

Original Article



Analysis on Water Hammer Resistant Characteristics of Pipeline Valves

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Abstract:

A steady-state and transient analysis & study of valve piping flow in the refrigeration industry is conducted by considering eight commonly used valves through Flowmaster technology. The steady-state characteristics show that the double eccentric butterfly valve has the highest stability, and the triple eccentric butterfly valve has a larger flow space. In terms of simple transient characteristics, the concentric butterfly valve has the best water hammer resistant characteristics, followed by the triple eccentric butterfly valve. Conduct transient analysis of the closing characteristics of various commonly used valves, and considering two time periods of fast closing and slow closing, the fast closing time accounted for 25% and 14% of the whole process, and the opening degree of the fast closing was 0.6-0.3, which stimulated the first weak wave of the closing period, and the pressure wave value after the valve closing period decreased rapidly. Considering the non-full stroke, the fast closing stroke occupies 1/3-2/3 of the full stroke, which has a better pressure wave control effect. These provide the valve with a water hammer resistance strategy.

Keywords: pipeline valve; transient characteristics; first weak wave; water hammer resistance

Introduction

With the increase of the number of pressure pipelines and the increase of running time, as a mode of transport, pressure pipelines has been called the fifth largest mode of transport along with road, railway, shipping and air transport, which is widely used in metallurgy, chemical industry, municipal engineering, and other industrial production as well as city gas and heating systems [1-3]. Water as a typical example of fluids of Newtonian nature has been studied numerously. Generally, unsteady friction models and the relevant computational methods have always been the subject of various research projects at the research centers all over the world [4]. Wiggert, Otwell, LesmeZ, Budny, and Hatfield et al. of Michigan State University of the United States, have conducted years of research

on pipeline systems and published many valuable papers [5-7]. The most widely used models consider extra friction losses to depend on a history of weighted accelerations during unsteady phenomena or on instantaneous flow acceleration. Procedures for improving the computational efficiency of Zielke's method [8] were proposed by Trikha [9], Suzuki et al. [10] and Schohl [11]. Moreover, Vardy et al. [12, 13] adopted an approach similar to that of Zielke [8] and developed a weighting function model to represent unsteady friction in turbulent flows. An alternative approach was proposed by Brunone et al. [14,15]. Subsequently, Vitkovsky et al, Ramos et al, and Triki addressed more advanced formulation to account for unsteady friction effects [16-18]. Papers such as [19-21] studied

flow start-up of viscoplastic fluid as well as thixotropic ones, which shows some similarities to the fluid hammer problem. In fact, water hammer following the tripping of pumps can lead to overpressure and negative pressure [22]. When water hammer occurs in the pressure pipeline, it is mostly caused by the action of the valve; the type and action of the valve affect the pressure distribution in the pipeline. From the initial four-equation model, to the six-equation model [23, 24] and later Valenin's eight-equation model [25], engineering practice cannot be applied well. Some scholars have also made a lot of efforts [26-34]. In this paper, with the help of Flowmaster software, and considering eight kinds of commonly used valves to conduct the steady-state and transient analysis & study of the flow in the valve pipeline, so as to seek measures to reduce the pressure fluctuation after the valve was closed.

1 Model of Valve Pipeline

Modeling is shown in Fig.1. The flow of the pipeline is powered by the high-pressure water tanks in the upstream and downstream, the output pressure of the upstream water tank is initially set

to 11 bar, and the downstream water tank pressure is 8 bar, for the pipeline 1, it has a diameter of 0.125 m with length of 5 m. Pipeline 3 has a diameter of 0.1 m with length of 100 m.

The Colebrook-White model is adopted for the friction resistance model of the pipeline because of the steady velocity in engineering. As long as the surface roughness of the pipeline is determined, the friction coefficient of the pipeline can be determined. 8 control valves are set before the downstream water tank, as shown in Fig.1. In the figure, number 9, 4, 11, 16, 15, 14, 12, and 13 respectively represent stop valve, gate valve 1 (Sluice valve seat area = pipeline area), gate valve 2, ball valve, butterfly valve, butterfly valve type A (single eccentric butterfly valve), butterfly valve C type (three eccentric butterfly valve) and butterfly valve B type (double eccentric butterfly valve). The pressure loss of different valves is similar to the partial loss. When the valve aperture is small, the laminar flow correction should be considered. The determination of the flow loss coefficient for different openings means the determination of the valve resistance of the full stroke.

