Numerical Analysis on Water Hammer Characteristics of Rocket Propellant Filling Pipeline

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Keywords: Propellant Filling System, Water Hammer, Flowmeter, Filling Accuracy.

Abstract: In order to investigate the water hammer problem of the filling pipeline during the rocket propellant filling process of the spaceflight launch site, the simulation calculation model and the real experimental system is established. It researches the water hammer characteristics of the filling pipeline, and analyses the law of pressure change when water hammer occurs. The improved schemes are proposed in this paper, and the simulation calculation and real experiment are carried through for the proposed schemes. It also carries through data analysis for the simulation and experimental results. The results show that the proposed scheme can effectively reduce the water hammer effect of the pipeline during the filling process, improve the rocket propellant filling accuracy and enhance the security and reliability of the system.

1 INTRODUCTION

The rockets propellant filling system is an important part of the spaceflight launch site. It's stability security and reliability is very important for the success of the spaceflight tasks. Because of risk and particularity of the propellant work, safety credibility and precision is the basic requirement for the filling system (Xiang, 2014).

The filling pipeline is a kind of key assembly of the rocket propellant filling system, it can provide routeway for the propellant transporting from the storehouse horizontal tank to the rocket tank, and it's stability could impact the filling accuracy and the security and reliability of the system. The water hammer is a water power phenomena in the pipeline that the water flow rate changed suddenly, leading to the pressure rise and fall sharply, caused by some external reasons, such as the valve suddenly open or close. In the process of rocket propellant filling in the spaceflight launch site filling system, it often appears the case that pressure gauges get full range, and it is far more than the normal working pressure range. It is a potential hazard.

The water hammer can damage equipment, reduce the safety and reliability of the system. It also can cause violent vibration of pipeline, result in measurement error for the vortex-shedding flowmeter (Yang, 2004). That will lead to the filling error of rocket propellant higher and reduce the real filling precision. Therefore, it requires analysis and research on water hammer in the filling system, to put forward effective improvement measures. It is of great significance for enhancing the propellant filling precision and ensuring the complete success of rocket launch.

At present, there are no special studies on water hammer effect based on the pipeline of rocket conventional propellant filling system. However, a lot of research works have been carried out in the aspects of water hammer in rocket engine system and some of the other system.

In literature (Yan, 2012), Yan Zheng studies the water hammer problem of the spacecraft propulsion system in the processes of priming and shutdown. On the basic of the established simulation model of the spacecraft propulsion system, the simulation research was conducted and the suppression effect of water hammer for the orifice and bent duct was analyzed. The result show that the frequency of water hammer is lower in the process of priming than that in the process of shutdown, and the peak pressure of water hammer in the process of shutdown is higher than that in the process of priming. Both the bend duct and the orifice can markedly suppress the pressure in the process of priming, but the suppression effect of water hammer is weak in the process of shutdown. In literature (Lin, 2008), Lin Jing-song researches the fluid transients of the propellant pipes after the liquid rocket engine shut down, and carries out numerical

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simulation of water hammer in shutting liquid rocket engine based o n the method o f characteristic line. The correctness of the simulation results was approved by comparison with the experiment data. It also calculates and analyzes the relationship between two locations that were in front of the closing valve and on the end of the pressure measuring pipe when the length and diameter of the pressure measuring pipe were changed. In literature (Nie, 2003), Nie Wan-sheng researches the pressure and the flow transients characteristic when the liquid rocket engine system shut down based on the method of finite difference characteristic line. The water-hammer phenomenon is analyzed in literature (Liu, 2010) based on the method of characteristic line, according to the actual construction of liquid hydrogen filling system. It proposes a useful method to reduce the peak pressure of water-hammer based on the analysis results, and it provides theory foundation for design liquid hydrogen loading system. However, it does not take the influence of pipeline accessories such as filter and flowmeter into account, so the precision is not high.

