaseous pressure is based on only mechanism, the fundamental of which is the measurement of displacement\textsuperscript{[5]}. It is effective that the pressure in cavity of a valve is measured by the deformation of a flexible part in the detection device indicated by some researchers\textsuperscript{[6][7][8]}. The structure of the pressure detection device in a certain automated-cutoff valve is shown in Fig. 1, which is composed of a rubber gasket, a spring and a control pole.

![Diagram of pressure detection device](image)

Figure 1 the schematic diagram of pressure detection device

The deformation of the gasket is the indication of gaseous pressure. The spring is designed for compensation of deformation and the control pole is for the action of cutting off the supply of gas rushing through the valve. There are two loads exerting on the gasket are considered. One is the gaseous pressure $p$. Another is the concentrated force $F$ which is the combination of the spring force and the gravity of control pole.

In order to estimate the deformation of the gasket in detection device affected by external force, a slice (thickness and width are 0) along the diameter of the gasket is taken as the research object, the deformation by pressure and concentrated force, which is studied respectively, as shown in Fig. 2.

2.1. The Estimation of Relationship between Deformation and Loads
The following hypotheses are indicated for the ease of analysis: The flexible rubber slice can only transfer tension while its shear and bending moment are ignored; the nonlinear deformation of the slice is ignored; the total deformation of the slice is simplified as a linear superposition of variables caused by pressure $p$ and external force $F$, as shown in Fig. 2 (a) and (b).
Figure 2  The deformation analysis of the pressure detection device exerted by external loads

2.1.1. The estimation of deformation $H_1$ produced only by pressure $p$

Study the left part of the slice shown in Fig. 2(c).

\[
\begin{align*}
T_1 - \int_0^y p\,dy &= T_1 \cos \theta_1 & (1) \\
\int_0^x p\,dx &= T_1 \sin \theta_1 & (2)
\end{align*}
\]

Suppose the contour of the deformed slice can be represented by function $y=f(x)$. Then it is obtained by Eq. (2) dividing Eq. (1) that:

\[
\frac{\int_0^x p\,dx}{T_1 - \int_0^y p\,dy} = \tan \theta_1 = y' \\
\int_0^x p\,dx = y'[T_1 - \int_0^y p\,dy]
\]

where $\int_0^x p\,dy$ represents the resultant force generated by the gas pressure in the horizontal direction. Because the deformation of gasket in the vertical direction is relatively small, the resultant force of the gas pressure in the horizontal direction is also far smaller than the tension $T_1$ of the gasket. Therefore, the equation can be simplified approximately as

\[
\begin{align*}
\int_0^x p\,dx &= y'T_1 \\
p\,x &= y''T_1 \\
y'' &= \frac{p}{T_1}x \\
y &= \frac{p}{6T_1}x^3 + C_1x + C_2
\end{align*}
\]

According to the initial condition $y(0)=y'(0)=0$, then

\[
y = \frac{p}{6T_1}x^3
\]

And the length $s$ of the curve $y$ can be calculated as follows
\[
s = \int_0^1 \sqrt{1 + y'^2} \, dx = \int_0^1 \left(1 + \frac{p^2 x^4}{4 T_i^2} \right) dx = x + \frac{1}{10} \frac{p^2}{4 T_i^2} x^5 \quad (6)
\]

Since the nonlinear part in the deformation process is ignored, the tensile force \(T_i\) inside the slice can be expressed as (\(E\) is the elastic modulus of rubber)

\[
T_i = 2(s - x) E = \frac{E p^2}{20 T_i^2} x^5
\]

Replace Eq. (5) with Eq. (7),

\[
y = \sqrt{\frac{20 x^2 p}{E}} \quad (8)
\]

Consequently, the maximum deformation of rubber gasket by gaseous pressure is

\[
H_i = y = \sqrt{\frac{20 R^4 p}{E}} \quad (9)
\]

2.1.2. The estimation of deformation \(H_2\) produced only by force \(F\).

Study the center of the slice shown in Fig. 2(d) according to elastic deformation and force balance in \(y\) direction

\[
\begin{align*}
2T_i \sin \theta_2 &= F \\
2(\sqrt{x^2 + y^2} - x) E &= T_i \\
2T_i \frac{y}{\sqrt{x^2 + y^2}} &= F \\
2(\sqrt{x^2 + y^2} - x) E &= T_i
\end{align*} \quad (10)
\]

Replace Eq. (10) with Eq. (11), then

\[
\begin{align*}
2E(\sqrt{x^2 + y^2} - x) \frac{y}{\sqrt{x^2 + y^2}} &= F \\
\frac{x}{\sqrt{x^2 + y^2}} &= 1 - \frac{F}{2 E y} \\
\frac{x}{x^2 + y^2} &= (1 - \frac{F}{2 E y})^2 \\
4E^2 y^4 - 4EFy^3 + F^2 y^2 - 4EFy^2 y + x^2 F^2 &= 0 \quad (12)
\end{align*}
\]

The equation can be simplified due to the maximum deformation at the place where \(x=0\).

\[
4E^2 y^2 - 4EFy + F^2 = 0
\]

\[
\therefore F = k(y + Y_0) + Mg
\]

\[
\therefore H_2 = y = \frac{k Y_0 + Mg}{2E - k} \quad (13)
\]

Where \(Y_0\) is the initial compression (absolute value) and \(M\) is mass of control pole, while \(k\) is the spring stiffness.

