

Study on pressure wave propagation in two phase flow in liquid oxygen feed pipe between pumps

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Abstract: A study on the character of pressure wave propagation was proposed for the gas liquid oxygen two phase flow in the pipe between pumps. According to the practical working conditions, the homogenous model based on the compressibility theory regarding a single bubble in an infinite liquid, and Redlich Kwong gas equation was derived a model for the low temperature and high pressure case, especially considering the change of the ratio of density of gas to one of liquid. The numerical tests were conducted. The results not only show the agreement between numerical simulation for this model and experiment at the normal temperature and pressure is good, but also show that the modifications of the model for the low temperature and high pressure condition are necessary. The study is of reference to further study of oscillation restrain and relative pipe tests.

Key words: two phase flow; pressure wave; pipe between pumps; phase velocity; attenuation

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Introduction

As the compressibility of gas, the pressure wave propagation in gas liquid two phase flow is much more complex than that in liquid flow. In the fields of power plant, nuclear reactor, petroleum transportation, chemical industry and so on, the pressure wave propagation in two phase flow was researched broadly, like the crevasse accident in nuclear reactor, the pressure oscillation of petroleum transportation, and the application of air bubble purdah in the damping measure in the underwater blast^[1-7].

However, there are few researches on the character of pressure wave propagation for the gas liquid oxygen two phase flow in the pipe between the pumps of the large scale launch vehicle. This problem is a key to analyze the liquid oxygen feed system of launch vehicle dynamic character. The dynamic character of liquid oxygen feed system is helpful to solve the problem

of interaction of structural vibrations with pressure and flow oscillations in the liquid feed system, which is called POGO.

For one type high pressure liquid oxygen kerosene staged combustion cycle rocket engine, the flow in the pipe between the pumps of the large scale launch vehicle is gas, liquid and solid three phase system. In this system, much components are liquid oxygen and oxygen rich gas (which is used to drive the turbine), and little components are solid H_2O , CO_2 and et al^[8]. This multiphase phenomenon roots in the designed engine cycle type. As the rated mixture ratio of the mass flux of oxygen to that of kerosene in preburner is 54, after combustion in preburner the main component of mixture is gas oxygen. After driving turbine, as shown in Fig. 1, from point A to point B, the gas oxygen mixes with the liquid oxygen in the pipe between the pumps. The mixed flow can be simplified as gas oxygen and liquid oxygen two phase flow.

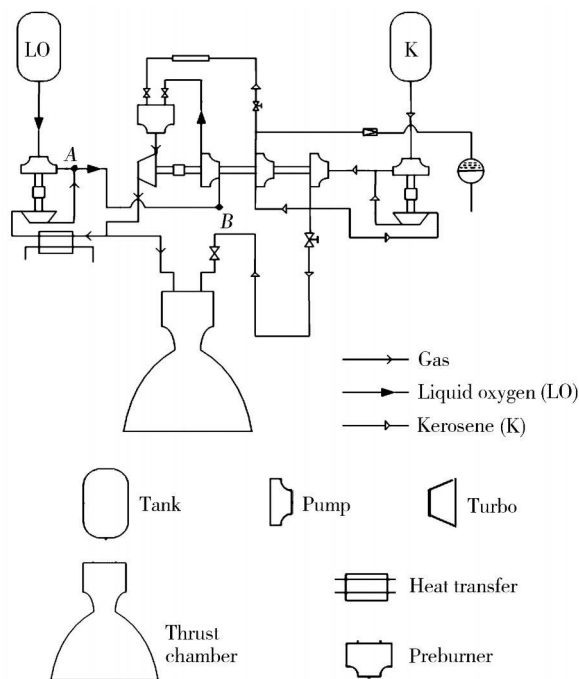


Fig. 1 High pressure liquid oxygen kerosene staged combustion cycle rocket engine hint

The sound velocity and the attenuation of two phase flow are our study interests, which can be used to analysis the pressure wave propagation in two phase flow. The analysis on the character of pressure wave propagation in gas-liquid oxygen two phase flow may facilitate the further study on oscillation suppression of the liquid oxygen feed system and launch vehicle POGO stability.

