Performance Analysis of New Air Circulation System Based on Random Matrices

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Received 18 April 2022; Revised 5 May 2022; Accepted 9 May 2022; Published 20 May 2022

Academic Editor: Ning Cao

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This paper studies the aircraft air circulation system and proposes a new architecture of the aircraft air circulation system. Combined with the neural network algorithm, the numerical simulation results of turbine, compressor, and heat exchanger are fitted and predicted, and the accuracy of the simulation model is verified by comparing with the experimental results. Comparing and analyzing the booster, F-15, F-35, and the newly proposed air circulation system, the engine bleed air volume consumed by the system under different flight conditions is obtained. The results show that the newly proposed air circulation system can save up to 71.4% of the engine bleed air compared with the simple boost and 29.8% of the engine bleed air compared with the F-35. The new air circulation system proposed in this paper can effectively improve the energy utilization rate of the system and reduce the consumption of engine bleed air.

1. Introduction

Aircraft environmental control system (abbreviated as “aircraft environmental control system”) is a vital part of the aircraft to ensure the life safety and normal operation of airborne personnel and electronic equipment [1–4]. The bleed system of the aircraft air circulation control system mainly takes the engine compressor as the pressurization source [5–8]. Due to the direct influence of engine operating conditions, the temperature and pressure of engine compressor bleed air fluctuate greatly and cannot directly enter the refrigeration system. It is necessary to preset absolute pressure regulator, precooler, and other components in the bleed air system to depressurize and cool the engine bleed air, and the cooled gas is introduced into the air circulation system. Depressurization and cooling treatment lead to the waste of engine bleed energy and reduce the utilization efficiency of engine bleed energy [9–11]. In addition, absolute pressure regulator and precooler increase the weight of the aircraft environmental control system [12, 13]. The engine bleed air directly enters the air system, so that the aircraft environmental control system will be affected by the changes of engine operating conditions, and when the engine bleed air is polluted, the cabin air supply quality will be reduced. This has a great impact on the stability and reliability of the aircraft air circulation system.

The power turbine air circulation system is first used in the verification aircraft of F-15 fighter. The system performance is twice that of the original, the fuel consumption is reduced by 35%, and the reliability is improved by 30% [14, 15]. In order to achieve efficient use of energy, the U.S. advanced fighter F-35 puts forward an adaptive power and thermal management system (APTMS) [16–18]. The aircraft environmental control system further uses the engine induced air energy by using the power turbine, but the fresh air in the cockpit still needs to be obtained from the engine. This paper further optimizes the system and puts forward a new power turbine air circulation system. The system uses a centrifugal compressor driven by a power turbine to pump the ambient atmosphere and provide fresh air for the engine room and ensure stable pressure. The engine bleed air is discharged to the atmosphere from the rear of the power turbine. This improvement cancels the absolute pressure regulator, precooler, and other components, which can
make maximum use of the engine bleed energy and reduce the bleed air flow of the engine compressor, thus reducing the takeoff quality of the aircraft [19–22]. In addition, the engine compressor bleed air does not directly enter the air circulation system, which realizes the isolation between the air circulation system and the engine bleed air. The aircraft air circulation system can avoid the influence of engine bleed parameters, which further improves the stability of the system, and the fresh air supplied to the cockpit can also avoid being polluted by the engine. The research methods of the performance of the air circulation system are divided into two categories: experimental research and simulation research. This paper provides data support for the design and improvement of the air circulation system.

2. System Schemes

The schematic diagram of the boost air circulation refrigeration system is shown in Figure 1. The engine compressor provides high-temperature and high-pressure gas for the pressurization source. It fully exchanges heat with the ram air in the primary heat exchanger. After cooling, it is compressed by the compressor, cooled by the secondary heat exchanger, and then enters the turbine. After expansion and cooling, it is supplied to the cabin. The turbine and the compressor work in the same axis, speed, and flow, and the gas expands in the turbine to do work, driving the compressor to pressurize, so as to realize the recycling of energy [23–25]. The boost air cycle refrigeration system is an open system. The gas at the outlet of the refrigeration turbine absorbs the heat of the refrigerant carried by the electronic equipment and is directly discharged from the aircraft. The cooling capacity of this part of the gas is not recovered, resulting in a waste of cooling capacity. The high-pressure and high-temperature induced air of the engine compressor needs pressure regulation and cooling treatment before entering the air circulation system, which wastes a lot of energy. From the perspective of energy efficiency, the air circulation system of APTMS in F-15 validator and F-35 uses the airborne power turbine air circulation refrigeration system (Figures 2 and 3).

