The Influence of Interstage-Turbine Mixing Cycle on Engine Performance

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Abstract. The optimization of the Brayton cycle has gained an increasing worldwide attention, in order to improve the specific thrust for achieving super cruise. This paper proposes a novel Interstage-Turbine Mixing (ITM) cycle, which guide vanes and rotor blades of turbine would be used as mixing chambers in the expansion process, and presents an analytical methodology by which ITM can be simulated at actual state. The motivation and the working principle of the ITM cycle are explained in detail. In this paper, the variable components method is used to establish the simulation program of the turbine stage mixing cycle. Then parametric cycle studies are performed with the variation of mixing ratio, bypass ratio and fan pressure ratio respectively. The interrelationships between cycle parameters and their effects on cycle performance are discussed. The results show that the mixing ratio of engine with the maximum specific thrust is 0.923, the mixing ratio with the maximum specific fuel consumption is 0.613, the mixing ratio with the best comprehensive performance is 1.127. The above conclusions are independent of the bypass ratio and fan pressure ratio. The predicted engine performance shows that the ITM cycle concept exhibits a competitive specific thrust with respect to engine in the state of non-afterburning, and might be a promising propulsion system for super-cruise air-breathing flying vehicles.

1. Introduction
With the increasing demand of military aircraft, the turbine inlet temperature is getting higher. Limited by the heat resistance of turbine blades, the turbine inlet temperature has an upper limit [1]. Therefore, under the existing technical conditions, it is unrealistic to improve engine performance by improving turbine inlet temperature.

In order to further increase the performance of aero engines, a new engine with new concepts is needed, such as new structure, new cycles, new technology and new materials. Therefore, kinds of improved turbofan cycles have been proposed to meet the requirements of the specific thrust, economy or fight conditions, including regenerative cycle [2,3], reheated cycle [4,5], staged-intercooled cycle [6-8], pre-cooled cycle [9], and so on. Because of the weight limitation of aero-engines, these cycles have not been applied to aeroengines. In recent years, the inter-stage turbine burner (ITB) is the main research content of this domain. The ITB chamber was proposed by K.H.Liew, E.U rip, S.L.Yang [10-12]. The performance of the engine can be improved by using ITB [13-14]. However, it is difficult to apply the technology to aero-engines due to its huge structure. Because ITB technology needs to be burned in Turbine channel with high speed, so it is difficult to form effective and stable combustion. Meanwhile, the increase of combustion chamber in Turbine channel poses new challenges to the size design of aero-engine.
This paper proposes a novel Interstage-Turbine Mixing (ITM) cycle, which guide vanes and rotor blades of turbine would be used as mixing chambers in the expansion process. By increasing the mixing ratio, the cooling effect of blades is enhanced. Therefore, the allowable temperature in front of the turbine is improved. Compared with the ITB, ITM increases the outlet temperature of the main burner, which avoids the problem of form effective and stable combustion in the second burner. As a result, the ITM cycle might become an effective way to improve the specific thrust of engine.

NOMENCLATURE

- $B_{i,bc}$: BIR number of thermal barrier coating
- $B_{i,met}$: metal BIR number
- $c_0$: Flight velocity
- $c_8$: Exhaust velocity
- $f$: Gas-oil ratio
- $F_S$: Specific thrust
- $K_{comb}$: Combustion chamber type factor
- $K_{cool}$: Cooling flow factor
- $\dot{m}_c$: Mass flow rate of cooling flow
- $\dot{m}_g$: The mass flow rate of the gas mainstream
- $\dot{m}_3$: The mass flow at combustor inlet
- $sfc$: Specific fuel consumption
- $R$: Ratio
- $T_4$: Combustor inlet temperature
- $T_5$: Turbine front temperature
- $T_{i,g,max}$: Maximum combustor outlet temperature
- $T_{r,g,relative}$: The relative total temperature of gas
- $T_{r,met,ext}$: The allowable total temperature of the metal
- $T_{r,c,in}$: The total temperature of the cooling gas.
- $\varepsilon_0$: Blade cooling efficiency
- $\varepsilon_f$: Blade air mode cooling efficiency
- $\psi$: Mixing ratio
- $\eta_{int}$: Blade internal cooling efficiency

2. Cycle description

In this paper, a double-rotor mixed exhaust turbofan engine is taken as the research object, and the variable component method is adopted to establish the performance simulation model of the turbine stage mixed cycle engine. Section division of the calculation model is shown in Figure 1, where 0~17 are section Numbers divided by engine parts. Inlet stands for the air Inlet; Fan stands for the Fan; HPC stands for the high pressure compressor; MB stands for the main combustion chamber; HT stands for the high-pressure turbine; LT stands for the low pressure turbine; Bypass stands for the outside Bypass; Mixer stands for the Mixing chamber; Nozzle stands for the exhaust nozzle.
On the basis of the traditional aero-engine, the turbine stage mixing model achieves the purpose of improving engine performance by controlling the mixing ratio. The turbine front temperature is determined by the mixing ratio. The parameters of the engine are shown in Table 1.

