Film-Cooling Techniques at the End of Combustor and Inlet of Turbine in a Gas Turbine Engine: A Review

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Abstract. This study was done to extend database knowledge about the film cooling holes function at the end of combustor and inlet of turbine. Using the well-known Brayton cycle, rising the turbine inlet temperature, is the key to get higher engine efficiency in gas turbine engines. But the high temperature of the combustor exit flow causes non-uniformities. These non-uniformities lead to a reduction in the expected life of critical components. Therefore a cooling technique should be designed to protect these parts. Film cooling is one of the most effective external cooling methods. In this system, a low temperature thin boundary layer such as buffer zone is formed and attached on the protected surface. In this study, a literature survey was done on the limited surveys.

Introduction

As stated by previous researchers [1-5], the famous Brayton cycle is a key to achieve higher gas turbine engine efficiency and power to weight ratio. To increase the efficiency, this thermodynamic cycle expressed that the combustor outlet temperature should increase. However, the operating temperature is such above that all materials cannot resist against this value of temperature and melted. Also, turbine inlet temperature increase prepared harsh environment downstream the combustor (Figure 1). Such condition can destroy the critical components. Therefore, a cooling technique must be applied to prevent the thermal degradation of turbine components. Film cooling is the most well-known method of preservation. In this system, a low temperature thin boundary layer is formed and attached on the protected surface.

Fig. 1: Schematic of annular combustor and the turbine first vane damage

Traditional Cooling Holes. Traditional cooling hole is the simplest form of cooling holes. In this type of cooling holes, the coolant runs through the holes and spread into the main flow with no change. Also, the coolant was injected in the stream wise direction at an angle of α degree from the horizontal surface.

The film cooling effectiveness of three different multihole schemes was determined by the researchers [6-8]. In this test study, they considered the effects of row spacing, span wise hole pitch and hole inclination angle. The findings indicated that the optimum cooling is attained by using a combination of different hole schemes. They showed that the higher downstream film cooling effectiveness is achieved by selecting short distance between neighboring jets in the span wise direction.
Many researchers [9-11] studied the effects of different hole injection angles. They considered different stream wise injection angles of cooling holes. The results declared that more cooling effectiveness is achieved at shallow hole angles, especially at higher blowing ratios compared to baseline case. But these findings rejected the Shin et al. [12] outcomes. They showed that increasing the tangential angle do not necessarily provide improvement in the film cooling performance. Also, this is rejected last findings (some may be found in [13,14]). They indicated that short holes don’t have sufficient length for mixing out the injected flow.

**Trenched Cooling Holes.** Another type of cooling holes is the trenched case. At the end of this hole, the area is expanded and as a result the coolant is suddenly spread before exiting the cooling hole and entering the main flow. These restructure lead to higher adiabatic effectiveness, especially at elevated blowing ratios [15]. Although, for the baseline holes, the coolant injected further, thereby rendering much of the coolant ineffective.

The effects of modified cooling flow direction at the vane-end wall interface were studied by former studies [16-17] under overall cooling effectiveness of $\phi=0.6$ as determined by Maikell et al. [18]. These studies was done with three individual and row trench depths of $h=0.4D$, $h=0.8D$ and $h=1.2D$. As expected, the row trench effectiveness was significantly higher than individual trench. The maximum cooling effectiveness is obtained at the trench depth of $0.80D$. However, using the trench depth of $0.8D$ has negative effect on the cooling performance downstream the cooling hole and increases this effectiveness inside a trenched hole.

**Shaped Cooling Holes.** Another category of these holes is the shaped cooling holes. In this type, the section area of the cooling hole is changed through the hole. Although, the inlet section area is circular, the exit section is changed to a specific shape such as fan-shaped, diffused-shaped and etc.

By measuring the concentrating secondary flow variations at different blowing ratios, researchers [19-21] experimentally investigated the effects of end wall fan-shaped and cylindrical cooling holes arrangements on the aerodynamic and heat transfer performance. With fan-shaped holes, the highest film cooling effectiveness is achieved due to the injection of massive flow at smaller momentum flux ratio. Also, the results indicated that the amount of total pressure loss is much lesser with fan shaped holes using compared to cylindrical case.