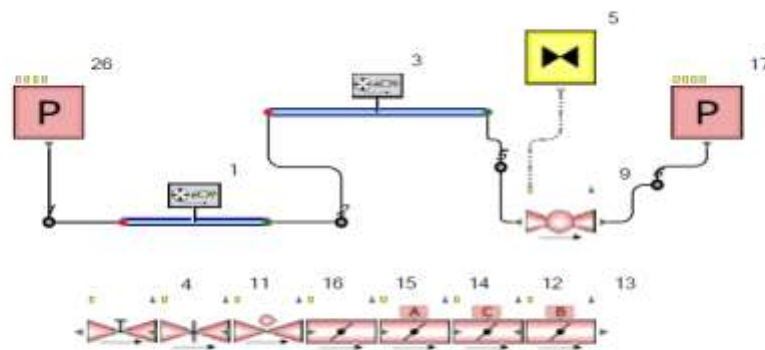


Fig. 1 Valve pipeline model

2 Analysis of Steady-State Results

Conduct analysis for the gate valve 2 and adjust the opening value to obtain different system flow rates. When the valve opening is 0.6, the velocity in the pipeline 3 is 5.91 m/s. Other valves adjust

the valve opening with a target of 5.91 m/s (Fig.2). For the stop valve and the sluice valve, 5.5 m/s is not reached even when the valve is fully open, while the other 6 valves are able to reach the target speed. Compared with the speed of gate valve 2, butterfly valve C type has a smaller

opening value of 0.74, and butterfly valve B type has a maximum opening of 1.0. Ball valve is 0.8, ordinary butterfly valve is 0.84, and butterfly valve type A is 0.89. The butterfly valve type C has a larger flow space.

For the following 6 types of valves, speed observations are conducted at different opening degrees, and the speed curve of gate valve 2 is relatively saturated. The ball valves are similar to butterfly valves type A. The ordinary butterfly valves have poor control characteristics, both butterfly valves type B and C have better control characteristics, and butterfly type C is the best. The C type butterfly valve does not change the flow rate significantly in large openings, the B

type butterfly valve has better control characteristics than in small openings, and it has certain adjustment ability in large opening degree.

The loss coefficient of the B type butterfly valve is almost linear in the whole stroke, while the loss coefficient of the C type butterfly valve is approximately linear in the whole stroke. The ordinary butterfly valve is linear below 0.75 degree of opening, and has a slope of -5.88 when the degree of opening is large. However, the consistency of coefficient of A type butterfly valve in the whole stroke is not strong. Combined with the resistance coefficient of the whole stroke, the B type butterfly valve has the highest stability, followed by the C type.

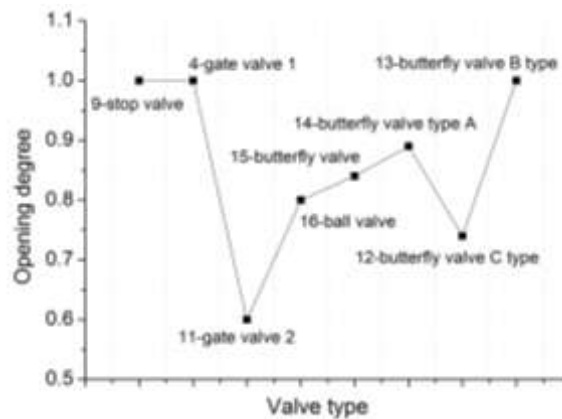


Fig. 2 Comparison of speed opening of different valves

3 Transient Characteristics of the Valve

For different valves, set the same valve closing rule, focusing on the dynamic characteristics on the basis of their respective steady states. First, steady state was maintained at 0-6s, then the relative opening was reduced from 6-8s to 0, and then calculated to 22 seconds later.

The pressure at point 2 (between the two pipes) of the stop valve was slightly lower than the static pressure in the steady state, after the closing stroke within 2 seconds, its maximum pressure was 13 bar, the minimum pressure was about 9 bar, and the fluctuation was 2 bar. The pressure at the 5 point (in front of the valve) was 8.59 bar in

the steady state, its maximum pressure was 34 bar, the minimum pressure was about -11 bar, and the fluctuation was 25.4 bar, which was approximately 3 times the steady state pressure. For the ball valve, under the action of 0.05 steps, the pressure fluctuation of ball valve at 5 points was about 17 bar. The 2 point fluctuation was about 2.5bar.

The transient characteristics of the sluice valve is shown in Fig.2. The velocity of 1 pipe was fluctuated from -0.93 to 0.95m/s, and the fluctuation period was about 4 seconds. The maximum peak pressure at the 2 points was 13 bar. A pressure of 35 bar was generated at point 5 when the valve was closed, minus 8.013bar,

which is about 3.5 times the pressure increment. The closing characteristics, speed and pressure of gate valve 2 were similar to the distribution of sluice valve.

The pipeline pressure of the concentric butterfly

valve fluctuated, with only the first wave appearing, after which the signal decreased rapidly. Reduced from 0.84 to 0, with sufficient water hammer resistance (in Fig.4). And the crest appeared while the valve was closed.

