# Numerical Investigation of Effusion Cooling in Gas Turbine Combustor Liner

*Seyhun DURMUŞ\** iD

*Balikesir University, Edremit School of Civil Aviation, Balikesir, Turkey

**Abstract**

In this study, a numerical analysis was performed to find the aerothermal characteristics of the effusion cooled gas turbine combustor liner. The analyzed geometric model is a scale model of an actual combustor liner. The study aims to investigate the effect of different blowing ratios by validating an experimental test setup. In experimental studies on effusion cooling, the sidewall effect is a serious problem that can distort the results. Numerical analyses provide advantages in visualizing temperature and velocity contours in different sections of physical model. The counter rotating vortex pairs, the horseshoe vortex and the recirculation zone are the main flow features of the jet mixture. At a blowing ratio of 3.35, numerical analyzes gave the highest value of cooling effectiveness. Although the blowing ratio slightly changes the cooling effectiveness in experimental data, it has been found that the effect of blowing ratio is more pronounced on the numerical results, especially at high blowing ratios.

*Keywords:* Effusion Cooling, Gas Turbine Combustor Liner, Blowing Ratio, Heat Transfer, Computational Fluid Dynamics.

## 1. Introduction

Film and effusion cooling are used to maintain the turbine blade and combustor liner temperature distribution of a jet engine. Relatively large and annular slots are used in film cooling, while many small-diameter holes are drilled on the plate for effusion cooling. In general, the factors affecting film cooling are the cooling and mainstream flow conditions, cooling hole geometry and other factors [1]. The cooling and mainstream flow conditions are

the blowing ratio, density ratio, momentum flux ratio, turbulence level and approach boundary layer thickness. The cooling hole geometry are the shape of the hole, injection angle, effect of composition angle, hole pitch, hole span, streamwise length / hole diameter (L/D), the number of hole arrays and total number of holes (porosity). The other factors include hole Reynolds numbers, surface curvature, surface roughness etc. Mcghee [2] worked on an

effusion cooling plate with an inclination of 30 and 90 degrees, with a distance of-L/D 6 in the direction of flow to the hole diameter, with a Reynolds number of holes of 8200, with a blowing ratio of 0.85-1.2, with a density ratio of 0.8, with a coolant temperature of 305 K and a main current temperature of 380 K. In that study, temperature measurements were made by infrared thermography and thermocouples. Gustafsson [3] studied on an effusion plate with 15, 20 and 30-degree inclined cooling holes, a L/D of 8, a hole Reynolds Number of 3900-5800, a blowing ratio of 14, a density ratio of 2, a coolant temperature of 298 K and mainstream temperature of 523 K. That study reported that the turbulence levels increased by around 25% at the exit of the jet near the wall and that the lateral velocity ratios increased when the Reynolds stresses increased. Grierson [4] made measurements by infrared thermography on a plate with 18 and 25-degrees inclined cooling holes, a L/D of 8.6, a blowing ratio of 0.5-4, a density ratio of 1.2, a coolant temperature of 300 K and a mainstream temperature of 360 K. It has been found that an increase in the hole diameter increases the efficiency, but an increase in the hole diameter reduces the cooling efficiency as the cooling jet velocity decreases and accordingly the mainstream mixing ratio decreases. Scrittore [5] studied on a plate with cooling holes inclined by 30-degree, a L/D of 8.9, a Reynolds Number of 8600, blowing ratio of 3.2-5, a density ratio of 1, a coolant temperature of 300 K and a mainstream temperature of 330 K. Axial (x/D) and lateral (z/D) velocity profile flow characteristics were extracted from velocity measurements by Laser Doppler Velocimetry (LDV). Zhong [6] performed a numerical analysis on a ceramic plate with 23 and 90-degree inclined effusion cooling holes, a L/D of 8.6, a blowing ratios of 0.2-1, a density ratio of 1, a coolant temperature of 160 K and a mainstream temperature of 320 K. Arcangeli et al. [7] studied on a plate with 30 and 90-degree inclined effusion cooling holes, a L/D of 10-43, a hole Reynolds Number of 6000, a blowing ratio of 0.3, a density ratio of 1, a coolant temperature of 300 K and a mainstream temperature of 325 K. That study is aimed to investigate how does L/D affect the cooling efficiency, keeping other factors constant. Cho et al. [8] conducted a study on a plate with 90-degree inclined cooling holes, a density ratio of 1.5,