Table 1. Selection of main engine parameters [15]

| Parameter                                      | Value |
|------------------------------------------------|-------|
| Flight altitude /km                            | 11    |
| Mach number                                     | 1.6   |
| Coefficient of total inlet pressure recovery    | 0.97  |
| Total compressor pressure ratio                 | 26.1  |
| Fan efficiency                                  | 0.87  |
| Compressor efficiency                           | 0.89  |
| Bypass ratio                                    | 0.3   |
| High pressure turbine efficiency                | 0.9   |
| Low pressure turbine efficiency                 | 0.9   |

3. Thermodynamic cycle

To investigate the thermodynamic performance of the ITM, each component in the system is regarded as a control volume to conduct the energy analysis, which is based on the mass and energy balances. The assumptions and the equations refer to previous work [16]. An original program based on Aspen Custom Modeler (ACM) is developed to simulate the performances analysis with various design parameters. The models have been validated in previous works.

The aircraft requires high mobility type and high combat radius, so the aero-engine not only requires higher unit thrust, but also has lower fuel consumption rate. The specific thrust and specific fuel consumption can be calculated by the following equations [17].

specific thrust:

$$F_s = c_s - c_0$$  \(1\)

specific fuel consumption:

$$sfc = \frac{3600 f}{F_s}$$  \(2\)

In general, if the specific thrust increases, the specific fuel consumption will increase. In order to comprehensively consider the influence of engine cycle parameters on the performance of the aero engine, the relative performance parameter \(R\) was defined as:

$$R_1 = \frac{F_s_{ITM}}{F_s_{MTB}}$$  \(3\)

$$R_2 = \frac{sfc_{ITM}}{sfc_{MTB}}$$  \(4\)

$$R = \frac{R_1}{R_2}$$  \(5\)
The subscript ITM stands for the interstage-turbine mixing cycle, and MTB stands for the traditional Brayton cycle with the same parameters. The physical meaning of R is the relative relation between the increase of specific thrust and fuel consumption rate of aeroengine. If R>1, it means that under the same parameter, the increase rate of fuel consumption in ITM is less than the increase rate of specific thrust, and the overall performance of the engine is improved. However, if R<1, more fuel consumption is needed to increase the specific thrust in ITM. The engine performance with ITM deteriorates.

In addition to the aerodynamic performance, the turbine front temperature is also conditioned here. The turbine front temperature is related to the mixing ratio, cooling structure design, and the quality of the cooling air. The turbine front temperature can be estimated according to the following empirical correlation. See Reference 18 for a detailed definition and values of each parameter.

\[ T_5 = \frac{T_{t, g, max} - T_{t, g, relative}}{K_{comb}} + T_4 \]  
(6)

\[ \epsilon_0 = \left( T_{t, g, max} - T_{t, out, ext} \right) / \left( T_{t, g, max} - T_{t, c, in} \right) \]  
(7)

\[ \frac{\dot{m}_c}{\dot{m}_e} = \frac{K_{comb}}{1 + Bi_{bc} - (\epsilon_0 - \epsilon_f) \times Bi_{met}} \times \frac{\epsilon_0 - \epsilon_f \times [1 - \eta_{met} \times (1 - \epsilon_0)]}{\eta_{met} \times (1 - \epsilon_0)} \]  
(8)

\[ \sum \dot{m}_c = \psi \dot{m}_3 \]  
(9)

According to the above relation, the turbine front temperature in ITM can be obtained, and then the engine performance can be evaluated.

4. Calculation results and analysis
Making use of the above-described simulation tool, we conduct a parametric analysis to assess the behaviour of ITM performances against the main design parameters, including the mixing ratio, bypass ratio, and fan pressure ratio.

4.1. Influence of different mixing ratio on engine performance
According to Formula 6-9, the mixing ratio increases, the cooling flow in turbine blades increases and the allowable turbine front temperature increases. As shown in Figure 2, when the mixing ratio is 1.7, the allowable turbine front temperature reaches 2676K.

