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Transient pressure characteristics in a pressure regulating system by using 1-D analytic valve modeling

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Abstract

Typically, a Pressure Control Valve (PCV) system is constructed with 3 to 4 PCV lines in order to prepare for both a future demand increase and a continuous supply of power after an emergency shutdown of the operating line. However, some operation failure cases that do not follow the original design concepts of a PCV system have been reported in the field. In this study, an accurate 1-D PCV system numerical model was built and a 1-D compressible flow theory was introduced for analytic valve modeling to find solutions for this problem. Several numerical analyses were successfully performed to examine the generation and propagation characteristics of the transient pressure and to clarify the relationships between the transient pressure or surge wave and each factor or parameter relating to fluid dynamics behavior in a PCV system. The relationship between the transient pressure and other factors, such as the size of pipe and header linked after a PCV, the pipe size of the added components linked after the header, and the generation time of the transient pressure and influence of the Slam Shut Valve were investigated in detail. Finally, in order to reduce the strength of the transient pressure and to delay its propagation, this study demonstrates the benefit both of enlargement of the pipe linked to the component added after the PCV system, and the installation of a dissipation component between the operation line and the other lines.

Keywords: Pressure Control Valve (PCV); Transient pressure; Valve modeling; Pipeline network; CFD

1. Introduction

Typically, a pressure regulating system is constructed by using 3 to 4 pressure regulator lines (PCV lines). Each PCV line normally has a worker pressure control valve (PCV), a monitor PCV and some additional components such as a slam shut valve (SSV), a pressure relief valve (PRV), a pressure safety valve (PSV), a motor operating valve (MOV), silencers, and meter-runs.

PCV systems are designed with multiple lines to prepare both for a future demand increase and to provide a continuous supply request after an emergency shutdown of the operating line. However, some operation failure cases that do not follow the original design concepts of a PCV system have been reported from several real PCV stations. Furthermore, in almost all cases, all of the PCV lines were shut down and the supply to customers was finally stopped even though there was considerable investment in multiple lines of construction.

These failure cases are directly related to the characteristics of the transient pressure, which is a kind of compressible wave generated when an SSV on the operating line is suddenly shut off, as in case of a PCV malfunction. Here, two critical properties related to the generation and propagation of transient pressure are wave strength and propagation time.

Therefore, in this study we examine the generation and propagation characteristics of transient pressure when a worker PCV is out of order and an SSV is suddenly closed on an operating PCV line. We also examine the relationships between the transient pres-

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sure or surge wave and each factor or parameter relating to the fluid dynamics behavior in PCV systems.

For these purposes, both a 3-D CFD PCV model and a 1-D numerical PCV system model with commercial software were built. A 1-D analytic valve modeling method based on compressible flow theory was devised and adopted to calculate the fluid properties for the valve modeling [1, 2]. Finally, we carried out several numerical analyses based on the 1-D numerical PCV system model and examined several critical relations between the transient pressure and each factor, such as the valve opening ratio, pipe diameter, header size, SSV shut time and the size of the additional components after the system.

2. Numerical modeling

2.1 1-D PCV system modeling

Fig. 1 is a schematic diagram of a 1-D numerical model of a PCV system based on the Flow-Master II commercial software used in this study. As the aims of this study were not the development of special schemes or numerical techniques, but rather the analysis and examination of the flow characteristics of a PCV system under certain circumstances, it was deemed reasonable to use some commercial software that has already been widely proven in terms of stability and reliability rather than developing in-house code.

The targeting PCV system is assumed to have three PCV lines. The target region of the analysis model starts from just before an 8" PCV, and passes through a 17 m pipe from the end of the PCV and linked to an 8m header pipe. It finally extends about 10 km to the delivery point. Of course, in field situations, there are many other types of components, including various types of other valves, meters and additional fluid machines, but for simplification any unimportant com pone nt not vital to the analysis was omitted in this model.

