Experimental study of full coverage film cooling optimization

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Abstract. Film cooling technique is often used to protect combustion and turbine walls of turbojet engine. The general principle is to inject cooling air coming from compressor, through drilled holes. This air flow provides a cold layer between the hot gases and the walls. In the present study, the effects of rows of holes number on the formation of cooling layer are experimentally investigated. Experiments were carried out on a wall with inclined staggered injection holes. Results indicate that it is necessary to have at least four rows of injection holes to form a cold layer. However, the latter fades away quickly after the last row of holes. So, the second part of the study concerns the influence if new rows of holes over the maintaining of the film. The addition of only one row of holes shows that its effect is independent of the additional row position. The addition of three rows of holes improves Nusselt number and adiabatic effectiveness values. The inter-rows distance also plays an important role. Among the additional injection patterns, a better cooling is noticed for the one with smaller inter-rows distance.

1. Introduction
Performance of jet engine has improved through the increase of Compressor Pressure Ratio (CPR) and of Turbine Inlet Temperature (TIT). This has led to an increase in the temperature of the gases leaving the combustion chamber. Nowadays, these hot gases may reach temperatures of nearly 2000°C. However, despite the recent advances in the field of new materials, these temperature levels can still not be withstood by combustion chamber walls. It is therefore important to cool the latter. Our study will focus on film cooling, one of a few techniques used in film cooling. The general principle of film cooling consists in injecting cool air withdrawn from a compressor, through drilled holes into the combustion chamber walls. This cool air will provide a cold layer between the hot gases and the combustion chamber walls in order to protect the latter. A significant number (more than 2700 since 1970 according to [1]) of papers on film cooling are available. Most previous researches were carried out with an injection wall equipped with only one hole [2] or one or two rows of holes [3], and furthermore, with multi-rows of holes [4]. Generally, these studies focused on the effects of geometric factors and aerothermic factors on the performance of film cooling. Geometric factors involve injection angle [5], arrangement of holes (inline or staggered)
[6], hole exit shape [2], inter-holes distance and inter-rows distance [7]. Aerothermic factors consist of blowing ratio [8], turbulence level Tu [9], temperature ratio $T_j/T_\infty$ [8], density ratio $\rho_j/\rho_\infty$ [10].

As far as we know, no existing investigation considers the effect of the successive injection rows leading to cold layer development except the study of Pêtre B et al. [11]. In this study, the holes are perpendicular to the injection wall surface ($\alpha=90^\circ$). The results indicate that it is necessary to have five rows of holes in order to have a developed cold layer. However, this layer fades away quickly if not maintained by additional rows of injection holes. So, in the present study, we decided to investigate the formation and the maintaining of cold layer in the case of inclined injections.

The present study has two main aims: Firstly, to observe the cold layer development in the case of an injection wall in which the holes are inclined ($\alpha=30^\circ$). This will allow us to determine the number of opening rows from which the cold layer begins to develop. Secondly, we propose to maintain this cold layer as far as possible by adding different injection holes patterns.

2. Experimental set-up

The experimental set-up is presented in Figure 1. Experiments have been carried out in a channel. Its square cross-section size is $100\times185\text{mm}^2$ (100mm high and 185mm wide which is also the width of the injection wall) and its length is 900mm. A mainstream air goes through the test section and another stream (coolant flow) is injected through the holes. This channel consists of an injection wall and an opposite probing wall.

The mainstream air is generated by centrifugal blower of MEIDINGER HP98/10-12. This mainstream is heated by a heat exchanger before entering the channel. The coolant stream is provided by a depressor. This one is placed downstream of the channel so as to allow both the mainstream and the coolant stream to be blown. Thanks to the manual valve type T placed between the channel and the depressor, it is possible to regulate the required stream flow rates. So, we have:

$$Q_{\text{dep}}=Q_\infty+Q_j \quad (1)$$

In fact, the depressor allows setting up a pressure at the outlet of the test section. The mass flow rate of each stream (mainstream and coolant stream) is measured by a venture meter.