The framework of the air circulation system in F-15 verifier is basically the same as that in F-35, and the main difference lies in the treatment of gas at the outlet of power turbine. The former supplies air for the air circulation system from the outlet of the power turbine because the air circulation needs to ensure the stability of the cabin pressure, increase the pressure at the outlet of the power turbine, and reduce the expansion ratio. At the same time, the coupling degree of the outlet parameters of the air circulation system and the power turbine is high, and the system matching design and control is complex. In the latter, the outlet gas of the power turbine is directly discharged outside the engine to obtain a larger expansion ratio, and the air circulation air supplement is provided by the engine compressor. Therefore, the operation of the power turbine and the air circulation system is relatively independent, and the system matching and control are relatively easy to realize. However, precooler and absolute pressure regulator are still needed to cool and depressurize the engine bleed, resulting in a waste of bleed energy and increasing the system weight and compensatory loss.

By comprehensively comparing the F-15 and F-35 air circulation systems and combining the advantages of power turbine, an additional centrifugal compressor is pressurized to provide fresh air for the cabin with ram air. The system structure is shown in Figure 4. After heat exchange with the refrigerator in the electronic cabin, the air is recycled to form a closed cycle, which recovers the cooling capacity of this part of the air and increases the energy utilization efficiency. The engine bleed works through the power turbine to provide shaft work for the air circulation system, eliminating the components such as absolute pressure regulator and precooler, for efficient use of engine bleed energy. The fresh air required by the cabin is provided by the atmosphere pumped by the centrifugal compressor, which improves the comfort of the cabin. In addition, the heat load required by the aircraft will be affected by the operating state of the aircraft and atmospheric environmental parameters. The adjustable nozzle of the power turbine can be adjusted to realize the free adjustment of the air intake of the engine, which further improves the utilization rate of the system energy.

3. Simulation Model

3.1. Mathematical Model

3.1.1. Air Inlet. Inlet temperature is as follows:

\[ T_{in} = T_h \left(1 + \frac{k - 1}{2} M a^2\right). \]  

Inlet pressure is as follows:

\[ p_{in} = \sigma p_h \left(1 + \frac{k - 1}{2} M a^2\right)^{(\frac{k}{k-1})}, \]  

where \( k \) is the adiabatic index, and \( K \) corresponding to \( air = 1.4; \) \( \sigma \) is the total pressure recovery coefficient; \( Ma \) is the Mach number; and subscripts \( h \) and \( in \) denote the environment and air inlet, respectively.

3.1.2. Air-to-Air Heat Exchanger. The heat exchangers in the air circulation system are air-to-air heat exchangers, in which the primary/secondary heat exchangers are non-phase change heat exchangers, and the regenerator and condenser are phase change heat exchangers.

Primary/Secondary Heat Exchanger. The cold side flow of the primary/secondary heat exchanger is greater than or equal to the hot side flow. Efficiency of heat exchanger is as follows:

\[ \eta = \frac{T_{hi} - T_{ho}}{T_{hi} - T_{ci}}. \]  

Outlet temperature of hot side is as follows:

\[ T_{ho} = T_{hi} - \eta(T_{hi} - T_{ci}). \]
where the subscripts \( h_i, h_o, \) and \( c_i \) are the hot side inlet, outlet, and cold side inlet, respectively.

Regenerator/Condenser. In the regenerator/condenser, there is sensible heat exchange and latent heat exchange between the wet air and the wall at the same time. Therefore, the mathematical model is expressed by enthalpy, and the efficiency is defined as follows:

\[
\eta = \frac{h_{hi} - h_{ho}}{h_{hi} - h_{ci}}
\]

(5)

where \( h \) is the specific enthalpy of air. The subscripts \( h_i, h_o, \) and \( c_i \) are the hot side inlet, outlet, and cold side inlet, respectively.

3.1.3. Turbine. Turbine outlet temperature is as follows:

\[
T_o = T_i \left[ 1 - \eta_i \left(1 - \pi_t^{-0.286}\right) \right].
\]

(6)

Unit output power of turbine is as follows:

\[
\omega_i = \eta_i c_p T_i \left(1 - \pi_t^{-0.286}\right),
\]

(7)

where \( \pi_t \) and \( \eta_i \) are the expansion ratio and efficiency of turbine, respectively; \( c_p \) is constant pressure specific heat capacity; and subscripts \( i \) and \( o \) are import and export, respectively.