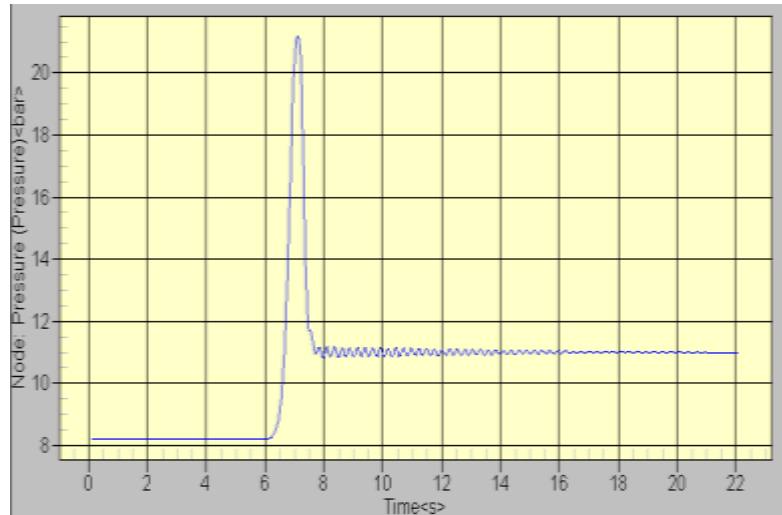


Fig.3 Pressure fluctuations of concentric butterfly valve pipeline nodes

The pressure value of butterfly valve type A at point 5 was slightly higher than that of concentric butterfly valve (in Fig.5), and the maximum value was 27 bar. The C type butterfly valve formed a slightly larger sharp wave while the valve was closed, with 22.2 bar at point 5 and 11.5 bar at point 2. Then the pressure fluctuation at point 5 was 2.5bar and 0.15bar at point 2. It accounts for 1/4 and 2/100 of the static value, indicating its

good stability. The pressure drop in pipe 1 and pipe 3 did not fluctuate much. At the end of the valve closing of the B type butterfly valve, a slightly larger sharp wave (21.2 bar) was formed at point 5. Then the pressure fluctuation was 8 bar at point 5 and 1.7 bar at point 2. The pressure drop fluctuations in pipe 1 and pipe 3 would exist for a long time.

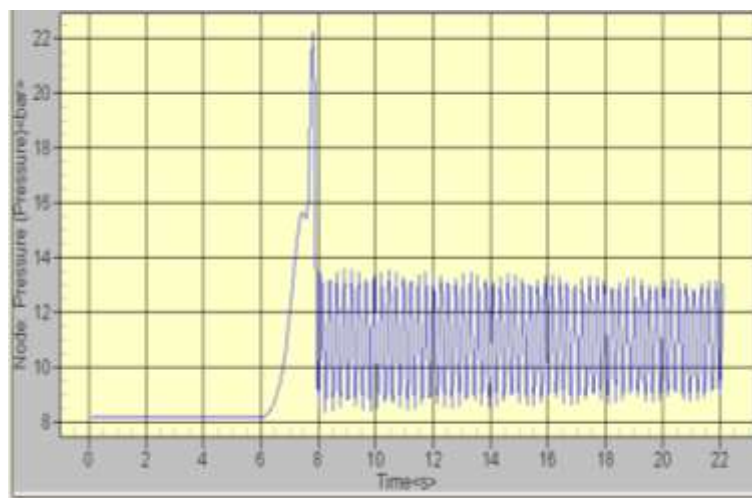


Fig.4 Pressure fluctuation of point 5 of C type butterfly valve

4 Research on Valve Control Characteristics

4.1 Valve Closing Characteristics of B Type Butterfly Valve

Set up seven kinds of scheme, the first three kinds

of opening are average speed, the latter four are based on plan two, there are two kinds of slow first and then fast, the last two are fast first and then slow.

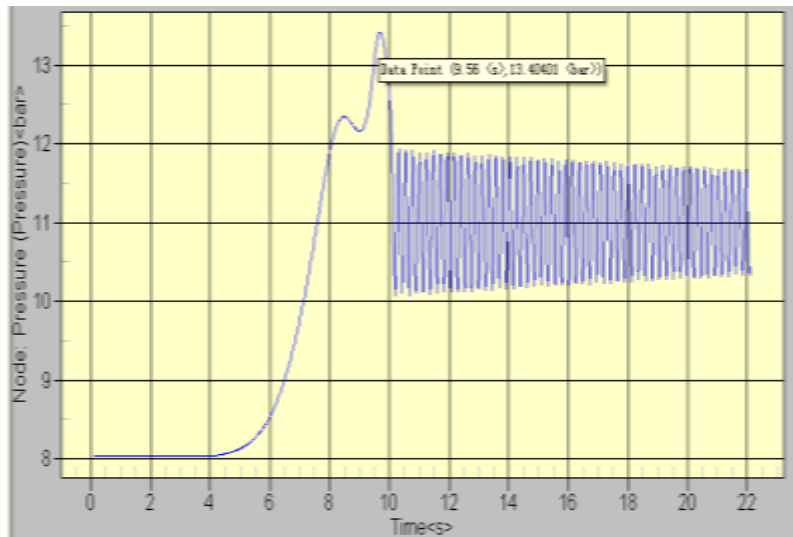
Table 1 Comparison of several schemes

Scheme number	Opening degree change 1 (%)	Time setting 1 (s)	Opening degree change 2 (%)	Time setting 2 (s)
I	1.0 ->0	4 ->6		
II	1.0 ->0	4 ->8		
III	1.0 ->0	4 ->10		
IV	1.0 ->0.8	4 ->6	0.8 ->0	6 ->8
V	1.0 ->0.6	4 ->6	0.6 ->0	6 ->8
VI	1.0 ->0.4	4 ->6	0.4 ->0	6 ->8
VII	1.0 ->0.2	4 ->6	0.2 ->0	6 ->8
VIII	1.0 ->0.2	4 ->5	0.2 ->0	5 ->8
IX	1.0 ->0.4	4 ->5	0.4 ->0	5 ->8
VV	1.0 ->0.6	4 ->5	0.6 ->0	5 ->8
XI	1.0 ->0.4	4 ->4.5	0.4 ->0	4.5 ->7.5

