Numerical investigation of the effect of coherent structures on adiabatic film cooling effectiveness of a flat plate.

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Abstract. We present a numerical simulation of the flat plate film cooling setup with an elliptical nozzle with a 35° inclination angle. The baseline simulation mimics an experimental setup from [1]. We introduce a modification to the nozzle channel shape by including a backward step with a fixed width, while keeping the nozzle outlet shape fixed. The modification leads to an appearance of a recirculation zone inside the nozzle, which eventually becomes unstable developing a periodic vortex street formation. This change in the flow behaviour improves overall effectiveness of the film cooling by reducing the vertical component and promoting the lateral component of the turbulent diffusion.

1. Introduction
Film cooling is one of the most-widely used thermal protection methods for highly heat-loaded elements (e.g., turbine blades, thermally loaded elements of combustion chambers). The effectiveness of film cooling depends critically on the wall-normal diffusion of the coolant near the wall.

One way to increase the cooling effectiveness is to influence the structure of the near-wall flow of coolant exiting through the holes in a thermally loaded area.

Changing the shape of the coolant outlet or introducing a bluff bodies into the flow can lead to a significant improvement of the cooling effectiveness [2,3].

However, changing the outlet shape does not allow for a dynamic control of the mixing process since this modification is static. Another way of possible improvement of cooling effectiveness is by introducing coherent fluctuations into the coolant flow. The dynamic nature of coherent structures and non-linear resonant effects may lead to a positive change of the near-wall flow, attaching the coolant to the wall and reducing the vertical diffusion.

In the current paper we introduce coherent fluctuations into the flow by utilizing a fluid dynamic instability, developing in a wake behind an abrupt edge of a bluff body. The backward step with an abrupt edge is included into the nozzle channel, separating the main flow and the coolant. Behind the step the coolant and the main flow are mixing which leads to the formation of oscillations similar to von Kármán vortex street. This way of introducing the oscillations enables the control of their frequency and spatial scale by changing the blowing ratio of the coolant or the width of a bluff body. The described method does not require any additional devices for flow modulation and is very simple which makes it attractive for practical applications.

Current paper is devoted to numerical investigation of the effects of such nozzle modification on the film cooling effectiveness.
2. Computational methodology

Incompressible Large Eddy Simulation equations for momentum and heat transfer (1-3) with a dynamic sub-grid viscosity model [4], including the equation on the subgrid part of turbulence kinetic energy (5) were solved numerically.

\[
\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial}{\partial x_j} \left( p\delta_{ij} + \tau_{ij} \right) + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} \tag{1}
\]

\[
\frac{\partial T}{\partial t} + \bar{u}_j \frac{\partial T}{\partial x_j} = \frac{\partial}{\partial x_j} \left( \nu_T + \nu \right) \frac{\partial T}{\partial x_j} \tag{2}
\]

\[
\frac{\partial \bar{u}_i}{\partial x_j} = 0 \tag{3}
\]

\[
k_{sgs} = \frac{1}{2} \left( \overline{u_i^2} - \overline{u_i} \right) \tag{4}
\]

\[
\frac{\partial k_{sgs}}{\partial t} + \bar{u}_j \frac{\partial k_{sgs}}{\partial x_j} = -\tau_{ij} \frac{\partial \bar{u}_i}{\partial x_j} - \varepsilon + \frac{\partial}{\partial x_j} \left( \nu_T \frac{\partial k_{sgs}}{\partial x_j} \right) \tag{5}
\]

\[
\tau_{ij} = -2\nu_T S_{ij} + \frac{2}{3} \delta_{ij} k_{sgs} \tag{6}
\]

\[
\nu_T = c_v \overline{k_{sgs}} \Delta \tag{7}
\]

Where \( k_{sgs} \) is the subgrid energy, \( \nu_T \) is the subgrid turbulent viscosity, \( \tau_{ij} \) is the subgrid stress tensor, \( \varepsilon = C_{\varepsilon} k_{sgs}^{3/2} / \overline{\Delta} \) is the subgrid dissipation rate, \( \overline{\Delta} \) is the filter used, \( S_{ij} \) is the strain rate tensor, and \( c_v \) is the model coefficient calculated from a dynamic procedure. The presented model is more resource-intensive in comparison with the classical Smagorinsky model, and has a number of advantages, e.g., it saves the history of accumulation of subgrid energy, which makes the calculation of the coefficients of subgrid viscosity and diffusion more consistent.

Numerical solver pimpleFoam (modified by including turbulent heat transfer equation (2)) from OpenFoam open-source CFD package (www.openfoam.com)[5] was used for the current simulations. OpenFoam utilizes finite volume discretization of the fluid. The simulations were conducted with a second order central difference approximation in space and second order implicit Krank-Nicolson scheme in time.

3. Results and discussion

3.1. Model verification

To verify the numerical method we choose the comparison with an experimental study of the film cooling adiabatic effectiveness with inclined cylindrical coolant nozzles [1].

