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Simulation on Release Characteristics of the Gas Extinguishing Agent in Fire Extinguisher Vessel with Different Filling Conditions Based on AMESim

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Abstract

To study the release characteristics of the gas extinguishing agent from fire extinguisher vessel at different filling conditions, a gas fire extinguishing agent jet test platform was established. The calculation model of jetting gas extinguishing agent from gas extinguisher vessel was constructed with AMESim and the jet performance of gas extinguishing agent was simulated by using the two-phase flow model. By changing the initial temperature and filling pressure, the pressure changed at the outlet of the vessel is simulated, and then the change of the outlet pressure and the discharge time were analyzed emphatically. The results showed that the outlet pressures of the fire extinguisher vessel had the same trend basically at different initial temperature; all of them declined rapidly with the jetting time and then tended to be gentle. When the filling pressure was lower, the outlet pressure of the vessel at different initial temperature was quite various, and the sudden slope change could be seen obviously during the discharge process at higher initial temperature. When the initial temperature ranged from -30 ℃ to 30 ℃, the jetting time shortened with the rising of the initial temperature at different filling pressure. In addition, the outlet pressure of the fire extinguisher vessel tended to be flat with the rapid decrease in the injection time. At different filling pressures, the outlet pressure of the vessel declined rapidly with the jetting time and then tended to be gentle.

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Keywords: AMESim, gas fire extinguishing agent, filling condition, outlet pressure, two phase flow simulation.

Nomenclature

ΔP	differential pressure between the outlet of the vessel and the inlet of nozzle (MPa)
P1	outlet pressure of the vessel (MPa)
P2	inlet pressure of the nozzle (MPa)
t	release time (s)

1. Introduction

In the event that a fire breaks out on an airplane which is flying at high altitude, it is most likely to cause a serious flight accident. To cope with this problem, automatic fire extinguishing systems are usually set in the cargo hold, engine nacelle, APU nacelle, bathroom and other places easy to catch fire to ensure the safety of passengers and the aircraft.

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In the fire extinguishing system of an aircraft, a vessel holds fire extinguishing agent, when the fire extinguishing system is triggered, the fire extinguishing agent flows from the vessel through the pipes and nozzles, and finally jets to the fire-caught place. Due to the resistance within the pipe, the agent has a differential pressure (ΔP) between the outlet of the vessel and the inlet of the nozzle, which is the difference between the outlet pressure of the vessel ($P1$) and the inlet pressure of the nozzle ($P2$). Since the jet of the fire extinguishing agent is related to $P2$ closely, the accurate calculation of $P1$ and ΔP is extremely important to the design of the fire extinguishing system in engineering design. In view of the fact that Halon 1301 is still used widely in the fire extinguishing system of a civil aircraft and the physical and chemical properties of Halon 1301 are complete. In this paper, Halon1301 is used as an example to study the effect of the initial temperature, filling density and filling pressure on the outlet pressure of the vessel.

Internationally, D. G. Elliott et al[1] from the Jet power Laboratory of the United States National Aeronautics and Space Administration (NASA) used a homogeneous equilibrium model of two-phase flow in 1984 to explain questions about the transient pipe and nozzle flow in halon systems, and established a pressure drop calculation model of Halon 1301 fire extinguishing agent flow which was pressurized with nitrogen. K. Tuzla et al[2] developed a fire extinguishing system simulation software based on Relap5. J. C. Yang et al[3] constructed a gas-liquid equilibrium model to simulate the transient discharge of a fire extinguishing agent through piping. A separate vapor-liquid equilibrium computer program which uses the model can obtain thermodynamic properties and filling conditions. T. G. Cleary et al[4] found in the study that the flow characteristics of HFC-227ea and Halon 1301 were influenced by the initial temperature, storage pressure and piping configurations of storage bottle. And they[5] built a device to study the pressure drop and flow time of the alternative agents and Halon 1301, held the design of different storage conditions and piping configurations. At the same time, the flow characteristics of three halon substitute fire extinguishing agents were studied. The three alternative agents showed similar pipe flow characteristics to Halon 1301, and they developed a computer calculation model which could simulate steady-state and transient discharge of the nitrogen-pressurized agent.