The rest part of this paper is organized as follows: Section 2 analyzes water hammer phenomena of the filling system. The mathematics model is established in section 3. The experimental results are analyzed in section 4. Finally, section 5 makes the conclusions.

2 ANALYSIS OF FILLING SYSTEM WATER HAMMER

The process diagram of the propellant filling system is shown in Fig.1. As shown in the Fig, the equipments such as except the rocket tank are all located in the pump room of the filling storehouse and on the same horizontal plane. The rocket tank are vertically located on the launch pad and on the other horizontal plane. The height from the 125# valve to the filling port of the rocket oxidizer tank is 30 meter or so, and they are connected together through the filling pipeline. In the process of filling, the state before interstage conversion is: the frequency of the pump inverter is 50Hz, the opening of the electric control valve is 30%, the state of the 134# and 124# valve is open, and the state of the 125# valve is close. At the time of interstage conversion, the program control process is: open the 125# valve, delay 1 second, after that close the 124# and 134# valve. In the process, the 121# valve has been open, the 122# valve has been close, the frequency of the pump inverter has been 50Hz, and the opening of the electric control valve has been 30%.

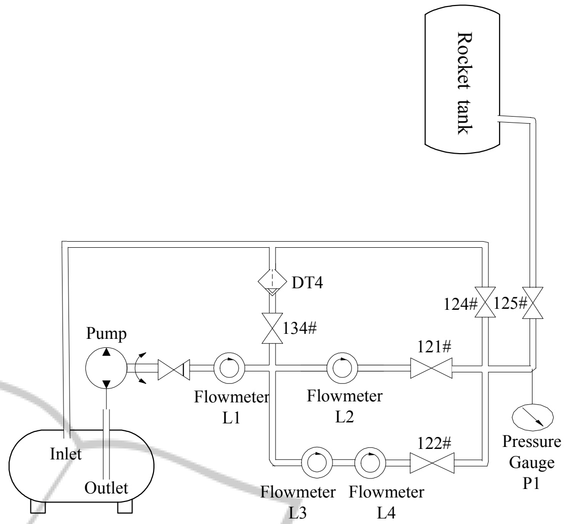

Figure 1: Process diagram of the filling system.

From analysis we can know, when open the 125# valve, the fluid in the vertical pipeline instantly lose the upward lift force, then it begin to fall under the action of gravity and achieve maximum quickly. The instant downward gravity can cause water hammer of the propellant filling pipeline. When water hammer occurs, the pipeline nearby 124# valve severe vibration and engender blare, the valve interface emits yellow smoke that shows slight leakage occurs on the interface, and range of the pressure gauge P1 achieves full scale.

From the data recorded in the real filling process, the pressure of the liquid pipeline is 0.24MPa before water hammer happening. When water hammer occurs, the peak pressure of liquid pipeline is more than 3MPa. It is obvious that great changes have taken pace for the pressure of liquid pipeline. The biggest difference is 15 times, and the water hammer peak pressure is far more than the design pressure. It can cause the equipment damaged more easily and increase the probability of the system failure.

3 ESTABLISH MATHEMATICS MODEL

3.1 Basic Differential Equation of Water Hammer

The theoretical basic of the basic equation of water hammer is the law of mechanics and continuous principle of water flow movement, including motion equation and continuity equation. It is the basic of the analysis and calculation of the hydraulic transient, containing motion equation and continuity equation expressed in differential equation. It also reflects changing rule of water head and flow velocity of instability flow in the process of hydraulic transient (Lin, 2007).

The continuous differential equation of water hammer is as follow:

$$\frac{\partial h}{\partial t}+v\frac{\partial h}{\partial s}+v\sin\theta+\frac{c^2}{g}\frac{\partial v}{\partial s}=0 \tag{1}$$

The motion differential equation of water hammer is as follow:

$$g\frac{\partial h}{\partial s}+\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial s}+\frac{f}{2D}v|v|=0 \tag{2}$$

In the above formula, v and h respectively express the flow velocity and piezometric head when the water hammer occurred. D, f, g respectively express the pipe diameter, pipe friction coefficient, acceleration of gravity. θ is the angle between pipeline and horizontal plane, c is the water hammer wave velocity, s is the distance, t is the time.