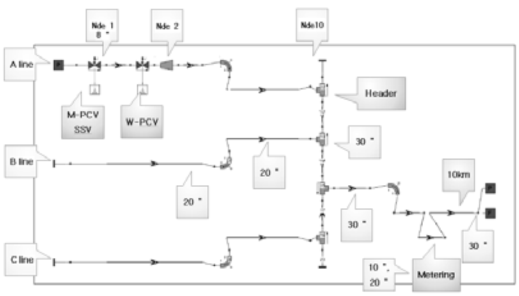


Fig. 1. Schematic diagram of a 1-D PCV system model.

2.2 1-D analytic valve modeling

Some modeling work for all main valves and components is needed to complete the 1-D pipeline network model of a PCV system. A common way to model a valve is by making charts of both the gas flow factor and the loss coefficient versus each opening ratio [3]. To obtain these charts, we naturally need to get almost all of the flow properties at both the inlet and the outlet of a PCV. However, since there are many types of valves and all experimental data are not available in practice, some other methods to calculate these properties are required.

At this point, some analytic methods based on the 1-D compressible flow theory are proposed in this study and applied to the 1-D numerical analysis model. In addition, it is known that the irreversible adiabatic process assumption is applicable in comparatively short pipelines such as these PCVs [4]. The irreversible adiabatic process assumption was introduced to this analysis and then a general trial and error numerical method was applied to solve the governing equation of irreversible 1-D compressible flow that accompanies the friction loss, as follows:

Continuity eqn : $$\frac{d\rho}{\rho}+\frac{dV}{V}=0 \quad (1)$$

Momentum eqn : $$dP+\frac{4\tau_w dx}{D}+\rho V dV=0 \quad (2)$$

Energy eqn : $$C_P dT + V dV = 0 \quad (3)$$

Ideal Gas Law : $$\frac{dP}{P}=\frac{d\rho}{\rho}+\frac{dT}{T} \quad (4)$$

Darcy-Friction eqn : $$\tau_w = \frac{1}{s} f\gamma p Ma^2 \quad (5)$$

where ρ : density, V: velocity, p: pressure
τ_w : stress at wall, C_P : specific heat at p
T: temperature, f: friction factor
γ : specific heat ratio, M_a :Mach number.

3. Validation and valve modeling results

3.1 3-D CFD valve model for validation

The monitor PCV was selected to be the target valve for the validation of the proposed valve flow analysis and modeling method. AutoCAD software was used to build the 3-D shape models. Fluent 6.1

software was adopted for CFD analysis, and Gambit 2.1 software was selected for grid generation. Fig. 2 is a perspective view of a 3-D grid that was generated for this CFD analysis.

An implicit coupled scheme having second order accuracy using a standard k - ε turbulent model was selected, and a working fluid was assumed to be natural gas of normal composition. As boundary conditions, constant stagnation pressure for the inlet and constant static pressure for the outlet was assumed. That is, it was assumed that a huge reservoir that can continuously offer constant pressure was linked to the PCV inlet, and the outlet contacted to the atmosphere. Some numerical analyses using the 3-D CFD model were conducted to verify the reasonability of this CFD model and the validity of the boundary conditions. A comparison between the results of the CFD analysis and the manufacture's data [5] is presented in Fig. 3.

The flow-rate-coefficient (KG) calculated from the analysis was about 2,000 higher than the manufacturer's data. This can be attributed to the simplification of the shape of the internal elements such as the spring. However, the gap is relatively small and the tendency is well understood, so it can be concluded that the 3-D CFD model was successfully built to analyze the internal flow within a monitor PCV.

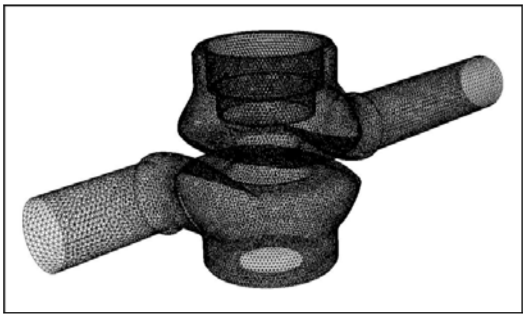


Fig. 2. 3-D view of the grid system of the monitor PCV.