By using the new turbulent model, Zhang and Hassan [22] studied the effects of jet-in-cross flow of new scheme on the cooling performance. They find out that with new scheme, the heat transfer coefficient reduced near the centerline of the shaped holes in comparison with the cylindrical case and as a result film cooling effectiveness is higher for the shaped cooling holes compared to the baseline case (Gao et al. [23]; Colban et al. [24]). In addition, the last researchers [25,26] showed that for the shaped holes, a better thermal protection capability is achieved, especially at higher blowing ratios.

**Compound Cooling Holes.** In the traditional cooling hole, the flow runs within a cooling hole and injected in the stream wise direction with an angle of $\alpha$ degree from the horizontal surface. But in the compound hole, the flow spread in the span wise direction at an angle of $\beta$ degree as well.

Aga and Abhari [27], Jubran et al. [28], Lee et al. [29], investigated the effects of lateral angle, blowing ratio and density ratio on the blade leading edge film cooling. The major finding from this study declared that at high compound angles of 60 degree and 90 degree, averaged adiabatic film cooling effectiveness is two times more than stream wise injection especially at high blowing ratios. In addition, increasing compound angles enhanced the jet free stream interaction and as a result raised normalized heat transfer coefficient.

The researchers [31,33] took computational results of flow behavior in different parts of a stationary gas turbine vane at blowing ratio of 1.50 and compound holes application at the leading edge by using LES model. The results declared that a suitable arrangement of compound angle holes made a condition to have the best cooling in both pressure and suction sides of turbine vane. On the
pressure surface, central part of vortex is away from blade wall and in addition, the area influence of vortex is noticeable as well.

**Trenched Shaped, Compound Shaped and Compound Trenched Shaped Cooling Holes.** The trenched shaped, compound shaped and compound trenched shaped cooling holes are constructed from a combination of both trench, shaped and compound geometries of holes. In fact, whereas, the section area of hole is varied from inlet to the exit, the flow can spread at the end of the hole for the trenched cases and injected along both stream and span wise directions for the compound configurations.

Baheri Islami et al. [34,35] studied the effects of cylindrical hole, forward diffused shaped hole, trenched forward diffused shaped hole, conically flared shaped hole, trenched conically flared shaped hole, laterally diffused shaped hole and trenched laterally diffused shaped hole on the film cooling effectiveness at the leading edge of turbine blade. The findings of this study indicated that trenching enhanced the span wise, centerline and laterally averaged film cooling effectiveness for all cases. However the most effective of trench using was seen for the forward diffused shaped hole.

Using the pressure sensitive paint method, researchers [36-38] studied the effects and properties of compound angle laid back fan-shaped holes on film cooling effectiveness for a high pressure turbine. Compared to compound cylindrical cooling holes, compound shaped holes provide higher film cooling performance especially for both suction and pressure sides especially at elevated blowing ratios.

Baheri Islami et al. [39] used computational fluid dynamics CFD to predict the variations of adiabatic film cooling holes with injection angle of 35 degree. The results indicated that adiabatic film cooling is influenced dramatically in the span wise and stream wise direction downstream of the injection by trenching the cooling holes. However, the highest film cooling is achieved by using the trenched compound angle injection shaped hole.

**Summary**

To have better engine performance, it is needed to increase the combustor’s outlet temperature. But such hot flows develop nonuniformities and adverse conditions can damage the critical parts downstream the combustion chamber. The most well-known kind of cooling preservation is film-cooling. However, the traditional cooling holes performance is not good at higher blowing ratios. So far, many researchers have concentrated to design new shapes of cooling holes to modify the film cooling performance. Generally speaking, the findings of these studies indicate that designing more rows of film cooling holes is more effective on film cooling performance because using more rows increases the accumulation. Also, when the distance between two adjacent holes is small, a better jet orifice cooling is achieved. Trenching cooling holes allows the injected coolant to spread before exiting the cooling holes. The studies considered the effects of width and depth of cooling holes for both the row trench and the individual trench. However, the results show that the row trench is more effective than other types. According to the findings, the narrow trench has better effect on film cooling performance. The best cooling performance is obtained at trench depth of 0.75. With shaped holes, the coolant attaches to the surface and the film cooling performance which is achieved thus is higher than with cylindrical ones. In compound angle holes, the jet’s free stream interaction increase leads to the enhancement of normalized heat transfer coefficient especially at the orientation angle of above 60 degrees.

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