In China, LIU Lian-xi et al.[6] illustrated the pressure loss of HFC-23 in gas-liquid and two-phase condition by analyzing the flow state and the flowing pressure-time curve of HFC-23 in each part of a pipe network. They deduced a calculation formula for pressure drop and it was proved that the theoretical results were in good agreement with the experimental results after comparison with practical test data. LUO Ming-hong et al.[7] studied the IG541 automatic fire extinguishing system profoundly. They chose the pipe diameter appropriately, determined the resistance coefficient and calculated the pressure drop along the pipeline. They also wrote an application for practical engineering. On the basis of the experimental study, HUA Wan-ren et al.[8] simulated the resistance loss of the flow of the HFC-227ea in the pipe network by using Fluent, a computational fluid dynamics (CFD) software application. It was considered that the flow of the HFC-227ea fire extinguishing agent in the pipe network could be simplified as a one phase flow of liquid. At the same time, they thought that computer software simulation can replace the experimental test, and simulation results can be used for practical engineering. Based on the Peng-Robinson (PR) equation of state and the Wong-Sandler (W-S) mixing rule, CHEN Meng-dong et al.[9] proposed a prediction method to calculate the filling mass of nitrogen. They also analyzed the change of pressure intensity and mole fraction of nitrogen with the temperature in the vessel, which laid a foundation for the subsequent analysis of the release process of fire extinguishing agents and nitrogen.

The above-mentioned researchers mainly focused on the flow characteristics of the pipe network of the fire extinguishing system, and the influence of the factors such as the filling conditions of fire extinguishing agents. The filling conditions, piping configuration and nozzle configuration, however, were less focused in their research.

LMS AMESim is an application that provides a graphical development environment and is used for modeling, simulation and dynamic performance analysis of engineering systems. It has a set of standard application library. The model provided in this paper is mainly composed of different application library components from two-phase flow library, pneumatic library, pneumatic component design library which make the main libraries, and the mechanical library and signal control library which make the supporting libraries. The different application libraries are compatible with each other, eliminating the need for a large number of additional programming work. Moreover, each of these models provides the most basic engineering module. They can describe any component or system functions through the combination of these engineering unit models.

Based on the simplified pipe structure of the flow of the fire extinguishing agent, this paper uses the special function module of the AMESim's application library to simulate the influence of the filling conditions of the fire extinguishing system on the outlet pressure (P1) of the vessel which lays a foundation for the further study of the flow diffusion characteristics of the agent in piping and the flow diffusion patterns after flowing out of the nozzle.

2. Modeling

2.1. Model

The fire extinguishing system consists of a fire extinguisher vessel, a cylinder valve, a pipe and a nozzle, as shown in Fig. 1. The vessel is a spherical tank made of stainless steel with a capacity of 1.4L. The pipe is 1 meter long with an internal diameter of 14.1mm. The nozzle is a straight-through one and its internal diameter is the same as that of the pipe. The fire extinguishing agent is Halon 1301, which is driven by the nitrogen gas. The gas-liquid ratio of Nitrogen and Halon1301 is 0.65: 0.75 in volume. The cylinder valve has the filling pressure of 2.5MPa, 4.2MPa and 10MPa. The initial temperature of the agent is -30 ° C, -20 ° C, 0 ° C, 20 ° C and 30 ° C, respectively.

