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ANALYSIS OF MODERN NUMERICAL APPROACHES TO FILM COOLING SIMULATION ON A FLAT SURFACE: TRENDS, ERRORS AND CORRELATION DEPENDENCIES

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An analysis of modern numerical methods for film cooling simulation on a flat surface, considering current CFD (Computational Fluid Dynamics) trends during 2019–2025, is presented in the paper. More than 25 recent studies devoted to 3D CFD simulations of film cooling effectiveness for various hole geometries – cylindrical, shaped, unsteady, and combined ones – are reviewed. The comparison of turbulence models, grid parameters, and validation methods against experimental data is provided. It is shown that even a small deviation in cooling effectiveness (± 0.02) can lead to temperature prediction errors exceeding 20 °C under real engine conditions. The study demonstrates that reverse-injection film cooling holes significantly increase effectiveness at high blowing ratios m, while forward-injection configurations perform better at low m. For shaped holes, the influence of the compound blowing angle β is found to be non-negligible and should be considered in engineering calculations. The importance of accounting for the ratio of specific heat capacities between coolant and mainstream gas during the scaling of laboratory data to engine conditions is emphasized. A comparative analysis of existing 1D correlations shows that the Baldauf formulas generally overpredict the effectiveness of cylindrical holes, while the Colban correlations underestimate that of shaped holes. This highlights the need for updated generalized dependencies that integrate modern CFD results and thermophysical parameters. Scientific novelty lies in the systematic review of modern CFD studies on film cooling, the identification of the influence of hole direction and blowing ratio m on cooling effectiveness, and the proposed inclusion of specific heat effects in scaling procedures.

Keywords: *film cooling, CFD modeling, blowing ratio, cooling effectiveness, gas turbine engine, gas turbine, combustion chamber.*

Introduction

Increasing the efficiency of turbine blade cooling systems without reducing their aerodynamic characteristics is one of the key areas of development in modern turbine engineering. Among the main methods of external cooling, film cooling occupies a prominent place, which allows reducing the heat flux to the blade surface by forming a cooling film with air escaping through perforation holes. At the same time, the accuracy of predicting the efficiency of film cooling directly affects the reliability and resource of turbine blades.

Thanks to the development of numerical methods of computational fluid dynamics (CFD), it has become possible to reproduce complex three-dimensional flows of the cooler and the main flow, however, the results of such calculations often significantly depend on the choice of turbulence models, the structure of the computational grid, the conditions of the boundary surfaces and the temperature range. This determines the relevance of systematizing modern CFD studies, analyzing their errors and comparing them with experimental data in order to refine engineering methods for assessing the film cooling efficiency.

Gas temperatures at the outlet of the combustion chamber of modern gas turbine engines have reached 2000–2100 K, but they significantly exceed the operating temperatures of existing materials. That is why, to ensure reliable operation of the blades, it is necessary to develop their cooling technologies. For this, along with convective (internal) one, film (external or barrier) cooling is used, which consists in releasing the coolant onto the surface of the blades being protected in order to push hot gas away from them. This reduces the heat flow from the gas to the blade. Modeling and calculation of film cooling at the early stages of design was and remains an urgent and difficult problem. At modern gas temperature levels, the error in determining the film cooling efficiency (1) of only about 0.1 leads to an error in determining T_f of more than 100 °C. [1].

$$\eta = \frac{T_g - T_f}{T_g - T_c}, \tag{1}$$

where T_g – gas temperature; T_f – temperature of the film, which is a mixture of gas and cooling liquid, i.e. air with a temperature T_c.

It should be noted that the inadmissibility of such errors and the importance to accurately determine the efficiency of film cooling of blades is confirmed by Riccardo Da Soghe et al. [2], according to which a decrease in the temperature of the cooling liquid by only 15 K can increase the service life of the rotor blades by half. At the same time, D. G. Bogard and K. A. Thole [3] emphasize that a decrease in the temperature of the blade profile by only 25 °C can increase the service life of the blades by half, although the paper deals with ground-based plants. According to [4], when the gas temperature is raised by 40 °C and temperature of the cooling air – by 18 °C, the estimated service life of the high-pressure turbine blade reduced by more than half.

The efficiency of film cooling is influenced by a number of factors, namely the location of the perforation holes relative to the gas flow (angles of inclination of the hole axis to the wall *α* and to the direction of the main flow β), the shape and density of the perforation holes of film cooling, the number of rows and the distance between the rows of holes, the relative length of the holes, the curvature and roughness of the surface, the presence of a thermal barrier coating, as well as the blowing ratio *m* of the film cooling hole

$$m = \frac{\rho_c \cdot w_c}{\rho_g \cdot w_g}, \quad (2)$$

where ρ_c and ρ_g – air and gas density; w_c and w_g – air and gas velocities.

The influence of almost all of the above factors on the efficiency of film cooling is verified experimentally or numerically on a flat plate. Today, numerical 3D CFD calculations on a flat surface are a common process for verifying new types and systems of film cooling. One of the important issues of such calculations is the validation of the numerical method, i.e. the selected grid, turbulence model and other calculation options with the results of experimental data. Some authors, giving an example of a satisfactory coincidence of the calculation results with the results of experiments, give an error value of the cooling efficiency of about 10%. This immediately raises the question of how justified the error estimation is for such a relative quantity as the cooling effectiveness *η*, expressed in relative units, i.e., in percent. Of course, when repeating the experiment with low temperatures of the cooler and gas, such an error is insignificant, but when transferring this error in determining the cooling efficiency to real engine conditions without changes, the situation changes significantly. It is obvious that, taking into account all of the above, at a film cooling efficiency level of $\eta \approx 0.5$, such an error of 10% can reach 50 °C in determining T_f, while at an efficiency of $\eta \approx 0.1$ it can reach only 10 °C.