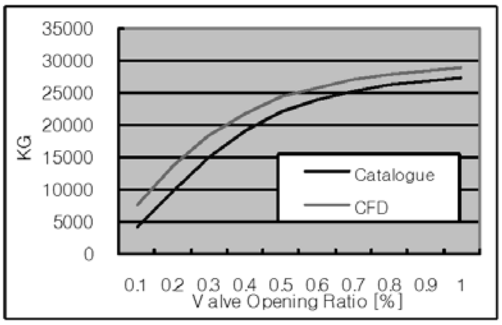


Fig. 3. Flow-rate coefficient comparison of the monitor PCV.

3.2 1D model validation with a 3D CFD model

Two series of 3-D CFD analyses were done to obtain data for validation of the proposed method. One is classified by several inlet-outlet pressure ratios between 1.5 and 8 bar, and the other is classified by the valve opening ratio at several inlet pressure conditions. In both cases, static pressure was set to 1 bar and temperature was set to 288.15 K at the outlet.

The proposed 1-D analytic method, which assumed the PCV's internal flow to be a 1-D compressible flow with irreversible adiabatic process, was calcu lated for comparison and verification. Fig. 4 is the velocity comparison graph between the 3-D CFD analysis results and the proposed 1-D analytic calcu lation results at several inlet-outlet pressure ratios. Fig. 5 is the same velocity comparison graph between several opening ratios at several inlet-outlet pressure ratios. In these figures, we can see that the results are almost the same, or at least that the gap between them is relatively small, so it can be concluded that the proposed 1-D analytic method is reasonable and

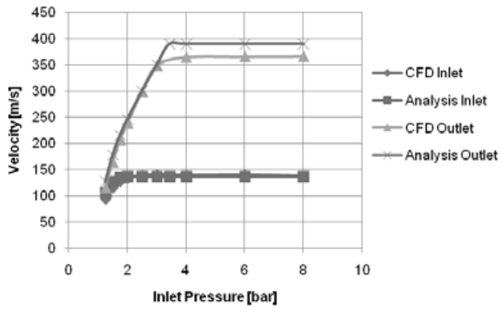


Fig. 4. Velocity comparison between CFD & Analysis by several inlet-outlet pressure ratios.

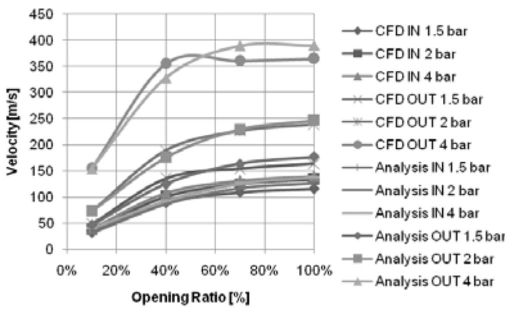


Fig. 5. Velocity comparison between CFD & analysis by valve opening ratios at several inlet-outlet pressures.

applicable for internal flow calculation and modeling of the valve [6, 7].

3.3 Valve modeling results

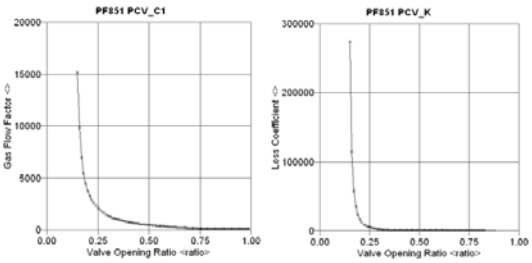
Several analyses using the proposed 1-D analytic method were carried out for the valve modeling of the worker PCV, monitor PCV and SSV. As a result, for every valve, the gas-flow factors defined in Eq. (7) and the loss coefficients defined in Eq. (6) were obtained as shown in Figs. 6 to 8 [8]. In Fig. 9, a graph comparing the flow-rate coefficients of the worker PCV shows a good fit, so it can be concluded that the valve modeling data produced by the proposed 1-D analytic method are reasonable and proper for application to 1-D PCV system analysis.

