Effusion Cooling In Gas Turbine Combustion Chambers - A Comprehensive Review

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Abstract. Effusion cooling technique is an advanced concept for reducing the wall temperature in combustion chamber liners and gas turbine blades by injecting cross flow secondary fluid (coolant) through an array of holes having small diameter at close spacing. From last two decades, extensive works have been done for improving the life of hot components of gas turbines by different cooling methods. This paper discusses the review of the literature related to the geometrical parameter effects and factors affecting the adiabatic effectiveness of effusion cooling.

Keywords
Effusion cooling, adiabatic effectiveness, combustion chamber liner, hole inclination angle ($\alpha$), hole shape and size.

1. Introduction
Modern gas turbines operate at very high temperatures continuously for a long operational hour. This causes excessive thermal loads on various sections of gas turbines such as combustion liners, turbine blades and nozzle guide vanes. So, different cooling technologies are being used to extend the life of these components. Insufficient cooling over the wall surface may result in local thermal crack and reduces the strength of material [1]. To enhance the life of hot components and protect the solid surfaces from high temperatures, a secondary flow is introduced into mainstream by means of holes or slots over the surface resulting in formation of “Film”. This film serves as a protection layer between high temperature gases and solid wall [2].

Many numerical and experimental investigations have been carried to study the mechanism of various cooling strategies by researchers to improve the overall cooling effectiveness ($\eta$). In this process several cooling strategies and setups are used to reduce the wall temperatures of gas turbine combustion liners, the most advanced is Film cooling, where secondary flow is made to pass by means of holes or slots over hot surface by generating a cool ‘film’ layer which acts as a thermal barrier in-between the mainstream flow and hot surface. The unpredictable behavior of the individual slots does not form a closed film cooling and lack of uniformity the effectiveness is considerably reduced. If the number of holes is considerably increased with an array of close spacing of holes, this cooling technique is known as
effusion cooling. Due to densely spaced holes the jets adjacent influence each other by forming a closed cool film without overshooting into the hot gas flow and settles close to wall surface which improves the cooling performance. Effusion cooling is an advanced concept for cooling the combustor liners and gas turbine blade. [3].

![Effusion Cooling Diagram](image1)

**Figure 1.** Main cooling techniques (a) film cooling (b) impingement cooling (c) effusion cooling (d) transpiration cooling.

The size and number of coolant holes differ between film and effusion cooling. Effusion cooling has holes down to 0.2 mm. Less amount of coolant is used in effusion cooling as it passes through small size holes which results less impulse on hot gas flow [4].

Unlike the above, transpiration cooling is fabricated with the porous material and the coolant passes through these porous walls by forming a protective layer between hot gas stream and wall [5]. Two heat exchange effects are associated in this cooling technique: convective cooling through the wall by coolant in plenum chamber and the other is by film which acts as thermal barrier in-between hot gas flow and wall. But transpiration concept suffers from two serious disadvantages. Porous materials do not have the strength to withstand the mechanical and thermal stresses required. The small pore size leads to clogging and causes overheating. Impingement cooling is a mechanism of heat transfer by means of collision of fluid molecules on to a surface. Impingement cooling is well known as a high speed velocity jet. As fluid molecules collide with higher velocity on surface better transfer of heat takes place between hot surface and secondary fluid flow. In this paper only, effusion cooling is considered to make a comparative study carried by researchers by discussing the geometrical parameters factors affecting the effusion cooling performance.

2. **Effusion cooling adiabatic effectiveness**

Effusion cooling performance is measured by parameter called adiabatic effectiveness ($\eta_{ad}$) as
\[ \eta_{\text{ad}} = \frac{T_o - T_{\text{aw}}}{T_o - T_c} \]

Where \( T_o \) is the main stream flow temperature, \( T_c \) is cold gas flow temperature, \( T_{\text{aw}} \) is temperature on adiabatic wall after film formation. Within adiabatic wall, the surface temperature exhibits the main stream temperature immediately next to surface. As a result, when effusion cooling is employed the adiabatic wall temperature \( T_{\text{aw}} \) indicates the reduction in main stream flow temperature near to wall due to injection of coolant gas through effusion holes. So, \( T_{\text{aw}} \) is assumed as the driving temperature potential for heat transfer into wall.

A high value of \( \eta_{\text{ad}} \) means the plate wall temperature is low and a low value of \( \eta_{\text{ad}} \) indicates the effusion cooling is inefficient. The parameter is independent of hot gas temperature and cold gas temperatures where the adiabatic wall temperature depends on these temperatures. In practical, the ‘wall’ refers to surface of effusion test plates which is composed of different materials having lower thermal conductivities. Therefore, the cooling performances measured on the effusion test plates are named as adiabatic effectiveness \( \eta_{\text{ad}} \).