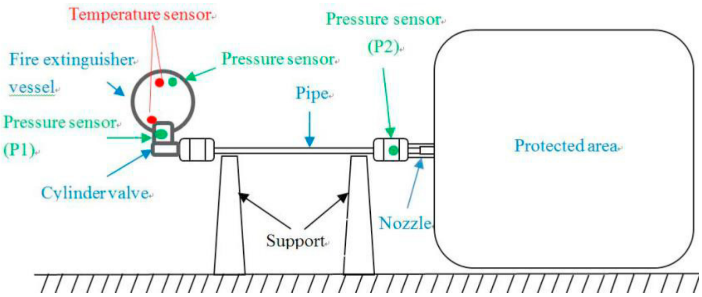


Fig. 1. The fire extinguisher test platform

2.2. Simulation

The two-phase flow model is used to simulate the release characteristics of the agent. The built-in solver of AMESim is used for the calculation of two-phase flow model. The physical quantity can be solved by the established simulation model and the preset initial conditions and the boundary conditions. According to the design of the model in Section 2.1, the related components are selected to construct the simulation model of the gas fire extinguisher vessel, including the pneumatic library, the mechanical design library and the two-phase flow library. The flow properties and the throttle valve provided by the two-phase flow library are used to construct the outlet components of the fire extinguisher. The simulation model of the vessel and the outlet components form the model of a release characteristics test system, the vessel of which is influenced by the filling conditions, as shown in Fig. 2. The components and parameter settings used in calculation are listed in Appendix 1. In view of the complexity of the actual industrial control, to simplify the calculation, this paper has taken the following assumptions in the simulation:

(1) The nitrogen and Halon 1301 do not mix in a fire extinguisher vessel;

(2) Only the Halon 1301 is ejected from the fire extinguisher cylinder during the spraying process;

(3) The fire vessel and the pipe do not exchange heat with the external environment.

In this system, the fire extinguisher vessel consists of the pneumatic volume (PNCH012), pneumatic piston with fixed body(PNPA001), mass(MAS005), two-phase flow piston with fixed body (TPFBAP12) and two-phase flow volume (TBFBHC11); the outlet of the vessel is connected to the sensor (TPFGS010) with signal port plug (SSINK). The temperature, pressure and density of the fire extinguishing agent at the outlet can be recorded and calculated by the sensor. The other side of the sensor is connected with an adiabatic smooth pipe (TPFP002), which simulates a simplified pipe through which the agent flow. Finally, a two-phase flow restriction (TPFGR00) is connected with a tank (TPFCPHS000) which simulates the external protected area where Halon 1301 is emitted. This design takes into account the presence of gas-liquid stratification. It can simulate the process in which nitrogen is used as a driving gas to push Halon 1301 out of the vessel in the first period.

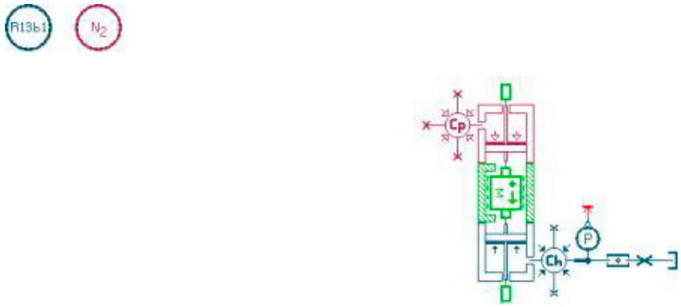


Fig. 2. Model of the release characteristics test system of a fire extinguisher vessel

3. Results and Discussion

3.1. Influence of initial temperature on the outlet pressure of fire extinguisher vessell

The simulation was carried out at a filling pressure of 2.5MPa, 4.2MPa and 10MPa respectively. The pipe length is 1m and the hydraulic diameter is 14.1mm. The pipe is horizontal, adiabatic and smooth. Nitrogen and Halon 1301 gas-liquid ratio is 0.65: 0.75 in the fire extinguisher vessel. When the initial filling temperature of the system is -30 ℃, -20 ℃, 0 ℃, 20 ℃, and 30 ℃,respectively, the pressure curve of the outlet of the vessel will be calculated, and the calculation results are shown in Figures 3 (a) through 3(c).

