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INVESTIGATION OF THE PROPELLANT PREHEATING IN AIR TURBINE ROCKET ENGINE

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In the air turbine rocket (ATR) engine, the compressor and turbine are droved by a small rocket engine that works as a gas generator instead of the main combustor in the jet engine. Compared with the single model engine, the specific impulse of ATR is much larger than the rocket engine but smaller than the jet engine. The specific impulse basically depends on the inlet gas temperature of turbine, the pressure ratio of turbine and the turbine efficiency. All these factors aim at decreasing the mass flow rate from the gas generator for fixed turbine power. This study investigates a new operating cycle that the propellant including fuel and oxidant are preheated in the combustor before entering the gas generator, which also is considered as a heat protection method. For a certain inlet gas temperature of turbine, the mixture ratio of oxidant and fuel decreases when the propellant is heated, then the working power is changed with the temperature. The engine performance is analyzed to investigate the specific impulse and total thrust particularly. Based on the simulated results, the specific impulse and total thrust are analyzed. In general, the specific impulse benefit from the propellant preheating.

I. INTRODUCTION

The air turbine rocket engine is called ATR for short, which is effectively combined with the rocket and turbine engine, and its characteristics are as follow:

(1) It has smaller structure dimension and larger thrust with unit discharge. In addition, it has smaller frontal area, slighter drag and larger thrust in the same air flow rate. Meanwhile, the acceleration capacity of ATR is outstanding[1,2].

(2) The turbine is drove by the rocket gas generator in different conditions during the whole trajectory and it has high reliability. The turbine is separated from the compressor, and the problem of low Reynolds number exiting in the high latitude is eliminated.

(3) There isn't modal transformation process and no dead weight exists during the flight trajectory. It is able to take off from a static condition and achieve the high flight velocity in Mach 0~3. Therefore, ATR engine is regarded as a kind of new combined dynamic system that works compatibly in the near space, and it has large range of flight altitude and velocity. The technical risk of ATR engine is moderate and it could be used in engineering application.

In the ATR engine of liquid propellant, the propellant combusts in fuel-rich condition and produces the gas with high temperature that generates work in turbine[3,4,5]. The compressor is drove by the turbine to condense and transport the inlet air. The fuel-rich gas drives the turbine and then is blended with the air in the mixer. It combusts in combustor and then is ejected through the exhaust nozzle to produce thrust eventually. For the working fluids in the combustor, the air mass is considered into the propellant mass. Therefore, the specific impulse performance of ATR engine is affected by the mass flow rate of fuel-rich gas[6,7]. If the propellant is preheated before entering the gas generator, the combustion efficiency will be theoretically improved. When the combustion temperature is same, the propellant consumption can be reduced in the preheating cycle, but the energy for preheating the propellant will influence engine performance accordingly[8,9]. So this paper studies the propellant preheating cycle in the ATR engine, and the rule of specific impulse and different preheating methods are analyzed.

II. PERFORMANCE ANALYSIS

II.I Engine System

The paper researches an ATR engine used in the missile and the schematic diagram of engine structure is as shown in Figure I, which consists of the intake, compressor, turbine, gas generator, combustor, exhaust nozzle and some other components. In the conventional method of ATR engine system, the propellant enters the gas generator with the supplied temperature. And the temperature of fuel-rich propellant can reach 1000K~1300K from the gas generator, which drives the turbine and produces power. The gas after driving the turbine blends with the compressed air in the mixer and then combusts in the combustor that is cooled with the air film.

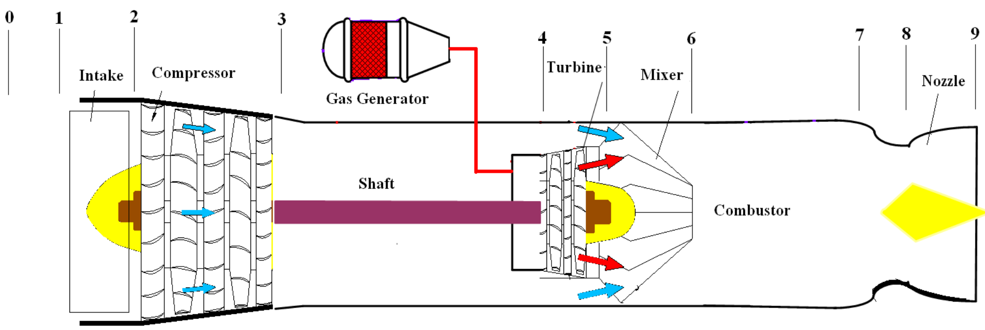


Fig. I: Schematic Diagram of Engine Structure

Because the turbine is driven by gas of generator, there isn't an aerodynamic coupling between compressors and turbine. The character of ATR engine is different from rocket engine or jet engine. The parameters on thrust and specific impulse need be studied, which include the compressor pressure ratio, turbine expansion ratio, component efficiency and gas physical properties of generator. So the optimized parameters will be decided to improve the engine performance.

