Study on flow and reaction characteristics in a swirling water ramjet

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Keywords: Swirling flow; Combustion; Numerical simulation; Magnesium powders

Abstract. A swirling-style propellant water ramjet model, which was established on the base of a particular model of column-style propellant water ramjet, was employed to numerically simulate the influence on engine performance at difference inlet velocities. The three-dimensional geometrical model was established by unigraphics (UG) software, and then the Fluent software was selected to simulate the temperature field and the turbulent flow field. Turbulent flow simulation was performed by the standard k-Ɛ two equation functions, and combustion reaction was calculated by finite-rate/eddy-dissipation model. The computed results show that the swirl vanes can produce stream-wise vortexes and span-wise vortexes, resulting in a better mixing effect and flame stability. With the increase of inlet speeds, the temperature in the combustor decreases, while the specific impulse increases firstly and then declines.

Introduction

With the raising of modern warship speed, torpedoes must increase their speed and voyage to ensure hit rate. The torpedo power propulsion system includes compressed air, electric power, thermal power and rocket engine[1]. Water ramjet originates in solid rocket motor, whose main antioxidant is water which comes from the ocean. Water ramjet is light and velocity unlimited, so researchers started to study it since 1990s.Water ramjet falls into two categories, column-style propellant water ramjet and powder-style propellant water ramjet. The column-style propellant water ramjet needs to bring antioxidant by itself, which will have a negative effect on speed and voyage [2]. By contrast, the antioxidant of powder-style propellant water ramjet is water, and it can be gotten from the ocean.

The metal inlet velocity of fuel and antioxidant is too high to burn steadily, so stable combustion equipment is needed. At present, the widely used methods are jets with large velocity difference[3], bluff bodies[4] and strong swirling flow[5]. The strong swirling flow has span-wise vortexes, which are generated from stream-wise vortex, so it has vortexes in two directions which are different from the single span-wise vortexes developed by other stable combustion equipment. As a result, the strong swirling flow has better performance than others. So far, there is no study on water ramjet with strong swirling flow[6].

A new model of powder-style propellant water ramjet is proposed in this paper. The metal powders are carried with gas, and this fuel supply method has been tested by Chao Han[7]. Nitrogen is chosen to carry metal powders in the combustor because it cannot react with them. Metal powders and antioxidants can be mixed very well because of strong swirling flow. Then the metal powders react with the antioxidants to produce product at high temperatures and pressures that finally discharged from nozzle to develop thrust.

Physical model and numerical simulation

Geometric structure and meshing. Fuel supply system and combustor are shown in Fig.1. The effect of different inlet velocities on temperature field and flow field in combustor is discussed to lay the foundation for further study.

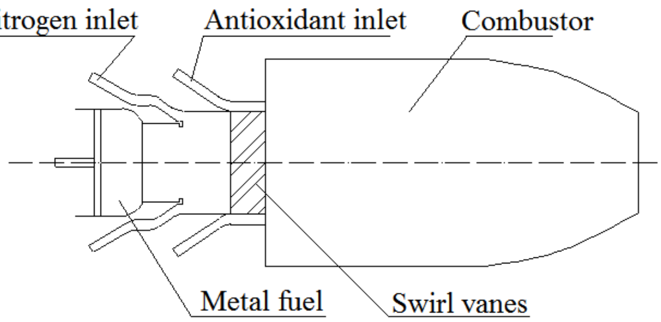


Fig. 1 A sketch of fuel supply system and combustor

The combustor structure is shown in Fig.2, and its length is 765mm in total that includes metal powders inlet, antioxidant inlet, swirl vanes, central axis and outlet. There are eight swirl vanes and their angel is 60º.

