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Fluid Dynamics Advances in Turbojet Engines: From Fundamental Mechanisms to Engineering Applications

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Abstract. Turbojet engines are the core power source of modern aerospace vehicles, and their performance is directly determined by internal fluid dynamics. With the increasing demand for high thrust-to-weight ratio and low fuel consumption, the fluid flow mechanism in turbojet engines has become a research hotspot. This paper systematically reviews the latest advances in fluid dynamics of turbojet engines from two dimensions: fundamental flow mechanisms and engineering application technologies. It summarizes the research progress of numerical simulation, experimental measurement and theoretical analysis in recent 10 years. The analysis shows that the development of high-precision turbulence models, the optimization of compressor/turbine blade flow channels, and the control of combustion chamber flow instability have significantly improved the efficiency and reliability of turbojet engines. The application of active flow control technology and additive manufacturing has brought new breakthroughs in engine fluid design. Finally, the key challenges and future development directions of turbojet engine fluid dynamics are prospected, including multi-physics coupling flow simulation, digital twin flow field optimization, and green energy-efficient flow design. This review provides a theoretical reference for the performance improvement and innovative design of next-generation turbojet engines.

Keywords: turbojet engine, fluid dynamics, flow mechanism, engineering application

1. Introduction

Aerospace technology is a key symbol of national comprehensive strength, and turbojet engines, as the "heart" of aircraft, directly determine the flight performance, range and safety of aerospace vehicles. With the rapid development of supersonic cruise, long-endurance flight and reusable aerospace vehicles, the performance requirements of turbojet engines are constantly improving, and higher requirements are put forward for the internal fluid flow control.

In the past decades, scholars have carried out a lot of research on the fluid dynamics of turbojet engines, and achieved important progress in compressor flow separation control, turbine cooling flow optimization, and combustion chamber flow organization. However, with the increase of engine pressure ratio and temperature, the complex flow phenomena such as high Reynolds number, strong shear, multi-phase flow and flow instability in the engine have not been fully revealed, and there are still many theoretical and technical bottlenecks.

Thrust formula of turbojet engine:

$$F=\dot{m}(V_j-V_0)+(P_j-P_0)A_j \tag{1}$$

where F refers to the thrust (Newtons, N), $\dot{m}$ refers to the mass flow rate (kilograms per second, kg/s), V_j refers to the jet velocity at the nozzle exit (meters per second, m/s), V_0 refers to the free-stream velocity (meters per second, m/s), P_j refers to the static pressure at the nozzle exit (Pascals, Pa), P_0 refers to the ambient static pressure (Pascals, Pa), and A_j refers to the nozzle exit area (square meters, m^2).

The in-depth study of the fluid dynamics mechanism of turbojet engines is of great significance for improving engine efficiency, reducing fuel consumption, extending service life and reducing emission pollution. It can not only promote the theoretical development of aerospace fluid mechanics, but also provide core technical support for the independent research and development of high-performance aero-engines in China, and help the development of aerospace industry.

This paper focuses on the fluid dynamics advances in turbojet engines, systematically combs the fundamental flow mechanisms in key components (compressor, combustion chamber, turbine) and the latest engineering application technologies, and analyzes the research status, key problems and development trends in this field.

This review adopts the method of literature induction and comparative analysis, collects and sorts out more than 30 high-level international conference papers and journal articles in the past 10 years, and summarizes the research progress and technical achievements in the field of turbojet engine fluid dynamics. Near ten years, the development of high-precision turbulence models and computational fluid dynamics (CFD) technology has provided a powerful tool for in-depth revealing the complex internal flow mechanism of engines. Meanwhile, the application of advanced experimental measurement technologies such as particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) has provided reliable experimental data for verifying numerical simulation results and quantifying flow losses [1].

The goal of this paper is to provide a comprehensive reference for researchers in the field of aero-engine fluid dynamics, and point out the future research direction. The structure of the paper is arranged as follows:

2. Fundamental fluid dynamics mechanisms in turbojet engines

2.1. Flow characteristics in compressor

The compressor is the core component of the turbojet engine, which is responsible for compressing the incoming air to increase the pressure ratio. The internal flow is a complex three-dimensional viscous flow with high Reynolds number, strong rotation and large pressure gradient, which is prone to flow separation, surge and stall.