a Reynolds Number of 3200-14000, a coolant temperature of 300 K and a mainstream temperature of 350 K. The heat transfer coefficients were investigated in terms of staggered, shifted, and inline arrays and it was suggested that the staggered arrays outweighed the others. Facchini et al. [9] worked on effusion plate with cooling holes inclined at 17 degrees, a L/D of 16, a hole Reynolds Number of 1200-20000, a blowing ratio of 5, 7 and 9, density ratio of 1, a coolant temperature of 306 K and a mainstream temperature of 322 K. It was found in the study that the elliptical holes give better adiabatic cooling efficiency values than cylindrical holes in all cases except for low Reynolds Numbers. Adreini et al. [10] numerically studied on a model plate with 30 degrees inclined effusion cooling holes, a L/D of 5.5, a density ratio of 1, a coolant temperature of 500 K and a mainstream temperature of 1200 K. Ligrani et al. [11] carried out a study on an effusion plate with 20-degree inclined effusion cooling holes, a L/D of 8.35, a blowing ratio of 2-5-10, a density ratio of 1.15-1.25, a coolant temperature of 300 K and a mainstream temperature of 380 K. In that study, the cooling efficiency values were calculated for the area/mainstream area. Wurm et al. [12] studied on an effusion plate with 30 and 45-degrees inclined holes, Reynolds Number of holes for values between 1400 and 6600. It has been concluded that 30-degree inclined holes without swirl effect provide better cooling efficiency than 45-degree holes, but 45-degree inclined holes with swirl effect provide better cooling efficiency. Andrei et al. [13] numerically investigated an effusion plate with 30 and 45-degree inclined cooling holes, a L/D of 6, a blowing ratio of 1-3, a density ratio of 1-1.5, a coolant temperature of 290 K and a mainstream temperature of 330 K. It has been reported that the film plate protection in the first series provides better protection due to the jet take-off effect at low blowing ratios, while due to superposition effect in the continuing series (14th array) protection drops to a degree that will almost disappear at high blowing ratios. Andreini et al. [14] studied on an effusion plate with 30-degree inclined effusion cooling holes, a L/D of 6, a blowing ratio of 0.5-5, a density ratio of 1-1.5, a mainstream turbulence level of 1.5%-17%, the coolant temperature of 290 K and a mainstream temperature of 330 K. It was concluded in that study that the film protection against high turbulence levels increased