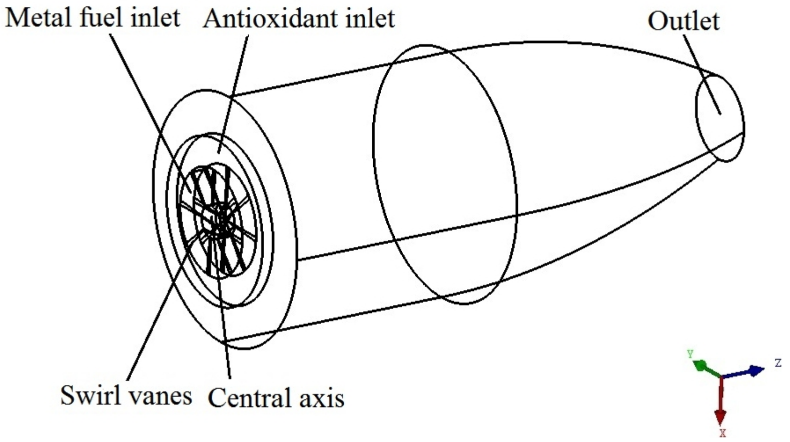
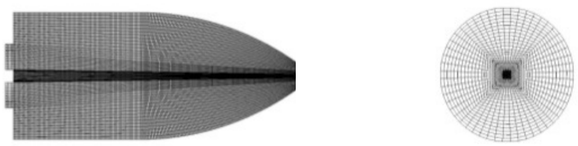


Fig. 2 Combustor structure

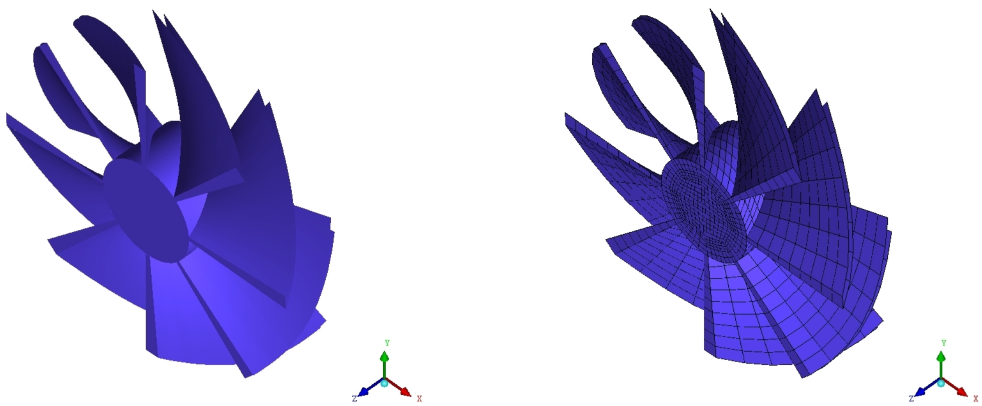
In order to ensure the mesh quality, "O" type mesh is used and the quantity of meshes is 63,000 in total, as are shown in Fig.3.



(a) Front view grid (b) Left view grid

Fig. 3 Grid cells

The geometry structure of swirl vanes and their grids are shown in Fig.4.



(a) Geometry structure of swirl vanes (b) Grids of swirl vanes

Fig. 4 Swirl vanes

Numerical method. Fluent software is selected and the implicit solver which is based on density is performed to calculate the temperature field and flow field as the flow can be compressed. The experimental data of Osama A. Marzouk[8] was used to select the suited turbulence model, since the swirling flow has its own characteristics. This paper selects several commonly used RANS turbulence models to do numerical verification, and the standard k-ε model's results are in good agreement with the experimental data. Therefore, this paper uses the model to simulate the swirling flow.

Finite-rate/eddy dissipation method is selected and pre-exponential factor and activation energy are from the reference[9].