The boundary layer separation on the blade surface is the main cause of compressor performance degradation. Typical flow structures inside a compressor blade is shown in Figure 1. Boundary layer separation on blade surfaces is the primary cause of compressor performance degradation. When separation develops to a certain extent, it will trigger rotating stall and surge, leading to sudden engine thrust loss or even structural damage [2]. Scholars have carried out a lot of research on the mechanism of boundary layer separation and stall inception.

With the development of high-load compressors, the flow separation phenomenon becomes more serious. In recent years, the research on the flow mechanism of high-load compressors has focused on the interaction between tip leakage flow and main flow, and the control of flow separation in transonic compressors [3].

Compressor efficiency is the core index to measure its energy conversion efficiency, and its isentropic efficiency is defined as follows [4]:

Compressor efficiency formula:

$$F=\dot{m}(V_j-V_0)+(P_j-P_0)A_j \tag{1}$$

$$\eta_c=\frac{h_2s-h_1}{h_2-h_1} \tag{2}$$

where η_c refers to the compressor isentropic efficiency (dimensionless), h_1 refers to the inlet specific enthalpy (kilojoules per kilogram, kJ/kg), h_2s refers to the isentropic outlet specific enthalpy (kilojoules per kilogram, kJ/kg), and h_2 refers to the actual outlet specific enthalpy (kilojoules per kilogram, kJ/kg).

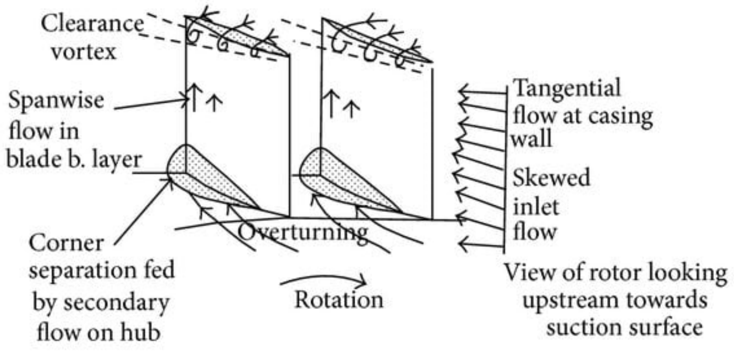

Figure 1. Typical flow structures inside a compressor blade

2.2. Flow dynamics in combustion chamber

As the structure of a combustion chamber shown in Figure 2, the combustion chamber is the component where fuel and air are mixed and burned, and its flow organization directly determines the combustion efficiency, emission level and flame stability. The internal flow is a complex multi-phase, multi-component, high-temperature reactive flow, involving fuel atomization, mixing, ignition, combustion and other processes [5].

The flow instability in the combustion chamber, such as thermoacoustic oscillation, will cause structural vibration and damage, which is a key problem restricting the performance of the combustion chamber [6]. In addition, the mixing characteristics of fuel and air directly affect the combustion efficiency and emission. Scholars have carried out in-depth research on the flow organization and instability control of the combustion chamber. The swirl structure can form a low-speed recirculation zone in the center of the combustion chamber, providing a stable ignition source for the flame, which is the most widely used flame stabilization technology at present [7].

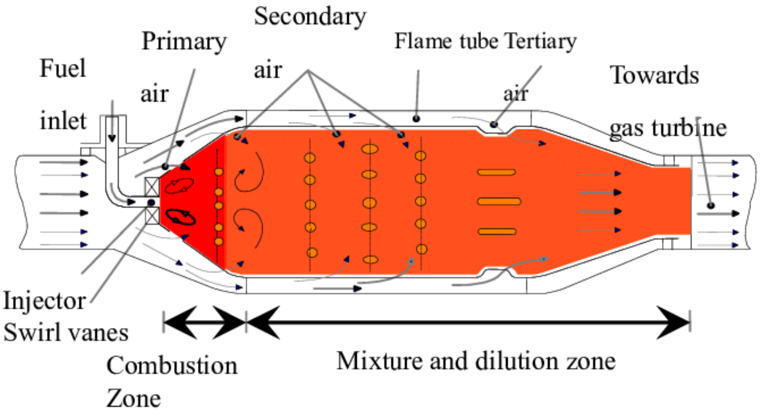

Figure 2. Schematic diagram of a continuous combustion chamber

2.3. Flow mechanisms in turbine

The turbine is the component that converts the high-temperature and high-pressure gas energy into mechanical energy to drive the compressor and accessories. The internal flow is a high-temperature, high-pressure, high-speed viscous flow with strong shock wave-boundary layer interaction and film cooling flow.