along the lateral axis and the L/D value was an effective parameter in effusion cooling. Da Soghe et al. [15] worked on an effusion plate with 30-degree inclined cooling hole, a L/D of 6, a hole Reynolds Number of 8600, density ratio of 1, a mainstream turbulence level of 16%-32%, a coolant temperature of 300 K and a mainstream temperature of 1000 K. In that study, it was aimed to find an empirical relationship between cooling holes and heat transfer increase over Reynolds Number, effusion porosity coefficient and pressure ratio. Oguntade [16] found that the hole sequence number flow vectors develop in a certain sequence, then becomes uniform after a certain sequence, and under the influence of boundary layer superposition in the forward axial direction. The study reported that the total hole area/plate area (porosity) ratio is also an important parameter in effusion cooling. Hasan and Puthukkudi [17] claimed that the two zones configuration provides very similar cooling efficiency compared to continuous hole arrays and significantly reducing cold air consumption. Jingzhou et al. [18] worked on an effusion plate with a spacing of 3.0, 4.0, and 5.0 by a blowing ratio of 0.5-1.5. The study reported that wall cooling efficiency rises as the center-to-center spacing of neighbor holes gets smaller or the blowing ratios rises. Walton and Yang [19] argued that in the isothermal case, the Reynolds Stress Transport model can reasonably well predict the penetration, injection, downstream disruption, and lateral interactions of jets. Murray et al. [20] experimentally investigated flat effusion plate effectiveness with two holes spacings 3.0D and 5.75D by pressure sensitive paint technique. The main finding of the study was that the superposition method provided good results in larger pitches, while a high level of jet mixing reduced the performance of the method in smaller pitches. In addition, some studies have been conducted in the literature on the combined effect of slot, effusion, and dilution holes. Ceccherini et al. [21] took the study of Scrittore [5] a step further, by studying the effects of slot, effusion, and dilution together. The study has been reported that the adiabatic efficiency coefficient reaches its maximum value after the 14th array (the array with the dilution hole) in the 29-array plate. Tarchi et al. [22] conducted a net heat flux drop (NHFR) based cooling study by Thermochromic Liquid Crystals (TLC) technique,

which together considered the effects of slot, effusion, and dilution. Inanli et al. [23] experimentally examined 2 effusion plates with hole angles of 30° and 75° with horizontal at 3 different blowing ratios. The analyzes performed in the current study were carried out by visualizing the temperature and velocity contours in different sections of the physical model. Study contributes to the literature by calculating the effects of blowing speeds on cooling efficiency by numerically validating the experimental study of Inanli et al. [23].

## 2. Material and Method

In this study, ANSYS 19.0 Fluent package was used for numerical solution and CFD-Post package was used for visualization of analysis results. Computed aided design (CAD) model was created by scale of a real combustor liner. The continuity equation, conservation momentum, and energy are the main governing equations in computational fluid dynamics. Continuity, momentum in the x-direction, and energy equations are given in Eq.1-Eq.3.

$$\frac{D\rho}{Dt} + \rho \nabla \cdot \vec{V} = 0 \qquad (1)$$

$$\rho \frac{Du}{Dt} = \rho g_x + \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \qquad (2)$$

$$\rho c_v \frac{DT}{Dt} = \nabla \cdot k \nabla T - p \nabla \cdot \vec{V} + \mu \Phi \qquad (3)$$

The blowing ratio (BR) is an important parameter that affects the heat transfer coefficients and effusion cooling efficiency. BR given in Eq. 4 is found by multiplying the ratio of the coolant density by the coolant velocity and the mainstream density multiplied by mainstream velocity.

$$BR = \frac{U_c \rho_c}{U_\infty \rho_\infty} \qquad (4)$$

The calculation of the whole film cooling efficiency (η) is given in Eq. 5. Since the wall temperature is directly measured at the whole film cooling efficiency ratio, the whole film cooling efficiency ratio is preferable than the adiabatic

efficiency ratio, where the temperature is calculated from the adiabatic wall assumption.
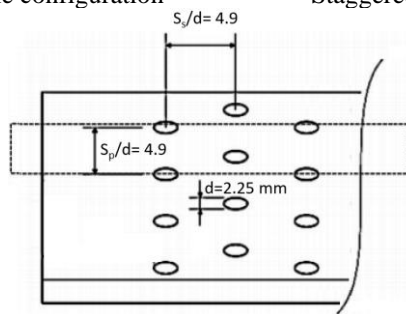
$$\eta = \frac{T_\infty - T_W}{T_\infty - T_C} \qquad (5)$$

The periodicity of the flow, which is ensured by placing enough holes in a row for the reliability and accuracy of measurements. The geometric features of effusion plate are given In Table 1.