In ATR engine, the air-fuel ratio is defined as:

$$\alpha = \mathrm{W}_{a2} / \mathrm{W}_{g4} \qquad [1]$$

The W_{a2} represents the mass flow rate of inlet air and W_{g4} is the gas mass flow rate of gas generator. The variation range of α is from 0 to large value in theory, when the α=0 is considered as the rocket model and the α>>1 is equivalent to turbofan engine pattern, which is the basic character of ATR engine. For different applications, α can be changed, which can achieve the larger thrust performance and lower specific impulse than the turbine engine. Also, the maximum speed limit is improved to Ma 3~4. Similarly, it has better specific impulse performance than the rocket engine but the thrust is lower. In addition, it is able to takeoff in the horizontal way.

The specific impulse definition of ATR engine is similar to combined cycle of jet engine. Without considering the air-entrainment and turbine cooling, the thrust, specific thrust and specific impulse of ATR engine are defined as:

$$F_N = (W_{a2} + W_{g4})\ c_9 - W_{a2}c_0 + (p_9 - p_0)\ A_9 \qquad [2]$$

$$F_s = F_N / W_{a2} \qquad [3]$$

$$I_{sp} = F_N / W_{g4} \qquad [4]$$

$$N_C = W_{a2} \times Cp_{a2} \times T_2^* \left(\frac{\pi_C^{\frac{k-1}{k}} - 1}{\eta_C} \right) \qquad [5]$$

$$N_T = W_{g4} \times Cp_{g4} \times T_4^* \times (1 - \pi_T^{\frac{1-k}{k}})\eta_T \qquad [6]$$

c_9 and c_0 in the equation represent the exhaust velocity of nozzle and the air velocity through the intake. A_9 and p_9 represent respectively the area of nozzle exit section and static pressure. p_0 represents the ambient atmosphere pressure. T_2^* and T_4^* represent the inlet total temperature of compressor and turbine respectively. The π_c represent π_T are the pressure ratio of compressor and turbine respectively. η_C and η_T represent the adiabatic efficiency of compressor and turbine respectively.

II.II Main Parameters Effects on Specific Impulse

According to the definition of engine thrust, specific impulse and system calculation analysis, the main influence factors on specific impulse are: turbine efficiency, turbine inlet temperature, turbine expansion ratio, combustion efficiency, compressor efficiency, compressor pressure ratio and some component parameters. In fact, the specific impulse is influenced by various conditions. According to the simulated engine performance of design point, the influence law can be quantitatively illustrated including main parameters on engine performance.

Taking the LOX/ CH_4 propellant for example, the relation of main engine parameters and specific impulse has been analyzed. The main engine factors in calculation are as shown in Table I and the design point of sea level (ground point) is set as the design point. BY changing each parameter only, the change rule of specific impulse performance will be obtained. The main engine parameters include: compressor efficiency, turbine efficiency, combustor efficiency, turbine expansion ratio, inlet temperature of turbine.

Parameters	Unit	Value
Rotating speed	r/min	30000
Mass flow rate of air	kg/s	5
Compressor pressure ratio	-	3
Compressor efficiency	-	0.85
Expansion ratio of turbine	-	12
Turbine efficiency	-	0.65
Gas temperature in the gas generator	K	1200
Gas generator efficiency	-	0.97
Inlet temperature of turbine	K	1196
Combustor efficiency	-	0.95
Rotor mechanical efficiency	-	0.99
Total pressure recovery coefficient of the bypass	-	0.99
Total pressure recovery coefficient of gas in the mixer	-	0.70
Total pressure recovery coefficient of air in the mixer	-	0.98
Total pressure recovery coefficient in the combustor	-	0.98

Table I: Main Engine Parameters of Design Point

The change rule of specific impulse with the compressor efficiency, turbine efficiency and combustor efficiency whose ranges are from 0.05 to 1.0 is as shown in Figure II. In the whole range, the specific impulse increases with three efficiencies linearly. With the specific impulse increasing 1%, the turbine efficiency has the most effect on specific impulse and the average improved value is 11.38s. The compressor efficiency has the second effect on specific impulse and the average improved value is 9.5s. The combustor efficiency influences least on specific impulse and the average improved value is 5.14s. However, according to the results of thrust in Figure III, with the compressor and turbine efficiency increasing, the engine thrust is reduced. And with the combustor efficiency increasing, engine thrust will ‘increase. The reason is that increasing compressor and turbine efficiency can improve the power capability of unit gas while the mass flow rate of air is constant. The amplitude reduction of gas flow rate in gas generator is more than thrust amplitude reduction, so the specific impulse is monotonic increased. But when the combustor efficiency increases, the mass flow rate in gas generator is unchanged. The combustion temperature will increase with it and the thrust will continue increasing, but the specific impulse increases slowly. On the basis of efficiency analysis and the structure realization considered, the compressor efficiency is 0.85, turbine efficiency is 0.6 and combustor efficiency is 0.9 in the preheating cycle analysis.