Because of considering the frictional head loss, the basic differential equation of water hammer is a first order quasilinear hyperbolic partial differential equation, and contains two dependent variables and two independent variables. It is very difficult to solve the equations.

3.2 Solve Basic Differential Equation of Water Hammer by Method of Characteristic Line

The method of characteristic line firstly changes the partial differential equation into ordinary differential equation along the characteristic line, and then changes into first order finite difference equation for obtaining the approximate solution. It can solve the water hammer problem of complicated piping system and boundary conditions, and the calculation accuracy is high. (Liu, 2005), (Wu, 2002)

The parameter uses x instead of s in formula 1 and formula 2, and this two formulas are carried through linear combination with arbitrary unknown parameters λ1. Then we can get the formula as follow:

$$\begin{aligned}L=&\left[\frac{\partial v}{\partial t}+\frac{\partial v}{\partial x}(v+\lambda_1\frac{c^2}{g})\right]\\&+\lambda_1\left[\frac{\partial h}{\partial t}+\frac{\partial v}{\partial x}(v+\frac{g}{\lambda_1})\right]+\lambda_1 v\sin\theta+\frac{fv|v|}{2D}=0\end{aligned} \tag{3}$$

According to the algorithms of compound function, and meet the conditions: $\frac{dx}{dt}=v+\lambda_1\frac{c^2}{g}=v+\frac{g}{\lambda_1}$, we can convert formula 3 into ordinary differential equation with unknown parameters v and h by selecting two value of λ1. The formula is as follow:

$$\frac{dv}{dt}+\lambda_1\frac{dh}{dt}+\lambda_1 v\sin\theta+\frac{fv|v|}{2D}=0 \tag{4}$$

In the above formula, $\lambda_1=\pm\frac{g}{c}$, that is, λ1 are two different real number, and $\frac{dx}{dt}=v\pm c$.

By respectively taking the two values of λ1 into formula 4, we can get equivalent two ordinary differential equations. Using C+ and C- respectively express characteristic line of two directions, the equations are as follows:

Along C+:

$$\begin{cases}\frac{dh}{dt}+\frac{c}{g}\frac{dv}{dt}+v\sin\theta+\frac{cfv|v|}{2gD}=0\\ \frac{dx}{dt}=v+c\end{cases} \tag{5}$$

Along C-:

$$\begin{cases}\frac{dh}{dt}-\frac{c}{g}\frac{dv}{dt}+v\sin\theta-\frac{cfv|v|}{2gD}=0\\ \frac{dx}{dt}=v-c\end{cases} \tag{6}$$

In view of C+ characteristic line, we can get the following formula by adopting the finite difference form.

$$\begin{aligned}&\left(h_{pi}-h_{i-1}\right)+\frac{c}{g}\left(v_{pi}-v_{i-1}\right)\\&+v_{i-1}\Delta t\sin\theta+\frac{f\Delta x}{2gD}v_{i-1}|v_{i-1}|=0\end{aligned} \tag{7}$$

In view of C- characteristic line, we can get the following formula by adopting the finite difference form.

$$\begin{aligned}&\left(h_{pi}-h_{i+1}\right)-\frac{c}{g}\left(v_{pi}-v_{i+1}\right)\\&+v_{i+1}\Delta t\sin\theta-\frac{f\Delta x}{2gD}v_{i+1}|v_{i+1}|=0\end{aligned} \tag{8}$$

The following are the steps that using the characteristic line to solve the water hammer problems. The first step: the partial differential equation that can't directly to solve should be changed into a specific form of ordinary differential equation, namely characteristic line equation. The second step: carrying through integral calculus for the ordinary differential equations, getting the approximate algebraic integral formula, namely finite difference equation. The third step: according to the finite difference equation and bound condition equation of piping system to calculate.