**Table 1.** Geometric features of effusion plate

| Property | Value |
|---|---|
| $\alpha$ | 30 deg |
| $t$ | 10 |
| $d$ | 2.25 |
| $t/d$ | 4.44 |
| $S_s$ | 11 |
| $S_p$ | 11 |
| $S_s/d$ | 4.9 |
| $S_p/d$ | 4.9 |
| Hole configuration | Staggered |

The coolant and mainstream parameters with blowing ratios are given in Table 2. The mainstream temperatures are set to 338 K and the coolant temperature are adjusted to 298 K for all cases. The mainstream velocity is kept constant at 3.7 m/s for all three cases, while the coolant air velocity as taken as 7.5, 11.0 and 13.0 m/s.

**Table 2.** Coolant and mainstream features with blowing ratios

| BR | $T_\infty$ | $T_c$ | $\rho_\infty$ | $\rho_c$ | $U_\infty$ | $U_c$ |
|---|---|---|---|---|---|---|
| | (K) | (K) | (kg/m³) | (kg/m³) | (m/s) | (m/s) |
| 2.30 | 338 | 298 | 1.043 | 1.184 | 3.7 | 7.5 |
| 3.35 | 338 | 298 | 1.043 | 1.184 | 3.7 | 11.0 |
| 4.00 | 338 | 298 | 1.043 | 1.184 | 3.7 | 13.0 |

Fig. 1 (a) shows the CAD model and the named selections used for boundary conditions. Mass flow inlet boundary condition was chosen for both hot mainstream and cooling plenum. A no-slip-condition was chosen for all walls and a symmetry boundary condition has been defined for side walls. The grid dependency process was carried out for BR=2.3 experimental study case of Inanli et al. [23]. Coarse (node number, 600X600), medium (node number, 900X900), and fine (node number, 1200X1200) mesh sizes were applied to the CAD models. Considering the average values of the normalized heat transfer, the fine grid gave more consistent results with a 0.5% margin of error than the other grids. Therefore, approximately 1.5 million node numbers were applied to all physical models. The near-wall mesh consideration-y+ the first cell next to a wall was kept under 3. Fig. 1 (b) shows that the near wall treatment adjacent to the cooling holes and plate surface.
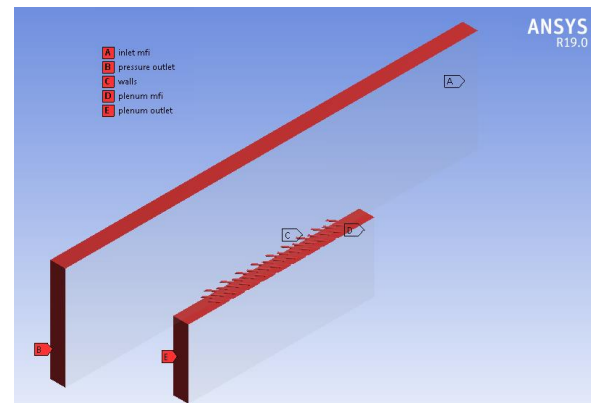