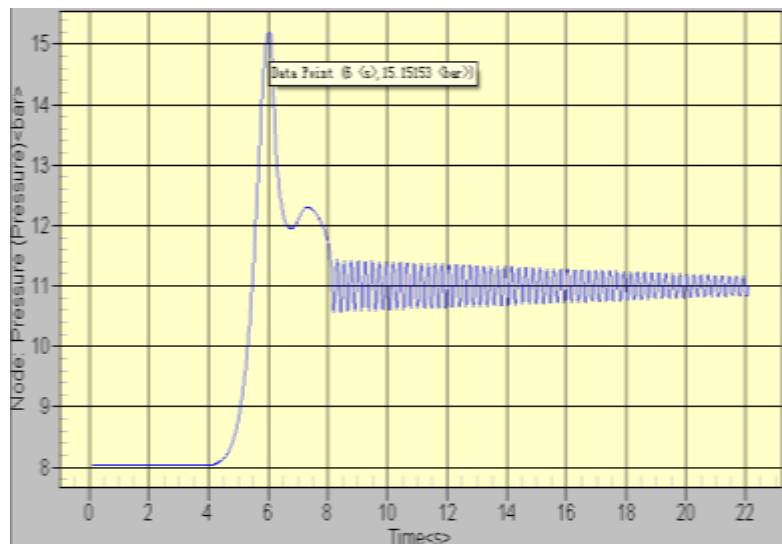
Scheme I, a sharp wave of 22.06 bar was generated in 5.9 seconds during the valve closing period. While in the scheme II, a sharp wave of 15.07 bar was generated in 7.74 seconds during the valve closing period. In the scheme III, a sharp wave of 13.04 bar was generated in 9.56 seconds during the valve closing period. In scheme II and III, during the closing period, the peak value was significantly smaller than that in scheme I, or in this case, the closing time was extended to twice, and the pressure value dropped by 7 bar. The closing time was extended to 3 times, and the pressure value dropped by 9.02 bar.

During the closing time, in scheme II and III, the peak pressure decreased, and there was a weak wave in front of it. After the closing period, the pressure fluctuation value was significantly smaller. Compared with the area under the valve closing pressure curve, the larger the area, the smaller the fluctuation value after the closing period. On the basis of scheme II, first close slowly to a certain opening degree of 0.8, and

then quickly close to 0, as in the scheme IV, the value of the pressure wave in front of the valve raised. First close slowly to a certain opening degree of 0.6, and then quickly close to 0, as in the scheme V, the value of the pressure wave in front of the valve was 16.17 bar, which is still larger than that of the scheme II. On the basis of scheme II, first close to a certain opening degree of 0.4, and then quickly close to 0, as in scheme VI, the value of the pressure wave in front of the valve decreased. First fast closing to a certain opening degree of 0.2, and then slow closing to 0, as in scheme VII, the value of the pressure wave in front of the valve was 15.15 bar, which was still a little larger than that of scheme II, but the value remained almost unchanged after the closing period. The first fast and then slow scheme increased the value of the weak wave during the closing period and increased the pressure area during the closing period, which has a better control effect on the pressure before the valve.



a) Scheme III Node pressure in front of valve



b) Scheme VII Node pressure in front of valve

Fig.5 Node pressure when valve closing at uniform speed

Schemes VIII to XI are detailed from schemes VI and VII. Compared with scheme VII, in scheme VIII, accelerated the fast closing speed, and the first wave increased during the valve closing, with a value of 19.5bar, the pressure fluctuation after the closing period was approximately zero. Compared with scheme VI, in scheme XV, accelerated the fast closing speed, and the first wave increased during the valve closing, and its value was equal to the second peak value, and the pressure fluctuation after the closing period was smaller, which is an ideal solution for the valve closing scheme. In scheme XI, with faster closing

