Research on the Initial Ignition of the Underwater Launching Solid Rocket Motor

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Abstract: The aim of this investigation is to research the initial ignition of the underwater-launching solid rocket motor. The MIXTURE multiple-phase model was set to simulate the initial ignition. The water vaporization was researched and the energy transfer was added to the energy equations. The flow field and the vaporization were calculated coupled. The initial ignition process of the underwater solid rocket motor is obtained and the vaporization influence to the underwater launching is analyzed. The "neck", "inverted jet" and "eruption" phenomenon of the bubble are observed. The bubble increases more rapidly because the steam mass added to the fuel. The temperature is lower considering the vaporization because the steam enthalpy is lower than the fuel enthalpy and the flow field of the initial ignition of the underwater-launching solid rocket motor is accordant well to the reference.

Key words: solid rocket motor; underwater launching; multiple phases flow; vaporization; coupled method
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The mixed gas includes the steam, fuel gas and cold water during the initial ignition of the underwater-launching solid rocket motor. The unsteady vibration of the initial ignition is serious[1]. The fuel bubble is influenced by the mass transfer generated by vaporization. The work proposed in Ref. [2] considers the heat conduction and vaporization using the steady axis symmetric method. The shrink and re-hit phenomenon is presented in Ref. [3]. The vaporization mechanism is also investigated deficiently.

The vaporization was researched through the vaporization and condensation algorithm detailedly. The energy transfer generated by the vaporization was added to energy equations. The flow field and the vaporization were calculated coupled. The initial ignition exhaust plume and the influence of the vaporization were calculated with the MIXTURE model in FLUENT. The "neck", "inverted jet" and "eruption" phenomenon of the bubble are observed. The bubble increases more rapidly and the temperature is lower considering the vaporization than the one without the vaporization. The results were accordant to Ref. [4].

1 Physical Model

1.1 The MIXTURE Model

Each phase is considered as continuous state which can fuse mutually in the MIXTURE model. The mixed momentum equation is solved in MIXTURE model, the relative velocity is appointed to describe the velocity of the minor phase. The model can be used to simulate the homogeneous multiphase flow if there is the zero relative velocity[5].

The mixture model can compute n phases by solving the momentum, continuity, and energy equations for the mixture, the volume fraction equations for the secondary phases, and algebraic expressions for the relative velocities. The equations are shown below:

The continuity equations are[6]

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$$\frac{\partial}{\partial t}(\rho_m) + \nabla \cdot (\rho_m \boldsymbol{v}_m) = 0. \quad (1)$$

Momentum equations of the mixture are obtained by cumulating the momentum equations of each phase and the momentum equations are

$$\frac{\partial}{\partial t}(\rho_m \boldsymbol{v}_m) + \nabla \cdot (\rho_m \boldsymbol{v}_m \boldsymbol{v}_m) = -\nabla p + \rho_m \boldsymbol{g} + \boldsymbol{F} + \nabla \cdot [\mu_m (\nabla \boldsymbol{v}_m + \nabla \boldsymbol{v}_m^T)] + \nabla \cdot \left(\sum_{k=1}^{n} \alpha_k \rho_k \boldsymbol{v}_{dr,k} \boldsymbol{v}_{dr,k} \right). \quad (2)$$

Energy equations of the mixture are

$$\frac{\partial}{\partial t} \sum_{k=1}^{n} (\alpha_k \rho_k E_k) + \nabla \cdot \sum_{k=1}^{n} (\alpha_k \boldsymbol{v}_k (\rho_k E_k + p)) = \nabla \cdot (k_{eff} \nabla T) + S_E. \quad (3)$$

Minor phase's volume fraction equations are

$$\frac{\partial}{\partial t}(a_p \rho_p) + \nabla \cdot (a_p \rho_p \boldsymbol{v}_m) = -\nabla \cdot (a_p \rho_p \boldsymbol{v}_{dr,p}) + \sum_{q=1}^{n} (\dot{m}_{qp} - \dot{m}_{pq}). \quad (4)$$

Relative velocity's algebraic equations are

$$\boldsymbol{v}_{qp} = \frac{\tau_p (\rho_p - \rho_m)}{f_{drag} \rho_p} \boldsymbol{a}. \quad (5)$$

1.2 Coupled with the Flow and the Vaporization Mass Transfer

When the temperature of the fluid element increase and there is liquid water in the element, the vaporization process may accur. The water vaporization rate is calculated according with the saturated temperature. The fuel gas and the water phase flow in every mesh are computed. The water absorbs heat and vaporizes to steam when the mixture temperature is higher than the water saturated temperature and the steam releases heat and condenses to water when the mixture temperature is lower than the water saturated temperature[7].