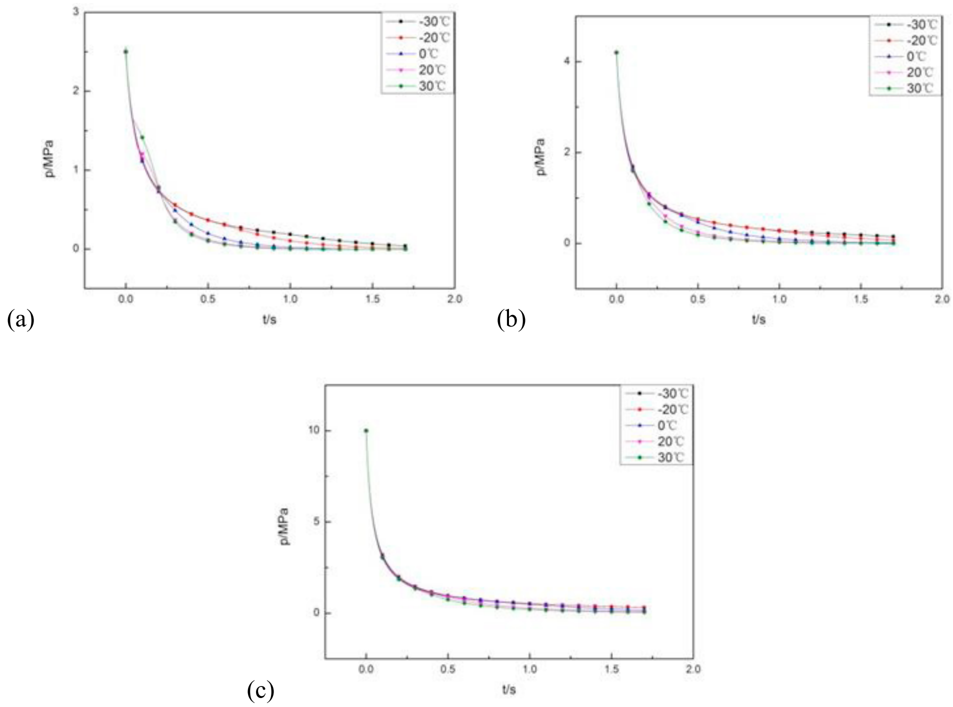


Fig. 3. The outlet pressure of fire extinguisher vessel at different initial temperature when (a) the filling pressure is 2.5MPa. (b) the filling pressure is 4.2MPa. (c) the filling pressure is 10MPa.

Fig. 3 (a) through 3 (c) show the pressure of the fire extinguisher vessel at the outlet (*P1*) varies with the release time (*t*) at different initial temperature. The pressure curve shows that the outlet pressure of the vessel has the same trend with the discharge time basically at different initial temperature. The pressure declines rapidly with the time and then tend to be gentle. When the filling pressure is small, the outlet pressure of the vessel at different initial temperature is quite different, and the obvious slope change can be seen during the discharge process. The higher the initial temperature is, the more obvious the sudden change shows. The main reason is that higher initial temperature causes the liquid Halon 1301 to be gasified earlier, which increases the pressure in the vessel and counteracts a portion of the pressure drop caused by the release of the agent. Consequently,the pressure curve of the outlet of vessel changes abruptly. However, under the condition of high filling pressure, the greater pressure drop during the release process makes the vapor pressure of fire extinguishing agent drop greatly, and the vapor pressure is much smaller than the pressure drop rate of release process of the fire extinguishing agent. Therefore, there is no significant difference in the outlet pressure of the vessel at different initial temperatures when the filling pressure is higher. And there is not a slope change as obvious as that of the outlet pressure curve when the filling pressure is low.

In Fig. 3 (a), when the filling pressure is 2.5MPa, the outlet pressure curve of the vessel shows an obvious slope change. In order to get the causes of the sudden change, the density of Halon 1301 at the outlet is calculated, and the calculation results are shown in Fig. 4.

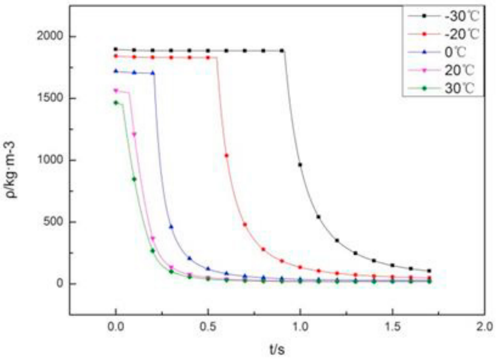


Fig. 4. The outlet density of fire extinguisher vessel at different initial temperature when the filling pressure is 2.5MPa.