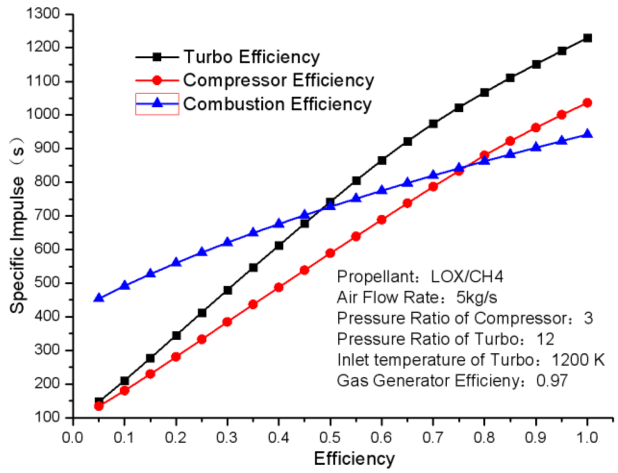


Fig. II: Effect of Component Efficiency on Specific Impulse

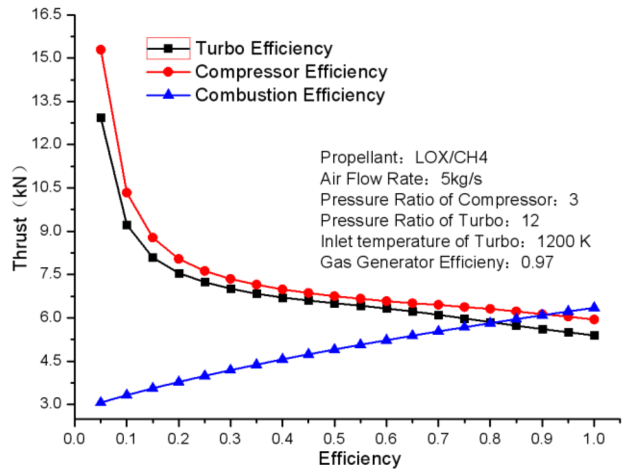


Fig. III: Effect of Component Efficiency on Thrust

The effects that the variable ratio of turbine expansion influences on the specific impulse of engine are as shown in Figure IV. With the turbine expansion ratio increasing, the performance ability of unit gas will increase. Due to the constant mass flow rate of air, the mass flow rates in gas generator and combustor are reduced, so the engine thrust decreases. Because the decreasing amplitude of gas flow rate is 74% (2.111kg/s~0.542kg/s), which is more than the decreasing amplitude of engine thrust 22% (7460N~5788N). So the expansion ratio will increase from 2 to 30 and the excess air coefficient of combustor increases rapidly from 0.34 to 1.31, which is from fuel-rich condition to oxygen-enriched condition. The amplification of specific impulse is 202% (360s~1088s). When the expansion ratio increases from 2 to 11 and the excess air coefficient of combustor increases from 0.34 to 1.0, the amplification of specific impulse is 150% (541s). When the expansion ratio increases from 11 to 30 and the excess air coefficient of combustor increases from 1.0 to 1.31, the amplification of specific impulse is 52% (187s). In conclusion, the argument of turbine expansion ratio benefits the specific impulse of ATR engine significantly. However there are some problems with turbine expansion ratio increasing, which are as following: the increased turbine stages, complex structure and increased weight. When turbine expansion ratio is too high, benefit to engine specific impulse will decrease. Therefore the optimized range of expansion ratio is 8~16 and 12 was determined in the preheating cycle analysis.

The effects that the turbine inlet temperature influences on the specific impulse are as shown in Figure V. The power capability of turbine gas is as shown in Equation 6, when the expansion ratio and turbine efficiency is constant, with turbine inlet temperature increasing, the performance of unit gas increases gradually. If the input power of compressor is constant, the gas flow rate in gas generator reduces. When the turbine inlet temperature increases, the gas flow rate reduces and the excess air coefficient in combustor increases accordingly. When it is from fuel-rich condition to oxygen-enriched condition, the specific impulse increases significantly and the thrust increases first and then reduces. The reason is that when the excess air coefficient is less than 1 with turbine inlet temperature increasing from 700K to 1200K, the turbine gas flow rate reduces 49%(1.337kg/s~0.688kg/s). The excess air coefficient is close to the equivalent value and the combustor temperature increases. The engine thrust increases 144% (2549N~6221N) and it reaches the maximum when the excess air coefficient is 1. The specific impulse in the range increases quickly to 373% (195s~923s). When the excess air coefficient is more than 1, with turbine inlet temperature increasing from 1200K to 2000K, the turbine gas flow rate reduces 38% (0.688kg/s~0.426kg/s). The excess air coefficient increases and combustor temperature reduces. The engine thrust reduces 28% (6221N~4492N) and specific impulse increases 19% (923s~1099s). In conclusion, the increased inlet temperature of turbine is able to enhancing power capability of gas and increasing the engine specific impulse. However, the feasible turbine inlet temperature is 1200K without cooling method. The system parameters can be optimized to adjust the excess air coefficient in combustor to 1, which can obtain feasible and better specific impulse performance. In the analysis of propellant preheating cycle, the inlet temperature of turbine is set 1200K.