The formulas of water vaporization are[8]

$$\dot{m}_l = \begin{cases} -0.1 V_l \rho_l |T_l - T_{sat}| / T_{sat}, & T_{mix} > T_{sat}, \\ 0.1 V_v \rho_v |T_{mix} - T_{sat}| / T_{sat}, & T_{mix} < T_{sat}. \end{cases} \quad (6)$$

The formulas of steam condensation are

$$\dot{m}_v = \begin{cases} 0.1 V_l \rho_l |T_{mix} - T_{sat}| / T_{sat}, & T_{mix} > T_{sat}, \\ -0.1 V_v \rho_v |T_{mix} - T_{sat}| / T_{sat}, & T_{mix} < T_{sat}. \end{cases} \quad (7)$$

The method to couple vaporization model with fluid control equations are

$$e = \begin{cases} Q_{lat} \dot{m}_l, & T_{mix} > T_{sat}, \\ -Q_{lat} \dot{m}_v, & T_{mix} < T_{sat}, \end{cases} \quad (8)$$

where $\dot{m}_l$ and $\dot{m}_v$ are the vaporization rate of liquid and the condensation rate of vapor in kg/(m^3·s); V_l and V_v are the volume fraction of liquid and gas; ρ_l and ρ_v are the density of liquid and gas in kg/m^3; T_l is the temperature of liquid in K; T_{sat} is saturated temperature of water, which is determined according to the local pressure; T_{mix} is the temperature of the mixture in K; e is the absorbing or releasing energy in W/m^3; Q_{lat} is the vaporization latent heat at different temperature in kJ/kg.

1.3 Calculation Methods

The finite volume method was used to simulate the underwater launching. The SIMPLE method was used to calculate the unsteady flow field. The energy source was added to consider the vaporization. The vaporization and the flow field were calculated coupled with the MIXTURE model.

2 Calculated Model and Boundary Conditions

2.1 Calculated Model

Two-dimensional axis symmetric model is used to calculate the initial ignition of the underwater-launching solid rocket motor. The calculation region length is 30 times and the width is 8 times to the nozzle exit diameter. The direction of the gravity is along the x axis. Fig. 1 presents the amplificatory of the grids of the nozzle nearby.

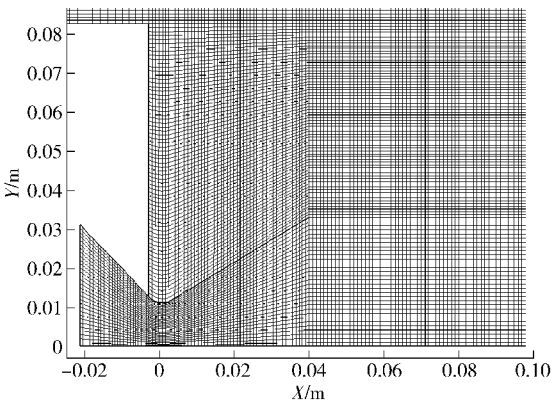


Fig. 1 Illustration of the nozzle exit meshes

2.2 Boundary Conditions

The pressure inlet boundary is used to the nozzle inlet. The total pressure increases to 6 MPa at 50 ms linearly and the total temperature is 2 000 K. The outer of the calculation region uses the pressure outlet boundary and the static water pressure is 0.5 MPa. The flow field is divided to water region and jet flow region. Fig. 2 presents the boundary conditions of the simulation.