In this aspect, the paper [5] is of great interest, as it is devoted to highlighting the issue of scaling the results on the plant to the expected results on the engine according to the *TR* (temperature ratio) criterion, which is rarely found in the literature and which, in this paper, is presented as the ratio of the temperature of the main flow to the temperature of the cooling air and was in the range of 0.5–2.3. The authors considered both internal and external film cooling and the result is given by the low-order model, which shows that when the combined scaling of the results is performed when going from a conventional plant with a typical value of *TR*=1.20 to an engine with a parameter of *TR*=2.0, the value of the total cooling efficiency of the stator vanes (not film cooling) increases from 0.418 to 0.450.

Perhaps this is one of the reasons for the appearance of another parameter when generalizing experimental and numerical works on the study of the film cooling efficiency. Thus, in recent years, the parameter *ACR* – advective capacity ratio [6, 7] (or its first name *HCR* – heat capacity ratio by Marc D. Polanka and J. L. Rutledge [8]) is found in scientific papers quite often. This parameter, in addition to the density and velocity of the coolant and gas, also operates on their specific heat capacity c_p (3)

$$ACR = \frac{\rho_c \cdot c_{pc} \cdot w_c}{\rho_g \cdot c_{pg} \cdot w_g}. \quad (3)$$

The *ACR* parameter is superior to the blowing ratio *m* or *I* – momentum ratio (4), or *DR* – density ratio (5), but it also has its drawbacks. Thus, according to the paper, at a value of the momentum *I* greater than 0.5 the *ACR* parameter loses its ability to accurately simulate the experiment

$$I = \frac{\rho_c \cdot w_c^2}{\rho_g \cdot w_g^2}; \quad (4)$$

$$DR = \frac{\rho_c}{\rho_g}. \quad (5)$$

Nevertheless, nowadays it is the blowing ratio m that is the main generalizing parameter in the study of the efficiency and other parameters of film cooling.

The modern (2019–2025) papers related to 3D CFD analysis of the efficiency of film cooling on a flat surface are analyzed in this paper. Current trends in such calculations and their results regarding cooling efficiency are presented. Data on the calculation parameters (experiment), grid, turbulence model and errors in determining the efficiency of film cooling are summarized in a table. In another chapter, some 1D correlations in determining the efficiency of film cooling on a flat surface are analyzed.

Aim of the paper

The purpose of this publication is to review current papers on 3D CFD calculations of film cooling efficiency on a flat plate for various types of holes, analyze the parameters of 3D calculations and analyze the error in determining the film cooling efficiency, as well as analyze 1D correlation dependencies for determining the film cooling efficiency on a flat plate.

3D CFD calculations of film cooling on a flat surface

Undoubtedly, the most widespread film cooling holes in the world today are the classical cylindrical holes, which are well studied and recognized as the simplest in terms of manufacturing. In recent years, numerical CFD studies of these holes on a flat surface in their pure form have been carried out only for cases of the basic option of further modernization of the hole shape or for verification of the calculation model. However, recently, many authors have used the cylindrical hole not in its pure form, but for CFD studies of the influence of additional factors on the cooling efficiency, i.e., the combination of a cylindrical hole with another geometric feature (Fig. 1). Such factors may include trench blowing [9–11] or craters blowing [12, 13], the use of upstream barriers for greater coolant penetration into the wall layer [14, 15] or downstream vortex generators [16], the effect of external blocking of the cylindrical hole by combustion products [17], or the influence of the internal structure of the coolant flow (before entering the hole) on film cooling [18–20].

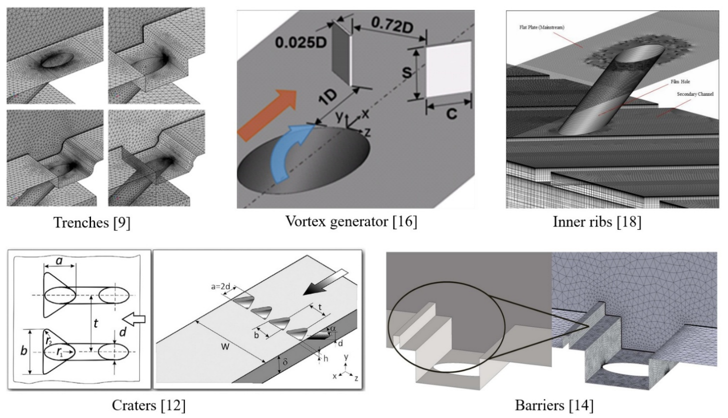


Fig. 1. CFD study of cylindrical film cooling holes with the influence of additional factors on a flat surface

The abovementioned examples using trenches, craters, preliminary barriers or vortex generators have not yet found widespread use in gas turbine blades. In addition to the possible decrease in manufacturability and strength of the blade, such solutions may have other negative effects, such as, for example, an increase in the heat transfer coefficient on the gas side, which can partially or completely offset the positive effect of the modernized (relative to the usual cylindrical hole) film cooling.