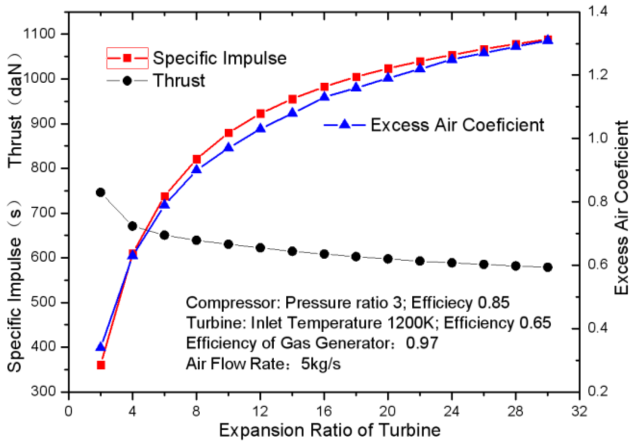


Fig. IV: Effect of Turbine Expansion Ratio

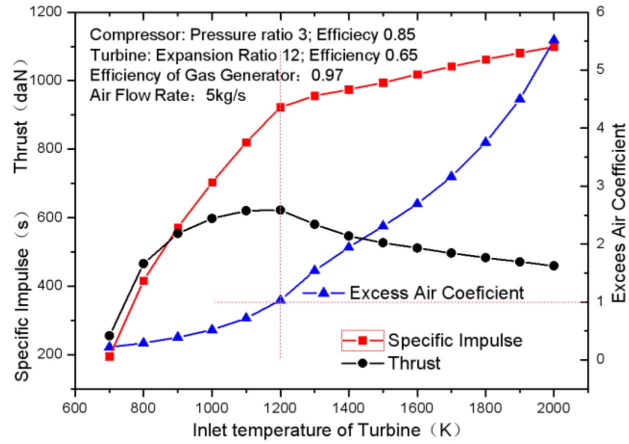


Fig. V: Effect of Turbine Inlet Temperature

III. POWER CAPABILITY OF FUEL-RICH GAS

The turbine is driven by fuel-rich gas in ATR engine, and the power capability of gas is as shown in Equation 7. The LOX/CH_4 propellant is used due to its best performance. The turbine expansion ratio is 12 and the turbine efficiency is 0.59.

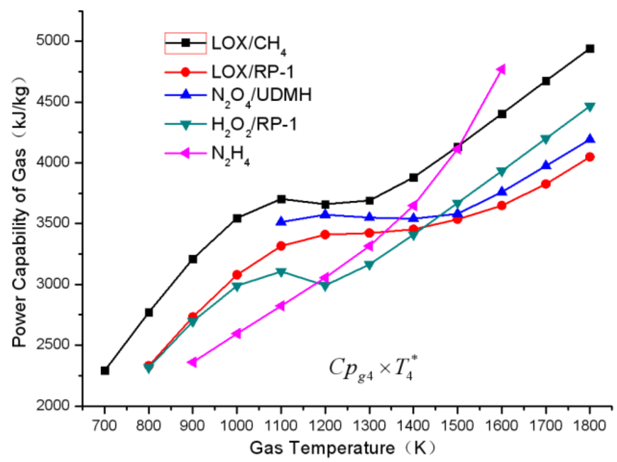
$$N_T = \frac{k}{k-1} R_{g4} \times T_4^* \times (1-\pi_T^{\frac{1-k}{k}})\eta_T = Cp_{g4} \times T_4^* \times (1-\pi_T^{\frac{1-k}{k}})\eta_T \quad [7]$$

III.I Propellant Effect

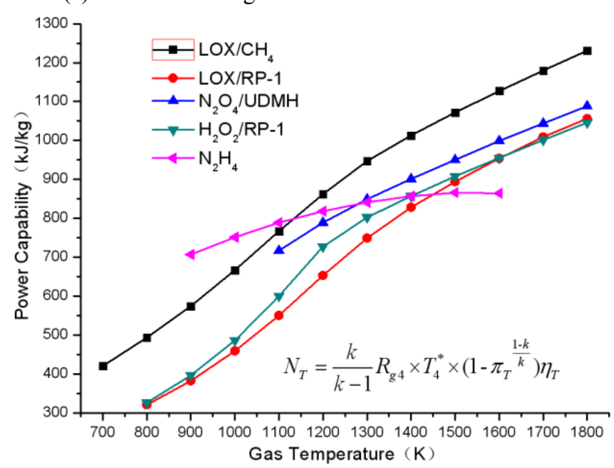
Several typical propellants of liquid rocket engine are chosen as working fluids to drive turbine, and they are LOX/CH_4, LOX/RP-1, N_2O_4/UDMH, H_2O_2/RP-1 and N_2H_4. The turbine effect is ignored or considered that is researched respectively in different conditions. The power capability of various propellants will be compared and analyzed and the gas pressure is 3 MPa.

