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MIXED-HYBRID FUEL FORMULATIONS:

COMPOSITION, REGRESSION RATE AND CONDENSED COMBUSTION PRODUCTS

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Abstract

An investigation of burning behavior of mixed-hybrid fuel is performed. The work presented in the poster is composed of experimental part and numerical activities. Combustion tests are performed in a lab-scale hybrid rocket motor at the Space Propulsion Laboratory (SPLab) of Politecnico di Milano. The numerical analysis is performed by NASA CEA2 code. Three kinds of oxidizer are used: O_2 direct comparison with experimental data, H_2O_2 and N_2O for comparison among different oxidizers. Computations are performed under different combustion pressures. The effect of combustion pressure and formulation of grain on vacuum specific impulse and flame temperature is analyzed.

1. Introduction

The hybrid rocket is usually composed of a solid grain and a liquid or gaseous oxidizer [1]. The first report of hybrid motor experiment was conducted in the late 1930's and in early studies, liquid oxidizer (LOX) were usually used. In the 1990's, studies on hybrid motor using gaseous oxidizer (GOX) began to be reported [2].

Hybrid propulsion combined the advantages of solid propulsion and liquid propulsion. Its main advantages include outstanding performance on safety, flexibility and low cost. The safety of storage and operation is mainly due to the separate storage of solid grain and oxidizer, and the chemical property of solid grain. Even unexpected contact of solid grain and oxidizer will not cause explosive or flammable reaction unless they are ignited on purpose. Besides, neither crack nor break of solid grain will affect the combustion [3]. The solid grain also has very high mechanical properties, which makes it attractive considering its manufacture. The most important advantage is that hybrid motor has the ability to change thrust over a wide range, which makes multiple shut-on and shut-off possible. Regenerative nozzle cooling and liquid injection thrust vector control are also advantages over pure solid propulsion.

However, the limitation of hybrid propulsion is also very obvious. First of all, because of the rough combustion process, the combustion efficiency is relatively low compared to solid propulsion or liquid propulsion. Secondly, the O/F ratio, which is one of the key parameters, changes with time, making the effective control of the thrust more complex. Finally, and the most importantly, the regression rate of solid grain is low, which forces the adoption of large burning surfaces to obtain appropriate level of thrust [4]. Another serious problem is the pressure oscillations under certain condition.

Researches on solving existing problems of hybrid propulsion mainly focus on composition of solid grain and oxidizer, methods of oxidizer injection, and issues of thrust throttling. To increase the regression rate, solid oxidizer, catalyst and particulate addictive were added in the solid grain. Frederick et al. added ammonium perchlorate (AP) and ferric oxide to the solid grain and found that when AP was added, an initial increase in regression rate to a level of 141-176% that of pure HTPB. When catalyst was added to solid grains containing 25% AP, regression rates are further increased to approximately 248-314% the rate of pure HTPB [5]. George, et al. conducted experiments on HTPB/ GOX hybrid rocket motor and studied the effects of addition of AP or aluminum in the fuel, the variation of oxidizer-to-fuel ratio, and the variation of characteristic dimensions of fuel grain [6]. Chiaverini et al. made an experimental investigation of the regression rate characteristics of HTPB solid fuel burning with oxygen and found that at lower mass flux levels, thermal radiation influences the regression rate significantly. Besides, the 20% by weight addition of activated aluminum to solid grain increased the fuel mass flux by 70% over that of pure HTPB [7].

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2. Simulation Reactant and Combustion Condition

In the simulation study in this paper, three kinds of solid grain formulation were used: pure HTPB, HTPB loaded with AP, and HTPB loaded with both AP and aluminum particles. Table 1and Table 2 show the formulations in detail. Liquid oxygen was used as the oxidizer. Simulation studies were conducted separately under chamber pressure of 0.5 MPa, 1.0 MPa, 2.0 MPa, 3.0 MPa and 7.0 MPa to see the effect of pressure on combustion. The area ratio was set to 40 and the oxidizer-to-fuel weight ratio was in the range from 1.2 to 3.0. Vacuum specific impulse and flame temperature were chosen for subsequent analysis since vacuum specific impulse is the most important rocket performance parameter, while flame temperature has great influence on the regression rate.