Nowadays, one of the most successful technologies for film cooling of blades is the use of profiled (shaped) holes, which allows to reduce the speed of the coolant at the exit of the hole by 2–3 times by increasing the outlet cross-section and expanding the jet in the transverse direction, which significantly increases the cooling efficiency and improves surface coverage [21]. The most common among the profiled holes are fan-shaped ones. They can expand not only in the lateral direction, but also in the vertical plane (laidback fan-shaped).

One of the most popular shaped holes for film cooling, belonging to the laidback fan-shaped group, is the 7-7-7 hole, in which two angles of expansion in the lateral β_{lat} and one in the forward β_{fwd} directions are equal to 7° each, which explains its name (Fig. 2). The paper [22] presents a numerical study of the effect of surface roughness of such a hole on the cooling efficiency. In the figure provided by the authors, the angle

α=30°, β_{lat}=7°, β_{fwd}=7°, the length of the hole is 6D, of which the length of the cylindrical section is 2.5D, and the length of the expansion section is 3.5D. The diameter of the hole was 7.75 mm. The authors showed that surface roughness strongly affects the cooling efficiency. At the blowing ratio m=1.5, the surface-averaged cooling efficiency of the hole with coarse roughness dropped by 44% compared to the smooth one. At a high blowing ratio m=3.0, the drop in cooling efficiency is 59%. The authors explain this effect by the fact that the roughness of the surface of the inner walls of the hole causes the formation of thicker boundary layers inside the cooling hole, which changes the core of the jet flow at the outlet of the cooling hole. Thus, the injected coolant mixes more with the hot gas of the main flow, and the efficiency of film cooling decreases.

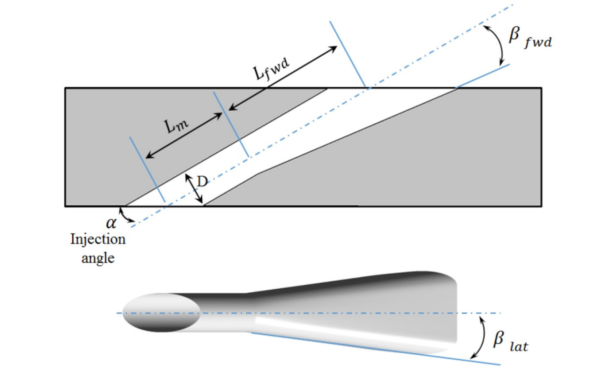


Fig. 2. Geometry of a fan-shaped hole with vertical expansion 7-7-7 (β_{lat}=7°, β_{fwd}=7°) [22]

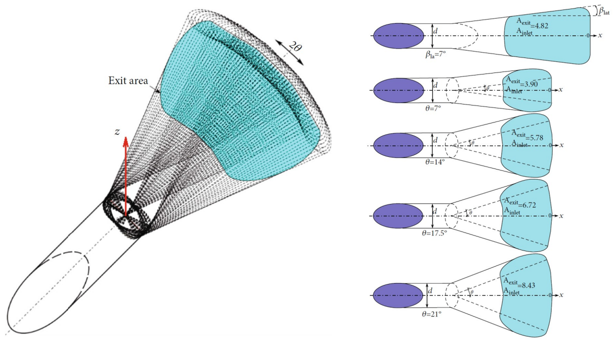


Fig. 3. Geometry of a fan hole with vertical expansion 7-7-7 [23]

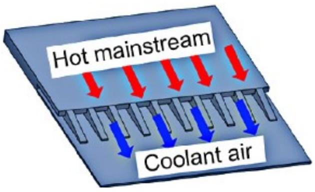
In the paper [23], the 7-7-7 hole and new types of curved holes based on it with lateral angles of deviation from the axis θ=7°, 14°, 17.5° and 21° are compared (Fig. 3). The expansion section is created by rotating a circular hole on an inclined plane around an axis normal to this plane. This shape was designed to reduce the negative impact of kidney vortices by properly distributing the coolant flow exiting the hole exit area. Based on this, the authors draw the following conclusions: with an increase in the angle θ, the efficiency of film cooling increases, and the highest efficiency indicators are achieved at the angle θ=21°, while at the angle θ=7° the efficiency indicators are the worst due to the small area of the hole at the exit. Holes with angles θ=14°, 17.5° and 21° demonstrate higher cooling efficiency than the standard 7-7-7 hole.

As with the classical cylindrical hole, a significant number of CFD studies on a flat surface address the effect of various additional factors on the efficiency of the already standard 7-7-7 fan-shaped hole. Only in the last year of 2025, several papers from the ETC and ASME conferences can be named. Thus, in [24] the effect of the Reynolds number on the efficiency of the 7-7-7 hole with blowing into the trench is studied, and in [25] – the effect of the protrusion upstream above the 7-7-7 hole, and in [26] – the effect of the internal cross flow on the cooling efficiency of the 7-7-7 hole.