Figure 1. General schematic diagram of the experimental set-up: (a) General view and (b) Test section

In our experiments, the mass flow rate of the mainstream is $Q_\infty=45\text{g/s}$. This corresponds to a mainstream velocity of $U_\infty=2\text{m/s}$. The temperature of the mainstream is $T_\infty=40^\circ\text{C}$. The mass flow rate of the coolant stream per injection is $Q_j=0.55\text{g.s}^{-1}$. The temperature of coolant stream is $T_j=20^\circ\text{C}$. The Reynolds number of the mainstream and the coolant stream which is based on hole diameter is 750 and 6650 respectively.
Figure 2. Coolant injection wall with an injection pattern containing seven opened holes rows

The injection wall is an epoxy plate. Its size is 880x185mm$^2$ and its thickness is 1.6mm. In this wall, 81 holes are drilled. Those holes are split in 17 rows in staggered configuration. Some holes, forming a pattern, are injected by coolant flow; these holes shall be named “open holes”. On the other hand, those that do not belong to the pattern will be blocked and known as “closed holes”. The possibility to open or close the injection holes makes it possible to obtain different injection patterns. The name of pattern is composed by considering three components: number of opened holes rows R, inter-holes distance $p$ and inter-rows distance $s$ (Figure 2).

The hole diameter is $D=6$mm. Each hole is connected to a pipe of 120mm length which ensures the coolant flow. Pipe to wall’s surface angle is $\alpha=30^\circ$. The injected flow goes through these pipes to obtain a fully developed injected flow. This guarantees that the injected flow is identical for all the holes. Inter-holes distance $p$ and inter-rows distance $s$ can range from $4D$ to $12D$. The first row is located $4D$ away from the injection wall leading edge. The injection wall surface which is in contact with the mainstream is equipped with a printed circuit. The plate is covered with a thin foil of copper. This foil is engraved by a circuit that is linked to a DC supply so as to heat the plate by Joule effect and to generate measurable heat flux density $\varphi_{\text{dist}}$ (W.m$^{-2}$). A layer of isolator is installed on the outside of the injection wall in order to reduce heat loss.

The probing wall, opposite to the injection wall, is equipped with IR windows so as to measure the injection wall surface temperature by infrared thermography. For that purpose, an infrared camera CEDIP Titanium is used. This technique requires a precise measurement of the wall’s emissivity. In order to achieve this, the injection wall surface was painted in black and the measure of the emissivity value was made up in a laboratory. Its value is equal to $\varepsilon=0.95\pm0.02$.

3. Measurement techniques

Usually, the law of Newton is used to characterize wall heat transfer:

$$\dot{\varphi}_\text{conv} = h_{\text{conv}}(T_w - T_{\text{ref}})$$

where $h_{\text{conv}}$ is the heat transfer coefficient and $T_w$ and $T_{\text{ref}}$ are wall and reference temperature, respectively. The mainstream temperature $T_\infty$ is often taken as the reference temperature $T_{\text{ref}}$. For film cooling, this consideration ($T_{\text{ref}}=T_\infty$) is no longer valid because of the coolant flow injection. Most previous researches [3] [8] … have proposed to take adiabatic temperature $T_\text{aw}$ as reference temperature $T_{\text{ref}}$. So, the wall heat transfer density on the injection wall can be rewritten as:

$$\dot{\varphi}_\text{conv} = h_{\text{conv}}(T_w - T_{\text{aw}})$$


Therefore, the study of film cooling will consist in investigating the distribution of heat transfer coefficient \( h_{\text{conv}} \) and of adiabatic wall temperature \( T_{\text{aw}} \) along the injection wall.

The equation (3) can be rewritten as follows:

\[
T_w = \frac{1}{h_{\text{conv}}} \phi_{\text{conv}} + T_{\text{aw}}
\]  

(4)

This equation is linear. It is possible to obtain the heat transfer coefficient \( h_{\text{conv}} \) and the adiabatic wall temperature \( T_{\text{aw}} \) from a linear extrapolation according to (4). When plotting \( T_w \) versus \( \phi_{\text{conv}} \), \( 1/h_{\text{conv}} \) and \( T_{\text{aw}} \) will respectively be the slope and the Y intercept. In order to be able to perform this extrapolation, at least two couples \((\phi_{\text{conv}}, T_w)\) are needed.