2.1.3. The global deformation

In summary, the relationship between deformation of the gasket in the external loads is

\[
H = H_i - H_2 = \sqrt{\frac{20 R^4 p}{E}} \frac{k Y_0 + Mg}{2E - k} \quad (14)
\]
3. The Analysis of Fluid Field in the Cavity of Valve

It is necessary to obtain the pressure value \( p \) in Eq. (14) before the parameters of detection device are designed.

Some scholars have indicated that it is helpful to carry out simulation about fluid field characteristics under various working conditions before designing and optimizing fluid machinery\(^{[9]}\)\(^{[12]}\).

The simplified fluid field in the cavity of valve illustrated in Fig. 3 is separated into four areas. Area 1 in red color is the inlet with a circular pipe of 20mm in diameter, in which the required flow is \( 0.9 \text{ m}^3/\text{h} \) and the rated pressure is near 2 kPa. Area 2 in green was designed for flow control, which is composed of 10 circular pipes of 1.3 mm in diameter. Area 3 in blue for pressure control is the location of pressure detection, the rubber gasket of which will deform under the effects of gaseous pressure and the spring force for compensation. Area 4 in brown is outlet, the pressure in which is estimated as high as 0.1 kPa.

In order to improve the efficiency of simulation, we only simulated the fluid field in area 3. Before that, the initial parameters should be calculated as follows:

![Figure 3 The areas division of fluid field analysis in cavity of automated-cutoff gas valve](image)

3.1. The judgement of fluid field type

The density of natural gas at room temperature is \( \rho = 0.79 \text{ kg/m}^3 \). The kinematic viscosity is \( \nu = 1.5 \times 10^{-4} \text{ m}^2/\text{s} \). The diameter of the pipe is \( d_1 = 20 \text{ mm} \). So the gas velocity at inlet is

\[
\begin{align*}
  u_1 &= \frac{Q}{A} = \frac{4Q}{\pi d_1^2} = 0.8 \text{ m/s} \\
  \Delta \rho &= \frac{u_1^2}{2} \frac{\Delta \rho}{\rho} = \frac{-5.5 \times 10^{-4} \Delta u_1}{u_1} \rho
\end{align*}
\]

(15)

It can be seen that even when the velocity \( u_1 \) changes by 100 %, the change of density \( \rho \) is far less than 0.1 %, which can be completely ignored. Therefore, in the following fluid field analysis, natural gas is regarded as an incompressible steady fluid.

3.2. Pipeline loss analysis

The length of pipe in area 1 is so short that the loss can be negligible.

3.2.1. However, in the junction between area 1 and area 2, the diameter shrinks sharply. The pipe with the diameter which is \( d_1 = 20 \text{ mm} \) turn to 10 mini pipes with the diameter \( d_2 = 1.3 \text{ mm} \) after shrink. The velocity in area 2 is

\[
\begin{align*}
  u_2 &= \frac{Q_{a_2}}{A_2} = \frac{u_1 \rho d_1^2}{10 \times \pi d_2^2} = 18.8 \text{ m/s}.
\end{align*}
\]

The areas where we show before and after change is

\[
\begin{align*}
  \frac{A_2}{A_1} &= \frac{10 \times \pi d_2^2}{\pi d_1^2} = 0.042
\end{align*}
\]

The approximate local loss coefficient is regarded as \( \zeta = 0.5 \). Then the resulting head loss is
3.2.2. In area 2, the Reynolds number

\[ \text{Re} = \frac{ud}{v} = \frac{18.8 \times 0.0013}{1.5 \times 10^{-5}} = 1629 \]

< 2000 (engineering critical Reynolds number). So it is the laminar flow in a pipe with length \( l = 24 \text{ mm} \), the resistance loss coefficient along which is

\[ \lambda = \frac{64}{\text{Re}} = \frac{64}{1629} = 0.04 \]

Then the obtained pipeline loss is

\[ h_2 = \lambda \frac{u^2}{2g} = 0.04 \times \frac{20}{1.3} \times \frac{18.8^2}{2 \times 9.8} = 11.1 \text{ m} \]