The requirements for the trailing edge of the blade are no less important than for the pressure side and the suction side, which is due to its geometric and aerodynamic limitations. To reduce aerodynamic losses, the trailing edge of the blade should be thin enough. However, this requirement contradicts the provision of an effective cooling system of the trailing edge, which cannot be fully ensured with its fine execution. Often, the search for a compromise between cooling and aerodynamics leads to the fact that it is the trailing edge that has the maximum blade cross-section temperatures. A cutout of the material on the part of the pressure side in the trailing edge, known as a "cutback", helps to reduce the thickness of the trailing edge, while at the same time it has slot film cooling properties. This type of slot film cooling is studied on a flat surface in [27] using the SAS (Scale Adaptive Simulation) method, capable of reproducing periodic phenomena and distinguishing coherent structures of vortices. The authors studied several options of the geometry of the cutout, namely straight and rounded forms of the trailing edge, as well as different shapes of rod columns in the channel – cylindrical and elliptical ones. According to the authors, the rounded shapes of the edge demonstrate an obvious increase in cooling efficiency at the back of the cutout surface and reduce the intensity of mixing. Elliptical rod columns, oriented in flow, significantly increase the cooling efficiency compared to basic cylindrical ones, while the same columns, which are oriented in height, drastically reduce the total cooling efficiency (Fig. 4).

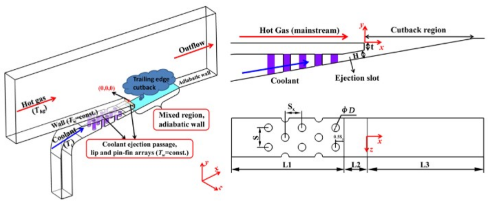
A special role in the application of promising types of film cooling holes is played by the development of additive 3D printing technologies, which allows to consider innovative film cooling systems. These holes cannot be obtained by conventional cutting in the blade body.

In the paper [28], Michael T. Furgeson et al. obtained holes with a complex shape with protruding dune-shaped surfaces on both sides of the hole as a result of optimizing the basic profile of the 7-7-7 hole on a flat surface (Fig. 5). As the authors note, these elevations affect the main flow, forming a pair of vortices rotating in opposite directions. These vortices complicate the separation of the cooler from the outer surface and at the same time increase the spreading of the jet. Thus, the calculated cooling efficiency of the two optimized shapes is significantly higher than the standard 7-7-7 hole.



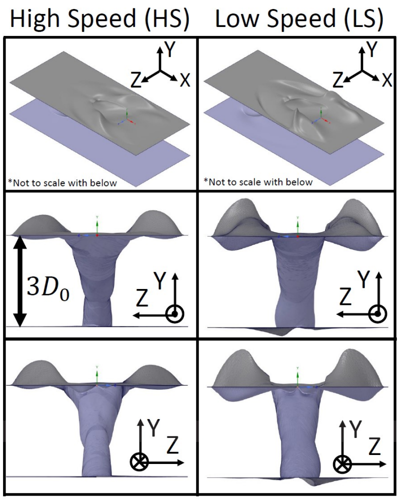
a

Dimensions	t	H	S	S_x	D	L_1	L_2	L_3
mm	4	4	10	8.66	4	58	12	60



b

Fig. 4. Slot film cooling of the trailing edge:
a – general view of the "cutback" section (from the Internet);
b – model of numerical study of slot film cooling
with rod columns according to [27]



a b

Fig. 5. Perforation hole design obtained according to [28] based on a 7-7-7 hole for Mach numbers:
a – 0.75 (high speed); b – 0.15 (low speed)

In [29] and [30], H. Sharma et al. numerically investigate a type of "sweeping jet" (SJ) film cooling hole on a flat surface, a new non-stationary cooling technology that uses periodic oscillations of a coolant jet from side to side due to two periodic vortices created inside the channel and rotating in opposite directions. The oscillation of the jet improves the film coverage of the surface. In [29], two types of holes, namely a stationary straight and a non-stationary jet hole (Fig. 6), are investigated in two options – with forward (downstream) and reversed (counter-stream) configurations in a non-stationary (URANS) setting. It is somewhat surprising, but, considering the results of the calculations, it can be concluded that with the blowing ratios m=0.7, m=1.0, m=2.0, it is the forward configuration, i.e. directed along the flow, that demonstrates the best lateral time-averaged cooling efficiency, and this gain is quite significant over the entire range x/d from 0 to 60. Only at a small blowing ratio m=0.35 the sweeping jet hole shows slightly better efficiency, but also with forward configuration. In the reversed configuration (directed against the flow), the sweeping jet hole and the forward hole demonstrate relatively low time-averaged cooling efficiency at all blowing ratios.

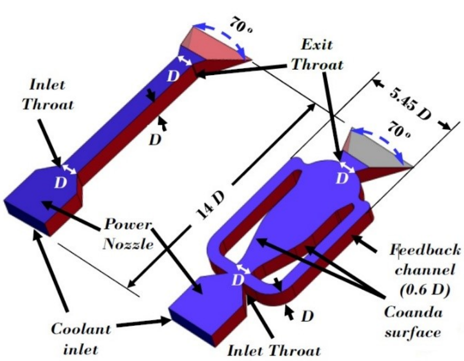


Fig. 6. Straight hole and sweeping jet hole studied in [29]

However, in contrast to the results of [29], the reversed configuration of film cooling holes seems to give a positive effect more often and is the greater the higher the blowing ratio m is. The reason is the possibility of obtaining a more uniform coverage of the surface by the coolant with a simultaneous decrease in the separation of the coolant jet from the surface.