In our experiments, we decided to make four measurements by injecting four different electrical flux densities for each configuration tested. Then, radiative and convective flux density losses toward front side and backside of the injection wall must be taken into account to obtain the convective flux density on the cool side \( \phi_{\text{conv}} \). The injection wall surface’s temperature is measured for each dissipated electrical flux. Thus, at any point on the injection wall, four couples \((\phi_{\text{conv}}, T_w)\) are measured, which corresponds to the four injected electrical densities so as to achieve the linear regression.

Usually, heat transfer coefficient \( h_{\text{conv}} \) and adiabatic wall temperature \( T_{\text{aw}} \) are adimensioned in the form of Nusselt number \( Nu \) and adiabatic effectiveness \( \eta_a \) as shown in the following equations:

\[
Nu = \frac{h_{\text{conv}} D}{\lambda_{\text{air}}}
\]

(5)

\[
\eta_a = \frac{T_{\text{aw}} - T_i}{T_j - T_i}
\]

(6)

where \( \lambda_{\text{air}} \) is thermal air conductivity at adiabatic wall temperature \( T_{\text{aw}} \).

Then, \( Nu \) number will be normalized using \( Nu_0 \) number into relative Nusselt number \( Nu^* \):

\[
Nu^* = \frac{Nu}{Nu_0}
\]

(7)

where \( Nu_0 \) is the Nusselt number without film cooling at the same location. The determination of \( Nu_0 \) is performed to validate our experimental set-up. Results show good agreement with the Nusselt number obtained from correlation of Colburn [12].

Each configuration of the injection wall is investigated with a blowing ratio \( M \) defined as:

\[
M = \frac{\rho \nu_j}{\rho_{\text{in}} V_{\text{in}}}
\]

(8)

where \( \rho \) and \( V \) are respectively the density and velocity of the two flows. In the present study, blowing ratio \( M \) is equal to 4.

Uncertainties are evaluated by using a statistical approach [13]. Thus, we have taken into account uncertainties of parameters such as: mainstream and coolant stream temperature, injection wall surface temperature, electrical flux density, radiative and convective flux densities, emissivities … A combination of these uncertainties lead to an average random uncertainty of 3% for \( Nu^* \) and of 7% for the \( \eta_a \). Overall uncertainties for Nusselt number values and adiabatic effectiveness values are no higher than 13% and 12%, respectively. All of these uncertainty values have been estimated at a 95% confidence level.

4. Results

4.1. Reference test: effect of the number of rows of holes on the formation of a cold layer

The aim of these reference experiments is to determine the minimum number of rows of injection holes for the formation of a cold layer. For this purpose, the tests have been carried out with three to seven opened holes rows.
Note that in Figure 3 and the others, the rectangular symbols at the bottom of these figures show the position of opened injections for the different patterns. Thus, the different injection patterns tested can be visualized more easily.

Figure 3a presents how the relative Nusselt number $\overline{Nu^*}$ varies along the plate for patterns with different numbers of injection rows and for a blowing ratio $M=4$. Firstly, the observation of these curves underlines two main areas:

- The first area for $x/D < 12$: $\overline{Nu^*}$ increases to a maximal value regardless of the number of open rows. In this area, $\overline{Nu^*}$ value is quite identical from one pattern to the other. This shows that the number open row has few effects on this area.
- The second area for $x/D > 12$: we may observe that $\overline{Nu^*}$ varies along with the number open rows. For $R=4, 5$ and $7$, we can see the presence of a bearing on profiles of $\overline{Nu^*}$ variations before reaching the end of the multiperforated area, while the latter isn’t observed for the case $R=3$. This presence of the bearing indicates a construction of the cold layer.