For pressure wave propagation in gas-liquid two phase flow, there are some models including elasticity model, homogeneous mixture model and single phase model. Cheng, Ruggles, Huang et al.^[1-3] investigated the problem by two fluid model with closure condition of each phase and interfacial exchange for pressure wave propagation in gas-liquid flow. Otherwise, Li and Shin et al.^[4-5] studied on homogeneous model in their study field. Li applied the two phase homogenous flow model to analyzed lubrication oil in bearing chamber^[4]. Shin proposed a numerical method applying a total variation diminishing MacCormack scheme with a cavitation model based on a homogenous equilibrium model of compressible gas-liquid two phase media,

which is applied to solve the cavitating flow^[5].

However, Chung et al.^[9] proposed a different model based the homogeneous mixture model and the study of a bubble immersed in an infinite liquid, for calculating the phase velocity and attenuation which were compared with existing data and were in good agreement. This model is more easy to be applied than the two phase model of Cheng and Ruggles et al.^[1-2], and better to understand the nature of sound and to study the relationships between sound velocity and the properties of two phase flow^[9].

However, most of researches focused on the gas-water two phase flow in normal temperature. There are few published researches on gas-liquid oxygen two phase flow which will be the key of oscillation restrain by two phase flow in the pipe between pumps and frequency calculation of feed pipe system. Using the theory of two phase fluid to solve the vibration problem is helpful to explain the mechanism of vibration phenomena and improve feed system work.

1 Computation scheme

As the fluid in the pipe between pre pump and main pump is mainly gas-fluid two phase system, the flow model simplified as gas-fluid two phase bubbly flow. We used the homogeneous mixture model and the theory of a bubble immersed in an infinite liquid, to analyze the character of sound velocity and attenuation of pressure wave between the pumps.

Considering the physical process of small disturbed wave propagation^[10-11], and referring the equation of wave propagation in single phase flow, in Lagrangian reference frame, the area of control volume of surround wave crest is assumed A . When the two surfaces of control volume is infinite close, the continuity equation is given as

$$c\bar{\rho}A = (c - dV)(\bar{\rho} + d\bar{\rho})A \quad (1)$$

Where c is sound velocity. dV is the change of velocity after small disturbed wave passing. $\bar{\rho}$ is the density of the compressible mix fluid. $d\bar{\rho}$ is

the change of the density.

The effect of shear stress is neglected. By momentum equation of control volume is derived as

$$pA - (p + dp)A = \bar{\rho}cA \cdot [(c - dV) - c] \quad (2)$$

Combing Eqs. (1) and (2), we can obtain

$$c^2 = \frac{dp}{d\bar{\rho}} = \frac{dp}{d[\alpha\rho_g + (1-\alpha)\rho_l]} \quad (3)$$

$$c^{-2} = \left[\alpha^2 + \alpha(1-\alpha) \frac{\rho_l}{\rho_g} \right] \frac{d\rho_g}{dp} + \left[(1-\alpha)^2 + \alpha(1-\alpha) \frac{\rho_g}{\rho_l} \right] \frac{d\rho_l}{dp} + (\rho_g - \rho_l) \frac{\alpha(1-\alpha)}{x_g(1-x_g)} \frac{dx_g}{dp} - \alpha(1-\alpha)(\rho_g - \rho_l) \frac{dS}{dp} \quad (4)$$

Assuming the gas oxygen proportion is fixed, we consider

$$\frac{dx_g}{dp} = 0$$

Using the result of momentum transport^[9]

$$\frac{dS}{dp} = - \frac{1}{c^2 \bar{\rho}} \left[\frac{(1-\alpha)(\rho_l - \rho_g) C_{vm}^{-1}}{(1-\alpha)\rho_l + \alpha\rho_g + (1-\alpha)\rho_g C_{vm}^{-1}} \right]$$