3.1.4. Compressor. Compressor outlet temperature is as follows:
To simplify, \( T_0 = T_i \left( 1 + \pi_c^{0.286} - \frac{1}{\eta_c} \right) \). (8)

Unit power consumption of compressor is as follows:

\[ w_c = c_p T_i \pi_c^{0.286} - \frac{1}{\eta_c}, \]  

where \( \pi_c \) and \( \eta_c \) are the expansion ratio and efficiency of turbine, respectively. Subscripts \( i \) and \( o \) are import and export, respectively.

**3.1.5. Water Separator.** It is considered that the air entering the water separator has no temperature drop, and only the pressure drop and water removal efficiency are considered.

\[ T_{sep,i} = T_{sep,o}, \] (10)

System moisture balance equation is as follows:

\[ (d_i - d_{sep}) \eta_{sep} = d_i - d_o, \] (11)

where \( \eta_{sep} \) is the efficiency of water separator. Subscripts \( i \) and \( o \) are system inlet and system outlet, respectively; the
inlet and outlet of the separator are sep, i and sep, o, respectively.

3.2. Neural Network Method. Turbine compressor assembly is an important part of the aircraft environmental control system. It can be solved theoretically through the theoretical knowledge of hydrodynamics and thermodynamics or interpolated through the performance characteristic curve obtained from the test. The calculation results of the former are quite different from those of the test. The latter does not need to consider the actual physical model and uses a method similar to “black box” for modeling; that is, it only pays attention to the relationship between temperature, pressure, and flow and ignores its internal specific structure. The flow field in turbine compressor is almost transient, and its thermal inertia is small. The influence of thermal inertia can be ignored, and it is considered that the temperature field is also transient. Therefore, most scholars use the latter method to solve the model numerically. Through each state point on the performance characteristic curve, they use the least square method or interpolation or intelligent algorithm to solve it. At the same time, there will be corresponding matching problems between turbine and compressor components. The model needs to be built through common speed, common flow, and common power.

Through the existing test data, Yu et al. [26] built a three-layer directional propagation neural network, which can simulate the performance characteristic curve of the compressor and further deduce it into the overall performance simulation of the nondesign model. Ghorbanifar and Gholamrezaei [27] studied the effects of different neural networks on predicting compressor performance. The results show that the prediction results of multilayer perceptual neural network are in good agreement with the experimental data. In this paper, BP neural network optimized by the genetic algorithm is further used to fit and predict the performance characteristic curves of turbine and compressor. The structure diagram of BP neural network is shown in Figure 5.

3.3. Model Validation. Figures 6 and 7 are the physical drawings of turbine compressor and heat exchanger, and Figure 8 is the experimental diagram of the combination of heat exchanger and turbine compressor. The steady-state performance of turbine compressor and heat exchanger can be obtained through experiments. Comparing the experimental values with the simulation results and modifying the simulation results can better simulate the performance characteristics of the air circulation system. The performance of turbine compressor and heat exchanger under different working conditions is analyzed by adjusting the inlet pressure of compressor and the inlet temperature of turbine. The simulation model for verifying the turbine, compressor, and heat exchanger mainly includes the verification of aerodynamic performance and the verification of flow characteristics. First, adjust the power of the electric furnace and the valve opening to control the inlet temperature and pressure of the centrifugal compressor. After the temperature and pressure are stable, start to record the inlet and outlet temperatures and pressures of the turbine, compressor, and heat exchanger. In the dynamic characteristic test of the heat exchanger, in order to obtain the accurate dynamic response of the heat exchanger, first adjust the corresponding bleed air temperature and pressure and run it stably for 30 minutes to ensure that the inlet and outlet temperatures of the hot and cold sides of the heat exchanger are stable and then adjust the bleed air. The temperature and pressure of the system are recorded, and the inlet and outlet temperatures of the hot and cold sides of the heat exchanger are recorded.
It can be seen from the results in Tables 1–3 that the simulation model is adopted in this paper, and the calculation results are close to the experimental values, which verifies the reliability of the simulation model and provides support for the modeling and simulation of the subsequent air circulation system.