Figure 3b presents adiabatic effectiveness $\overline{\eta}$ variations along the plate. As for $\overline{Nu^*}$, $\overline{\eta}$ variations also show two distinct areas: the first area (until $x/D=12$) on which the number of open rows has only very little effect, whilst in the second area (beyond $x/D=12$), $\overline{\eta}$ increases with the increase of open rows number. We can note that as from four open rows there is a significant increase of $\overline{\eta}$. Thus, the maximum difference of $\overline{\eta}$ value is 0.1 between ($R=4, R=5$) and 0.14 between ($R=5, R=7$) while the $\overline{\eta}$ values of $R=3$ and $R=4$ are close.

With regards to these analyses, we can note that there must be at least four rows of holes in order to form a cold layer. So, the pattern R4p4s4 (corresponding to the configuration with four opened rows of holes $R=4$, inter-hole distance $p=4D$ and inter-row distance $s=4D$) is chosen as a basic configuration. To this configuration, we will now add an additional injection pattern in order to maintain the cold layer as long as possible. To achieve this, one or three rows of holes are added with different inter-rows distances.

4.2. Maintaining the cold layer

As previously mentioned, the purpose of this experimental part is to maintain the cold layer by adding new injection pattern. This will be done by adding one or three additional rows of injection holes to the basic configuration R4p4s4.
We will begin with an additional row of injection holes with two different inter-row distances: one with \( s=4D \) and the other with \( s=12D \). This leads to two new configurations: \( R4p4s4-R1p4s4 \) and \( R4p4s4-R1p4s12 \) (Reference to figure 2 for the name of the configuration).

Figures 4(a) and 4(b) present \( \text{Nu}^* \) variations and \( \eta_{ad} \) variations for those two configurations and the basic configuration \( R4p4s4 \). Figure 4(a) shows that the \( \text{Nu}^* \) values are quite identical, regardless of the configuration, in the area \( x/D=[0, 14] \) which is the common multiperforated area. Beyond \( x/D=14 \), we may observe that the \( \text{Nu}^* \) values for \( R4p4s4-R1p4s4 \) begins to differ from that of the basic configuration, while, in the case of \( R4p4s4-R1p4s12 \), this observation occurs much later. Indeed, in the last case, the \( \text{Nu}^* \) curve continues to follow that of the basic configuration until \( x/D=22 \) where a small increase is initiated at \( x/D=26 \). These increases of \( \text{Nu}^* \) values are probably due to the turbulence created by the additional row. Downstream, for \( x/ > 38 \), \( \text{Nu}^* \) values are identical for both configurations with the additional injection row. We observe that \( \text{Nu}^* \) values decrease progressively to reach that of the basic configuration.

![Figure 4. Comparison of three configurations R4p4s4 / R4p4s4-R1p4s4 / R4p4s4-R1p4s12](image)

As far as \( \eta_{ad} \) variations are concerned, we may observe a quite similar behavior to \( \text{Nu}^* \) variations. Indeed, \( \eta_{ad} \) values are identical to those of the basic configurations until \( x/D=14 \). Downstream this point, \( \eta_{ad} \) values begin to improve for the additional injection patterns compared to the basic configuration. The \( \eta_{ad} \) values of the case \( R4p4s4-R1p4s4 \) is more important than those of the case \( R4p4s4-R1p4s12 \) at \( x/D=[18, 22] \). For both configurations with additional row, we may observe improvement of \( \eta_{ad} \) until \( x/D=44 \). However, this improvement begins to decrease downstream of the additional row (\( x/D=30 \)) for joining the \( \eta_{ad} \) values of the basic configuration. In addition, in the area where \( \eta_{ad} \) values are improved (\( x/D=[24, 48] \)), we can note that \( \eta_{ad} \) values have the same level wherever the position of the additional row. It means that the influence of the position of the additional injection row on the \( \eta_{ad} \) is negligible.

We will now investigate the addition of three injection rows. Two patterns are chosen: one with \( s=4D \) and the other one with \( s=12D \) respectively named \( R4p4s4-R3p4s4 \) and \( R4p4s4-R3p4s12 \). The results – \( \text{Nu}^* \) variations and \( \eta_{ad} \) variations – are shown in Figure 5(a) and 5(b).
Figure 5. Comparison of three configurations R4p4s4 / R4p4s4-R3p4s4 / R4p4s4-R3p4s12

For the $\overline{\text{Nu}}^*$ variations, we may distinguish two different areas (Fig. 5a):

- The first one ($x/D<16$) is the multiperforated area common to all configurations. In this area, we observe very little difference (0.1-0.2) in the $\overline{\text{Nu}}^*$ value, regardless of the configurations.