It can be seen from Fig. 4 that the outlet density of the Halon 1301 at different initial temperature declines abruptly and coincides with the time point of the sudden change of pressure. The density change point indicates that Halon 1301 begins to make phase transition during the flow and it changes from the liquid phase to the gas phase gradually. The process of phase change produces a large amount of saturated vapor of Halon 1301, supplementing a portion of the pressure drop caused by the release of the agent, thereby slowing the rate of outlet pressure drop of the vessel. And the phase transition time at the temperature of -30 ℃, -20 ℃, 0 ℃, 20 ℃ and 30 ℃ occurred at 0.91s, 0.55s, 0.21s, 0.07s and 0.04s respectively, which is in agreement with the point of the sudden change of the slope of the pressure curve as shown in Fig. 3 (a). This demonstrates that phase transition is the important cause of the sudden change of the outlet pressure of fire extinguisher vessel.

3.2. Influence of initial temperature on discharge time

Here the discharge time is the time when the mixed gas fire extinguishing agent is sprayed to 95% of the designed amount. In this paper, the residual pressure of the vessel is a sign when dropping to 5% of the filling pressure.

When the filling pressure is 2.5MPa, the pressure curve is shown in Fig. 3 (a), and 5% of the filling pressure is 0.125MPa. When the initial temperature is -30 ℃, -20 ℃, 0 ℃, 20 ℃, and 30 ℃, the corresponding discharge time is 1.22s, 0.94s, 0.61s, 0.49s, and 0.46s respectively.

When the filling pressure is 4.2MPa, the pressure curve is shown in Fig. 3 (b), and 5% of the filling pressure is 0.21MPa. When the initial temperature is -30 ℃, -20 ℃, 0 ℃, 20 ℃, and 30 ℃, the corresponding discharge time is 1.34s, 1.15s, 0.76s, 0.54s, and 0.47s respectively.

When the filling pressure is 10MPa, the pressure curve is shown in Fig. 3 (c), and 5% of the filling pressure is 0.5MPa. When the initial temperature is -30 ℃, -20 ℃, 0 ℃, 20 ℃, and 30 ℃, the corresponding discharge time is 1.07s, 1.05s, 0.98s, 0.73s, and 0.64s respectively.

The above data are plotted and the results are shown in Fig. 5.

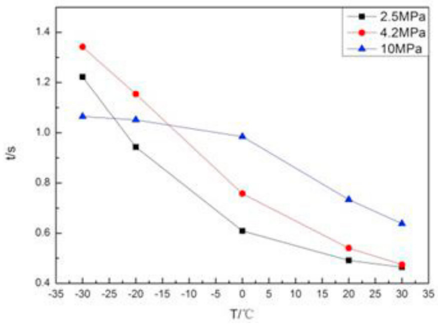
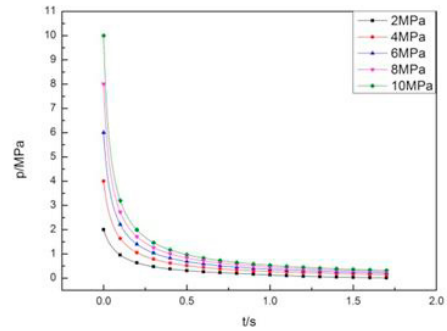


Fig. 5. Release time at different filling pressure

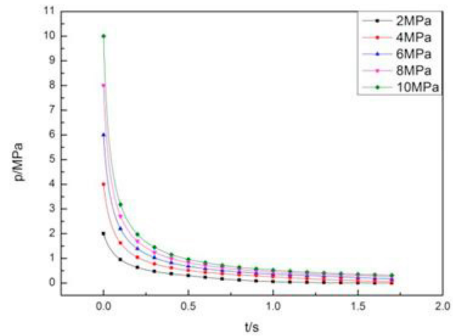
Fig. 5 shows the initial temperature – discharge time curve at different filling pressures. It can be seen that slopes of the discharge time over initial temperature are in basic agreement. And the initial temperature shortens with the increase of the initial temperature.