3.3. The initial parameters for simulation

According to Bernoulli equation,

\[ z + \frac{p}{\rho g} + \frac{u^2}{2g} = C \quad (16) \]

When fluid flows into area 3 from area 2, the pressure is

\[ p_3 = \rho g [(z_1 - z_3) + \frac{u_1^2 - u_3^2}{2g} + \frac{p_1 - p_3}{\rho g} - h] \quad (17) \]

Where \( z_1 \) and \( z_3 \) are the heights of center in area 1 and area 3 while \( p_1 \) and \( p_3 \) are the pressures in area 1 and area 3. The \( h \) is the global loss. Because

\[ z_1 = z_3, \quad u_3 = u_2, \quad h = h_1 + h_{1.2} + h_2, \]

\[ p_{30} = \frac{\rho (v_1^2 - v_3^2)}{2} + p_1 - \rho g (h_1 + h_{1.2} + h_2) \]

\[ = p_1 - 295 \quad (18) \]

It is meant that when the input pressure is as higher as the rated one, namely 2kPa, the pressure at the inlet of area 3 is \( p_3 = 2000 - 295 = 1705 \text{ Pa} \).

3.4. The result of simulation

The simulation graph of pressure distribution shown in Fig 4 presents that is value \( p \) in Eq. (14) varies between 175Pa and 427Pa (the value of \( p \) is the difference between the data shown in Fig 4 and 1 atm).

Figure 4 The FEM simulation of pressure distribution in the fluid field in the valve (The values of depicted pressure are the absolute ones which have included 1 atm)
4. Main Parameters Design of Detection Device

Considering the dimensions of the valve, the radius of gasket $R(10mm)$, the maximum deformation $H(±3mm)$ and the spring stiffness $k(1.9N/mm)$ are designed based on the Eq. (14) and the value of $p$ in the simulation after Mass $M$ and initial compression $Y0$ are assigned referring to the dimension of other parts.

![Image](image1.png)

Figure 5 The FEM simulation of pressure distribution in the fluid field in the valve

4.1. The simulation of linearity

In order to achieve the accuracy of control, the linearity of the deformation of detection device should be considered on the basis of simulation of different shapes of gaskets (the average thickness is 2mm) with FEM. The resulting curves of deformation are shown in Fig. 5(a).

It is clear that the rubber gasket with thick center and thin edge shows more ideal performance in linearity. According to the requirement of process and sealing, its shape has been further modified, the deformation of which is shown in Fig. 5(b).

4.2. Validation of data in testing

The rationality of designed parameter has been validated by the tested data of 20 valves of 300 samples. The test was performed in underpressure and overpressure respectively and every valve with the designed pressure detection device was tested for 3 times. The data shown in Tab. 1 indicate that the designed detection device can help valves cut off gas supply effectively when the value of pressure enters the ±15 range of limits, both the upper one and the lower one.

5. Conclusion

The detection device of gaseous pressure based on only mechanism was essential to be studied for the security purpose of an automated-cutoff valve.

In accordance with the structure of the detection device and the hypotheses of rubber gasket, the mathematical model of the device is established by analysis of the effects of gaseous pressure and concentrated force separately. According to the model, the corresponding parameters are designed by the simulation of fluid field and the rubber gasket in the valve, the data in the test validate the effectiveness of the design finally.

It is significant to improve the accuracy and sensitivity of the detection device in the further study. It is also a challenge to optimize the linearity of the detection when the process and cost of the device are considered.
TABLE 1  THE TESTED CUTOFF DATA IN OVERPRESSURE AND UNDERPRESSURE

| No. | The pressure when cut off due to overpressure (Pa) | The pressure when cut off due to underpressure (Pa) |
|-----|-------------------------------------------------|--------------------------------------------------|
| 1   | 7200                                           | 850                                               |
| 2   | 6900                                           | 800                                               |
| 3   | 7600                                           | 910                                               |
| 4   | 7450                                           | 810                                               |
| 5   | 7300                                           | 760                                               |
| 6   | 7700                                           | 820                                               |
| 7   | 8200                                           | 880                                               |
| 8   | 7500                                           | 845                                               |
| 9   | 6900                                           | 880                                               |
| 10  | 7300                                           | 880                                               |
| 11  | 7400                                           | 910                                               |
| 12  | 7600                                           | 880                                               |
| 13  | 7200                                           | 810                                               |
| 14  | 7800                                           | 850                                               |
| 15  | 7400                                           | 800                                               |
| 16  | 7100                                           | 840                                               |
| 17  | 7050                                           | 680                                               |
| 18  | 6850                                           | 735                                               |
| 19  | 7100                                           | 840                                               |
| 20  | 7750                                           | 860                                               |

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