![Schematic of effusion test plate with hole pattern](image)

Figure 2. Schematic of effusion test plate with hole pattern

where \( \alpha \) is the inclination angle to surface, \( L \) is length of the plate in x-direction, \( W \) is test plate width in z-direction, \( t \) is test plate thickness, \( \delta x \) is stream wise pitch between adjacent holes in x-direction, \( \delta z \) is span wise pitch between adjacent holes in z-direction, \( \rho_c \) and \( \rho_o \) are densities of cold and hot gases flow, and \( U_c \) and \( U_o \) are the velocities of cold and hot gases flow respectively.

3. Effusion cooling mechanism

Grootenhuis et al. [5] demonstrated the temperature distribution in the effusion wall while the coolant is made to pass through the holes when one side of it is exposed to heat. The mechanism of cooling is two-
fold: First one, some heat is withdrawn from the wall as the coolant flows through the holes and second one, the cool film layer formed by coolant over the wall surface acts a thermal barrier in-between main stream flow and surface of wall. Less amount of heat reaches over surface of the wall and is completely dependent on flow rate and specific heat.

4. Influence of geometrical parameters on effusion cooling performance

Geometrical parameters such as hole inclination angle, cooling hole diameter, shape of hole, Streamwise (\(\delta x\)) and span wise (\(\delta z\)) pitch between two adjacent holes and flow conditions such as velocity ratio (VR), blowing ratio (BR), density ratio (DR), momentum flux ratio (I), Reynolds number (\(R_e\)) etc., have strong effects on the cooling performance. Many experimental and numerical analyses had been carried to study the physics underlying the heat transfer and flow field characteristics of effusion cooled combustor liners. As per the aim of this paper it has been focused only on geometrical parameters and their effects on adiabatic effectiveness.

4.1. Effect of hole inclination angle to surface (\(\alpha\))

Effusion cooling performance is mainly due to hole inclination angle (\(\alpha\)) towards the surface. When the angle gets shallower the holes get longer leading to increase in cooling effectiveness as it increases the convective cooling inside the holes. Hu and Ji et al. [6] conducted the experimentation and compared the effusion cooling performance with inclination angles (\(\alpha\)) of 30\(^{\circ}\), 60\(^{\circ}\), 90\(^{\circ}\) for simple cylindrical holes having diameter 0.5 mm at BR=0.5

![Figure 3. Comparison of adiabatic effectiveness for different inclination angles at blowing ratio (BR) =0.5 [6]](image)

The Fig.3 reveals that there is a slight difference in adiabatic effectiveness (\(\eta_{ad}\)) between 30\(^{\circ}\) and 60\(^{\circ}\) because of more convective cooling inside the holes as shallower angles gets longer and the coolant flow remains for longer period over the hot surface.

V Vishal and J Sriram [7] numerically investigated the adiabatic effectiveness for \(\alpha= 30^{\circ}, 45^{\circ}, 60^{\circ}\) and 90\(^{\circ}\) and concluded that for \(\alpha=90^{\circ}\) the coolant injects in a perpendicular direction to hot gas flow by increasing its penetration meanwhile increases the lifting of the secondary flow jet by separating quickly from the surface. Various investigators ([8], [9]) have suggested that by decreasing hole inclination with diffuser
shaped hole results a better cooling performance as there will be less over shooting of coolant flow and side wise spread of coolant flow over surface will be increased. Andreini et al. [10] investigated both theoretical and experimental on effusion cooling performance on different perforated flat plates seeming real combustion liner of gas turbine. Seven different flat plates with different geometry similar to effusion arrays are conducted with several BR between the range 0.5–5 at geometry condition of $d=1.8$ mm, $\delta x=13.7$, $\delta z=11.06$ mm and $\alpha=30^\circ$. It has been observed that using a low BR with more inclination angle ($\alpha$) to the surface performs better. On the contrary using high blowing ratios with normal holes gave a slight increase on overall efficiency.

4.2. Effect of hole spacing
The spacing of cooling holes also influences the adiabatic effectiveness ($\eta_{ad}$). Andreini et al. [11] conducted experiment and studied the influence of hole spacing in stream wise pitch distance ($\delta x$) and span wise pitch distance ($\delta z$). The stream wise distance ($\delta x$) is varied from 12 to 30d while as span wise distance ($\delta z$) is varied from 8 to 12d. It has been observed that increase in ($\delta z$) and ($\delta x$) prevents coalescence of the jets thereby leading to decrease in effectiveness. The authors [7] investigated numerically the influence of spacing of holes on both $\delta x=2.5$, 3.5, 4.9 & 6.0 and $\delta z=2.5$, 3.0, 3.5 & 4.9 concluded that there is slight increase in adiabatic efficiency for dense spacing as the number of coolant holes per unit surface area is increased by decreasing distance between the cooling holes in both stream wise and transverse direction as there is increase in coolant mass flow. Andrews et al [12] investigated the influence of heat transfer for constant hole diameter1.4 mm and number of holes per m$^2$, N, over a range of $\delta x$ 4.7 to 21 and concluded that for higher $\delta x$ there is inadequate surface coverage and very low for $\delta x<10$.