Loss Coefficient : $$K = \frac{P_1}{\rho V} \quad (6)$$

Gas Flow Factor : $$C_1 = 24.0\times 10^{-6}\frac{C_g\sqrt{K}}{\sqrt{2A}} \quad (7)$$

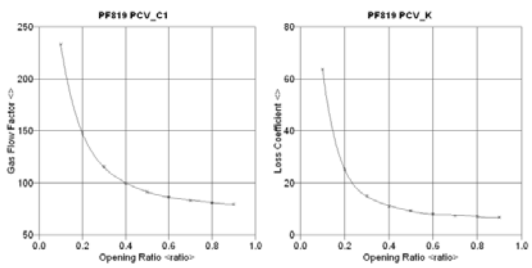
Gas Sizing Coefficient : $$C_g = \frac{Q}{\sqrt{520P_1\gamma / GT}} \quad (8)$$

where P: pressure (1:in, 2:out), ρ : density
V: velocity, γ : subcritical flow factor
Q: gas flow rate, G: gas specific gravity
T: temperature[$^\circ R$], A: area.



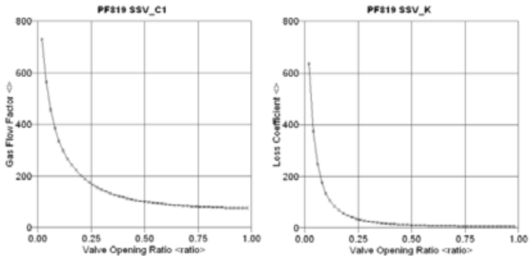
(a) Gas flow factor (b) Loss coefficient

Fig. 6. Worker PCV model data.



(a) Gas flow factor (b) Loss coefficient

Fig. 7. Monitor PCV model data.



(a) Gas flow factor (b) Loss coefficient

Fig. 8. SSV model data.

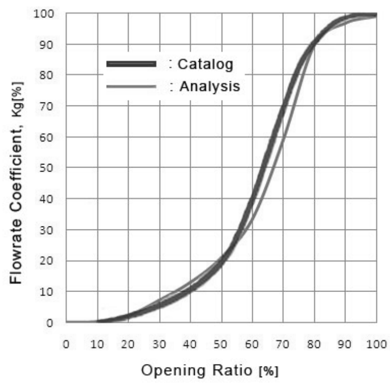


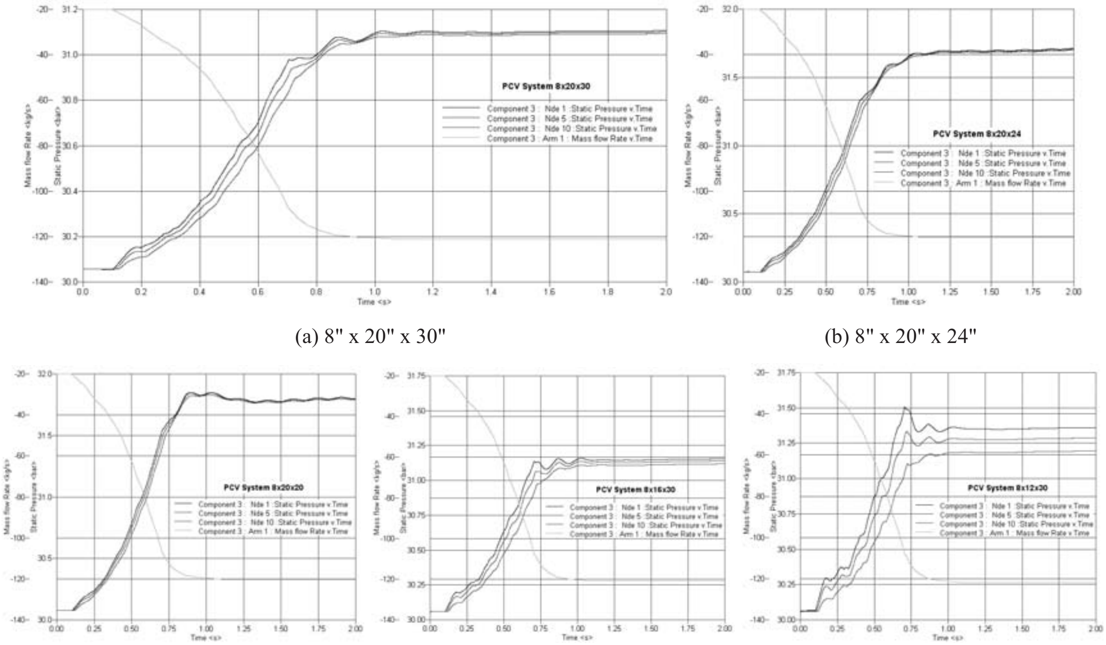
Fig. 9. Flow-rate coefficient comparison of the worker PCV.

