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Research Paper

Experimental investigation on the overall cooling effectiveness of t-type impinging-film cooling

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HIGHLIGHTS

- The streamlined inducting slab shows a good cooling effect.
- The effects of flow and geometry parameters on cooling performance were obtained.
- The empirical correlations of overall cooling effectiveness were summed up.

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ABSTRACT

This paper presents an experimental investigation of impinging-film cooling concerning the effects of various factors on overall cooling effectiveness η. The factors include blowing ratio M ($0.31 \le M \le 1.84$), non-dimensional jet-to-plate pitch Zn/d ($1 \le Zn/d \le 2$), non-dimensional spacing of jet holes Yn/d ($1.6 \le Yn/d \le 2.4$) and diameter of jet hole. The results show that overall cooling effectiveness invariably increases with a raise in blowing ratio. As non-dimensional jet-to-plate pitch increases, the cooling performs better. The decline of non-dimensional spacing of jet holes improves the overall cooling effectiveness at higher blowing ratios ($M \ge 0.91$), which was not observed in cases with low blowing ratios ($M \le 0.61$). The variation of hole diameter (1.0–1.8 mm) has little influence on cooling performance.

1. Introduction

With the development of modern aero-engine, temperature rise of combustor is improving continuously for high performance, which requires the augment of air for combustion. In addition, more air is demanded in combustion for low emission of NO_x to meet stricter legislation requirements. Hence, the accessible amount of cooling air for protecting engine components declines. Besides, the cooling capability of combustor inlet air drops due to higher total pressure ratio of compressor which increases the temperature of the air. Therefore, it is critical to develop advanced cooling method for combustor cooling with limited coolant amount and cooling capability (see Lefebvre [1]).

In aero- engines, the combustor liner is usually cooled with bleed air from the compressor. Holes and slots are fabricated in the liner in order to inject cool air into combustor to form a cold film protecting liner from hot gases, which is known as film cooling. However, it is usually found that there exist hot spots in the liner cooled by discrete jets only because of the non-uniform distribution of velocity between jets, which results in thermal fatigue and thermal barrier coating damage. Slot film may solve this problem. Nevertheless, full-coverage slot in liner is not feasible considering structural strength, thermal stress and fabrication of combustor components. Impinging-film cooling is a combination of holes and slots, as shown in Fig. 1. Coolant from jet holes impinges against the inducting slab, merging in the inducting cavity, forming a uniform film at the exit owing to pre-mix of jets in slots. Impinging-film cooling shows an excellent cooling performance and widely used in aero-engine combustor. It usually has two different frameworks according to installation method (see Fig. 1). T-type layout has a simple structure which is easy to be installed. However, it disturbs the mainstream. The mixing at the exit of inducting channel between hot gas and coolant decreases the cooling efficiency. In contrast, f-type layout has a smaller mixing owing to the uniform velocity distributions of the mainstream, which is good for cooling effect. However, this layout requires

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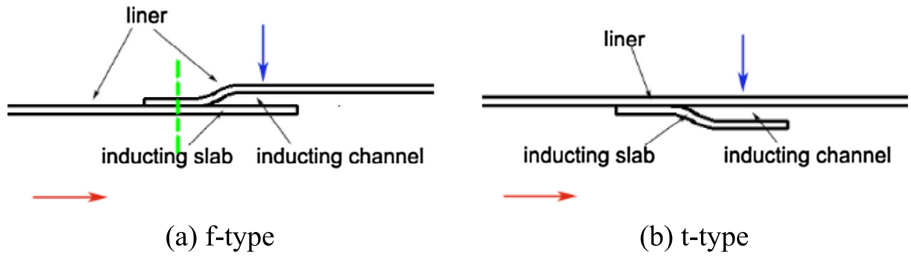

Fig. 1. The layout of impinging-film cooling.

synchronous design with combustor liner. This layout has been used in combustor liner of AL-31F engine, as shown in Fig. 2.

For impinging-film cooling, the distribution of wall temperature is determined to great extent by the mixing characteristic between coolant and hot gas. A velocity distribution of ideal two-dimensional film in the initial stage is presented in Fig. 3. It can be divided in to three regions, boundary layer, potential core and shear layer. The boundary layer and potential core act as cool barrier between liner and hot gas, the shear layer is the mixing region between coolant and hot gas. Practical film structure is greatly different from idea two-dimensional film owing to turbulence density, surface roughness and so on, which complicate mechanism of flow and heat transfer. A heat transfer schematic of impinging-film cooling scheme is showed in Fig. 4. Substantially, there exit five aspects of heat transfer including radiation and convection from hot combustion gases which heat the liner, conduction in the internal liner, convection by the cooling air and radiation to the outer casing which cools the liner. The relative magnitudes of the radiation and convection components depend on the flow filed, gas temperature, gas composition, particle concentration and other operating conditions of the system.