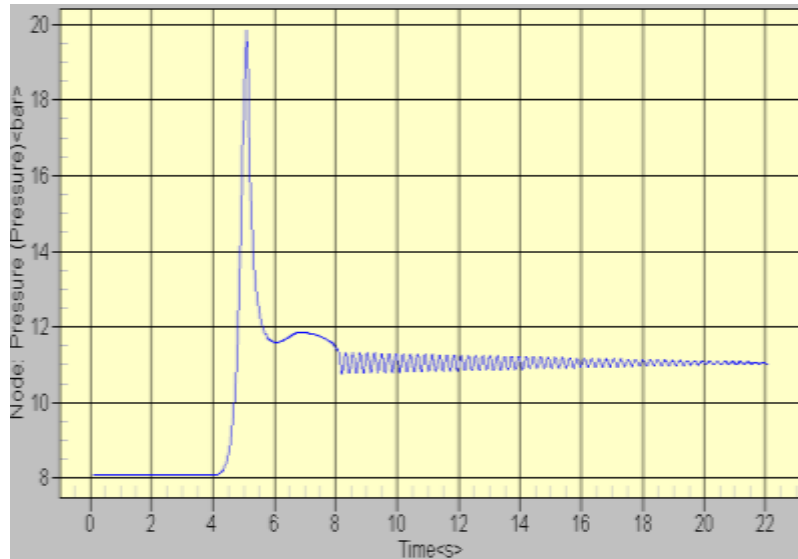
speed, and the value of the first wave was slightly higher than the second wave, it's also a good solution. The opening degree at this time was 0.4, and the total time was 4 seconds (scheme XV) and 3.5 seconds (scheme X), the fast closing time accounted for 25% and 14% of the whole stroke. In combination with scheme X, considering that, the opening of the fast closing is 0.6-0.3, and the best opening value is 0.4, at this time, the fast closing stroke was 3/5 of the whole stroke, generally, the range is 0.4~0.7 of the whole stroke.

4.2 Valve Closing Characteristics of Other

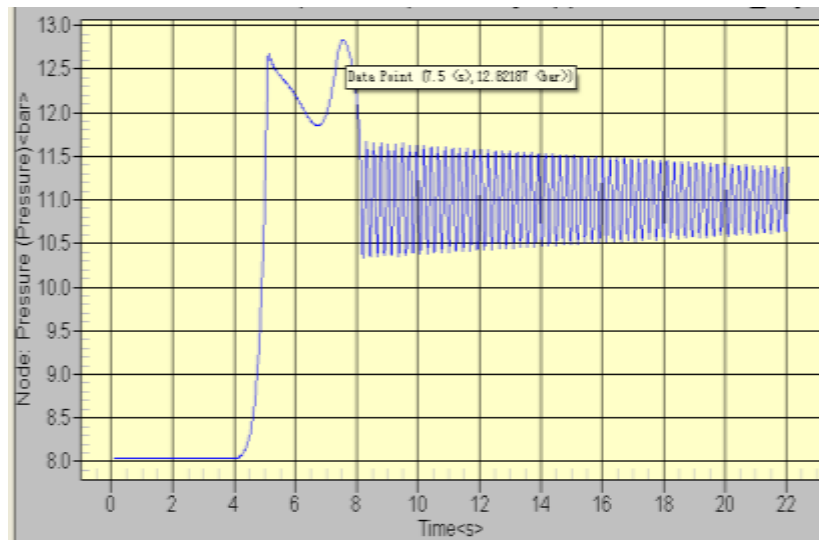
Valves

For the closing control of the C type butterfly valve, formulate two schemes, and follow the conclusion of B type butterfly valve, see Fig. 6. Scheme I: The opening degree was reduced from 1.0 to 0.4, starting from 4 second to closing in 4.5 second, the opening degree was decreased from 0.4 to 0, starting from 4.5 second to closing in 7.5 second. Scheme II: The opening degree was

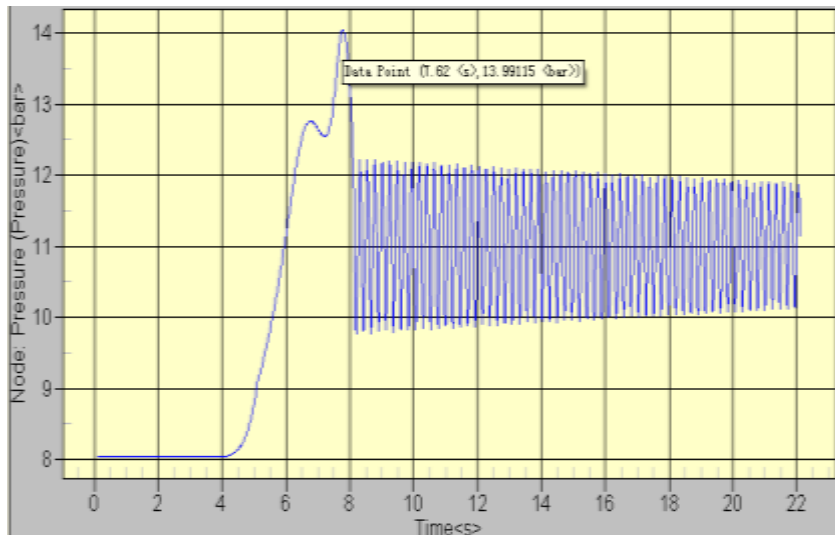
reduced from 1.0 to 0.4, starting from 4 second to closing in 5 second, the opening degree was decreased from 0.4 to 0, starting from 5 second to closing in 8 second, with faster closing speed, the value of the first wave would surpass that of the second wave, and the pressure fluctuation after the closing period was zero, which indicating that it has good stability performance.