The simulation replicates the experimental configuration for the coolant blowing ratio \( M = U_c / U_\infty = 0.75 \) assuming the same densities of the coolant and the main flow. The temperature difference between the coolant and the main flow \( \Delta T = T_c - T_\infty = 10K \). The value of \( M = 0.75 \) had given the best thermal cooling performance for elliptical coolant outlets inclined by 35° in the experiment [1].
Figure 1. Adiabatic cooling effectiveness profile in the central axis of the channel: a) – experiment [1], b) – LES simulation, c) – simulation with a modified nozzle.

The Reynolds number was 2500 based on the diameter of the coolant nozzle and the coolant velocity. The Prandtl number was set to 0.75, mimicking the experimental conditions.

The computational domain was $25D \times 4D \times 10D$ in the longitudinal, transverse, and vertical directions, respectively ($D$ is the diameter of the nozzle). Periodic boundary conditions were set at the lateral boundaries of the domain mimicking an array of holes which were studied in the experiment.

A study of grid convergence has shown that the minimum required number of nodes to ensure convergence is $\sim 10^7$. In this case, the dimensionless coordinate of the node closest to the wall ($y^+$) should not exceed 10.

The results of comparing the adiabatic cooling effectiveness $\eta = (T_c - T_{wall}) / (T_c - T_e)$ (where $T_c$ is the temperature of coolant, and $T_{wall}$ is the temperature of adiabatic wall), obtained in the simulation and in the experiment are presented in Fig. 1.

Results show a good agreement with experiment. The simulation correctly reproduces the position of the point of reattachment of the jet at a distance of $\sim 3$ nozzle diameters from the outlet. We can conclude that the chosen numerical model is adequate for this configuration.

3.2. Investigation of influence shape of the nozzle on the cooling effectiveness
The main subject of the paper is to show how the change in the shape of the nozzle channel may affect the film cooling effectiveness while keeping the nozzle outlet shape the same.

The cylindrical nozzle channel was modified by introducing the horizontal rectangular channel which is morphed smoothly to an initial cylindrical shape (Fig. 2b). When entering the cylindrical part of the nozzle an abrupt edge was introduced to separate the horizontal channel and the main flow. The width of the channel was equal to the width of the step. The inlet velocity magnitude was kept the same for the simulation with initial and modified nozzles.

Fig.2a b shows the distribution of the adiabatic cooling effectiveness in the wall plane. It can be seen that introducing a backward step into a nozzle channel significantly improves the cooling effectiveness near the nozzle outlet (see also Fig 1c). This is achieved because of the effect of periodically shed vortices (coherent structures) which are developing behind the edge of the backward step in a stagnant region of the flow. The formed recirculation zone at the place of the jet mixing with the main flow is unstable (similar to the wake behind a bluff-body) leads to the occurrence of self-sustained oscillations and the periodic shedding of vortices into the region of the main flow. The
frequency of the vortex shedding $Sh = fD/U_c$ was close to 0.2 being the well-known value for the von Kármán vortex street.

The vortices then interact with the cooled wall. This effect locally intensifies the transfer of coolant toward the wall. Depending on the sign of vorticity the vortices are either attached to the wall or getting away from it while interacting with the main flow (Fig. 2d). The net effect leads to a stronger attachment of the coolant jet with its expansion in the transverse direction at the outlet of the nozzle. The change in the jet structure leads to its faster spreading in horizontal direction which is reflected in a stronger lateral diffusion of the coolant that in turn improves the cooling effectiveness far from the nozzle outlet (Fig. 1c, Fig. 2b).

![Figure 2](image_url)

**Figure 2.** Adiabatic cooling effectiveness: (a) in the case of a cylindrical nozzle, (b) in the case of a nozzle with a step; temperature isosurfaces ($T = 0.5(T_\infty - T_1)$) (c) for a nozzle without modifications, (d) for the case of a nozzle with a step.
Additional research is required to investigate the possible resonant effects if the flow is modulated at the frequency of vortex shedding. We assume that in this case a significant change in the jet structure may be possible with a strong influence on the cooling effectiveness.

Conclusion
The setup for generating coherent oscillations in the film cooling flow by introducing a backward step into the nozzle channel has been presented. It is shown that such setup might lead to a significant improvement in film cooling effectiveness because of the interaction process between the coherent vortices and the main flow. The authors have proposed a possible way of dynamic control of cooling effectiveness by changing the coolant blowing ratio or step width, leading to the change in the vortex shedding frequency and their spatial scale, respectively.

A numerical model used in the work is verified with the experimental data showing a good agreement.

The proposed method of inlet channel modification may be combined with classical methods of changing the coolant nozzle outlet shape or introducing the bluff bodies into the main flow with some possible improvement of the film cooling effectiveness.

The method is also perspective if the main flow contains some coherent oscillations, which is the case for a turbine blade or vane flows, where the blades rotation creates a periodic disturbance of the flow. In such case if the frequency of vortex shedding coincides with the frequency of the main flow some resonant effects may appear and change the near-wall flow structure significantly.

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