**(a)**
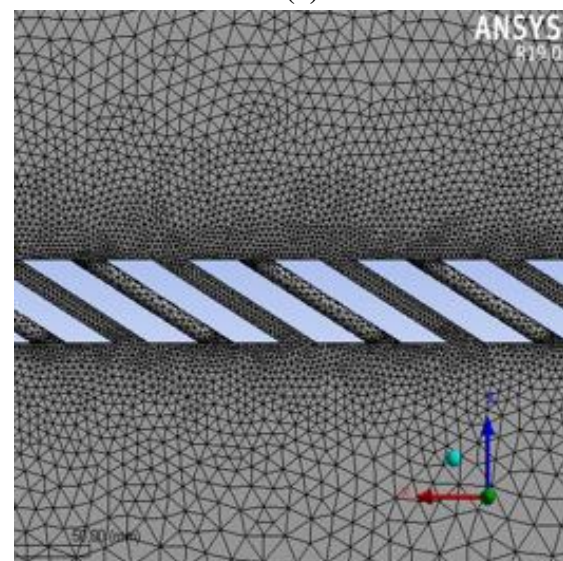


**(b)**

**Figure 1.** Boundary conditions and the generated mesh.

The thermophysical property data entry of the plexiglass used as the material in the experimental study was carried out in the Ansys Fluent. Since the thermal conductivity of plexiglass is low, it is suitable for use in jet mixture studies. The Reynolds Stress Transport model, which has proven its success in numerical analyses performed in the literature, has been selected for use in turbulence modeling. Second order schemes were utilized for analysis. SIMPLE algorithm, widely studied in the literature, was utilized for pressure-velocity coupling analyzes [24]. The convergence standard for dependent variables is taken as $10^{-5}$.

## 3. Results

The sidewall effect is a serious problem in experimental studies of effusion cooling, which will seriously affect the results. Comparing the experimental results with numerical studies has the potential to provide a solution for understanding the sidewall effect. In this paper, a numerical study was performed on the effusion cooling plate for the cases of 3 different blowing ratios, i.e., BR of 2.3, 3.35, and 4.0. The surface temperature contours of the effusion plate for different blowing ratio are shown in Fig. 2. As can be seen from the temperature contours, there was a small difference between the contours of blowing ratio of 3.35 and 4.0, while BR=2.3 case performed worse.
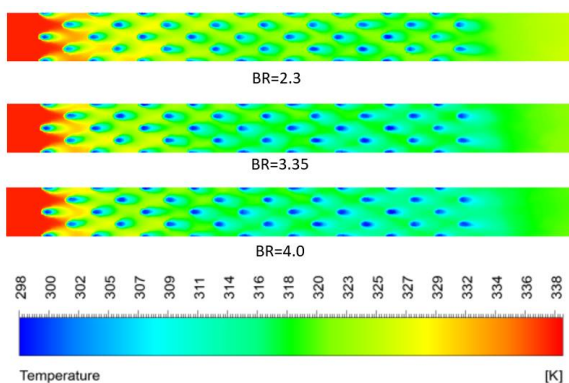


**Figure 2.** Surface temperature contours of the effusion plate for different blowing ratio

In order to understand the aerothermal properties of the effusion cooling plate, a symmetry plane was defined. The results of the temperature contour distribution in plane of symmetry are given in Fig. 3. At the blowing ratio of 3.35 and 4.00; it is clearly

seen that the 30-degrees inclined jets form a potential film core between two effusion holes.
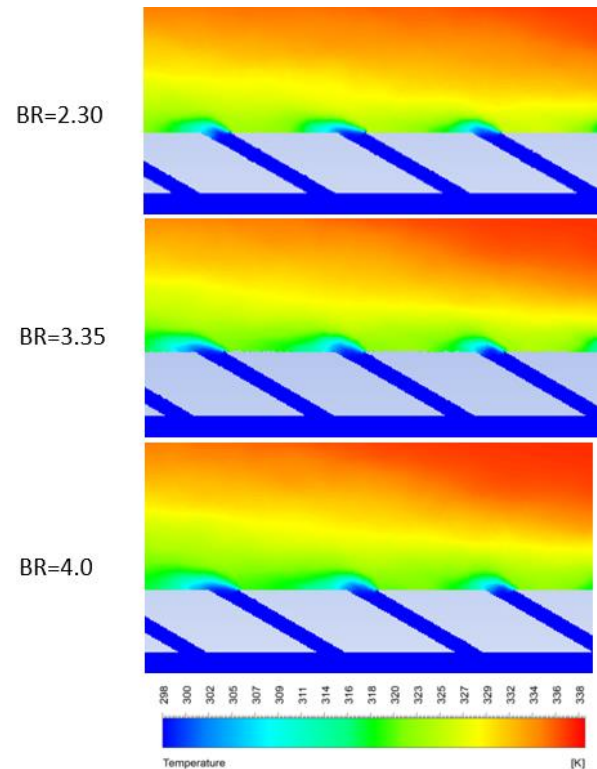