### 4. Results and Discussion

Based on the flight data in hot weather, the air intake of engine compressor at different flight altitudes is calculated in this paper. The fresh air required for the cockpit is set at 800 kg/h and the heat load is 5 kW. The circulating flow of the electronic cabin is 4320 kg/h, and the heat load is 40 kW.

Keep the flight speed and ground ambient temperature unchanged, increase the flight altitude from 0 km to 8 km, and the air intake of the engine required by the booster air circulation system is constant, which is not affected by the external environment. For the other three air circulation systems, the air intake of the engine decreases with the increase in height, as shown in Figure 9. This is because as the altitude increases and the aircraft Mach number remains unchanged, the temperature of the ram air gradually decreases, and the outlet temperature of the hot side of the secondary heat exchanger also decreases synchronously, so that the expansion ratio required to ensure the constant outlet temperature of the refrigeration turbine decreases, and the shaft work of the power turbine also decreases. Compared with the APTMS air circulation system, the

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**Table 1: Comparison between turbine experimental results and simulation.**

<table>
<thead>
<tr>
<th>Inlet pressure (kPa)</th>
<th>Inlet temperature (K)</th>
<th>Expansion ratio</th>
<th>Adiabatic efficiency</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulation</td>
<td>Experimental</td>
</tr>
<tr>
<td>300</td>
<td>357</td>
<td>4.69</td>
<td>0.75</td>
<td>0.72</td>
</tr>
<tr>
<td>300</td>
<td>312</td>
<td>5.52</td>
<td>0.79</td>
<td>0.75</td>
</tr>
<tr>
<td>410</td>
<td>315</td>
<td>5.27</td>
<td>0.75</td>
<td>0.73</td>
</tr>
<tr>
<td>520</td>
<td>315</td>
<td>6.36</td>
<td>0.84</td>
<td>0.81</td>
</tr>
</tbody>
</table>

**Table 2: Comparison between experimental results and simulation of compressor.**

<table>
<thead>
<tr>
<th>Inlet pressure (kPa)</th>
<th>Inlet temperature (K)</th>
<th>Pressure ratio</th>
<th>Adiabatic efficiency</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulation</td>
<td>Experimental</td>
</tr>
<tr>
<td>138</td>
<td>304</td>
<td>1.11</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td>226</td>
<td>302</td>
<td>1.48</td>
<td>0.75</td>
<td>0.72</td>
</tr>
<tr>
<td>293</td>
<td>293</td>
<td>1.55</td>
<td>0.77</td>
<td>0.75</td>
</tr>
<tr>
<td>324</td>
<td>288</td>
<td>1.71</td>
<td>0.81</td>
<td>0.78</td>
</tr>
</tbody>
</table>

Figure 8: Experimental diagram of turbine compressor and heat exchanger.
four-wheel power turbine air circulation system saves 21.8% of engine bleed at 0 km and 51.4% of engine bleed at 8 km. The saved engine bleed flow is realized by eliminating the absolute pressure regulator and precooler and making full use of the engine bleed energy. Compared with the three-wheel air circulation system driven by the power turbine, the four-wheel power turbine air circulation system has 3% more air intake of the engine at 0 km, 7.8% less air intake of the engine at 4 km, and 9.2% more air intake of the engine at 8 km. The cabin air replenishment of the three-wheel air circulation system driven by the power turbine is obtained from the outlet of the power turbine. Under the ground condition, the cabin pressure is close to the ambient pressure and does not affect the expansion ratio of the power turbine. The work required by the air circulation system is similar to that of the four-wheel air circulation system driven by the power turbine. At 4 km, the cabin pressure is higher than the ambient pressure, which makes the power turbine unable to expand fully and wastes part of energy, making the induced air volume slightly higher than that of the four-wheel air circulation system. At 8 km, the expansion ratio of the power turbine is greater than 10, and the efficiency is already very high. If the expansion ratio of the turbine is increased, the efficiency will decline. The engine bleed air has been fully expanded and can no longer provide more shaft work. Therefore, the air intake of the four-wheel power turbine air circulation system is basically the same as that of the three-wheel power turbine air circulation system.