In the paper [31], three types of holes are numerically studied, namely, a classic cylindrical perforation hole, a shaped profiled hole expanding in the lateral and forward directions, and a fan-shaped hole (Fig. 7). All of them are inclined at an angle α=35° with a step of 3D. In addition, all types are studied in two options - forward (downstream) and reversed (counter-stream) configurations at eight blowing ratios from 0.25 to 2.0. Reversed injection, unlike forward one, forms vortices that quickly collapse, and therefore there is no mixing of the main and cooling flows, which improves the uniformity of cooling and its efficiency. Thus, according to the data of the paper, for the blowing ratio *m*=1, the transition from the forward configuration of the cylindrical hole to the reversed one can increase the efficiency of surface cooling by 86.4%, namely from 0.131 to 0.245. Thus, the higher the blowing ratio is, the more benefit from the reversed configuration of the cylindrical hole. This is due not only to the well-known fact of a decrease in the efficiency of the forward cylindrical hole with an increase in the blowing ratio, but also to a continuous increase in the cooling efficiency of the reversed cylindrical hole with an increase in the blowing ratio. For the other two profiled types of holes made in the direction opposite to the gas, the surface cooling efficiency also increases with an increase in the blowing ratio. Thus, with the blowing ratio *m*=2.0, the maximum surface cooling efficiency of the reversed holes is achieved, which for a cylindrical hole is 0.32, for a hole expanding in the lateral and forward directions – 0.50, and for a fan-shaped hole – 0.55. An interesting nuance that should be noted is that according to the paper, there are blowing parameters below which the surface cooling efficiency of the reversed configuration will be lower than the forward configuration: for a cylindrical hole – this is *m*=0.5, for a hole expanding in the lateral and forward directions – this is *m*=0.75 and for a fan-shaped hole – this is *m*=1.25.

Similar data to the above were obtained in [32]. The authors also note that at low blowing ratios, namely at *m*=0.25 and *m*=0.5, classical cylindrical holes directed along the flow have an advantage in cooling efficiency, and at high blowing ratios (*m*=1.0 and *m*=1.5) reversed holes are more effective. Moreover, at *m*=1.5, the overall efficiency is higher for the reversed hole by 677% compared to the forward one.

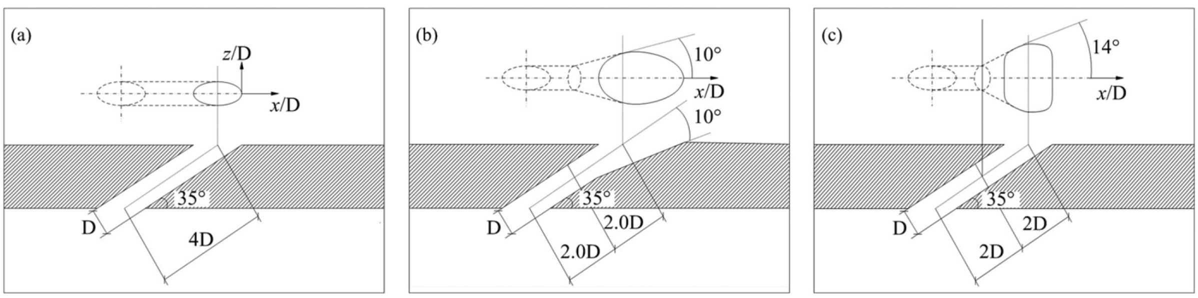


Fig. 7. Film cooling holes according to [31]

In [33], a numerical study of the efficiency of cylindrical holes is carried out in comparison with fan holes of the FDH ("Forward diffuse hole") type with a forward expansion angle of 15°, oriented at an angle β=0°, 45°, 90°, 135° and 180° to the gas flow at different blowing ratios *m*. The inclination angles *α* in all cases were equal to 35°. The studies were conducted for two blowing ratios: *m*=0.6 and *m*=1.25. FDH holes demonstrated the highest plane-averaged cooling efficiency when they were arranged at an angle of β=90°, namely 0.377 at *m*=0.6 and 0.483 at *m*=1.25. Cylindrical holes showed the highest plane-averaged cooling efficiency when they were arranged at an angle of β=180° (Fig. 8). The results presented in this paper partially contradict with [21], where it is noted that for shaped holes, unlike cylindrical ones, the effect of the complex angle on the efficiency of film cooling is insignificant, it can be ignored in engineering calculations. The FDH hole turned out to be even more sensitive to the complex angle than the classic cylindrical hole.

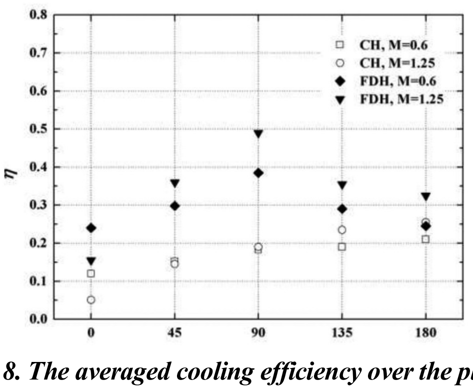


Fig. 8. The averaged cooling efficiency over the plane depending on the angle β according to [33] for a round hole (CH) and a fan hole (FDH) for two injection parameters

Table 1. Overview of calculation parameters in modern papers on the study of film cooling on a flat surface