Ballal and Lefebvre [2] presented an expression of adiabatic film effectiveness in different blowing ratios and locations for slot film. Sturgess et al. [3,4] gave a dimensionless grouping of internal geometric parameters for slot film cooling. Experimental investigation was made for influences of the grouping number on adiabatic film effectiveness. The results show that cooling performance requires a low value of this grouping. Bunker et al. [5] conducted the experiments about adiabatic film effectiveness for different film cooling geometries. The holes-in-slot geometries show an insensitivity of cooling effectiveness to blowing rate and no film blow-off at high blowing rate. Mongia et al. [6–8] investigated the effects of coolant injection angle, shape of slot lip, shape of slot exit, thickness of slot lip, thickness of thermal barrier coating, taper angle of starting edge of thermal barrier coating and shape of the nugget overhang on adiabatic cooling efficiency by performing a CFD design of experiments. In addition, they gave an overview on the use of several complex multi-swirler devices in gas turbine combustion and

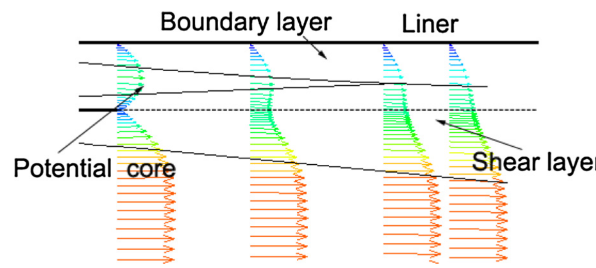

Fig. 3. Velocity distribution of ideal two-dimensional film.

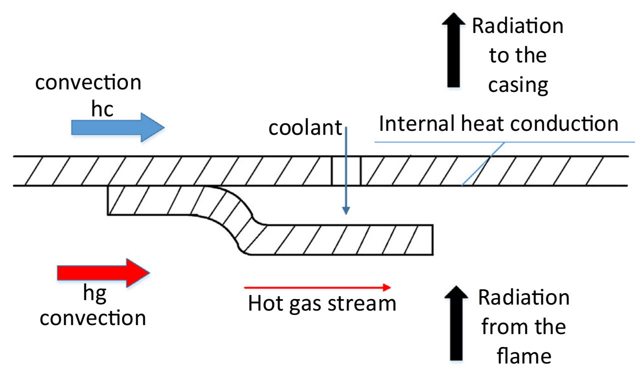

Fig. 4. Heat transfer model of combustor liner.

investigated impinging-film cooling scheme in an annular combustor liner which is showed in Fig. 5 (numbers in picture represent the percentage of coolant). Park et al. [9] investigated the change of the first slot angle under recirculation flow and the influence of wiggle strip on slot film cooling experimentally. They found

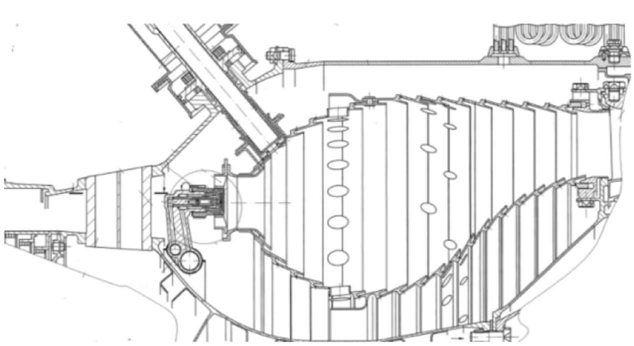

Fig. 2. Combustor of AL-31F.

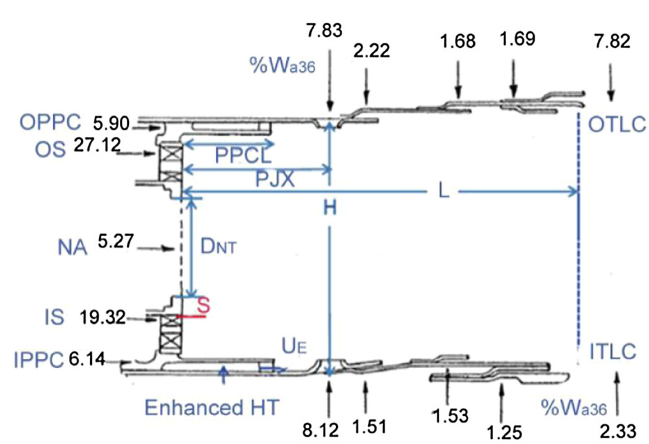

Fig. 5. Impinging-film structure on combustor liner (from Mongia et al. [4]).