Boundary condition

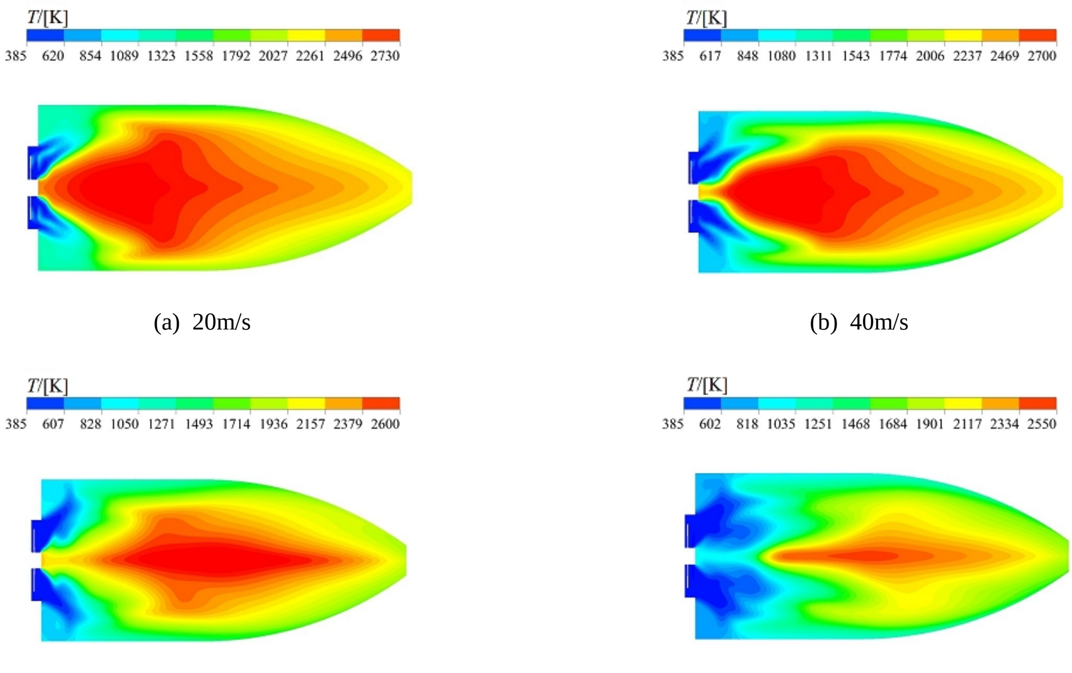
Magnesium is chosen as the metal fuel because of its high energy density and low ignition temperature and the steam is the antioxidant. The inlet boundaries are decided by the velocity of magnesium powder and the steam. The walls are the adiabatic walls. The outlet boundary is decided by the pressure. Four cases are calculated and the only difference of them is inlet velocity of magnesium powders. The inlet boundaries parameters can be seen in Table 1.

Table1 Inlet boundary parameters

Case	Mg velocity /(m/s)	Mg mass flow rate /(kg/s)	Water velocity /(m/s)	N_2 velocity /(m/s)
1	20	0.13	15	20
2	40	0.26	30	40
3	60	0.39	45	60
4	80	0.52	60	80

The results of calculation and analysis

Temperature field. Fig.5 illustrates the temperature field of four cases in YOZ surface (axes orientation can be seen from Fig.2). From these pictures we can see that high-temperature regions become smaller and move towards the outlet as the inlet velocities increase.



(a) 20m/s (b) 40m/s

(c) 60m/s (d) 80m/s

Fig. 5 The temperature field of four cases in YOZ surface

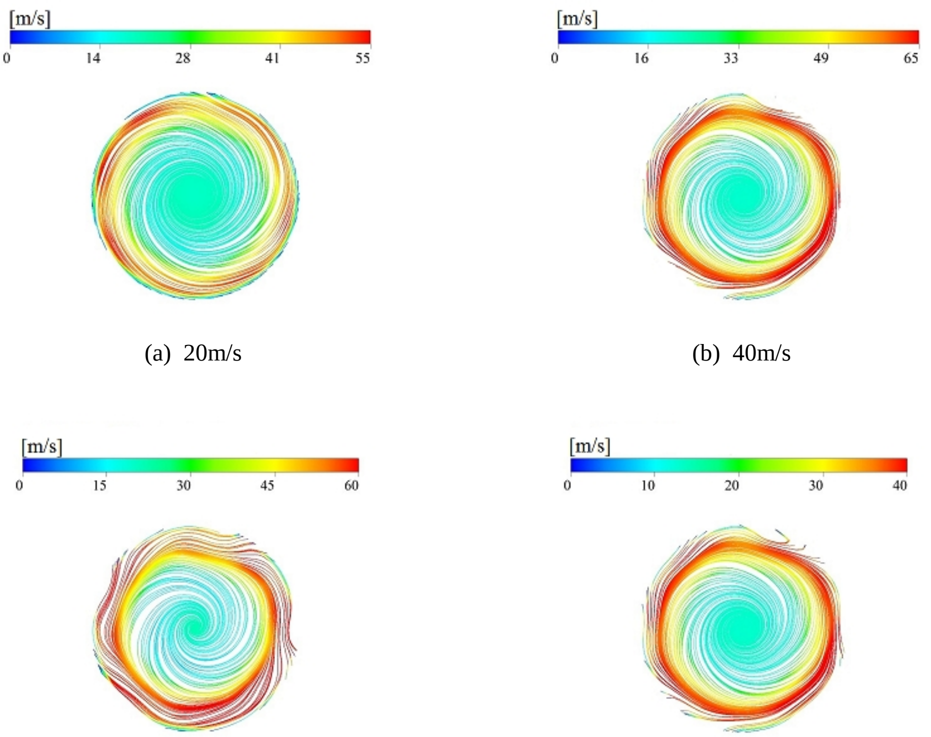
The burn-off rate of four cases is shown in Table 2. When the inlet velocity is 20m/s, the burn-off rate is as much as 92.30%. But the burn-off rate becomes smaller and smaller and the gap increases gradually with the increase of inlet velocity. Finally, there are only 60.27% of magnesium react with steam when the inlet velocity raises 80m/s.