4. Analysis and results

4.1 Analysis and procedure

As explained in Section 2.1, a 1-D PCV system model has been built and used for the main purposes in this study. The schematic diagram of the basic system is presented in Fig. 1. At the start, we assumed that the worker PCV was under normal operation conditions, defined as an inlet pressure at 65 bar and outlet pressure at 30 bar, and that it would maintain this steady state and then suddenly the worker PCV would be open wide. It is supposed for the simulation that the transient pressure is generated and increased due to some difficulty with the PCV. In this situation, if the pressure exceeds the SSV operation limit, the SSV will operate simultaneously with the monitor PCV. As a result, the SSV shuts off the operating line rapidly and the fluid cannot flow anymore, until finally the increased pressure will start oscillating and propagating toward the end of the pipeline. In this study, this increased and oscillating pressure has been defined as the transient pressure.

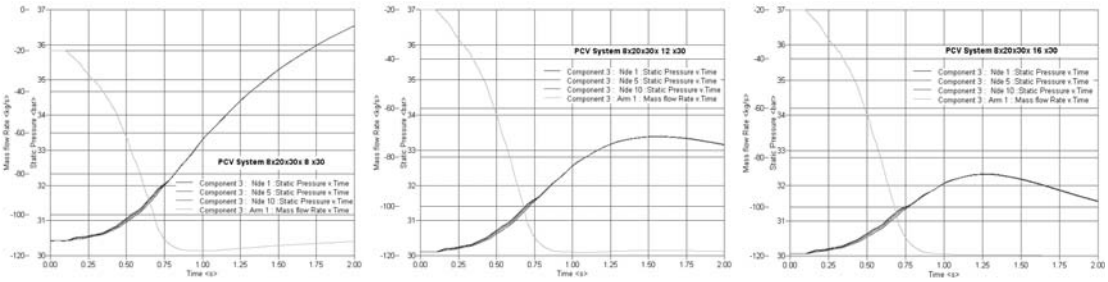
Finally, we are ready to examine the generation and propagation characteristics of the transient pressure



(a) 8" x 20" x 30" (b) 8" x 20" x 24"

(c) 8" x 20" x 20" (d) 8" x 16" x 30" (e) 8" x 12" x 30"

Fig. 10. Comparison of pressure by pipe diameter.



(a) 8"x20"x30"x8"x30" (b) 8"x20"x30"x12"x30" (c) 8"x20"x30"x16"x30"

Fig. 11. Pressure variations by additional components.

induced by PCV malfunctions and to clarify the relationships between the transient pressure or surge wave and each factor or parameter relating to the fluid dynamics in the PCV system.

4.2 Influence of diameter and header size

Diameters are noted in the form of "pipe after PCV x header x pipe to the exit." And the time to open the worker PCV due to malfunction is assumed to be 1 second (between 0.1 and 1.1 sec after steady-state). Notations in the resulting graphs are defined as follows: Nde1 (worker PCV outlet), Nde5 (monitor PCV outlet), Nde10 (the end of the PCV line), Comp.3 (operating line: A line), Comp.4 (preparation line: B line), Comp.5 (emergency line: C line) and Arm 1 (mass flow rate through the worker PCV in the A line).