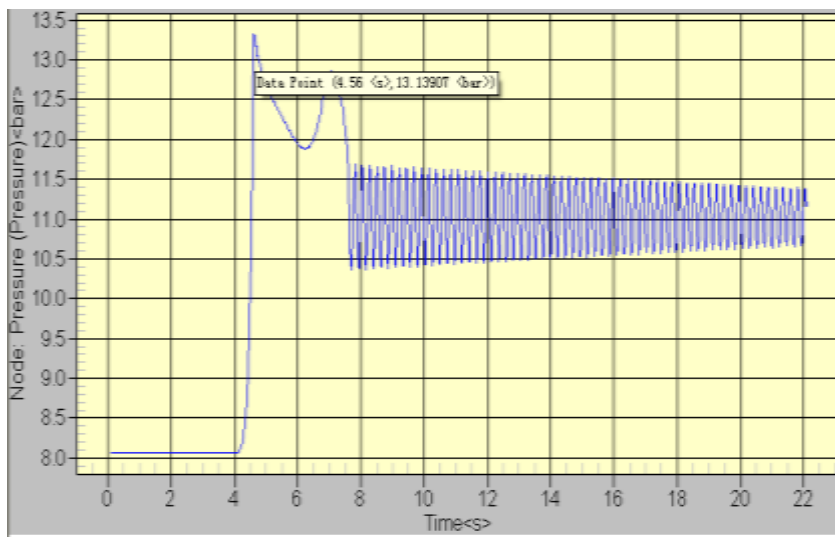
a) Scheme VIII Node pressure in front of valve



b) Scheme IX Node pressure in front of valve



c) Scheme X Node pressure in front of valve



d) Scheme XI Node pressure in front of valve

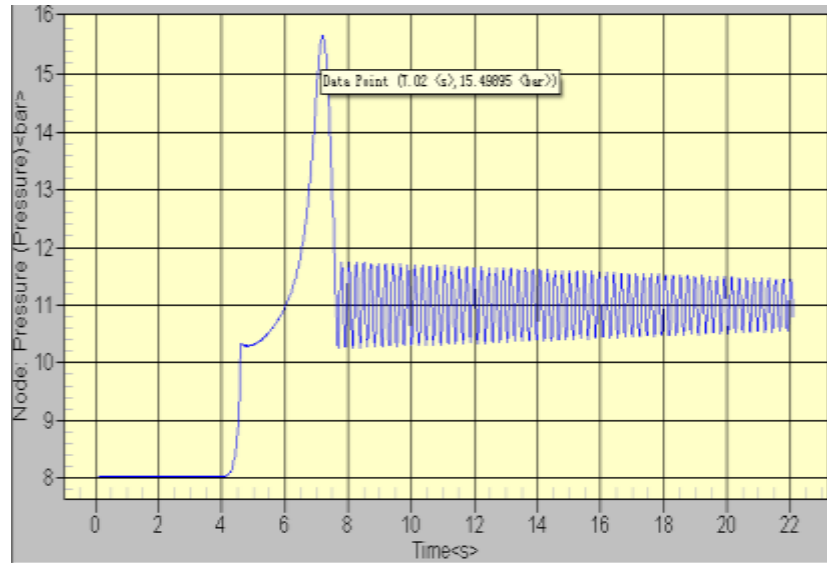
Fig. 6 Node pressure when valve closing at variable speed

For the closing control of gate valve 2, formulate three schemes, and follow the conclusion of B type butterfly valve, see Fig.7. Scheme I: The opening degree was reduced from 1.0 to 0.6, starting from 4 second to closing in 5 second, the opening degree was decreased from 0.4 to 0, starting from 5 second to closing in 8 second. Scheme II: The opening degree was reduced from 1.0 to 0.4, starting from 4 second to closing in 4.5 second, the opening degree was decreased from 0.4 to 0, starting from 4.5 second to closing in 7.5 second. Scheme III: The opening degree was

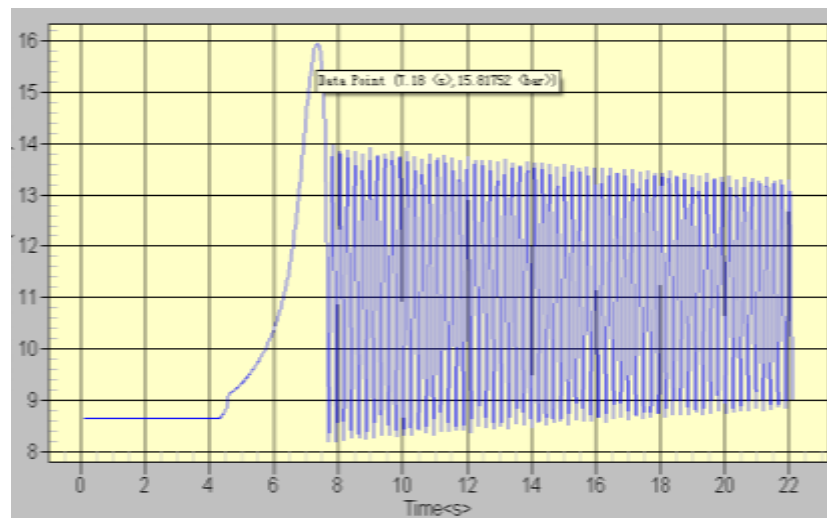
reduced from 1.0 to 0.2, starting from 4 second to closing in 4.5 second, the opening degree was decreased from 0.4 to 0, starting from 4.5 second to closing in 7.5 second. In the best stroke scheme of the butterfly valve to close the valve, the first weak wave in the closing period was not stimulated. Increase the range of stroke, and based on the scheme III, the first weak wave in the closing period was stimulated, and the pressure wave value after the valve closing period decreased rapidly For the stop valve, considering the gate valve factor, the setting scheme: the opening degree decreased from 1.0 to 0.4, starting