For liquid, there is

$$\frac{d\rho_l}{dp} = \frac{1}{c_l^2}$$

Sound velocity can be derived as

$$c^2 = \frac{1 - \alpha(1-\alpha)(\rho_g - \rho_l) \frac{1}{\rho_l} \left[\frac{(1-\alpha)(\rho_l - \rho_g) C_{vm}^{-1}}{(1-\alpha)\rho_l + \alpha\rho_g + (1-\alpha)\rho_g C_{vm}^{-1}} \right]}{\left[\alpha(1-\alpha) \frac{\rho_l}{\rho_g} \frac{d\rho_g}{dp} + \frac{(1-\alpha)^2}{c_l^2} \right] + \left[\alpha^2 \frac{d\rho_g}{dp} + \frac{\alpha(1-\alpha)\rho_g}{c_l^2 \rho_l} \right]} \quad (5)$$

As the high pressure, the ratio of the density of the gas to that of the liquid ρ_g/ρ_l can not be neglected.

For the high pressure and low temperature gas, the ideal gas law is not fit for it^[12]. Redlich and Kwong proposed Redlich-Kwong equation to describe the gas, which make high precision and easy application to our model. In this model, the Redlich-Kwong equation is applied for the low temperature gas in our study as below

$$p_g = \frac{R_g T_g}{v - b} - \frac{a}{T^{0.5} v(v + b)} \quad (6)$$

Where p_g is pressure. R is the gas constant. T_g is the Kelvin temperature. v is specific volume of gas. a and b is two inherent value of material, which can be got from experiments. If lacking

Where, α is the void fraction, which can be written as

$$\alpha = \frac{x_g \rho_l}{(1-x_g)S\rho_g + x_g \rho_l}$$

Averaged density can be expressed as

$$\bar{\rho} = \alpha\rho_g + (1-\alpha)\rho_l$$

S is slip ratio, x_g is quality, ρ is density, subscripts g is gas, subscripts l is liquid. S is the slip ratio. Sound velocity can be written as

these data, they can be confirmed by the critical point parameters as below

$$a = \frac{0.427480 R_g^2 T_c^{2.5}}{p_c} \quad (7)$$

$$b = \frac{0.08664 R_g T_c}{p_c} \quad (8)$$

Using Eq. (6), we can get

$$A_g \frac{dp_g}{p_g} + B_g \frac{dv}{v} - C_g \frac{dT_g}{T_g} = 0 \quad (9)$$

Where A_g , B_g and C_g are three coefficients. If A_g , B_g and C_g all equal one, Eq. (9) is same as the ideal gas law equation.

If we nondimensionalize and take small perturbations of Eq. (9), with considering the definition of specific volume $v = V/m$ and a gas bubble volume $V = (4/3)\pi R^3$, we obtain

$$A'_g P + 3B'_g x - C'_g \phi_g = 0 \quad (10)$$

Where A'_g , B'_g and C'_g are three coefficients. R is radius of a bubble. m is mass of a bubble.

$$P = \frac{p_g}{p_{g0}} - (1 + W^{-1})$$

$$W = \frac{p_{g0} R_0}{2\sigma}$$

$$x = \frac{R}{R_0} - 1$$

$$\phi_g = \frac{T_g}{T_\infty} - 1$$

Subscripts 0 denotes unperturbed value, ∞ denotes value at radius position. σ is surface tension of a gas bubble.

Considering study of a bubble immersed in an infinite liquid^[9], the nondimensionalized bubble dynamic equation and energy balance equation can be written as

$$\left(\frac{1}{1 + ik_1 R} \right) \frac{d^2 x}{d\tau^2} - \frac{B}{W} x = B(P - \varepsilon) \quad (11)$$

$$K_1 \frac{d\phi_g}{d\tau} + K_2 \frac{dx}{d\tau} = -\phi_g Nu_1 \quad (12)$$

$$F(\Omega) = \frac{\Delta R/R}{\Delta p/p} = \left[-\frac{3B_g}{A_g} - \frac{C_g}{A_g} \frac{K_2 i \Omega}{K_1 i \Omega + Nu_1} + \left(\frac{1}{1 + ik_1 R_{10}} \right) \frac{\Omega^2}{B} + W^{-1} \right]^{-1} \quad (13)$$