Table2. The burning rate under different inlet velocity

Mg inlet velocity /(m/s)	20	40	60	80
The burning rate /%	92.30	89.71	81.03	60.27

We can know from reference that the flame will move towards burned gases with the improvement of flow rate, which conforms to the phenomenon in Fig.5. So, high-temperature regions migrate downward gradually when the inlet velocity increases. Besides, the area of these regions is ever smaller because of the geometry of combustor. Both of these two variation trends have an adverse impact on the combustion of magnesium. As a consequence, the burn-out rate and temperature decline.

Flow field. The streamlines in transverse section are shown in Fig.6 (the section is perpendicular to z-axis and 0.3 meters away from inlet), and it is clear that swirl vanes can develop stream-wise vortices.

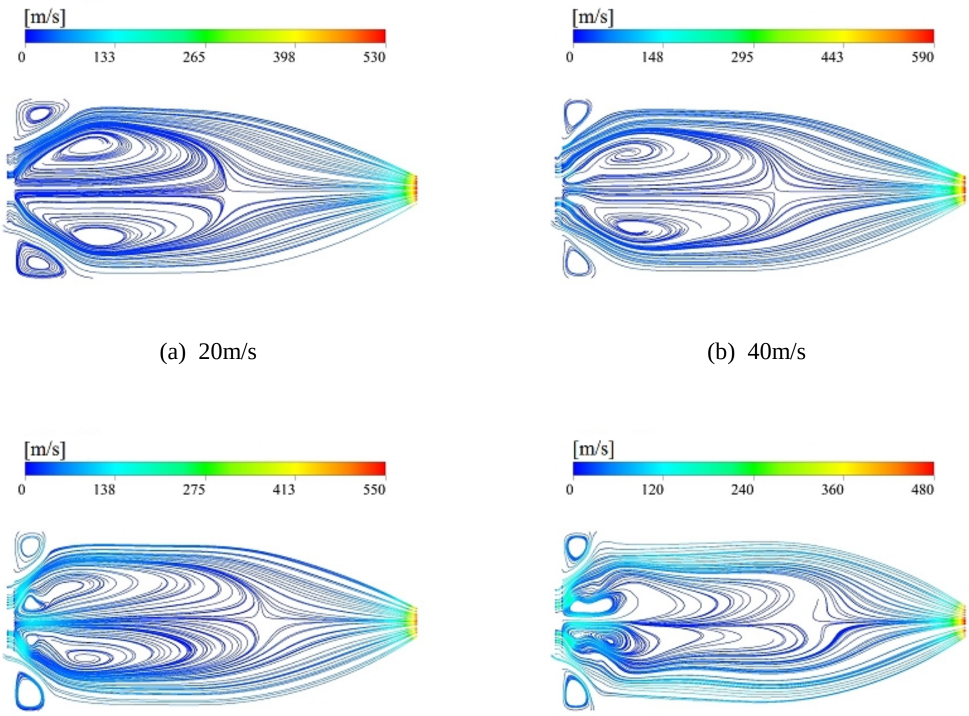


(a) 20m/s (b) 40m/s

(c) 60m/s (d) 80m/s

Fig. 6 The streamlines in transverse section

Fig.7 shows four cases' the streamline in longitudinal section, and there are two types of span-wise vortexes. One kind of them locates close to the combustor wall and they are developed by sudden enlargement, while the other is generated by stream-wise vortexes. As a result, it is the combination of vortexes in two directions that can produce stable recirculation zones in the combustor which is beneficial to mixing and combustion. And, we can know from further analysis that recirculation zones are plump and near the inlet when the inlet velocity is relatively low. Nevertheless, recirculation zones get close to the outlet and the shape is becoming narrower, and this phenomenon matches with distribution of high-temperature zones. Thus it is feasible to apply the swirl vanes to the water ramjet in order to develop recirculation zones that are good for the mixing and stable combustion.