from 4 second to closing in 4.5 second, the opening degree was decreased from 0.4 to 0, starting from 4.5 second to closing in 7.5 second.

The specific situation is similar to scheme II of the gate valve. The conclusion is similar.



a) Scheme III Node pressure in front of gate valve



b) Stop valve closing node pressure

Fig.7 Node pressure when valve closing at variable speed

4.3 Considerations for Non-Full Stroke

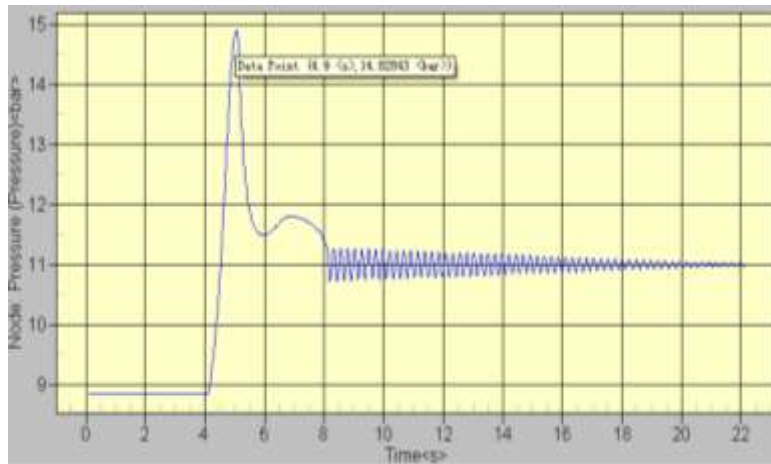
Considering the first opening of B type butterfly valve 0.6, refer to Table 2. The fast closing stroke accounts for 1/3-2/3 of the whole stroke, and all

of them have good pressure wave control effect. The first opening of gate valve and stop valve was 0.6, and the fast closing stroke accounted for 2/3 of the whole stroke, which has a very good pressure wave control effect.

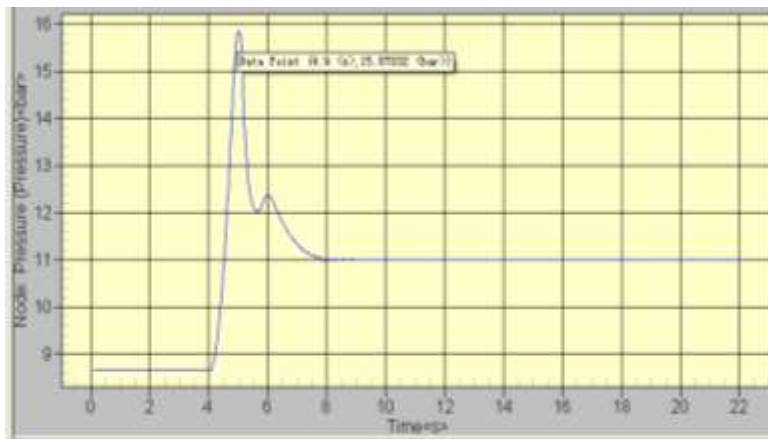
Table 2 Non-full opening scheme

Scheme and No.	Opening degree change 1 (%)	Time setting 1 (s)	Opening degree change 2 (%)	Time setting 2 (s)
Butterfly valve 1	0.6 ->0.2	4 ->5	0.2 ->0	5 ->8