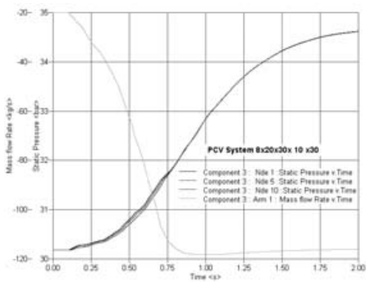
The strength of the transient pressure is directly affected by the variation of the mass flow rate during a moment, and it can also be affected by the size of the pipeline after a PCV system. Therefore, the relationships between the transient pressure and the size of the pipe or header were examined with the 1-D PCV system model in this section. It is assumed that the worker PCV is only open in case of a PCV malfunction, and that the SSV is not operating.

Fig. 10(a) is the result of an 8" x 20" x 30" base system and (b) and (c) are graphs when the diameters of the pipe from the header to the end are reduced to 24" and 20" from 30" of (a), respectively. It can be seen in these figures that the transient pressure is increased by the pipe reductions, that is, they have a relationship of inverse proportion. Fig. 10 (d) and (e) are graphs when the header diameters are reduced to 16" and 12" from 20" of (a), respectively. These figures show that the transient pressure is increased by the reduction of the header and new pressure peaks appear in these graphs. Therefore, it can be said that they have similar effects to the previous relations of the diameter cases in Figs. (a)-(c).

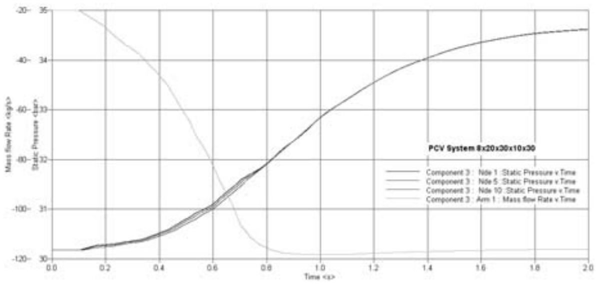
4.3 Influence of additional components

Following the results above, the transient pressure never exceeds the SSV operating limit in cases where the pipe diameter linked after the system is sufficiently larger than the PCV diameter. This means that the transient pressure, which can cause problems, is never generated and the SSV never functions[FO1]. However, it does not work in the model as we know it to work in real cases. It can be supposed that one of the reasons transient pressure occurs is related to the added components after the PCV system. Therefore, we undertook some investigation of the relationship between the transient pressure and the pipe size of the added components linked after the PCV system. For modeling, a 100 m pipeline element with an assumed added component block was inserted after the header.

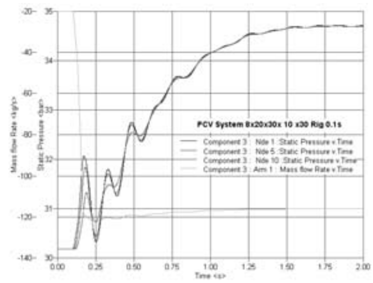
The results are shown in Fig. 11 and the diameter notations are modified to the form of “pipe after PCV



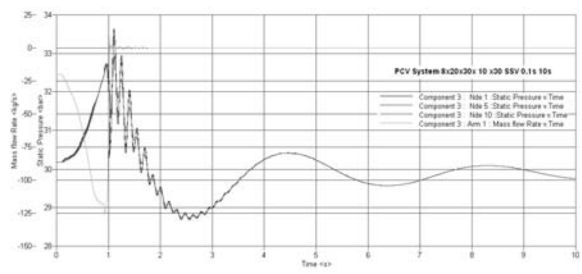
(a) 1 sec



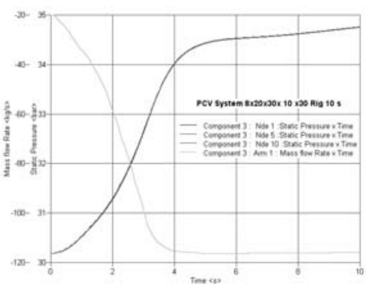
(a) Pressure variation at SSV not working