**Figure 3.** Temperature contours on plane of symmetry for different blowing ratio

Due to the jet crossflow effect, counter-rotating kidney vortices were formed to the right and left of the jets. Horseshoe vortices were observed in the lower region due to the crossflow structure. due to the crossflow structure, a recirculation bubble formed in the area following the jet holes Fig. 4(a) shows the velocity contours and flow properties on the orifice. In the plane taken from the mid-section of the effusion plate, jets emerging from the staggered array holes are seen in Fig. 4(b). At the orifice, the uniform velocity vectors are seen in the plenum, while in the cross flow. counter-rotating vortex pairs (CRVP) are seen in the jet mixture. CRVPs are normally created when the cooling hole jet run across through the mainstream; however, in the staggered array, recirculation zones are created due to interaction with neighboring jets.

Fig. 5 shows a comparison of the laterally averaged cooling effectiveness values at different blowing ratios calculated for the L/D ratio of between 40-140 in the streamwise direction. At a blowing ratio 3.35, the CFD gave the highest value of cooling effectiveness.
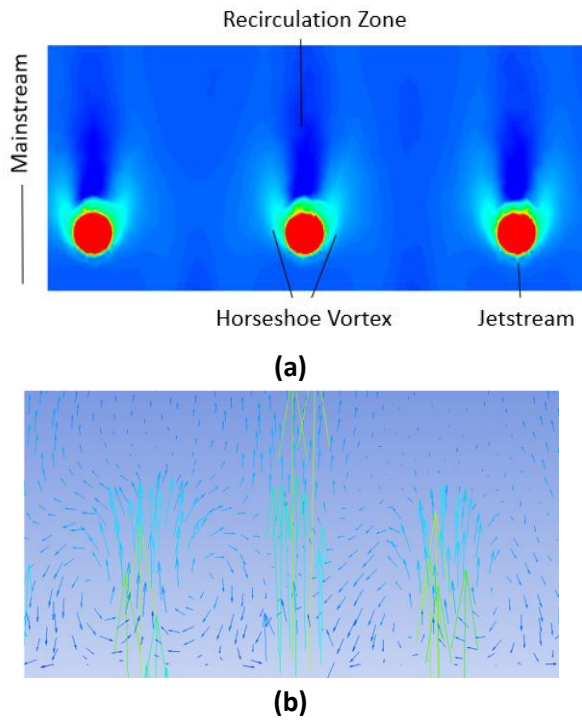
**(a)**



**(b)**

**Figure 4. (a)** Velocity contours on the hole surface including horseshoe vortex and recirculation zone **(b)** Counter Rotating Vortex Pairs (CRVP) in the upstream regions of jet

There was a more pronounced cooling effectiveness between the blowing ratio of 2.3 case and other cases. Further interaction between the mainstream flow and effusion plate surface causes a drop in the cooling effectiveness, this is the reason why 3.35 blowing ratio outperforms the 4.00.
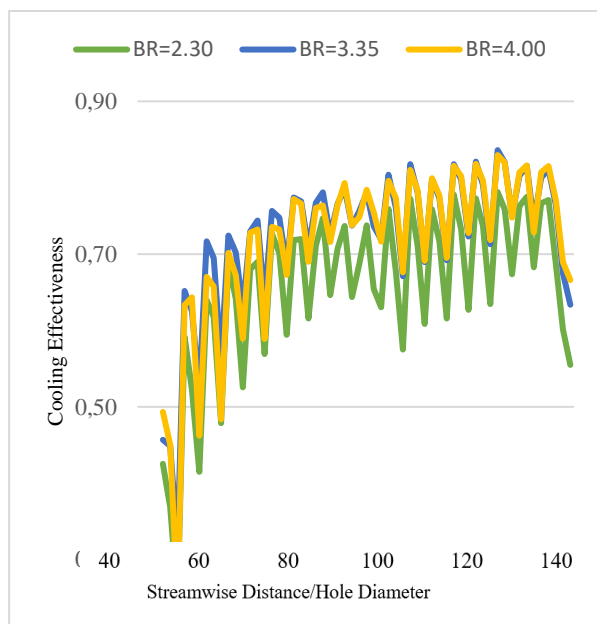