(1) When turbine mechanical effect is ignored and fuel-rich gas character is considered, as showing in Figure VI(a). Only specific heat and total temperature is evaluated. With gas temperature increasing, power capability of various propellants increase totally. Comparing the upward trend of liquid monopropellant, hydrazine is smooth and H_2O_2/RP-1 propellant reduces a little firstly and then increases from 1200K. In the condition with same gas temperature and the range is 1100K~1300K, the order of power capability is LOX/CH_4, N_2O_4/UDMH, LOX/RP-1.

(2) If turbine mechanical effect is considered in power capability of the gas, as showing in Figure (b). The wheel power produced by unit gas is considered. With gas temperature increasing, except liquid monopropellant hydrazine keeping steady after 1300K, the power capability of other propellant increase significantly. In the range of 1100K~1300K, the order of power capability is LOX/CH_4, N_2O_4/UDMH, LOX/RP-1. The power capability of hydrazine is equivalent to N_2O_4/UDMH.



(a) Not Considering the Turbine Mechanical Effect



(b) Considering the Turbine Mechanical Effect

Fig. VI: Power Capability of Various Propellant

Therefore, based on the analysis of gas power capability, LOX/CH_4 propellant possesses the best power capability with turbine and it has higher specific impulse. Therefore, LOX/CH_4 is used in the analysis of propellant preheating cycle.

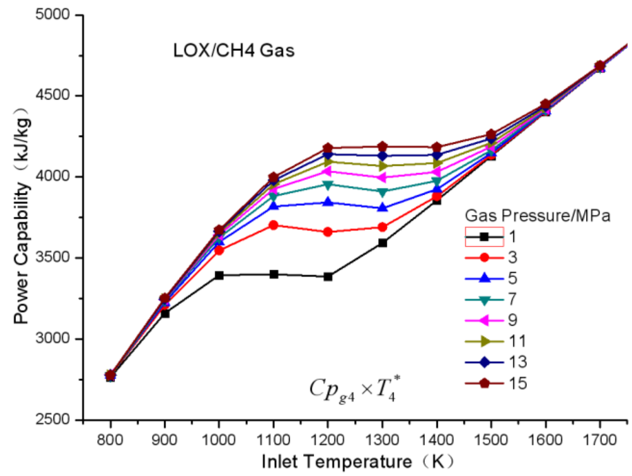
III.II Pressure Effect

The power capability of unit fuel-rich LOX/CH_4 is as shown in Figure VII. The turbine effect is ignored or considered that is researched respectively in different conditions. The gas power capability is analyzed and compared when the combustor pressure is changed.

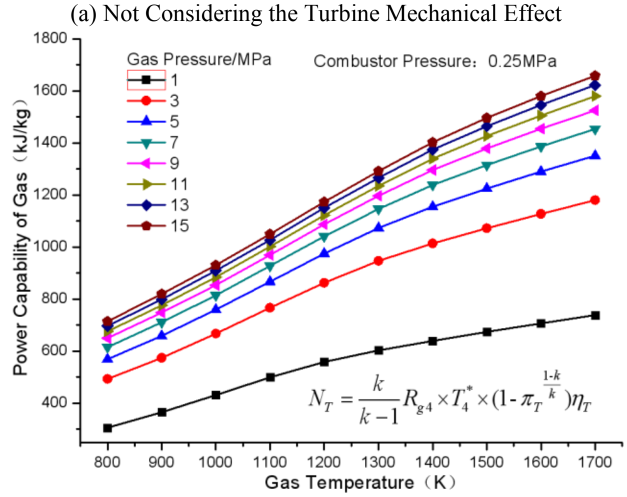
(1) When turbine mechanical effect is ignored and fuel-rich gas character is considered, as showing in Figure 7 (a). Only specific heat and total temperature is evaluated. When the combustor pressure is constant, the power capability of gas increases with the gas temperature increasing between 800k and 1700K, but there is reduction process during 1000K~1400K with the relative highest value existing. For example, the power capability in 1100K is higher than 1200K in 3MPa combustor pressure. When the gas temperature is constant, the power capability of gas increases with combustor pressure increasing from 1000K to 1400K.

(2) If turbine mechanical effect is considered in power capability of the gas, as showing in Figure 7 (b). The wheel power produced by unit gas is considered. When the pressure in gas generator is constant, the wheel power increases approximately linearly between 800K and 1700K. Because the combustor pressure is constant, the turbine expansion ratio increases in different gas generator pressure. When gas temperature is constant, the wheel power increases with pressure increasing, but the increasing range gradually reduces. However, the extortionate pressure will cause the difficulties to the engine supply system and the extortionate turbine expansion ratio is difficult to be achieved.