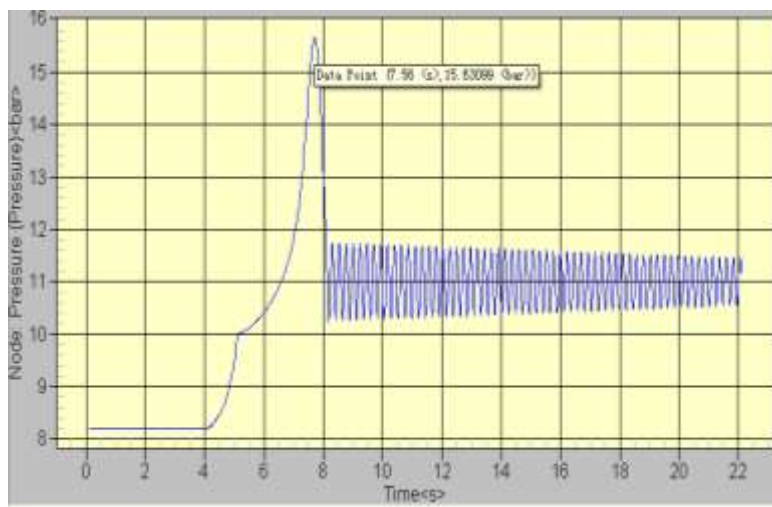
type B	2	0.6 ->0.4	4 ->5	0.4 ->0	5 ->8
Butterfly Valve	3	0.6 ->0.2	4 ->5	0.2 ->0	5 ->8
Type C	4	0.6 ->0.4	4 ->5	0.4 ->0	5 ->8
Gate valve 2	5	0.6 ->0.2	4 ->5	0.2 ->0	5 ->8
	6	0.6 ->0.4	4 ->5	0.4 ->0	5 ->8
Stop valve	7	0.6 ->0.2	4 ->5	0.2 ->0	5 ->8



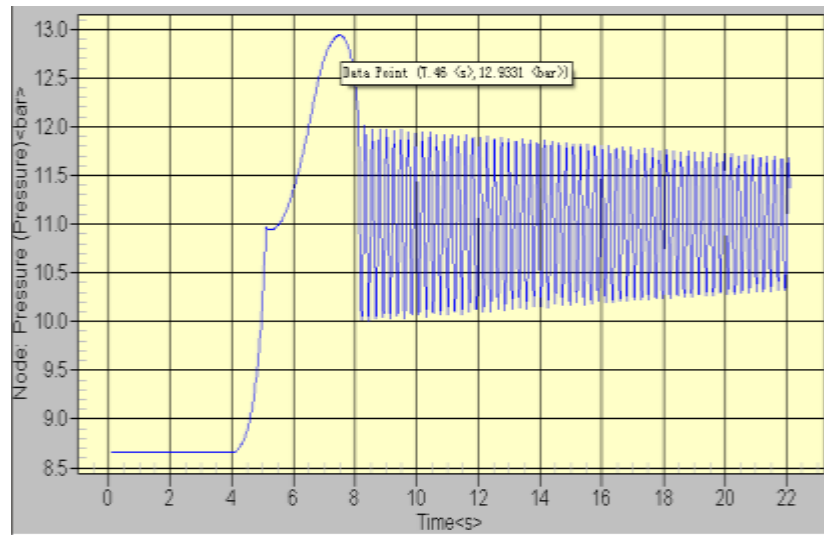
a) Scheme II Node pressure in front of butterfly valve



b) Scheme III Node pressure in front of butterfly valve type C



c) Scheme V Node pressure in front of gate valve



d) Stop valve closing node pressure

Fig. 8 Node pressure when valve closing at variable speed

5 Conclusion

This project uses Flowmaster software to perform one-dimensional steady-state and transient analysis calculations on valve pipelines, and conducts analysis for the valve's control closing time. The steady-state characteristics show that the B type butterfly valve has the highest stability, the loss coefficient of the B type butterfly valve is almost linear in the whole stroke, while the loss coefficient of the C type butterfly valve is approximately linear in the whole stroke. The butterfly valve type C has a larger flow space, The ordinary butterfly valves have poor control characteristics, both butterfly valves type B and C have better control characteristics.

In terms of transient characteristics, the concentric butterfly valve has the best water hammer resistant characteristics. Followed by the C type butterfly valve. B and C type butterfly valves formed high pressure fluctuations during the closing period. All other valves were after closing the valve. The pressure generated by sluice valve is the largest, followed by gate valve and stop valve, the pressure peak generated by B type butterfly valve is the smallest, while that of C type valve is the smaller.

Considering the two time periods of fast closing and slow closing, the B type butterfly valve was reorganized in an optimized scheme, the fast closing time accounted for 25% and 14% of the whole stroke, which stimulated the first weak wave in the closing period, and the pressure wave value after the valve closing period decreased rapidly. Summing up, the suitable opening of the fast closing is 0.6-0.3, and the best opening value is 0.4, at this time, the fast closing stroke is 3/5 of the whole stroke, generally, the range is 0.4~0.7 of the whole stroke. For the consideration of non-full stroke, the first opening degree of Type B and Type C butterfly valves is 0.6, and the quick closing stroke accounts for 1/3 to 2/3 of the whole stroke, both of which have good pressure wave control effect. For gate valves and globe valves, the fast closing stroke occupies 2/3 of the full stroke, which has a very good pressure wave control effect. The closing and opening directions of the valve are opposite, the pressure values are the same, so the controller rule of the valve resistance to water hammer is initially obtained.

Acknowledge

Thanks is to the Natural Science Research Project of Henan Science and Technology Department (182102310018), and the Horizontal Project of

Henan University of Engineering (HKJ2023217).

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