**Figure 5.** Laterally averaged cooling effectiveness values for different blowing ratios according to L/D ratio of between 40-140

Fig. 6 shows a comparison of experimental data with the numerical results on the average cooling efficiency. As research finding, although the blowing rate changes the average cooling efficiency very little in the experimental study, the effect of the blowing rate on the effusion cooling efficiency becomes more obvious, especially at high blowing ratios.
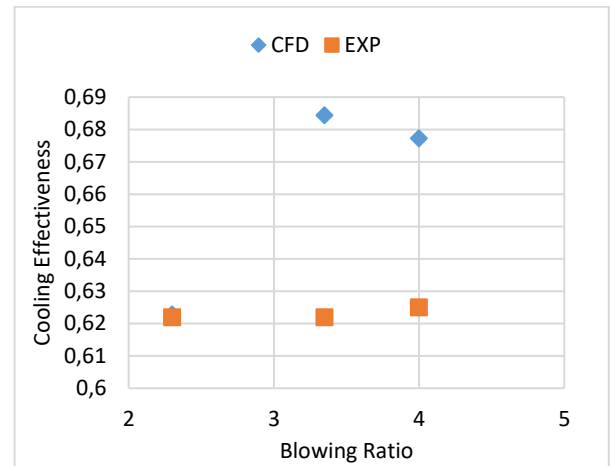


**Figure 6.** Comparison of numerical results (CFD) with experimental data (EXP) in terms of laterally averaged cooling effectiveness

## 4. Conclusion

In this study a numerical study was carried out on validation of an experimental case for 3 different 2.3, 3.35, 4.0-blowing ratios and to find out the aerothermal characteristics of effusion cooled gas turbine combustor liner.

Numerical studies provide a validation method for parameters that will affect results such as measurement errors and side wall effects in experimental studies. Numerical analyses provide advantages in observing the effects of flow on temperature in terms of providing both surface temperature contours and visualization of temperature contours on the axis of symmetry. In particular, the distribution of temperature contours effusion holes on the axis of symmetry gives the characteristic of the flow in the jet mixture region. In the experimental study, the highest cooling efficiency value was obtained at the ratio of 4.0 blowing, while the highest cooling efficiency value was obtained at the ratio of 3.35 blowing in numerical analyses. Further interaction between the mainstream flow and the effusion plate surface can lead to a decrease in cooling efficiency, which can

be explained as the possible reason that the blowing ratio of 3.35 outperforms that of 4.00. In experimental data, it was found that the blowing rate changes the cooling efficiency less. In numerical analyses, the effect of the blowing ratio gave a more significant change in cooling efficiency coefficient, especially at high blowing rates. When the ratio of streamwise distance/hole diameter (L/D ratio) increases, the laterally averaged cooling effectiveness values increase. In experimental data, the cooling effect value was about 0.62 at high blowing rates, while in numerical analyses this value was 0.68.

## Nomenclature

| t | [mm] | Plate thickness |
| D | [mm] | Hole diameter |
| L | [mm] | Streamwise distance |
| S | [mm] | Inter-hole distance |
| T | [K] | Temperature |
| U | [m/s] | Velocity |

**Greek Symbols**

| $\alpha$ | [°] | Effusion hole angle |
| $\eta$ | [-] | Cooling effectiveness |
| $\rho$ | [kg/m³] | Density |

**Subscripts**

| $\infty$ | [-] | Mainstream |
| c | [-] | Coolant |
| f | [-] | Film |
| p | [-] | Span |
| s | [-] | Pitch |
| w | [-] | Wall |

**Ethical Approval**
Not applicable

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