3.3 Establish Calculation Model

The mathematical model of the rocket propellant filling system is established by the Flowmaste software, taking the influence of the equipments into account. The equipments include storehouse horizontal tank, pump, flowmeter, pipeline, valve, regulating valve, filter, etc. The equipment parameters use the data in the actual product manuals. The physical parameter of fluid N_2O_4 at the temperature of 20℃ is: viscosity $\mu=0.4189\times10^{-3}$Pa·s, $\rho=1.446$g/cm^3, saturation pressure Ps=0.096MPa.

The calculation formula of water hammer wave velocity is (Xu, 2012): $c=\sqrt{\dfrac{K/\rho}{1+(K/E)(D/\delta)}}$. In the formula, K is the fluid bulk modulus, ρ is the fluid density, E is the piping materials elastic modulus, D is the pipe diameter, δ is the pipe wall thickness.

According to the calculation formula of water hammer wave velocity, the water hammer wave velocity of oxidant pipeline in the propellant filling system can be get through calculation, c=850m/s. In the calculation model, we set pipeline that length longer than 40m as elastic pipeline, the rest as rigid pipeline.

On the basis of water hammer wave velocity and elastic pipeline length, in order to make the time step to meet the transient stability conditions which is $\Delta t/\Delta x \le 1/c$, we set the time step of transient calculation $\Delta t=0.00125$s.

4 EXPERIMENTAL RESULT ANALYSIS

For further analyzing the generating mechanism of water hammer effect in the filling system and the pressure change law when water hammer occurs influenced by the filling control process, and researching the scheme that can reduce the water hammer effect in the filling system, the simulation calculation and real experiment are carried through.

The simulation calculation is carried through according to the method of mathematics model mentioned in the above section. The real test scheme is designed for the real experiment, the state and parameter is set according to the real filling. We adopt the pressure acquisition system to capture water hammer phenomena in the filling system, and record pressure change law when water hammer occurs in real time. The position of pressure gauge P1 is shown in Fig.1.

Experiment 1: According to the existing filling process, when state transition started, the program in the filling process is: open up 125# valve, delay of 1 second, at the same time close 124# and 134# valve, the pump speed is 50Hz, the opening of electric control valve DT4 is 30%. The simulation calculation results and the real experimental results are shown in Fig.2.

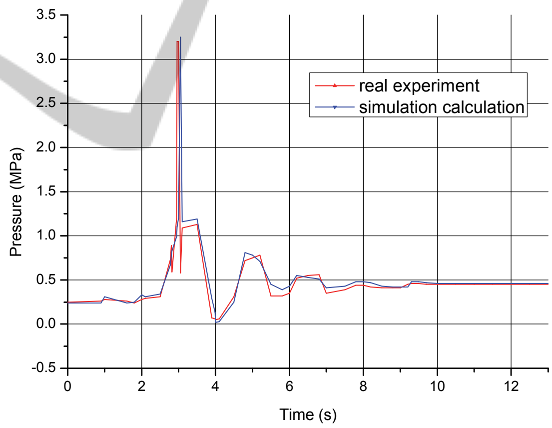

Figure 2: Pressure change law when water hammer occurs in the existing process.

Fig.2 shows the pressure change law when water hammer occurs in the existing process. The abscissa expresses the test time, the ordinate expresses the pressure. The read curve expresses the real experimental data of pressure, and the blue curve expresses the simulation calculation data of pressure. As is shown in the Fig, the pressure is 0.5MPa before water hammer occurs. When water hammer occurs, the pressure increases rapidly and the water hammer peak pressure can achieve 3.25MPa. The pipeline internal pressure has changed dramatically when water hammer occurs, and the biggest gap can be up to 13.5 times.

Experiment 2: On the basis of the existing filling process, we change the closed sequential of the related valve when water hammer occurs. When state transition started, the existing program in the filling process is: at the same time close 124# and 134# valve. The changed program is: close 124# valve, delay of 1 second, then close 134# valve. The simulation calculation results and the real experimental results are shown in Fig.3.