Year	Author	Hole type	DR	T_g, K / T_c, K	Turbulence of the main flow, %	Calculation grid	Method / Turbulence Model	Software package	Error in validating cooling efficiency with experiment
2019	Z. Zhao et al. [31]	C, S	1.60	370 / 310	2.5	ST	RANS / *k*-ε realizable	–	+0.02 (C) good (SA)
2019	D. Zheng et al. [14]	T	0.97	298 / 318	2.0	T	RANS / *k*-ε standard	CFX	good (C)
2020	A. Khalatov et al. [12]	K	1.20	293 / 353	1.0	T	RANS / *k*-ω SST	CFX	+0.04 (L)
2020	S. Hussain, Xin Yan [15]	C	1.60	298 / 188	0.2	ST	RANS / *k*-ω	CFX 11.0	+0.20 (C) -0.04 (L)
2020	C.S. Lee et al. [16]	C	1.60	298 / 188	-	ST	RANS / *k*-ε realizable	Fluent	–
2020	B. Li et al. [18]	C	–	–	0.9	ST	RANS / *k*-ε realizable	–	good (L)
2020	J. Wang et al. [32]	C	1.20	300 / 250	–	ST	RANS / *k*-ε standard	Fluent 18.0	+0.04 (C)
2020	S. Tamang et al. [33]	C, S	–	300 / 188	0.2	ST	RANS / *k*-ω SST	Fluent 1-9.1	good (C)
2020	A. Zamiri et al. [22]	S	1.50	295 / 196	0.5	ST	LES / WALE	CFX 19.3	good (B)
2020	Y. Li et al. [27]	SC	–	500 / 293	7.0	P	SAS	Fluent 18.0	good (SA)
2021	R. Zhang et al. [9]	T	1.08	321 / 296	–	T	RANS / *k*-ε realizable	–	good (SA)
2021	A. Bakhshinejad Bahambari et al. [10]	T	–	300 / 320	3.0	G	RANS / *k*-ε realizable	Fluent 18.0	+0.02 (SA)
2022	F. Yang, Mohammad E. Taslim [23]	S	0.97	320 / 300	3.9	ST	RANS / *k*-ε realizable	Fluent	-0.06 (Sa) -0.08 (P)
2022	H. Zhu et al. [19]	C, P	–	303 / 293	1.2	ST	RANS / *k*-ε realizable	Fluent 15.0	-0.03…+0.03 (L)
2022	R. Liu et al. [20]	C	–	600 / 303	–	T	RANS / *k*-ω SST	CFX 19.3	–
2023	Т. В. Доник et al. [13]	K	0.83	303 / 363	1.0	N	RANS / k-ω SST	–	+0.06 (SA)
2023	М. Данилов, Т. Доник [17]	C	–	293 / 353	1.0	T	RANS/ *k*-ω SST	CFX 19.2	good (SA)
2023	L. Fischer et al. [11]	T	2.00	373 / 187	1,0	T	RANS / *k*-ω GEKO (adapted)	Fluent 22.1	-0.1…+0.05 (L)
2024	H. Sharma et al. [29]	N	1.80	300 / 167	5.0	T	URANS / *k*-ω SST	Fluent 21.0	–
2025	H. Sharma та ін. [30]	N	1.80	300 / 167	0.5	P	URANS / *k*-ω SST	Fluent 21.0	–
2025	G. Barigozzi et al. [24]	S	–	295 / –	–	G	LES / WALE	Fluent 23.1	good (L)
2025	G. Barigozzi et al. [25]	S	1.50	295 / 196	3.0	G	LES / WALE	Fluent 21.1	–
2025	M. T. Furgeson et al. [28]	S	–	315 / –	≤1.0	P	RANS / *k*-ε realizable	Fluent	+0.05…0.15 (P)
2025	S. Avcun et al. [26]	S	1.50	295 / –	0.5	P	RANS / *k*-ε realizable	Fluent	good (L)

Hole type: C – cylindrical holes, T – cylindrical holes with blowing into the trench, K – cylindrical holes with blowing into craters, P – cylindrical paired holes, S – shaped holes, SC – slotted cut on the pressure side (cutback), N – non-stationary holes according to the principle of operation.

Calculation grid: ST – structured (block) grid, T – tetrahedral grid, P – polyhedral (polyhedral grid), N – unstructured grid, G – hybrid polyhexahedral or tetrahexahedral grid.

Comparison with experiment: (C) – along the centerline, (L) – lateral averaged, (SA) – spanwise averaged, (A) – area averaged, (B) – visual comparison of the cooling efficiency distribution on a flat plate.

The modern, i.e. 2019–2025, papers [9–33] presented in this chapter concerned the calculation of various types of film cooling on a flat plate. Some of the main calculation parameters (the ratio of the density of the coolant to the density of the main flow *DR*, the temperature of the main flow T_g and the coolant T_c, the turbulence of the main flow), as well as the type of calculation grid and the turbulence model with the software package used, obtained by the authors of the papers published during 2019–2025, are summarized in Table 1. The main category in this table is the determination of the absolute, not relative, error in the calculation of the cooling efficiency when compared with the experiment.

The magnitude of the error in Table 1 when compared with the experiment is an absolute value with a plus sign (if the calculation of the cooling efficiency exceeded the experimental value) or minus sign (when the calculation is lower than the experiment). A dash instead of an error value means that the comparison was made according to other criteria, for example, according to the flow rate or heat transfer coefficient. The table shows the maximum absolute error among the various blowing parameters while maintaining its stable trend, i.e. this is not a local "peak", but a clearly pronounced difference between the experiment and the calculation. The difference in cooling efficiency, less than 0.02, is marked as "good".

It should be noted that these are approximate comparison data with the experiment, which do not take into account the experimental error tolerances [10], or good agreement with the calculated data of other authors and poor agreement with the experiment [15], or the difference between the geometric and regime parameters of the calculation and the experiments that were taken as a basis.