Substituting Eq. (13) into Eq. (5), the equation can be written as below

$$c^2 = \frac{1 - \alpha(1 - \alpha)(\rho_g - \rho) \frac{1}{\rho} \left[\frac{(1 - \alpha)(\rho - \rho_g) C_{vm}^{-1}}{(1 - \alpha)\rho + \alpha\rho_g + (1 - \alpha)\rho_g C_{vm}^{-1}} \right]}{\left[-3F(\Omega)\alpha(1 - \alpha) \frac{\rho}{p} + \frac{(1 - \alpha)^2}{c_1^2} \right] + \left[-3F(\Omega)\alpha^2 \frac{\rho_g}{p} + \frac{\alpha(1 - \alpha)\rho_g}{c_1^2 \rho} \right]} \quad (14)$$

2 Presentation of result

The complex sound velocity can be solved by Eq. (14), from which the phase velocity and the attenuation coefficient all can be get. The results of the phase velocity and the attenuation calculated by the Eq. (14) are compared with the test data of the gas water two phase in Ref. [9], and are in good agreement. The results are shown as below Fig. 2 and Fig. 3.

For one type high pressure liquid oxygen kerosene staged combustion cycle rocket engine, the liquid pressure is 1.0MPa, the gas temperature is 100K, the radius of gas bubble is 2mm.

Where k_1 is wave number of liquid. τ is dimensionless time.

$$K_1 = \frac{\rho_g C_{vg}}{3\rho_{cl}}$$

$$K_2 = \frac{p_{g0}}{\rho_{cl} T_\infty} (1 - W^{-1})$$

$$B = \frac{p_{g0} R_0^2}{\rho \alpha^2}$$

$$\tau = \frac{t \alpha_1}{R_0^2}$$

$$Nu_1 = \frac{h R_0}{\lambda}$$

$$\Omega = \frac{\omega R_0^2}{\alpha_1}$$

$$\varepsilon = \frac{p_\infty}{p_{g0}} - 1$$

c_{vg} is specific heat at constant volume of gas, t is time. ω is frequency. h is heat transfer coefficient. λ is thermal conductivity of liquid.

Combing Eqs. (10), (11) and (12), we can obtained

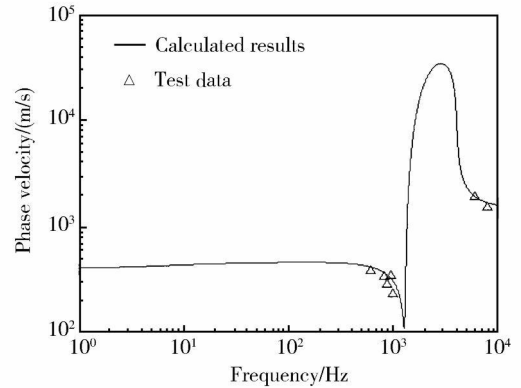


Fig. 2 Phase velocity of air water two phase flow compared with frequency

Based these condition, using the Eq. (14) the information about sound velocity and attenu-

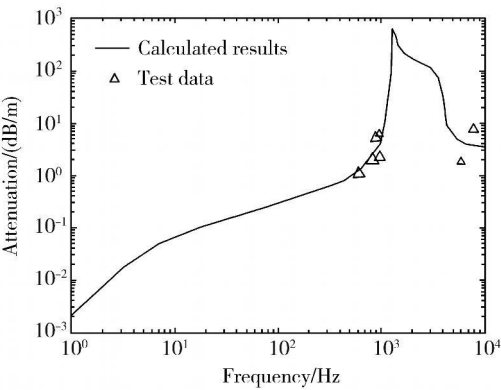


Fig. 3 Attenuation of air water two phase flow compared with frequency

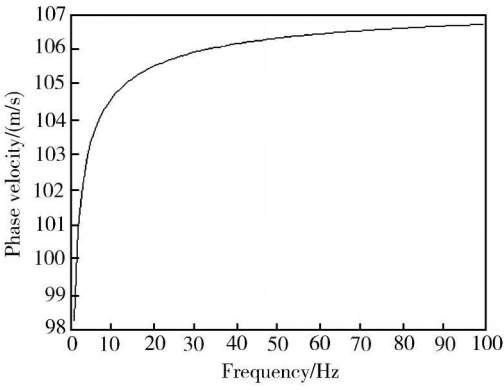


Fig. 6 Phase velocity of gas liquid oxygen two phase flow compared with frequency

ation of gas liquid oxygen two phase flow can be got which shown as Fig. 4~ Fig. 7. In these two figures, disturb frequency is assumed 10 Hz.