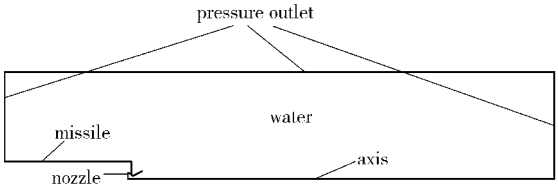


Fig. 2 Illustration of calculation model and boundary conditions

3 Results and Discussion

3.1 Analyses on the Process of Initial Ignition

Fig. 3 presents the fuel gas bubble molding. As Fig. 3 shows, the inverted jet appears as a result of the water inertia to the shock wave dashing out of the nozzle. The foreside pressure of the exhaust plume decreases until less than the static pressure of the water. The "neck" phenomenon appears and the bubble diffuses along the radial position as Fig. 3c and Fig. 3d show. The foreside pressure decreases rapidly with the movement of the shock wave while the rearward pressure keeps steady causing the shrink of the plume as Fig. 3f and Fig. 3g show. When the jet shrinks to a narrow channel, the "eruption" appears at the "neck" position. Ref. [9] also referred to the "eruption" of the initial ignition of the underwater-launching solid rocket motor.

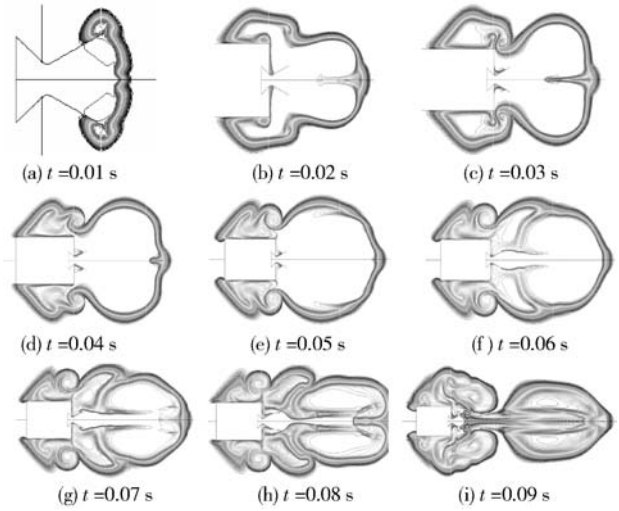


Fig. 3 Volume fraction of the fuel gas at 0.01 s – 0.09 s

The inverted jet of the nozzle is obvious because the nozzle expansion angle is large.

Fig. 4 – Fig. 7 show the axis density, pressure, velocity and temperature between 0.025 s – 0.100 s respectively. The parameters are discontinuous because of the shock wave movement. Fig. 4 shows the gas