Analyzing Table 1, several conclusions can be drawn:

– RANS methods are still used in the vast majority of cases. The two most popular turbulence models for modeling various types of film cooling among RANS methods are the two-parameter *k*-ε realizable and *k*-ω SST models;

– all calculations were performed at the same temperatures at which the experiment was performed, therefore, the temperatures of conditional air and conditional gas generally do not exceed 350 K and are quite close to each other;

– only in half of the cases the estimated error between calculation and experiment is less than 0.02, which in the conditions of a modern engine can mean an error of up to 20 °C in determining the film temperature.

1D correlations for determining the efficiency of film cooling for a flat plate

In the framework of engineering work when designing a cooled crown at the stage of preliminary design, a tool is needed for fast and fairly accurate calculations of the temperature state of a number of proposed cooling options to select the optimal design. The use of a full three-dimensional CFD model is expensive and time-consuming. At the early stages (conceptual or preliminary design) it makes sense to carry out dozens of calculations on simplified models.

In 2002, Baldauf et al. [34] presented the results of experimental studies of the efficiency of film cooling behind a series of cylindrical holes located on a flat plate. Measurements were carried out in a fairly wide range of geometric and operating parameters: the angles of inclination of the hole axis to the wall α=30°, 60°, 90° and to the direction of the main flow β=0°, with a relative pitch of the holes *t*/*D*=2, 3, 5, with a relative longitudinal length downstream of the flow *x*/*D*=0–80, with a parameter *DR*=1.2, 1.5, 1.8, blowing ratio *m*=0.2–2.5, Reynolds numbers Re=6800–14000, which were determined by the diameter of the hole and the parameters of the main flow. The turbulence of the main flow was 1.5% and 4.0%. As a result of generalizing the experimental data, the authors obtained empirical relations for calculating the efficiency of film cooling by a row of cylindrical holes on a flat plate.

In the paper of Baldauf et al. an example of calculating the efficiency of film cooling is given. The calculation of the parameter b_0 according to formula (31), given in this paper, showed that the calculation results do not coincide with the value of this parameter, given in the example. Comparison of the results of calculating the efficiency of film cooling at different operating and geometric parameters demonstrated a better coincidence of the calculation results with the experimental results when artificially changing the parameter b_0 of the formula.

When comparing the results of the experimental work of K. Watanabe et al. [35] with the results of the Baldauf formulas for holes at an angle of α=30° and with a relative pitch of 5D, but with the parameter *DR*=0.9, which is somewhat beyond the parameters studied in the Baldauf paper, it can be concluded that the lateral efficiency of film cooling obtained by the Baldauf formulas at low blowing ratios *m*=0.5 and *m*=1.0 is on average 0.04 higher than in the experiment, and the maximum difference is at *x*/*D*≈7, where the Baldauf formulas demonstrate maximum efficiency. At high blowing ratios m=1.5 and m=2.0, this difference is halved. An experimental study for the same holes at an angle of α=30° and with a relative pitch of 5D is given in comparison with the Baldauf results in the paper of U. Sandri et al. [36]. The results according to Baldauf also give a slightly higher efficiency than in the experiment at x/D>5, but in this case the difference does not exceed 0.02 anywhere, which can be called a good agreement. The discrepancy between the calculations and the Baldauf results at small values of x/D at the blowing ratios m=0.5 and m=1.0 is also demonstrated in [37]. It is shown that some experimental data are also lower than the Baldauf results over the entire range of x/D at m=1. Therefore, it can be concluded that in most cases the Baldauf method gives overestimated results of the efficiency of film cooling of cylindrical holes.

In 2011, Will F. Colban et al. [38] presented the correlation dependence (6–7) for profiled perforation holes with an angle of inclination of the hole axis to the wall α=30°. The formulas also have a fairly significant range of application for various geometric and operating parameters: blowing ratio m=0.2–2.5

$$\overline{\eta} = \frac{1}{\frac{P}{t} + C_1 M^{C_2 \xi C_3}}, \tag{6}$$

in which

$$\xi = \frac{4}{\pi} \frac{X/D \cdot P/D}{M \cdot AR}. \tag{7}$$

In the paper, the authors note that these formulas give a result that is in good agreement with the experimental results. However, in the abovementioned paper by U. Sandri et al. [36], the results of calculating the profiled hole of the 7-7-7 film cooling by the correlations of Will F. Colban et al. [38] demonstrate clearly underestimated results compared to the experiment. Moreover, the lateral cooling efficiency according to the experiment is on average 0.1 higher than according to the Colban correlations over the entire range x/D=0–20 and for all the studied blowing ratios m=0.5–1.5. It should be noted that the trend of the cooling efficiency according to the formulas is close to the experimental data (Fig. 9).

In [39], it is also noted that the available correlations for calculating profiled holes, including the Colban correlation, tend to underestimate the cooling efficiency.