3.3. Influence of filling pressure on the outlet pressure of fire extinguisher vessel

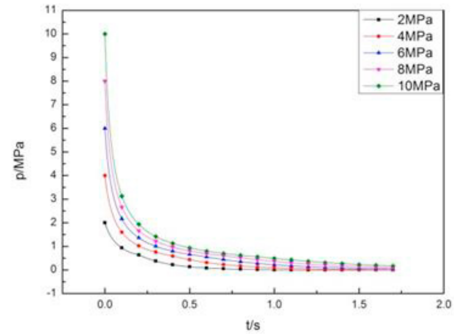
The pressure curve of the outlet of the vessel will be calculated, and the calculation results are shown in Figs. 6 (a) through 3 (e).



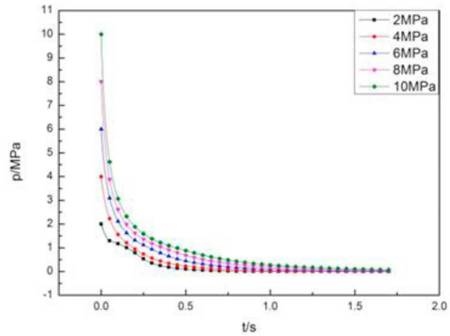
(a)



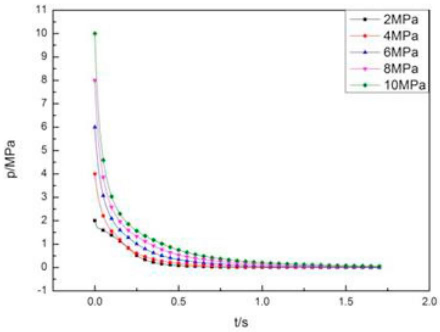
(b)



(c)



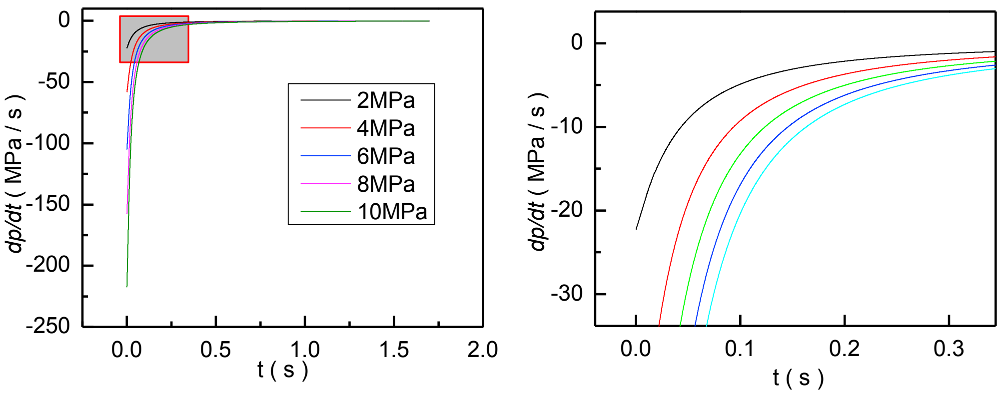
(d)



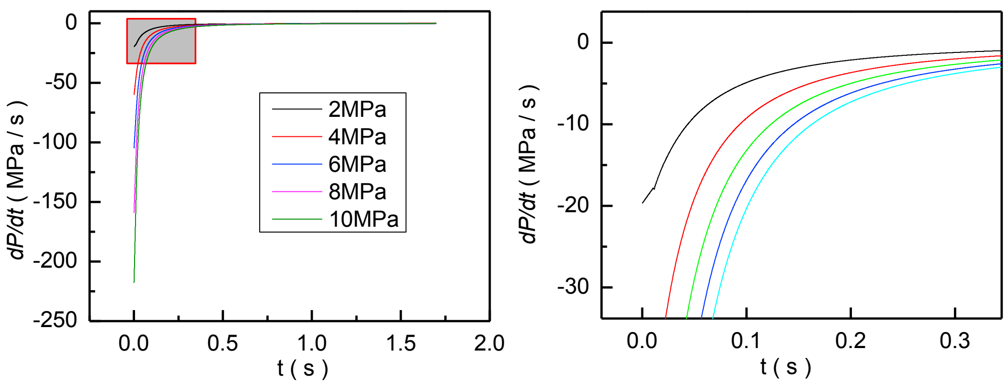
(e)

Fig. 6. The outlet pressure of fire extinguisher vessel at different filling pressure when (a) the initial temperature is -30℃ (b) the initial temperature is -20℃. (c) the initial temperature is 0℃. (d) the initial temperature is 20℃. (e) the initial temperature is 30℃.