In the transonic turbine, the shock wave generated by the blade will interact with the boundary layer, causing flow separation and loss, which reduces the turbine efficiency [8]. In addition, the film cooling flow on the blade surface will interact with the main flow, affecting the cooling effect and flow loss [9].

With the increase of turbine inlet temperature, the research on turbine flow mechanism focuses on the optimization of film cooling flow structure, the control of shock wave-boundary layer interaction, and the flow loss reduction of high-load turbines.

Turbine efficiency reflects its ability to convert gas energy into mechanical work, and its isentropic efficiency is defined as follows [4]:

Turbine efficiency formula:

$$\eta_t = \frac{h_3 - h_4}{h_3 - h_{4s}} \tag{3}$$

where η_t refers to the turbine efficiency (dimensionless), h_3 refers to the specific enthalpy at the turbine inlet (kilojoules per kilogram, kJ/kg), h_4 refers to the actual specific enthalpy at the turbine outlet (kilojoules per kilogram, kJ/kg), and h_{4s} refers to the specific enthalpy at the turbine outlet under an isentropic process (kilojoules per kilogram, kJ/kg).

3. Engineering applications of fluid dynamics in turbojet engines

3.1. Flow control technology for compressor

Active flow control technology is an important means to improve compressor performance and expand stable working range. Common active flow control technologies include plasma actuation, synthetic jet, boundary layer suction, etc., which can effectively suppress flow separation and prevent surge and stall [10].

Plasma actuation technology has been widely studied in compressor flow control. It can generate body force in the boundary layer to suppress flow separation, improve compressor efficiency by 1%-3%, and expand the stable working range by more than 10% [11]. Synthetic jet technology also has a good effect on controlling tip leakage flow and flow separation.

At present, the main challenges of active flow control technology in engineering application are the reliability of actuators, the integration of control systems and the influence on engine weight. In the future, the development of intelligent flow control technology based on machine learning will become an important direction.

3.2. Combustion chamber flow organization and optimization

The flow organization technology of the combustion chamber is the core to improve combustion efficiency and reduce emissions. Common technologies include staged combustion, lean burn, swirl flow stabilization, etc., which can optimize the fuel-air mixing and flame stability. By optimizing the angle and number of swirl vanes, the fuel-air mixing characteristics can be improved, and the flame stability under low working conditions can be enhanced [7].

In recent years, the lean burn staged combustion technology has become the mainstream of low-emission combustion chamber design. By optimizing the swirl flow structure and fuel injection mode, the fuel-air mixing is more uniform, the combustion temperature is reduced, and NOx emissions are reduced by more than 50% [12].

The key challenge of lean burn technology is the stability of flame under low working conditions. In the future, the flow organization technology of the combustion chamber will develop towards intelligent optimization based on numerical simulation and digital twin, to achieve high efficiency and low emission combustion.

3.3. Turbine cooling flow optimization and additive manufacturing

The internal cooling structure of traditional turbine blades (shown in Figure 3) has the problem of energy loss, resulting in low efficiency. Turbine cooling flow optimization is the key to improve turbine inlet temperature and engine performance. Common cooling technologies include film cooling, impingement cooling, ribbed channel cooling, etc., which can effectively reduce the blade temperature and improve the service life [9]. The shape, arrangement and blowing ratio of film cooling holes are the key parameters affecting film cooling efficiency. By optimizing these parameters, the cooling effect can be improved while reducing the amount of cooling air [13].

Additive manufacturing technology has brought new breakthroughs in turbine cooling flow design. It can manufacture complex cooling channel structures, such as lattice cooling, which can improve the cooling effect by 20%-30% compared with traditional structures, and reduce the flow loss [14].

At present, the main challenges of additive manufacturing cooling structures are the surface roughness and flow loss. In the future, the research will focus on the optimization of cooling structure, the control of surface roughness and the multi-physics coupling design of cooling flow.