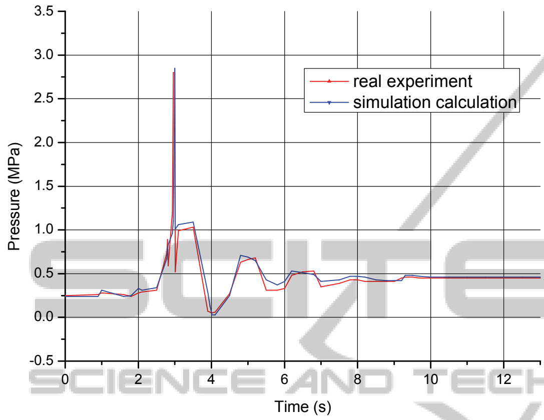

Figure 3: Pressure change law when water hammer occurs after changing the sequential.

The pressure change law when water hammer occurs after changing the closed sequential of the related valve is shown in Fig.3. In the Fig, the abscissa expresses the test time, the ordinate expresses the pressure. From contrasting Fig.2 and Fig.3, we can know that it can effectively reduce the water hammer effect of the filling pipeline by changing the closed sequential of the related valve. The water hammer peak pressure reduces from 3.25MPa to 2.85MPa, and it is reduced by 12.3% compared with the data in experiment 1.

Experiment 3: On the basis of the existing filling process and experiment 2, we change the speed of the filling pump when water hammer occurs. When state transition started, the existing pump frequency is 50Hz. The changed pump frequency is 40Hz. The simulation calculation results and the real experimental results are shown in Fig.4.

Fig.4 shows the pressure change law when water hammer occurs after changing the pump speed. As is shown in the Fig, the abscissa expresses the test time, the ordinate expresses the pressure. From contrasting Fig.3 and Fig.4, we can know that it can effectively reduce the water hammer effect of the filling pipeline by changing the speed of the filling pump. The water hammer peak pressure reduces from 2.85MPa to 2.57MPa, and it is reduced by 9.8% compared with the data in experiment 2.

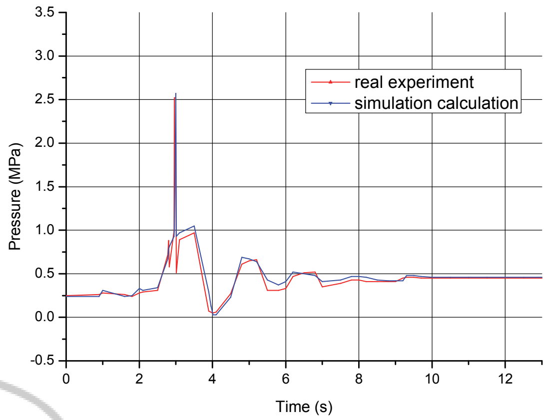

Figure 4: Pressure change law when water hammer occurs after changing the pump speed.

Experiment 4: On the basis of experiment 2 and experiment 3, we change the opening of the electric control valve DT4 when water hammer occurs. When state transition started, the existing opening of the electric control valve is 30%. The changed opening of the electric control valve is 60%. The simulation calculation results and the real experimental results are shown in Fig.5.

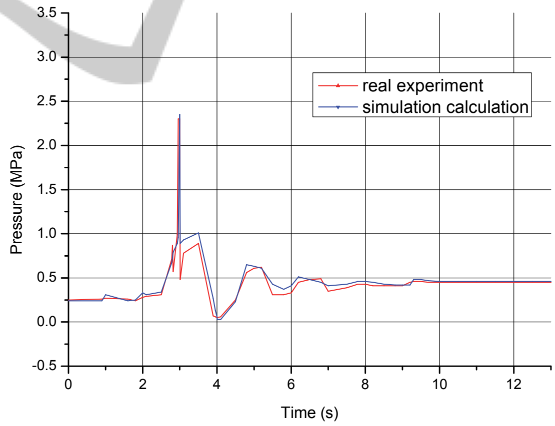

Figure 5: Pressure change law when water hammer occurs after changing the opening of electric control valve.