4.3. Effect of hole shape and size
When the shape and size of hole is concerned, Andrews et al. [13] observed that adiabatic efficiency $\eta_{ad}$ have been increased from 0.54 to 0.63 for highest blowing ratio (BR) with different hole sizes $d=1.18$ mm, 1.42 mm and 2.16 mm. The increase in adiabatic efficiency is due to increase in hole size as the coolant velocity is decreased without overshooting into hot gas flow and allowing the coolant jet to attach the wall for a longer period. Andrews and Asere [14] have shown that the effusion cooling effectiveness will be improved by enlarging the hole diameter or lowering the pressure loss as there will be reduction in the secondary flow jet mixing with the effusion cooling boundary layer.

Andrew et al. [15] explained that as number of coolant holes increases per unit area and reducing the diameter of holes will improve the $\eta_{ad}$ because the secondary fluid effused through the small holes leads improper mixing over the surface boundary layer.

Saumweber and Schulz [16] compared cooling adiabatic effectiveness with two different hole shapes at different turbulence levels. The advantage for such a fan shaped hole the coolant exit velocity is reduced and tendency for separation of coolant is reduced. Bell at el [23] performed experiments on different hole shapes and studied the performance of effusion cooling. They examined and compared simple angle with cylindrical hole and laterally diffused hole, compound angle with laterally diffused and forward diffused hole, simple angle with forward diffused hole.

The results showed that the better effusion cooling performance can be achieved with compound angle with laterally diffused hole shape angle for higher operating BR. The enhancement of adiabatic effectiveness by shaped holes is due to the enlargement of the hole size at the other end of exit which reduces the momentum flux and thereby lowers the over shooting of coolant into main stream flow. In the process the diverging exit provides the better film spread and full coverage on the surface than the round holes.
Figure 4. Comparison of adiabatic effectiveness for different shaped holes [16]

Shih et al [24] suggested that placing tabs or strut over each film cooling holes provide better adiabatic effectiveness as these do not generate unnecessary vortices on the surface which lowers the adiabatic effectiveness. The authors [25][26] studied the behaviour of upstream ramp by placing near first row of coolant holes and suggested that the adiabatic effectiveness increasing by placing an upstream ramp when the blowing ratio is low.

Figure 5. Schematic of different cooling hole shapes [23]
Mikki et al [27] compared the adiabatic effectiveness of trapezoidal shaped holes with circular holes for a constant mass flow rate and observed that trapezoidal holes have 23% improvement on adiabatic effectiveness as former one provides slower jets than circular holes. The lower velocity causes less disturbance on the boundary layer of the surface as a result improvement in effectiveness takes place.

Figure 6. Comparison of the adiabatic effectiveness $\eta_{ad}$ with different geometrical and flow parameters by different authors.

Nomenclature

- **BR**: Blowing Ratio $\left(\frac{P_{in}U_e}{P_oU_o}\right)$
- **DR**: Density Ratio $\left(\frac{\rho}{\rho_o}\right)$
- **VR**: Velocity ratio $\left(\frac{U_e}{U_o}\right)$
- **d**: Effusion hole diameter, mm
- **$\alpha$**: Effusion hole angle
- **$\eta$**: Cooling Effectiveness
- **$\delta x$**: Streamwise hole pitch distance, mm
- **$\delta z$**: Span wise hole pitch distance, mm
- **$Re_{main}$**: Reynolds number
- **I**: Momentum flux ratio $\left(\frac{P_{in}U_e^2}{P_oU_o^2}\right)$
5. Conclusions

Effusion cooling is most attractive from cost-effective viewpoint and application in many of the current production engines suggests that efficient cooling may be achieved with proper design [28]. Based on the comprehensive literature on various geometrical aspects for increasing the adiabatic effectiveness $\eta_{ad}$ of effusion cooling, the following conclusion has been drawn.

- The study of different geometrical parameters of effusion cooling clarifies that adjusting the diameter of hole, Spacing of holes over the surface, shape of holes can achieve better cooling performance with minor effects on effusion system.
- Inclined holes provide better adiabatic effectiveness in downstream of Streamwise flow compared to normal holes with the same diameter and stream wise hole to hole distance.
- Dense spacing of holes for a given area increases the adiabatic efficiency as the jets adjacent will influence each other and provides proper coalescence of jets.
- Shaped holes with expanding exit provide better efficiency than normal cylindrical holes.

Lot of research is going on by combining effusion-impingement cooling and effusion-transpiration cooling for ensuring best protection from hot gas stream.

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