In the preheating cycle analysis with the paper, the gas generator pressure is 8.4MPa and fuel-rich temperature is 1300K, which is used in the preheating cycle analysis.



(a) Not Considering the Turbine Mechanical Effect



(b) Considering the Turbine Mechanical Effect

Fig. VII: Power Capability of Unit Fuel-rich LOX/CH_4 Propellant

VI. PROPELLANT PREHEATING CYCLE

In the ATR engine, by preheating the propellant entering into the gas generator, the initial enthalpy of the propellant is increased and the ratio of oxygen and fuel for the gas generator can be reduced. In addition, the ratio of air and fuel in the combustor can be increased and the specific impulse will be improved.

VI.I Performance comparison of Ground Point

Based on analysis of LOX/CH_4 propellant used in ATR engine, the parameters and engine performance in various preheating temperature at the ground point (0km, Ma0) and the high point (20km,Ma3) are shown in Table II. When the pressure and temperature of gas generator is constant, the mixing ratio of gas generator reduces and the propellant flow rate decreases. Therefore the combustor temperature and the thrust increase, and the specific impulse increases. The temperature of methane has great influence on specific impulse and the temperature of liquid oxygen has little effect on specific impulse.

Case number	Oxygen temperature	Methane temperature	Mixing ratio of gas generator	Ratio of specific heats	Gas constant	Gas temperature	Thrust	Specific impulse	Promotion percentage	Gas flow rate	Excess air coefficient
Unit	K	K	/	/	J/kg·K	K	N	s	%	kg/s	/
0	90.17	111.64	1.0975	1.2685	627.74	1300	5032	908.1	0	0.565	1.52
1	400	600	0.8291	1.2504	655.57	1300	5081	970.9	6.92	0.534	1.2
2	400	800	0.7353	1.2433	666.80	1300	5110	998.9	10.00	0.522	1.13
3	500	800	0.7263	1.2426	667.94	1300	5112	1001.6	10.30	0.521	1.11
4	500	1000	0.6167	1.2341	682.74	1300	5136	1035.7	14.05	0.506	1.04
5	600	1000	0.609	1.2335	683.86	1300	5137	1038.2	14.33	0.505	1.03
6	90.17	600	0.8861	1.2547	649.36	1300	5060	954.4	5.10	0.541	1.27
7	90.17	800	0.7859	1.2472	660.73	1300	5095	983.7	8.33	0.529	1.17
8	90.17	1000	0.6674	1.2381	675.76	1300	5126	1019.8	12.30	0.513	1.08

Table II: Ground Point Performance of Preheating Cycle

VI.II Performance of Typical Trajectory Point

According to the above analysis, it can be known that preheating the liquid oxygen is able to increase the specific impulse. Meanwhile, the safety and complexity of preheating two kinds of propellants are evaluated, so the method of preheating methane and not preheating liquid oxygen has been chosen. With the reliability considered, it is appropriate to preheat the methane up to 600K. Therefore, the sixth method has been chosen and the engine performance parameters of typical ballistic point are calculated. Several typical points have been compared with engine performance in preheating or not preheating method, which are shown in Table III. At each typical point, the performance after preheated is improved, and the increased range is 3.3%~5.6%.

		No preheat				Preheat				Increased Specific impulse
Altitude	Mach	Thrust	Specific impulse	Gas flow rate	Air fuel ratio	Thrust	Specific impulse	Gas flow rate	Air fuel ratio	
km	/	N	s	kg/s	/	N	s	kg/s	/	/
0	0	5032	908.1	0.565	7.96	5060	954.4	0.541	8.32	5.1%
5	1	4373	873.3	0.511	8.02	4407	919.6	0.489	8.38	5.3%
8	1.4	4506	919.6	0.500	8.13	4545	969	0.479	8.49	5.4%
12	1.8	3985	968.9	0.420	8.32	4022	1021.5	0.402	8.69	5.4%
16	2.5	3942	957.6	0.420	8.74	3985	1011.4	0.402	9.13	5.6%
20	3	2197	973.1	0.230	19.2	2573	1005.3	0.261	12.5	3.3%

Table III: Performance Comparison

VI.III Comparison of Major Engine Parameters

Six cases of different engine parameters are simulated and compared when the propellant is preheated or not including different compressor pressure ratios. The engine performance is compared in design point of sea level condition. The results are as shown in Table IV.

(1) According to comparison between case1 and case3, when propellant is not preheated and the turbine expansion ratio increases from 8 to 16, the engine specific impulse increases from 825s to 950s and the percentage is 15%. Because the turbine flow rate is reduced, engine thrust reduces from 5730N to 5294N and the amplitude reduction is 8%.

(2) According to comparison between case3 and case4, when the excess air coefficient of combustor is more than 1, the compressor pressure ratio is 2.5. When propellant is preheated, the mixing ratio of gas generator reduces and combustor temperature increases. The engine specific impulse increases from 950s to 1022s and the percentage is 7.6%. The engine thrust increases from 5294N to 5419N and the amplification is 2.3%.