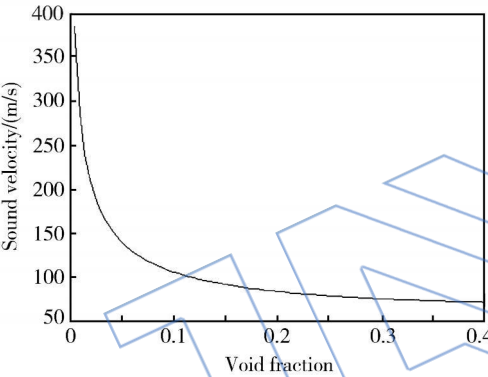


Fig. 4 Sound velocity of gas liquid oxygen two phase flow compared with void fraction

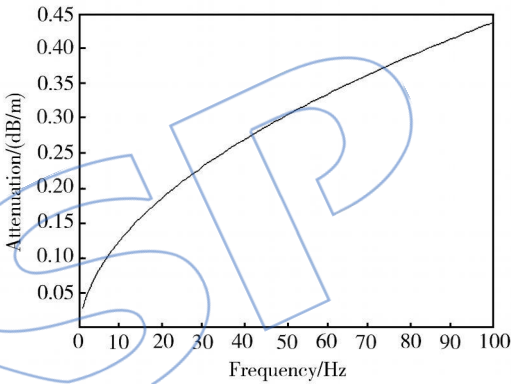


Fig. 7 Attenuation of gas liquid oxygen two phase flow compared with frequency

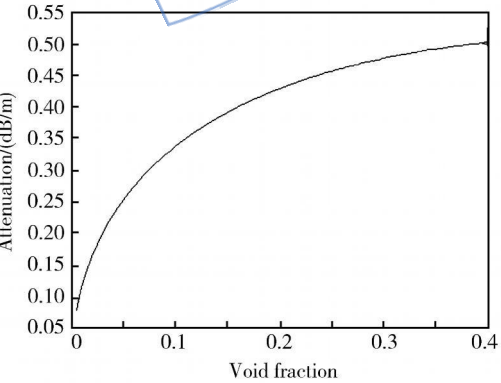


Fig. 5 Attenuation of gas liquid oxygen two phase flow compared with void fraction

The curve of the sound velocity compared with the void fraction at 50 Hz of disturb frequency is shown as Fig. 4. From 0 to 100 Hz the trend

of the curve is same as the curve of the gas water two phase flow at normal temperature and normal pressure. In the Fig. 4 the sound velocity sharp decreases from void fraction 0 to 0.05. And from void fraction 0.05 to 0.4, the sound velocity decreases with void fraction slowly. The Fig. 5 shows the attenuation increases with the void fraction. This trend is the effect of compressibility of gas phase, which enhances the two phase system momentum and energy exchange between two phases.

As shown in Fig. 6 and Fig. 7, the phase velocity and attenuation increase with frequency at low frequency. In these two figures, the void factor is assumed as 0.1. The curve trend well reflects the character of the phase velocity and attenuation change with the disturb frequency change, which is called as dispersion of pressure wave in gas liquid two phase flow^[1-3]. The in-

crease of disturb frequency promote propagation of pressure wave. Furthermore, the increase of disturb frequency causes more loss of the momentum and energy exchange between two phases.

3 Conclusions

The current model is derived from the homogeneous model considering the ratio of the density of gas to that of liquid, the compressibility of a single bubble in an infinite liquid, and the Redlich-Kwong gas equation. The model had a good agreement with the gas-water two-phase test data at the normal temperature and normal pressure condition, and was used to predict the gas-liquid oxygen two-phase flow at low temperature and high pressure. The predict results give a reference to the two-phase pipe test, as well as facilitate the further study on oscillation suppression.

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