Figs. 6 (a) through 6 (e) show the outlet pressure of the fire extinguisher vessel at varies with release time (t) at different filling pressure. It can be seen that the pressure of the vessel at the outlet pressure have the same trend with discharge time basically at different filling pressure, the curve declines rapidly with the time and then tend to be gentle. For this reason, this paper solves the derivative of the outlet pressure, and the pressure change rate curve is shown in Figs. 7 (a) through 7 (e).



(a)



(b)

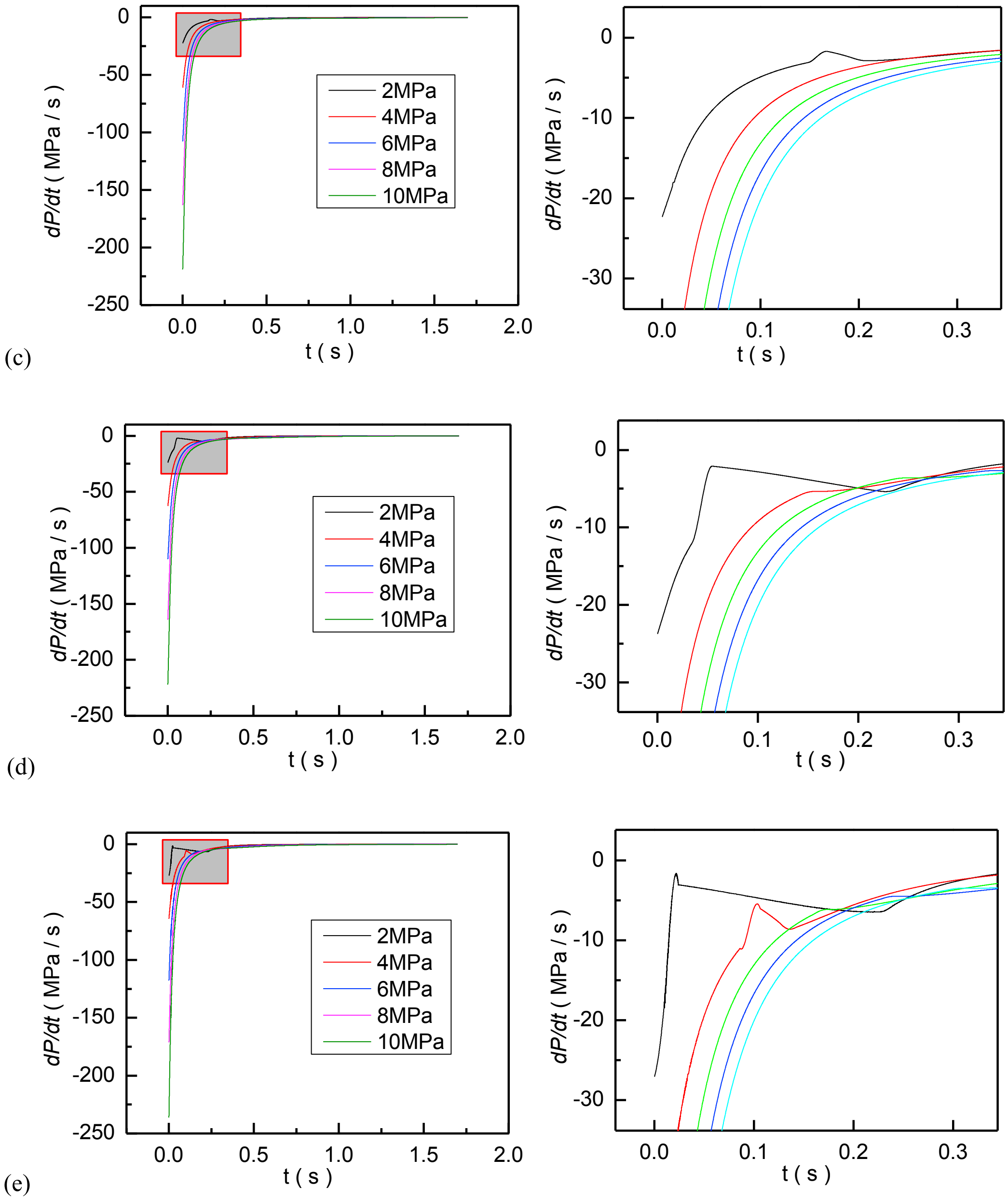


Fig. 7. The outlet pressure change rate of the vessel at different filling pressure when (a) the initial temperature is -30℃. (b) the initial temperature is -20℃. (c) the initial temperature is 0℃. (d)The initial temperature is 20℃. (e) The initial temperature is 30℃.

It can be seen that the pressure change rate at the outlet of the fire extinguisher is obviously abrupt when the initial temperature is above 0 ℃. When the initial temperature is below 0 ℃, the pressure variation rate does not change significantly. When the initial temperature is higher, the lower filling pressure is, the more obvious the sudden change of the pressure curve of the outlet pressure is. When the initial temperature is lower, the change of filling pressure doesn’t have obvious effect on the sudden change of the outlet pressure change rate curve. When the filling pressure is common, the higher the initial temperature is, the sharper the sudden change in the change rate of the outlet pressure curve, and the more prominent bulging in the pressure curve.

4. Conclusions

Based on the simplified pipe structure of the flow of fire extinguishing agent, this paper uses the special function module in the AMESim's application library to simulate the influence of the filling conditions of the fire extinguishing system on the outlet pressure (*P1*) of the fire extinguisher vessel. Main conclusions are as follows:

(1)The *P1* at different initial temperature has the same trend basically and declines rapidly with the release time (*t*) and then tends to be gentle. When the filling pressure is low, the initial temperature has a great influence on the outlet pressure of the vessel (*P1*). And the obvious slope change can be seen on the *P1* ~ *t* curve. The higher the initial temperature is, the more obvious the sudden change is.