(3) According to comparison between case5 and case6, when the excess air coefficient of combustor is less than 1, the compressor pressure ratio is 5.0. After propellant is preheated, the mixing ratio of gas generator and combustor temperature reduce. The

engine specific impulse increases from 739s to 747s and the thrust decreases from 8032N to 7724N.

(4) If engine excess air coefficient is lower, propellant preheating can reduce the mixing ratio of gas generator. But temperature of combustor is also lower and it reduces the engine performance.

Based on different comparison methods, the turbine expansion ratio can be promoted when the turbine efficiency is close, which can improve engine performance. When the compressor pressure ratio is low and the excess air coefficient of combustor is more than 1, propellant preheating can enhance engine thrust and specific impulse performance.

Parameters		Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
		Expansion ratio 8		Expansion ratio 16			
		No preheat	Preheat	No preheat	Preheat	No preheat	Preheat
		Pressure ratio 2.5		Pressure ratio 2.5		Pressure ratio 5.0	
Altitude	km	0	0	0	0	0	0
Velocity	-	0	0	0	0	0	0
Rotate speed	r/min	30000	30000	30000	30000	30000	30000
Thrust	N	5730	5706	5294	5419	8032	7724
Specific impulse	s	825.6	861.1	950.6	1022.5	739.3	747
Air flow rate	kg/s	5	5	5	5	5	5
Gas flow rate	kg/s	0.708	0.676	0.568	0.541	1.109	1.055
Excess air coefficient	-	1.08	0.92	1.35	1.16	0.69	0.59
Compressor pressure ratio	-	2.5	2.5	2.5	2.5	5	5
Compressor efficiency	-	0.85	0.85	0.85	0.85	0.85	0.85
Turbine expansion ratio	-	8	8	16	16	16	16
Turbine efficiency	-	0.589	0.589	0.589	0.589	0.589	0.589
Turbine inlet temperature	K	1300	1300	1300	1300	1300	1300
Combustor total temperature	K	2137.4	2096.3	1952.5	2050.1	1966.5	1787

Table IV: Performance Comparison of Different Preheating approaches

V. PROPELLANT PREHEATING METHOD

The propellant preheating cycle is able to improve the engine specific impulse theoretically, but the heat source has great influence on propellant preheating method, which determines the final feasibility. Three possible preheating methods are analyzed in this section.

V.I Heat Transfer Inside Combustor

Heat exchanger has been set up inside the combustor and the propellant is preheated by high temperature gas in combustor, whose structure is shown in Figure VIII. The heat source is the energy transferred from the high temperature gas of combustor, which can bring down mixing ratio of gas generator and promote engine specific impulse. But the larger resistance is a problem. After the propellant is preheated, the engine specific impulse increases from 908.1s to 954.4s when the resistance of heat exchanger in combustor is considered. If the total pressure recovery coefficient of combustor reduces from 0.98 to 0.9, the engine specific impulse decreases from 954.4s to 908.8s but thrust drops 214N. The reason is that the pressure decreases because of the increased combustor flow resistance. And the exhaust velocity of nozzle reduces, so the thrust and specific impulse decreases. In addition, the methane flow rate is small and there are some structure challenges when heat exchanger is installed in the combustor. It can be seen that heat exchanger inside the combustor is not able to promote specific impulse obviously. On the contrary, the engine thrust will be reduced.

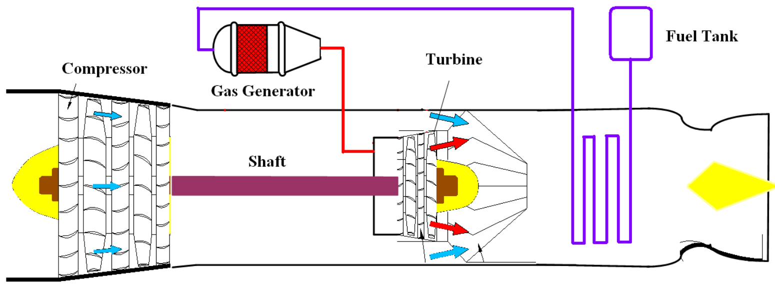


Fig. VIII: Heat Transfer inside Combustor

V.II Regenerative Cooling of Combustor

The methane is used in the coolant of combustor regenerative cooling system as a preheating approach, which is shown in Figure IX. Meanwhile, the flow resistance in combustor doesn't increase and the specific impulse increases 5.1% theoretically at design point of sea level. The air film cooling method is usually used for ATR combustor while the air through combustion liner and combustor outer wall in order to cool the combustor. If the cooling position is the combustor outer wall, the temperature of film cooling is too low to pro-heat the methane to 600K.