Keep the flight altitude unchanged, and the aircraft speed changes from 0.3 Ma to 1.1 Ma. The variation trend of engine air intake of the four air circulation systems is shown in Figure 10. When the aircraft altitude remains unchanged, the increase in flight Mach number makes the phenomenon of aerodynamic heating more serious, and the recovery temperature of ram air in cold air duct increases synchronously. In order to keep the cabin air supply temperature unchanged, a higher expansion ratio is required when the turbine inlet temperature increases, which requires more engine air intake. Compared with the F-35 environmental control system, the four-wheel air circulation system saves 28.6% of engine bleed at 0.3 Ma and 22.4% of engine bleed at 1.1 Ma. Compared with the three-wheel power turbine air circulation system, the engine bleed is saved by 6.7% at 0.3 Ma and 23.52% at 1.1 Ma.

Keep the flight state unchanged, and the ambient temperature increases from the standard weather to hot weather conditions. The variation trend of engine air intake of the four aircraft air circulation systems looks like Figure 11. The increase in ambient temperature also increases the recovery...
In order to meet the heat load of cockpit and electronic cabin, more power turbine shaft work is required. Compared with the APTMS environmental control system, the four-wheel air circulation system saves 58.1% of engine air bleed in standard days and 43.6% in hot days. Compared with the three-wheel power turbine air circulation system, the air intake of the engine changes very little.

With the increase in flight speed, the ram air recovery temperature will gradually increase. In order to ensure the constant outlet temperature of refrigeration turbine, it is necessary to increase the compressor pressure ratio (as shown in Figure 12). The pressure ratio of the three-wheel air circulation system driven by the power turbine increases the fastest because the inlet gas of the compressor of the system is obtained behind the precooler, and the gas temperature also increases with the increase in flight speed, which makes the turbine inlet temperature higher at the same pressure ratio, so the compressor pressure ratio of the system increases the fastest. The pressure ratio of the four-wheel system driven by the power turbine increases slowly because when the flight speed increases, the recovery pressure of the atmospheric environment also increases synchronously, reducing the temperature rise of the fresh air after passing...
through the compressor. At 1.1 Ma, the pressure ratio of the power turbine driven four-wheel air circulation system is 32.2% lower than that of the power turbine driven three-wheel air circulation system. Therefore, the four-wheel air circulation system driven by power turbine has better performance at high Mach speed.

The compressor with a pressure ratio of more than 5 belongs to the compressor with high-pressure ratio. The design of the compressor with high-pressure ratio is difficult, and the efficiency is low. When the Mach number is high, the fuel heat sink should be introduced to take away more heat, reduce the compressor pressure ratio to the range of design working conditions, and make the system operate in a more efficient state.

The fuel oil heat exchanger can achieve good results in high Mach flight because in low Mach flight, the cold air duct temperature is low and the air temperature and fuel temperature difference entering the fuel oil heat exchanger are small, so it cannot take away more heat and better consumption. For example, the air temperature entering the fuel oil heat exchanger at 0.5 Ma is 47°C, and the fuel oil heat exchanger cannot take away more heat. When the air temperature entering the fuel oil heat exchanger at 1.3 Ma is 145°C, the fuel oil heat exchanger can play a good effect (Figure 13), take away a lot of heat, and reduce the compressor pressure ratio and engine air intake. When the fuel heat sink is 50 kW, the compressor pressure ratio can be reduced by 31.6%, and the engine bleed can be reduced by 35.5%.

5. Conclusion

Based on the air circulation system of F-15, APTMS, a new type power turbine air circulation system, namely, four-wheel power turbine air circulation system driven, is further optimized and improved in this paper. The accuracy of the numerical model is illustrated by the comparison between numerical simulation and experimental results. Based on numerical simulation, the performance characteristics of the proposed new air circulation system architecture are studied and analyzed and compared with the existing air circulation system. The main advantages of the proposed new system are as follows:

1. The centrifugal compressor driven by the power turbine sucks the ambient atmosphere to provide fresh air for the cabin, realizes the isolation between the air circulation system and the engine bleed, and improves the stability of the air circulation system and the cleanliness of the cabin air.

2. Compared with the APTMS air circulation system, the four-wheel semiclosed air circulation system proposed in this paper can save engine bleed air by 58.1%.

3. Under the condition of high Mach number flight, the four-wheel air circulation system proposed in this paper has better performance. The pressure ratio of the four-wheel air circulation system is 32.2% lower than that of the three-wheel air circulation system, and the engine bleed is saved by 43.3%.

Compared with the traditional air circulation system, the four-wheel air circulation system driven by power turbine proposed in this paper greatly improves the utilization efficiency of aircraft energy and can provide a reference for the design of the aircraft environmental control system in the future.

Data Availability

The dataset used in this paper is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding this work.

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