- The second one is downstream of the common area ($x/D>16$). Adding three additional injection rows causes the apparition of a bearing which maintains the value of $\overline{\text{Nu}}^*$. The $\overline{\text{Nu}}^*$ values of these bearings are 3.3 and 2.5 for configurations R4p4s4-R3p4s4 and R4p4s4-R3p4s4, respectively. Indeed, the bearing is located in the range $x/D=[16, 28]$ for the configuration R4p4s4-R3p4s4 whilst for the configuration R4p4s4-R3p4s12 it is located in the range $x/D=[16, 52]$. The R4p4s4-R3p4s4 has a higher $\overline{\text{Nu}}^*$ level compared to that of R4p4s4-R3p4s12 till $x/D=32$ while this observation is reversed farther, downstream $x/D=40$. As the additional injection rows are closer in the case of R4p4s4-R3p4s4, a higher interaction produces a higher turbulence level which results in a higher $\overline{\text{Nu}}^*$. We may note that $\overline{\text{Nu}}^*$ values begin to decrease as from the last row of holes, regardless of the configuration.

The adiabatic effectiveness $\eta_a^*$ remains unchanged until the end of the common multiperforated area ($x/D<16$). Beyond this area, adiabatic effectiveness value passes from 0.5 to 0.75 and from 0.5 to 0.68 in the case of the configuration R4p4s4-R3p4s4 and R4p4s4-R3p4s4, respectively. Moreover, this improvement is maintained until the end of the injection plate. However, the pattern with a small interrows distance ($s=4D$) produces a better effectiveness. Indeed, at $x/D=28$ for the injection pattern R4p4s4-R3p4s4 the totality of the mass flow rate of coolant stream is completely injected which can explain its better effectiveness.

Table 1 presents $\overline{\text{Nu}}^*$ and $\overline{\eta_a}$, the averaged overall surface of the injection wall for the tested configurations. We can note (Table 1a) that by adding one row of holes, $\overline{\text{Nu}}^*$ shows an increase of about 15-18% while $\overline{\eta_a}$ varies a little (about 3% - order of uncertainty) compared to the basic configuration. However, this $\overline{\text{Nu}}^*$ improvement is locally observed only for the area where the additional injection row is located.

| (a) Case of one additional row | (b) Case of three additional row |
|------------------------------|---------------------------------|
| Configuration                | $\overline{\text{Nu}}^*$       | $\overline{\eta_a}$ |
| R4p4s4                       | 1.53                           | 0.52                 |
| R4p4s4-R1p4s4                | 1.84                           | 0.54                 |
| R4p4s4-R1p4s12               | 1.80                           | 0.52                 |
Adding three injection rows, $\overline{\text{Nu}}^2$ increases about 25% and $\overline{\eta}$ increases about 13-20%, depending on the disposition of the additional rows of injection holes (Table 1b). The additional rows adjacent to the basic configuration appear more interesting than the other pattern. However, it should be noted that the mass flow rate of coolant stream in the configurations with three additional rows (25g.s$^{-1}$) is more important in comparison to that of basic configuration (14g.s$^{-1}$).

5. Conclusion
This present experimental study has been conducted to investigate both the effect of successive open injection rows on the formation of a cold layer and the continued presence of this layer with an additional injection pattern. The conclusions and recommendations are summarized below:
- Film cooling layer formation is observed after the fourth row of injection. However, it fades away quickly if not maintained.
- Adding only one row of holes has little effect on the continued presence of cold layer. Moreover, it is observed that its effect is the same whichever the position of the added row.
- The addition of three rows of injection holes has an important effect. The results indicate that inter-rows distance between additional injection rows plays an important role. An adiabatic effectiveness enhancement of 20% is observed in the case of closer additional injection rows while this enhancement is only of 13% in the case of three distant rows. But, with regards to the air consumption, the gain in cooling is not as interesting as we could hope.

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