Table 1. Formulation of AP-loaded solid grains

	HTPB, wt %	**AP, wt %**
1-1	95	5
1-2	90	10
1-3	85	15
1-4	80	20
1-5	75	25
1-6	70	30

Table 2. Formulation of AP-loaded and Al-loaded grains

	HTPB, wt %	**AP, wt %**	**Al, wt %**
2-1	90	5	5
2-2	85	10	5
2-3	80	15	5
2-4	75	20	5
2-5	70	25	5
2-6	65	30	5
2-7	65	5	10
2-8	80	10	10
2-9	75	15	10
2-10	70	20	10
2-11	65	25	10
2-12	60	30	10

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3. Results and Discussion

3.1 Effect of Pressure and Formulation

Figure 1 shows the trend of vacuum specific impulse and flame temperature of pure HTPB grain under different pressure. It can be seen that when the pressure increases, under the same O/F weight ratio, the vacuum specific impulse increases, and the maximum vacuum specific impulse is obtained at higher O/F weight ratio. As for flame temperature, when the O/F is 1.5, higher flame temperature is obtained under higher pressure. However, when the O/F weight temperature is in the range of 1.6 to 2.5, flame temperature decreases as chamber pressure increases. Then after the O/F weight ratio is higher than 2.5, flame temperature increases with the pressure increases again. And the from this trend it can be seen that the maximum flame temperature is higher when the chamber temperature is higher.

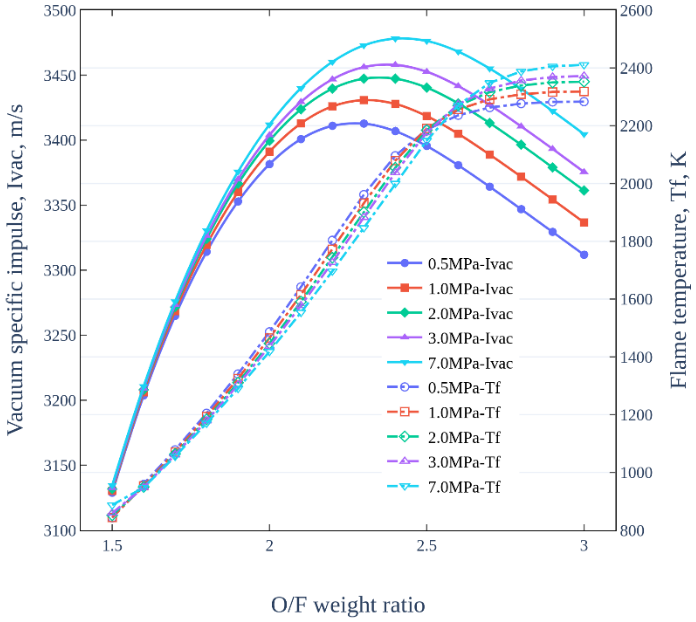

Figure 1. Vacuum specific impulse and flame temperature of pure HTPB solid grain burning under different pressures

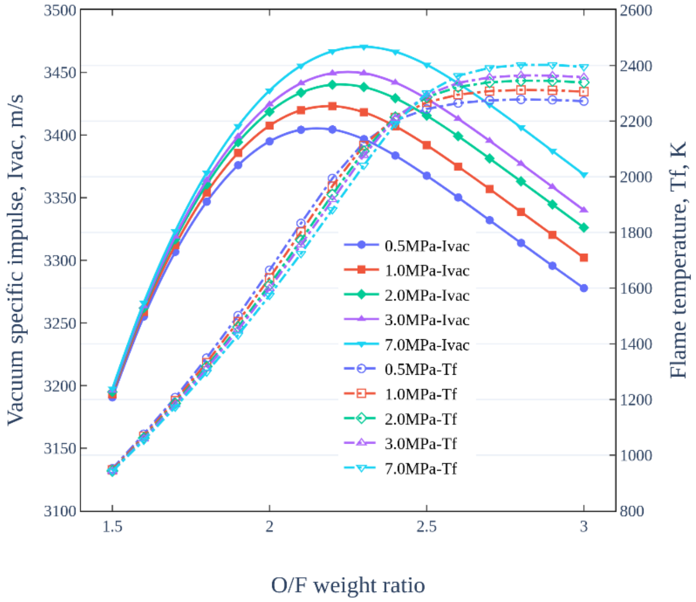

Figure 2. Vacuum specific impulse and flame temperature of solid grain 1-1 burning under different pressures