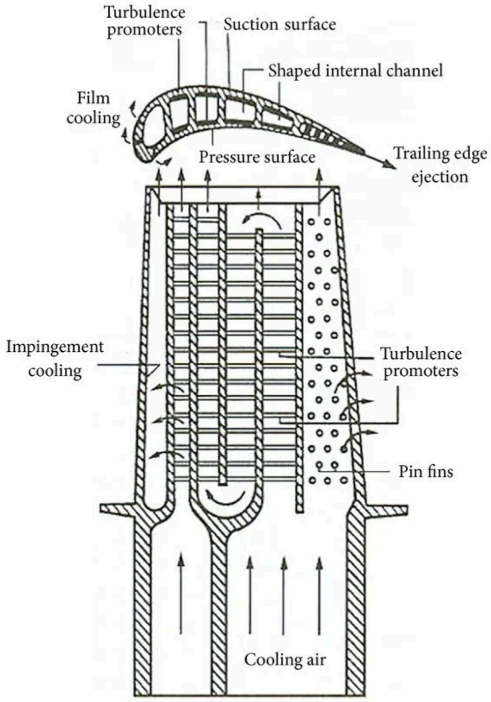

Figure 3. Typical internal cooling arrangement for a multipass turbine blade

4. Conclusion

This paper systematically reviews the advances in fluid dynamics of turbojet engines from fundamental mechanisms to engineering applications. The analysis shows that the in-depth study of complex flow mechanisms in key components (compressor, combustion chamber, turbine) is the basis for improving engine performance, and the application of active flow control, additive manufacturing and other technologies has brought significant performance improvements.

The key factors affecting the performance of turbojet engines are the control of flow separation, the optimization of flow organization and the reduction of flow loss. The development of high-precision numerical simulation and experimental measurement technology has promoted the in-depth understanding of the internal flow mechanism of engines.

This review fills the gap in the systematic summary of turbojet engine fluid dynamics in recent years, provides a comprehensive reference for researchers in the field of aero-engines, and has important guiding significance for the independent research and development of high-performance aero-engines.

In the future, the research on turbojet engine fluid dynamics will focus on multi-physics coupling flow simulation, digital twin flow field optimization, green energy-efficient flow design and intelligent flow control technology, to achieve higher efficiency, lower emissions and higher reliability of turbojet engines.

References

[1] Arts, T., & Lambert, D. (2015). Experimental methods for turbomachinery fluid dynamics. Experimental Thermal and Fluid Science, 66, 1–18.

[2] Hah, C. (2016). Flow physics and control of compressor stall and surge. Progress in Aerospace Sciences, 83, 1–27.

[3] Greitzer, E. M., & Moore, F. K. (2006). A theory of post-stall transients in axial flow compressors. Journal of Fluids Engineering, 128(2), 283–294.
[4] Horlock, J. H. (2008). Axial Flow Turbines: Fluid Mechanics and Design. Cambridge University Press.
[5] McDonell, V. G., Samuelsen, G. S., & Lee, S. (2017). Fuel–air mixing in gas turbine combustors. Combustion and Flame, 182, 112–125.
[6] Lieuwen, T. C. (2012). Combustion instabilities in gas turbine engines. Cambridge University Press.
[7] Liu, Y., & Dowling, A. P. (2025). Research progress on thermoacoustic instability in gas combustion. Journal of Engineering for Gas Turbines and Power, 147(3), 031001.
[8] Schulz, H. D., & Fottner, L. (2011). Shock wave–boundary layer interaction in transonic turbines. Journal of Fluids Engineering, 133(7), 071102.
[9] Bunker, R. S. (2019). Gas turbine blade cooling: A review. ASME Journal of Turbomachinery, 141(1), 011002.
[10] Xu, H., & Zhang, W. (2024). Flow control, active and passive applications. In Encyclopedia of Aerospace Engineering (pp. 1123-1142). Springer.
[11] Wang, X., Li, Y., Zhang, H., & Liu, Z. (2020). Plasma actuation for compressor boundary layer separation control. Aerospace Science and Technology, 106, 106128.
[12] Richards, G. M., & Straub, D. L. (2018). Lean burn combustion for low-emission gas turbines. Journal of Engineering for Gas Turbines and Power, 140(1), 011506.
[13] Raugh, A. C., & Lynch, S. P. (2021). Film cooling effectiveness on high-pressure turbine blades. International Journal of Heat and Mass Transfer, 179, 121668.
[14] Mizukoshi, H., Tanaka, K., & Sato, T. (2022). Additive manufacturing for turbine cooling structures. Additive Manufacturing, 58, 103068.