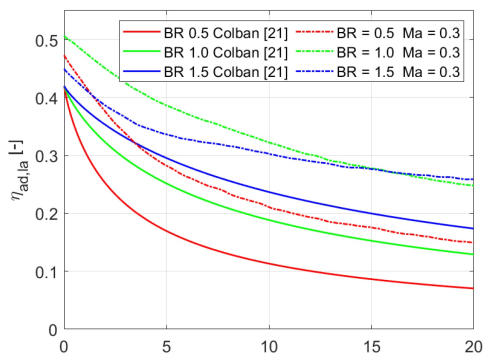


Fig. 9. Comparison of the calculation of the cooling efficiency of the profiled hole 7-7-7 according to the Colban formulas and according to the experiment at the Mach number of the main flow Ma=0.3 [36]

It is also emphasized in the paper that there is a very large deviation between the different correlations and that no correlation can give an acceptable prediction of the efficiency of the reference data set for the entire range of studied parameters. Also, no correlation can be defined as the "best", but this paper indicates clearly false correlations, among which the first work by Baldauf (1997) and Brown (1979) can be found.

Prospects for further research

Further development of the topic involves:

– creation of an extended CFD calculation database for various types of film cooling holes in conditions close to the real parameters of a gas turbine engine (T_g>1500 K, Ma>0.5);

– development of new generalized dimensionless criteria that will include the influence of heat capacity, density and momentum of the coolant;

– formation of refined 1D correlations for engineering prediction of film cooling efficiency;

– verification of the reliability of CFD modeling results through direct experimental studies at high temperature conditions.

The implementation of these directions will allow to increase the accuracy of prediction of the thermal state of blades and the reliability of turbine elements in modern gas turbine engines. Thus, the systematization of modern CFD studies of film cooling will allow to create a method of calculating film cooling for various shapes of holes and their location in the body of gas turbine blades.

Conclusions

1. The analysis of modern CFD studies of film cooling on a flat surface showed that the vast majority of papers use RANS methods with k-ε realizable and k-ω SST turbulence models.

2. The structure of the computational grid (structured or unstructured) is not a decisive factor in ensuring the accuracy of the results, instead, the boundary conditions have a significant impact.

3. A regularity of the influence of the direction of the film cooling holes was revealed: the reversed configuration provides an increase in efficiency at high values of the blowing ratio m, while the forward configuration is more effective at small m.

4. For shaped (profiled) holes, the influence of the complex blowing angle β is significant and must be taken into account in the engineering design of cooling elements.

5. In most CFD studies, calculations are performed at low gas and coolant temperatures (up to 350 K), which does not take into account the influence of the real ratio of specific heat capacities of the media. When scaling the results to engine conditions, it is necessary to introduce corrections for c_p, otherwise systematic overestimation or underestimation of efficiency is possible depending on the type of holes.

6. An attempt to fix the cooling efficiency obtained on a flat plate and scaled by the blowing ratio without taking into account c_p for engine conditions threatens to shift the cooling efficiency graph by the scaled parameter to the right. If we assume that the cooling efficiency of cylindrical holes decreases with increasing blowing ratio, and the cooling efficiency of shaped holes, on the contrary, increases, then we can conclude that when moving from the plant to the engine, if the value of c_p is neglected, the cooling efficiency of cylindrical holes is underestimated and the efficiency of shaped holes is overestimated. The opposite is also true: when taking into account c_p, the efficiency of film cooling with cylindrical holes in engine conditions should increase somewhat, and for shaped holes it should decrease (compared to calculations on a flat plate).

7. Analysis of existing correlations showed that Baldauf formulas [34] mostly overestimate the cooling efficiency for cylindrical holes, while Colban [38] formulas underestimate it for shaped holes. This confirms the need to develop new empirical models based on modern CFD results and taking into account the thermophysical properties of the working media.

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Аналіз сучасних чисельних підходів до моделювання плівкового охолодження на плоскій поверхні: тенденції, похибки та кореляційні залежності

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У статті проведено аналіз сучасних чисельних методів моделювання плівкового охолодження на плоскій поверхні з урахуванням тенденцій розвитку CFD-технологій у 2019–2025 рр. Розглянуто понад 25 публікацій, присвячених тривимірним (3D CFD) розрахункам ефективності плівкового охолодження для різних типів отворів — циліндричних, фасонних, нестаціонарних та комбінованих. Наведено порівняння застосовуваних моделей турбулентності, параметрів сітки та методів валідації з експериментальними даними. Показано, що навіть незначна похибка у визначенні ефективності охолодження (± 0,02) може спричинити відхилення понад 20 °C у прогнозі температури плівки при реальних умовах двигуна. Встановлено, що зворотне виконання отворів плівкового охолодження забезпечує суттєве підвищення ефективності при великих параметрах вдуву m, тоді як пряме виконання є переважним для малих m. Для фасонних отворів вплив складного кута вдуву β не є незначним і повинен враховуватися в інженерних розрахунках. Виявлено необхідність урахування відношення питомих теплоємностей газу та охолоджувача при масштабуванні результатів з лабораторних до двигунних умов. Здійснено порівняльний аналіз відомих 1D-кореляцій: показано, що формули Baldauf переважно завищують ефективність охолодження циліндричних отворів, а залежності Colban — занижують для фасонних. Це вказує на потребу розробки оновлених узагальнених залежностей, що враховують сучасні CFD-дані та параметри теплоємності. Наукова новизна роботи полягає у систематизації сучасних CFD-досліджень плівкового охолодження, встановленні впливу напрямку отворів і параметра m на ефективність охолодження, а також у пропозиції врахування теплофізичних властивостей середовищ при масштабуванні результатів.

Ключові слова: *плівкове охолодження, CFD-моделювання, параметр вдуву, ефективність охолодження, газотурбінний двигун, газова турбіна, камера згоряння.*

Література

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