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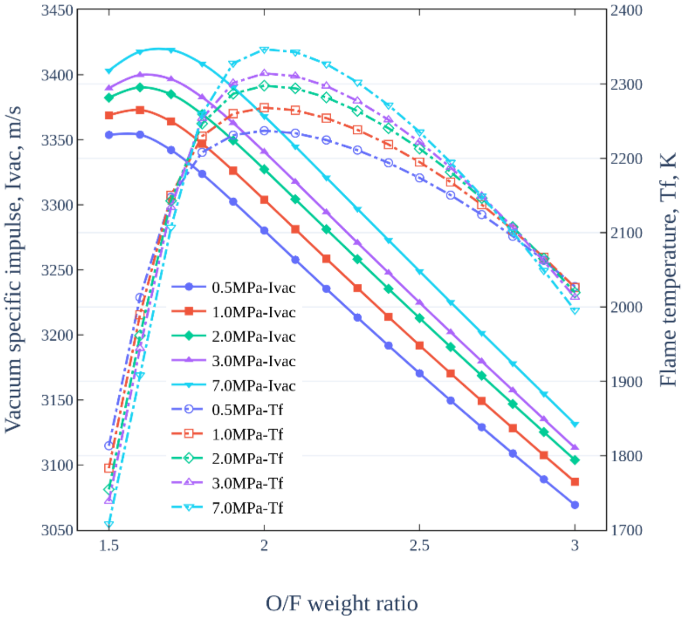

Figure 3. Vacuum specific impulse and flame temperature of solid grain 1-6 burning under different pressures

Figure 2 and Figure 3 show the trend of vacuum specific impulse and flame temperature of AP-loaded solid grain under different chamber pressure. It can be seen that the trend is almost the same with that of pure HTPB. However, when the weight percentage of AP increases, the maximum vacuum impulse decreases and was obtained at lower O/F weight ratio. The crossing of flame temperature lines under different pressures appears at lower O/F weight ratio when the solid grain has higher AP weight ratio. Besides, both maximum vacuum specific impulse and flame temperature decrease with the increase of AP weight ratio. What else can be seen from Figure 3 is that when the O/F weight ratio is high enough, flame temperature decreases as chamber pressure increases again.

Figure 4 and Figure 5 show the trend of vacuum specific impulse and flame temperature of AP-loaded and Al-loaded solid grain under different chamber pressure. The trend is still same with that of pure HTPB solid grain and AP-loaded solid grain. Comparing Figure 4 and Figure 5 with Figure 3, it can be seen that when weight percentage of aluminum increases, the maximum flame temperature increases obviously while the maximum vacuum specific impulse increase too, although not so obviously. Besides, with the increase of weight percentage of aluminum, the maximum flame temperature is obtained at higher O/F weight ratio while the maximum vacuum specific impulse is obtained at lower O/F weight ratio.

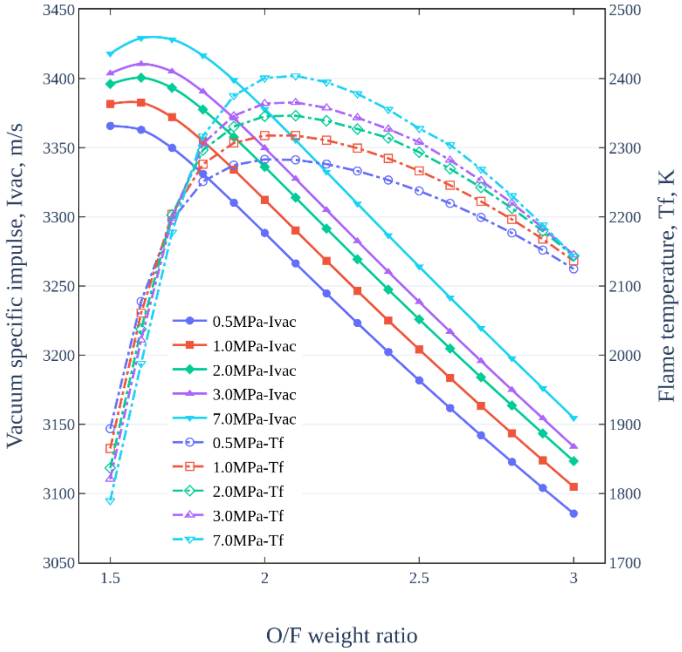

Figure 4. Vacuum specific impulse and flame temperature of solid grain 2-5 burning under different pressures