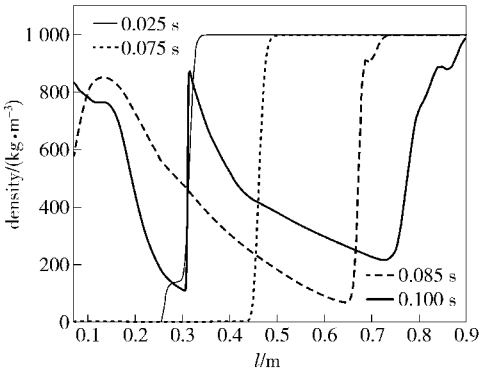


Fig. 4 Comparison of axis density at different times

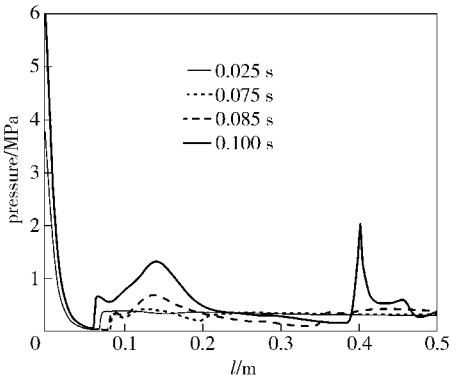


Fig. 5 Comparison of axis pressure at different times

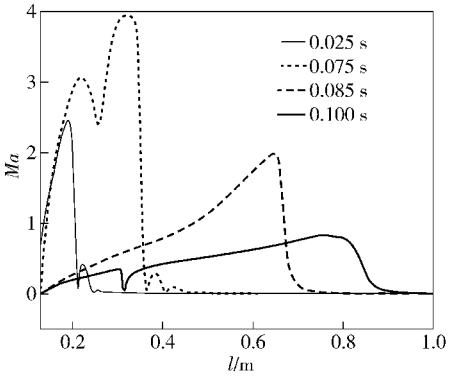


Fig. 6 Comparison of axis velocity at different times

ejects out of the nozzle with big density because the mixed gas includes the steam. The "eruption" happens at about 0.09s – 0.10 s and the density peak appears at 0.10 s. Fig. 5 also presents that the "eruption" happens at about 0.09 – 0.10 s because there is a pressure peak appears. It is accordant to the Ref. [10]. The shaping process of the bubble is similar to the velocity change presented in Fig. 6.

Fig. 7 shows the high temperature region pushes along with the bubble shape. The temperature is complicated considering the vaporization. The temperature decreases largely at 0.10 s because of the bubble cracking.

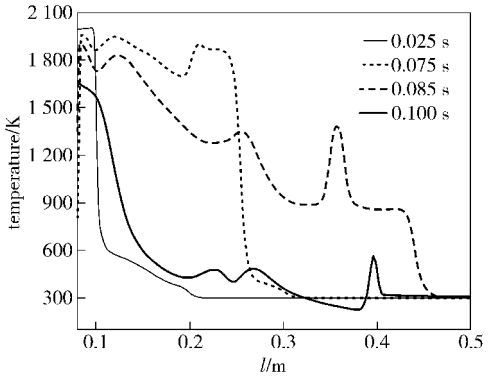


Fig. 7 Comparison of axis temperature at different times

3.2 Analyses on the Effect of the Vaporization Mass Transfer

Now we demonstrate a preliminary parametric study investigating the effect of vaporization on exhaust plume. Fig. 8 and Fig. 9 show the computation results with vaporization shown in the upper portion while the one without vaporization shown in the lower portion. There is a slight but noticeable effect due to vaporization mass transfer. Apparently Fig. 8 shows that on the upper portion more steam is vaporized than liquid is condensed causing the mass increase of the jet. The

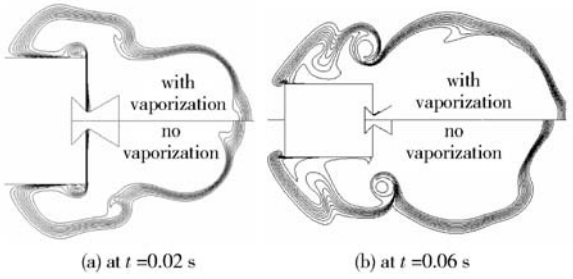


Fig. 8 Bubble shape parallel at different times

velocity of the mixed gas considering vaporization develops more rapidly than the lower portion. The bubble increases quicker and the "neck" is obvious than the one without vaporization. The trends are accordant to Ref. [4].

Fig. 9 presents the higher temperature of the lower portion. The reason is that the total enthalpy of the steam is lower than the fuel gas[11].

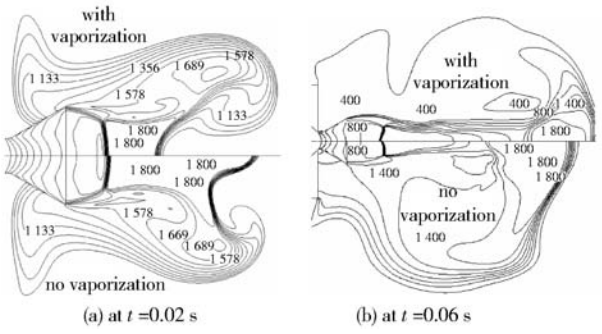


Fig. 9 Temperature contour parallel at different times

4 Conclusions

The conclusions are obtained through the simulation and analyses on the initial ignition process of the underwater-launching solid rocket motor.

① The "inverted jet", "neck" and "eruption" are observed. The results were reasonable through comparing to Ref. [4].

② The axis parameters are obtained and there is a pressure peak and density peak at the eruption location of the bubble.

③ The bubble increases more rapidly because the steam mass added to the fuel. The temperature is lower considering the vaporization because the steam enthalpy is lower than the fuel enthalpy.

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