(2)When the initial temperature ranges from -30℃ to 30℃, The release times are basically the same as the change trend of the initial temperature and shorten with the rising of the initial temperature at the different filling pressure.

(3)At different filling pressures, the outlet pressures of the vessel are basically the same as the change trend of the discharge time and decline rapidly with the time and then tend to be gentle.

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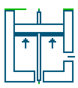
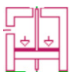
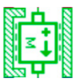
Appendix A. The components and key parameter settings

Table 1. The components and parameter settings

icon	Component Name	Code of Submodel	Application library	Title	Setting Value
	definition of fluid properties	TPF_FP01	Two-phase Flow	Fluid index in database	R13b1
	two phase flow piston with fixed body	TPFBAP12	Two-phase Flow	piston diameter rod diameter	200 mm 0 mm
	two phase flow volume with temperature and pressure dynamics	TPFBHC11	Two-phase Flow	type of initialization pressure dead volume	pressure and temperature 2 MPa 0.75 L
	generic sensor	TPFGS010	Two-phase Flow		

	adiabatic pipe	TPFP002	Two-phase Flow	pressure length cross-sectional area hydraulic diameter	101.325 kPa 1 mm 14.1*14.1/4*pi mm**2 14.1 mm
	generic restriction	TPFGR00	Two-phase Flow	cross-sectional area hydraulic diameter	14.1*14.1/4*pi mm**2 14.1 mm
	tank	TPFCPHS000	Two-phase Flow	type of initialization pressure	pressure and temperature 1.013 barA
	zero mass flow rate source	TPFSINK00	Two-phase Flow		
	pneumatic nitrogen	PN_NITROGEN	pneumatic		
	pneumatic volume	PNCH012	pneumatic	temperature pressure dead volume thermal exchange coefficient	20 degC 2 MPa 0.65 L 0 J/m**2/K/s
	pneumatic piston with fixed body	PNPA001	pneumatic	piston diameter rod diameter	200 mm 0 mm
	zero pneumatic flow source	PNPL01	pneumatic		
	mass with 2 ports and end stops	MAS005	mechanical	mass	0.1 g
	zero force source	F000	mechanical		
	plug for signal port	SSINK	Signal, control		