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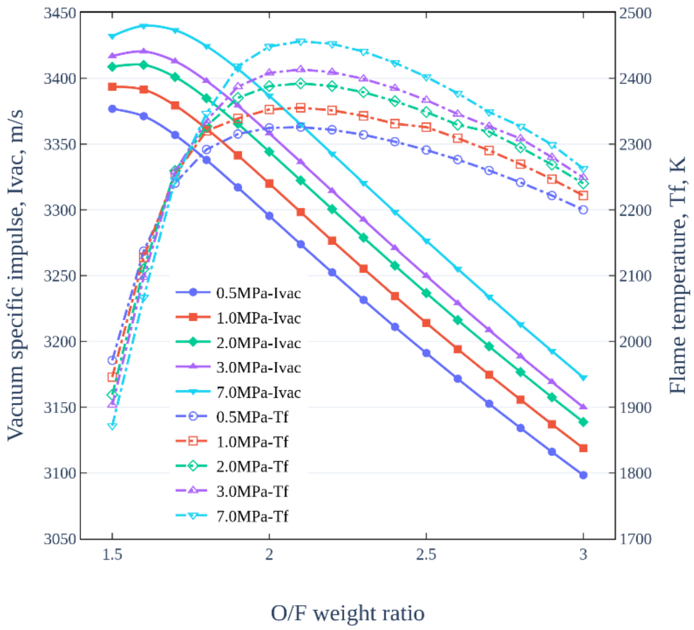
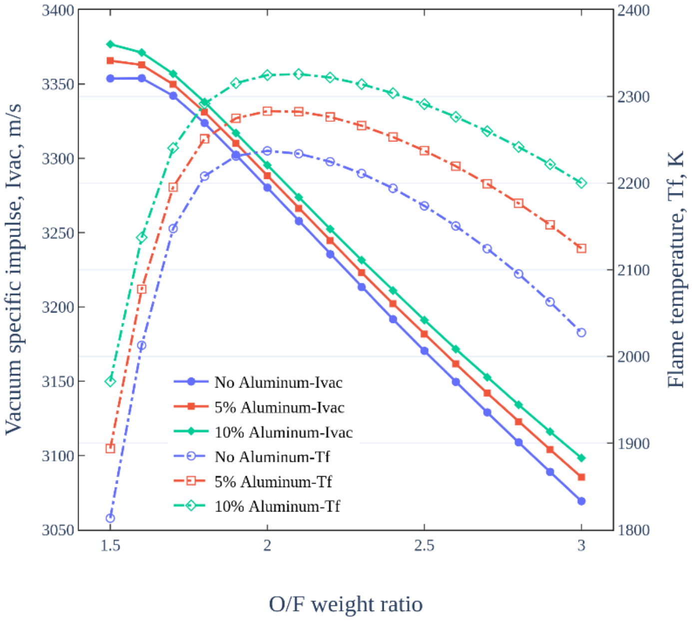


Figure 5. Vacuum specific impulse and flame temperature of solid grain 2-10 burning under different pressures

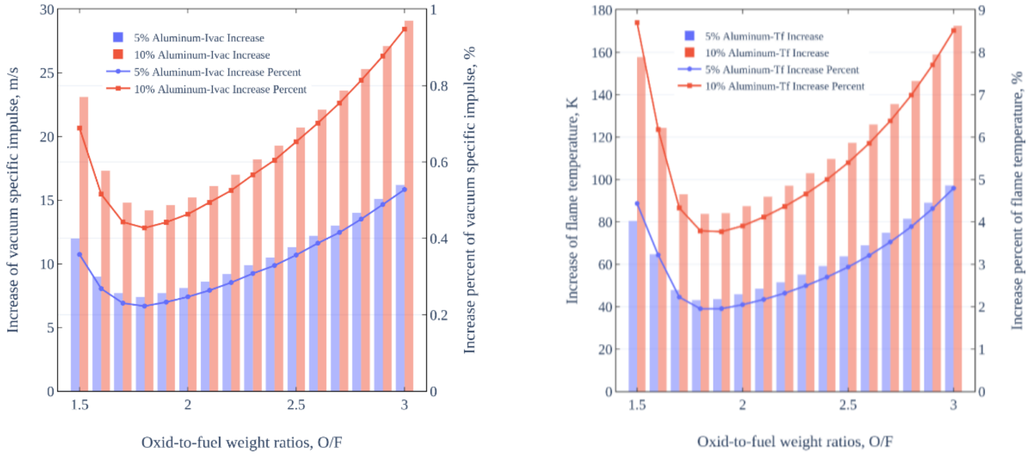
3.2 Effect of Aluminum under Same Amount of HTPB