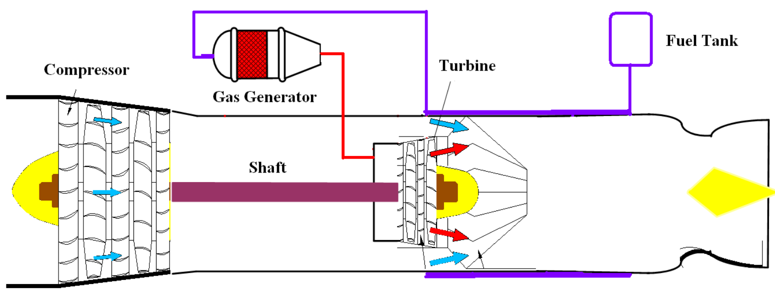


Fig. IX: Regenerative Cooling of Combustor

V.III Heat Transfer with Incoming Air

When the fuel is preheated, the air of high Mach number can also be considered as a heat source. This method combines the pre-cooling incoming air and the propellant preheating together, which is shown in Figure X. When the inlet temperature of compressor reduces, the input power of compressor decreases with same pressure ratio. So the gas flow rate of turbine reduces, which finally improve the specific impulse. In addition, the fuel preheated can improve the specific performance also.

However, the total temperature of air is only 606K at 20km/Ma3. The Mach number is smaller and the total temperature of air is lower. And the methane is not possible to be preheated to high enough temperature. Due to the ratio of air flow rate to methane flow rate is nearly 20, the air temperature decreases 0.14K when the methane temperature increases 1K. So the reduction of air temperature is too small to promote the specific impulse. Also, the heat exchanger is set up before compressor that can augment the flow resistance and the system complexity increases. Therefore, this method is not feasible in low Mach number condition and the engine performance can be promoted limitedly in high Mach number.

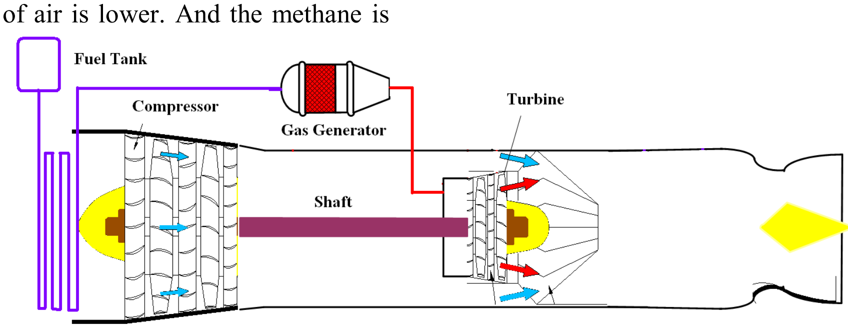


Fig. X: Heat Transfer with Incoming Air

VI. CONCLUSIONS

The performance of ATR engine is analyzed in the paper. The influence raw of main engine parameters on specific impulse and the power capability of different propellants are analyzed. Due to the most excellent power capability, LOX/CH_4 propellant is used in the preheating cycle analysis. Three kinds of feasible approaches for preheating the have been analyzed. The major conclusions are as follow:

(1) When the specific impulse is improved 1%, the turbine efficiency has the largest influence on specific impulse, whose average improved value is 11.38s. And then the second one is the compressor efficiency, whose average improved value is 9.5s. The combustor has the least effect on specific impulse and its value is 5.4s. With turbine and compressor efficiency increased, the engine specific impulse increases but the thrust reduces. With combustor efficiency increased, the engine specific impulse and thrust increase together.

(2) Increasing turbine expansion ratio can improve the specific impulse significantly, however the number of turbine stage will be increased, the structure is more complex and the weight is larger. When turbine expansion ratio is too high, the benefit to engine specific impulse decreases. Therefore the optimized range of expansion ratio is 8~16.

(3) For the propellant of LOX/CH_4, LOX/RP-1, N_2O_4/UDMH, H_2O_2/RP-1 and N_2H_4 in the range of 1100K~1300K, when the turbine effect is ignored or considered, the power capability of LOX/CH_4 gas is the largest. When the temperature of gas is same, the power capability of gas increases with combustor pressure increasing during the temperature range from 1000K to 1400K.

(4) In the propellant preheating cycle, the combustion temperature increases if the excess air coefficient of combustor is larger than 1. Therefore, the specific impulse and thrust increase. When the excess air coefficient is slightly less than 1, the specific impulse increases but the thrust decreases. When the excess air coefficient is much less than 1, the specific impulse and thrust reduce together due to the combustion temperature is too low.

(5) When the excess air coefficient of combustor is more than 1, propellant preheating is able to decrease the ratio of oxygen and fuel in gas generator and the mass flow rate of gas reduces. So the specific impulse and thrust increase. When the methane is preheated to 600K, the specific impulse increases 3.1%~5.1%.

(6) By analyzing three methods of heating propellant, the method of heat transfer inside combustor will increase the flow resistance inside the combustor, and the specific impulse increase slightly. The method of combustor regenerative cooling is not possible due to the air film heat protection. The method of heating propellant with incoming air is not feasible in low Mach number and the engine performance can be improved limitedly in high Mach number.

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