The pressure change law when water hammer occurs after changing the opening of electric control valve is shown in Fig.5. In the Fig, the abscissa expresses the test time, the ordinate expresses the pressure. From contrasting Fig.4 and Fig.5, we can know that it can effectively reduce the water hammer effect of the filling pipeline by changing the opening of electric control valve. The water hammer peak pressure reduces from 2.57MPa to 2.35MPa, and it is reduced by 8.6% compared with the data in experiment 3.

Fig.6 shows the comparison of water hammer peak pressure under different experimental conditions. As is shown in the Fig, the water hammer peak pressure in experiment 1 is the highest, and it reduces in experiment 2, 3 and 4 in turn, the water hammer peak pressure in experiment 4 is the lowest. There is no significant different between the simulation calculation data and real experimental data under different experiment. The data consistency is good.

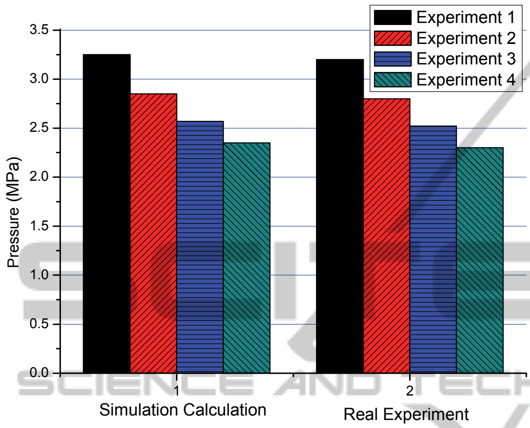

Figure 6: Comparison of water hammer peak pressure under different experimental conditions.

As is shown in Fig.6, contrasting experiment 2 and experiment 1, the water hammer peak pressure reduces from 3.25MPa to 2.85Mpa, and it is reduced by 12.3% compared with the data in experiment 1. Contrasting experiment 3 and experiment 1, the water hammer peak pressure reduces from 3.25MPa to 2.57Mpa, and it is reduced by 20.9% compared with the data in experiment 1. Contrasting experiment 4 and experiment 1, the water hammer peak pressure reduces from 3.25MPa to 2.35Mpa, and it is reduced by 27.7% compared with the data in experiment 1. From the experimental results we can know that it can effectively reduce the water hammer effect of the filling pipeline by adopting the schemes proposed in this paper.

Through data analysis for the simulation calculation data and real experimental data, it provides theoretical basis and data support for reducing water hammer effect of the filling system and optimizing filling process.

5 CONCLUSIONS

The rocket filling system is an important part of the spaceflight launch site, the filling pipeline is one of the key components in the filling system. Accurately grasp it's work state in the rocket propellant filling process is very important for the filling accuracy and the security and reliability of the system.

This paper analyzes the water hammer effect of the rocket propellant filling pipeline during the filling process of the spaceflight launch site, and studies the influence of filling process on water hammer. It researches the pressure change law of filling pipeline when water hammer occurs. In order to reduce the water hammer effect of the filling pipeline, improved scheme in the aspects of filling control process is put forward as follows: change the closed sequential of the related valve, reduce the speed of the filling pump, and augment the opening of the electric control valve. Meanwhile, simulation calculation and real experiment are carried through in allusion to the proposed scheme, and carries through data analysis for the simulation and experimental results. The experimental results show that the proposed scheme can effectively reduce the water hammer effect of the pipeline during the filling process, reduce the error of filling quantity caused by water hammer, improve the rocket propellant filling accuracy and enhance the security and reliability of the system.

The water hammer effect of the rocket propellant filling pipeline during the filling process is analyzed in this paper only in the aspects of filling control process. In order to further eliminate the water hammer effect, the research direction in the future is to improve process design for the filling system.

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