Figure 6 to Figure 8 show the how the amount of aluminum in the solid grain affect the vacuum specific impulse and flame temperature more directly. The increase of aluminum amount can always increase the vacuum specific impulse and flame temperature. When the weight percentage of aluminum is 10%, the lowest increase percentage of both vacuum specific impulse and flame temperature always appears at the O/F weight ratio of 1.8, whatever the chamber pressure is. When the weight percentage of aluminum is 5%, the lowest increase percentage of vacuum specific impulse also always appear at the O/F weight ratio of 1.8. However, when the pressure becomes higher, the lowest increase percentage of flame temperature appears from at O/F weight ratio of 1.8 to 1.9.

Besides, when the pressure increases, the increase amount and increase percentage of both vacuum specific impulse and flame temperature increases. In another words, aluminum makes a more obvious effect on the combustion under higher chamber pressure.



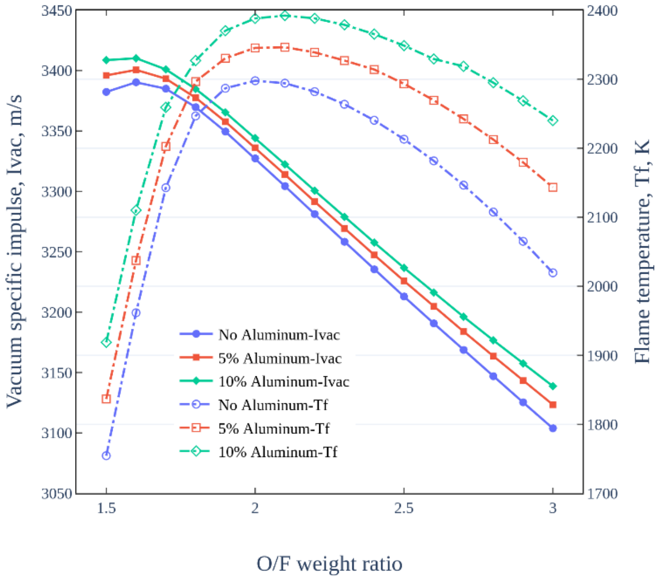
(a) Vacuum specific impulse and flame temperature of solid grain 1-6, 2-5 and 2-10 under pressure of 0.5 MPa



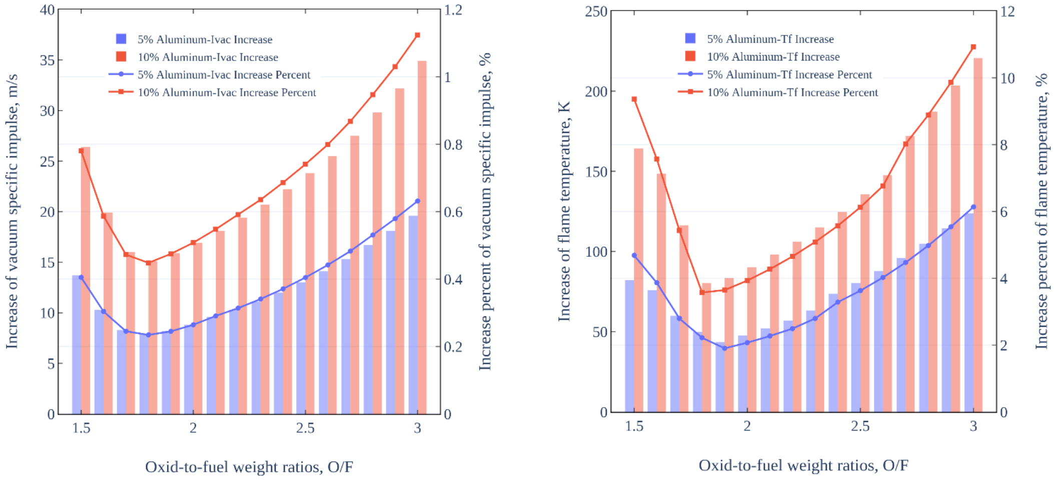
(b) Increase amount and increase percentage of vacuum specific impulse