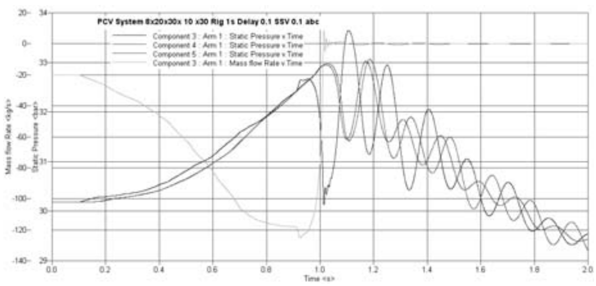
(b) 0.1 sec



(b) Pressure variation at SSV working



(c) 10 sec



(c) Pressure variation of the other lines at SSV working

Fig. 12. Comparison of pressure by opening time.

Fig. 13. Comparison of pressure by SSV working.

x header x pipe after header x pipe on added component x pipe to the exit." These graphs show that the pipe size reduction of the added component induces a sufficient increase in the transient pressure strength. Therefore, it can be said that the pipe size of the added component shows a relationship of inverse proportion to the strength of the transient pressure. This factor can be one of the most critical factors governing the transient pressure.

4.4 Influence of valve opening time

In this study, it was assumed that the valve opening time represents the generation time of the transient pressure, because the transient pressure generation is directly induced from the bursting diaphragm. In addition, there are no other ways to simulate the bursting time of a diaphragm in the worker PCV. As some relationship seems to exist between the time and the transient pressure, we investigated the influence of the valve opening time. Here, an 8" x 20" x 30" x 10" x 30" PCV system was used as the basic analytical system for this section.

Fig. 12 (a), (b), (c) show the result when the valve opening time is 1 second, 0.1 second and 10 seconds, respectively. In all cases, the transient pressure is increased rapidly and proportional to the valve-opening ratio. The graphs suggest that the faster the valve opens, the more rapidly the transient pressure increases, but the highest values of the transient pressure are almost the same in every case. Therefore, it can be said that the increase of the transient pressure is faster when the valve opening time become shorter, but the maximum value of the transient pressure is not affected by the valve opening time.

4.5 Influence of SSV closing

In a case where the SSV works automatically due to the transient pressure exceeding the limit, a type of surge effect can be generated. Fig. 13(a) is the graph of cases when the SSV did not work, (b) shows the cases when SSV worked and then shut off the line and (c) is the graph of activity on other lines in the same case as (b).

First, it can be seen that the transient pressure is immediately decreased by the action of the SSV and some kind of surge wave is generated and propagated to the outside. Here, particularly, we can see that the transient pressure propagates with almost the same strength and at almost the same time compared with that of the operating line. Once the transient pressure is generated in the operating line, the propagation is so rapid that the transient pressure is propagated to the other lines almost simultaneously with almost the same strength. This finding clarifies why all the PCV lines are shut down and the PCV system then fails to sustain continuous supply.

5. Conclusions

In this study, we successfully built a 1-D PCV system numerical model and effectively introduced a 1-D compressible flow theory for analytic valve modeling. Several numerical analyses were successfully carried out to examine the generation and propagation characteristics of the transient pressure, and to clarify the relationships between the transient pressure or surge wave and each factor or parameter relating to the fluid dynamics behavior in a PCV system. The major conclusions in this study are as follows:

(1) Transient pressure is inversely proportional to the size of the pipe and header linked after a PCV, but these are not critical factors.

(2) Transient pressure is inversely proportional to the pipe size of the added component linked after the header, and this factor can be one of the most critical because this pipe size is much smaller than others in standard PCV systems.

(3) The generation time of the transient pressure is proportional to the valve opening time, but the strength of the transient pressure is not seriously affected by this relationship.

(4) When the SSV is working, transient pressure is propagated to the other lines with almost the same strength, enough to operate the other SSVs on those lines. Therefore, this explains why all the PCV lines are shut down and the PCV system then fails to maintain continuous supply.

(5) Finally, in order to reduce the strength of the transient pressure and to delay its propagation, we propose both enlargement of the size of the pipe of the component added after the PCV system and installation of a dissipation component between the operation line and the other lines.

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