(a) 20m/s (b) 40m/s

(c) 60m/s (d) 80m/s

Fig. 7 The streamline in longitudinal section

Specific impulse. Specific impulse I_s is thrust which is generated by per unit mass fuel, and it is an important performance indicator. The calculation formula is written as follows:

$$I_s = \frac{\int_0^{t_b} F dt}{M_p}$$

where M_p is the fuel quality. t_b is the time the ramjet works. F stands for thrust.

The specific impulse under different inlet velocities is shown in Fig.8. It is clear that the specific impulse increases from 4597 [N •s/kg] to 5257 [N •s/kg], and then declined to less than 4000 [N •s/kg] when the inlet velocity reaches 80 [m/s]. Although the inlet velocity increases gradually, the burn-out rate shows an opposite trend which means there are not efficient heat converted into kinetic energy, so the specific impulse begins to decline when the inlet velocity reaches 40 [m/s].

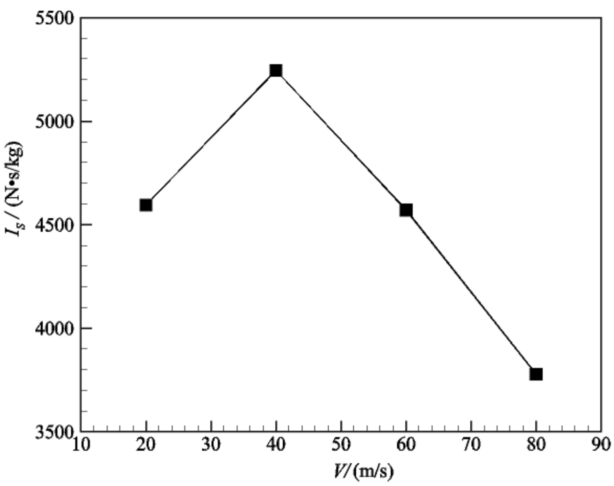


Fig. 8 The specific impluse at different inlet velocities

Conclusions

(1) The swirl vanes can develop steam-wise vortexes which generate span-wise vortexes, and the vortexes in two directions produce stable recirculation zones that are conducive to combustion.

(2) With the increase of inlet velocity, the high-temperature regions are ever smaller and move towards the outlet and these phenomena are corresponded with recirculation zones.

(3) With the increase of inlet velocity, the burn-out rate decreases while the specific impulse increases firstly and then decreases.

References

[1] Bing Chen, Pengfeng Zhang, Kun Guo. Review of the development in torpedo thermal power technologies. Journal of Propulsion Technology, 2011,32(3):447-450. (in Chinese)

[2] Jie Zhou, Shuzong Wang. Discussion on design of su-percavitating torpedo propulsion. Torpedo Technology, 2006,14(5):27-57. (in Chinese)

[3] Xiaoqing Huang, Lihong Chen, Lixing Zhou. Numerical modeling of three-dimensional turbulent recirculating gas-particle flows in a combustor of co-flow jets with large velocity difference. Acta Mechanica Sinica, 1990,22(1):28-34. (in Chinese)

[4] Tombazis N, Bearman P W. A study of three-dimensional aspects of vortex shedding from a bluff body with a mild geometric disturbance[J]. Journal of Fluid Mechanics, 1997,330:85-112.

[5] Jianxing Zhou, Ying Pu, Meining Chen, et al. Numerical study on flow field in three supersonic combustors. Journal of Aerospace Power, 2008,2(1):150-155. (in Chinese)

[6] Yong Huang, Yuzhen Lin, Weijun Fan, et al. Combustion and combustor[M]. Beijing: Beihang University Press: 2009:164-175.

[7] Chao Han. Research on the powder fuel feed system for powered fuel ramjets[D]. Changsha: National University of Defense Technology, 2006. (in Chinese)

[8] Marzouk O A, Huckaby E D.Effects of turbulence modeling and parcel approach on dispersed two-phase swirling flow[C]. Proceedings of the World Congress on Engineering and Computer Science.2009, 2.

[9] Wei Zhang, Weihua Zhang, Xing Zhou. Magnesium-based hydro-reactive metal fuel[M]. Beijing: National Defense Industry Press:2013:37-165.