![Figure 2. Influence of different mixing ratios on turbine inlet temperature](image_url)

As shown in Figure 3, with the increase of mixing ratio, specific thrust and fuel consumption have the same change trend. Increasing the turbine front temperature can improve the specific thrust and
efficiency of the engine, while increasing the cooling air flow will reduce the specific thrust and increase the loss of the aero-engine. Therefore, when the mixing ratio is 0.923, the specific thrust of the engine reaches the upper limit, which is 732.9 m/s, and the propulsion performance is the best. When the mixing ratio is 0.613, the fuel consumption rate of the engine reaches the maximum value (0.09914 kg/(N hr)), and the economy of the engine is the worst.

In order to evaluate the comprehensive performance of the engine, this paper studies the changes of $R_1$, $R_2$, and $R$ based on the traditional Brayton cycle (turbine front temperature 1950K). As shown in Figure 4, when the mixing ratio is less than 0.39, the increment of fuel consumption rate is greater than the increment of specific thrust, and the comprehensive performance of the engine deteriorates. When the mixing ratio is greater than 0.39, the increment of fuel consumption rate is greater than the increment of unit thrust, the engine performance is improved. When the mixing ratio is 1.127, the $R$ value reaches the maximum value and the comprehensive performance of the engine is the best.

4.2. Influence of mixing cycle on engine performance with different bypass ratio
In this paper, the influence of mixing cycle on engine performance is studied for engines with small bypass ratio. The bypass ratio is selected in the range of 0.1-0.9. As shown in Figure 5, there is an optimal mixing ratio, at which point the specific thrust reaches maximum. The mixing ratio corresponding to the best propulsion performance is independent of the bypass ratio, that is, when the mixing ratio is 0.923, engines with different bypass ratios reach the upper limit of propulsion. Similarly, as shown in Figure 6, when the mixing ratio is 0.613, the fuel consumption rate is the highest and the economy is the worst. It is also independent of the bypass ratio.
As shown in Figure 6, the mixing ratio increases, the comprehensive performance of the engine first increases and then decreases. For different bypass ratio engines, when their comprehensive performance is the highest, the corresponding mixing ratio is 1.127.

4.3. Influence of mixing cycle on engine performance with different fan pressure ratio

Under the conditions of the total pressure ratio of 26.1, the effect of fan pressure ratio on the specific thrust and fuel consumption rate is investigated for both ITM and MTC. As shown in Fig. 8-9, the specific thrust and fuel consumption rate will increase with the increase of mixing ratio respectively at first and will decrease at last. With the increase of fan pressure ratio, the upper limit of thrust of ITM decreases, and the corresponding fuel consumption rate decreases. The largest specific thrust is obtained at the appropriate mixing ratio (0.923). When the mixing ratio is 0.613, the specific fuel consumption is the largest.

Therefore, according to the requirements for propulsion performance and economic performance, an optimal mixing ratio independent of the fan pressure ratio exists. It can be seen in Fig.10 that the largest specific thrust increase is obtained at the optimal mixing ratio (1.127). When the fan pressure ratio changes from 2.0 to 5.0, the maximum value of R is decreased from 1.088 to 1.062. The comprehensive performance of ITM is improved.
5. Conclusion
Components are not added to the engine with ITM. As a result, the ITM cycle might be less difficult and easy to realize. According to existing studies, ITM cycle can effectively improve engine performance with appropriate mixing ratio.

1. ITM cycle can effectively increase the upper limit of engine thrust, which can be increased by 5% at most.
2. The mixing ratio of engines at the maximum specific thrust is 0.923; The mixing ratio with the highest fuel consumption rate is 0.613. They are independent of the bypass ratio and fan pressure ratio.
3. The mixing ratio with the best comprehensive performance is 1.127. When the mixing ratio is 1.127, R decreases with the increase of bypass ratio respectively at first and increases at last, and R decreases with the increase of fan pressure ratio.
4. When the mixing ratio is greater than 0.39, the ITM cycle can effectively improve the comprehensive performance of the engine.

As mentioned previously, guide vanes and rotor blades of turbine would be used as mixing chambers. ITM cycle is a feasible way to improve engine performance. It is worthy of further researches on the detailed assessment of the comprehensive performance of ITM using a more integrated model that can conduct the simulation of taxiing, taking off, cruising, and landing.

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