(c) Increase amount and increase percentage of flame temperature

Figure 6. Effect of aluminum amount under 0.5 MPa



(a) Vacuum specific impulse and flame temperature of solid grain 1-6, 2-5 and 2-10 under pressure of 2.0 MPa



(b) Increase amount and increase percentage of vacuum specific impulse

(c) Increase amount and increase percentage of flame temperature

Figure 7. Effect of aluminum amount under 2.0 MPa

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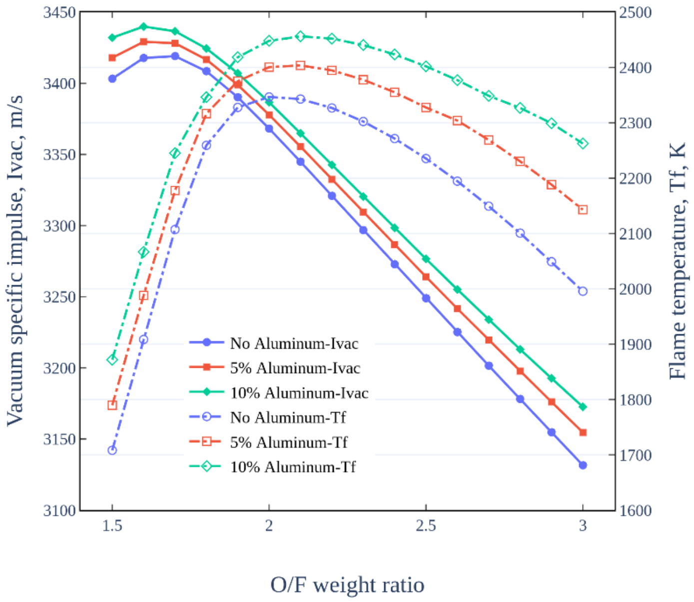
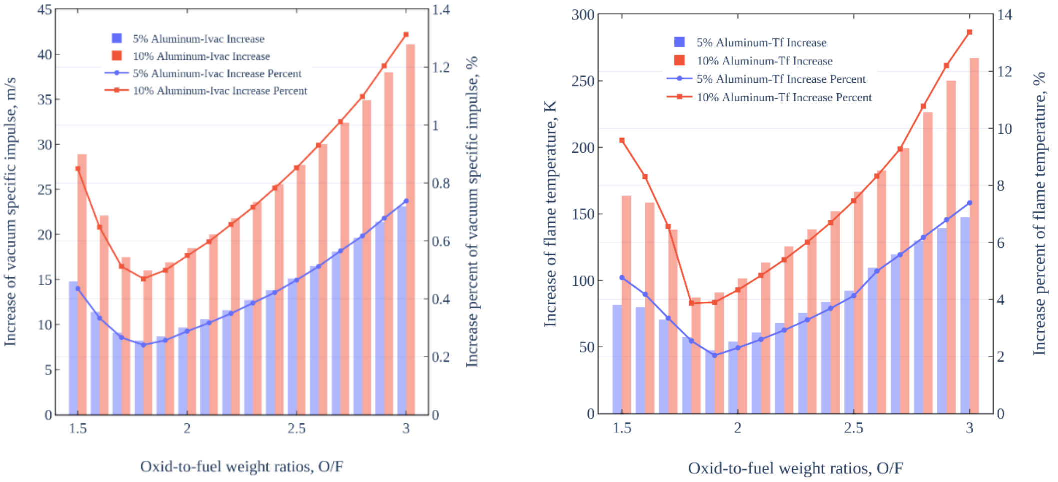


(a) Vacuum specific impulse and flame temperature of solid grain 1-6, 2-5 and 2-10 under pressure of 7.0 MPa



(b) Increase amount and increase percentage of vacuum specific impulse

(c) Increase amount and increase percentage of flame temperature

Figure 8. Effect of aluminum amount under 7.0 MPa

4. Conclusion

Simulation studies were conducted to invest the effect of formulation of solid grain and chamber pressure on vacuum specific impulse and flame temperature. The following results are found:

(1) The increase of pressure can increase both maximum vacuum specific impulse and maximum flame temperature.

(2) The addition of AP causes a decrease of both maximum vacuum specific impulse and maximum flame temperature. The more AP is added, the higher the decrease amount is.

(3) The addition of aluminum can increase both the vacuum specific impulse and flame temperature, not only the maximum. The effect can be more obvious under higher pressure.

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