

RESEARCH INTO THERMAL EFFICIENCY OF FILM COOLING ALONG COMBUSTION CHAMBER WALL OF LOW-THRUST ROCKET ENGINE

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The paper focuses on experimental study of the film cooling efficiency in combustion chambers of liquid propellant low-thrust engines. A completeness rate of the research into different parameters affecting the thermal efficiency of film cooling is analyzed. The thermal efficiency proves to be mostly influenced by such factors as a coolant mass flow-rate, a coolant feed slot design, and flow parameters of both the main flow and a cooling component. Combustion chamber pressure produces slight effect on the film cooling thermal efficiency. Guidelines for film cooling in low-thrust rocket engines are presented. The authors use the results of both Russian and foreign studies, which are publicly available.

Keywords: low-thrust rocket engines, thermal efficiency of film cooling, chamber wall temperature.

One of the most important current trends in rocket propulsion engineering is the design of reliable and highly efficient low-thrust rocket engines (LTRE) powered by environmentally friendly nonhypergolic propellant components.

High efficiency (high specific impulse) can be obtained in case the propellant composition is close to the stoichiometric ratio. At this ratio the temperature of combustion products is about 2800...3500 K (at $p_k = 1$ MPa chamber pressure and the excess oxidizer ratio $\alpha = 1$ for a propellant component, kerosene + O₂, kerosene + H₂O₂, H₂+O₂, CH₄+O₂) [1–3]. Therefore, when high-energy propellants are used, the problem of the reliable thermal protection of LTRE remains relevant.

The most frequent method of protecting LTRE combustion chamber walls from high-temperature combustion product gases (convective and radiative heat flows) is so called internal cooling (also referred to as film, barrier, curtain or spray cooling).

Film cooling occurs along the low-temperature near-wall gas or liquid layer (depending on the aggregate state of the propellant components). This paper focuses on gas films. The propellant component creating the film (oxidizer or fuel) is fed onto the inner surface of the combustion chamber wall through holes or slots of various configuration. Film cooling in LTRE results in significant losses of specific impulse. The lower the near-wall layer temperature is, the greater the losses are. The near-wall layer is formed when two flows are mixed: the film and the flow from the periphery row (which is closest to the chamber wall) injectors. The near-wall gas temperature in its turn depends on such factors as the equivalence ratio of the components in the injectors of the closest to the wall row (when

two-component injectors are used), film coolant flow-rate, cooling system design, film coolant flow-rate in the periphery injectors, etc. The main criteria for selecting the film cooling parameters are thermal and energy efficiency. Thermal efficiency is defined as an ability of the film to prevent the combustion chamber wall from heating above the maximum operating temperature of material. Energy efficiency is defined as minimizing specific impulse losses due to film cooling. These two criteria are contradictory. The paper analyzes the factors affecting the thermal efficiency.

In [4] the thermal efficiency of film cooling at subsonic velocities of both the film and the main flow is determined as follows

$$\eta = \frac{T_w - T_\infty}{T_f - T_\infty}, \tag{1}$$

where T_w is the wall temperature gas side; T_∞ is the main flow thermodynamic temperature; T_f is the film gas temperature.

In [5] the adiabatic efficiency of film cooling is determined according to the following criterion:

$$\eta = \frac{T_0 - T_{ad}}{T_0 - T_f}, \tag{2}$$

where T_0 is the main flow temperature on the boundary layer edge; T_{ad} is the adiabatic wall temperature.

Ambiguity of T_0 , T_∞ estimation as well as an assumption of the wall adiabaticity make it impossible to use these criteria for estimating the LTRE film cooling efficiency. Due to these reasons, the approach suggested in [6] is more suitable:

$$\theta = \frac{T_{w,wof}(x) - T_{w,f}(x)}{T_{w,wof}(x) - T_f}, \tag{3}$$

where $T_{w,wof}(x)$ and $T_{w,f}(x)$ are the wall temperatures without and with film cooling; x is the current coordinate.

Further in this paper this criterion is used for estimating the film cooling thermal efficiency.

Gas films have become the subject of numerous experimental and theoretical studies both in Russia and abroad.

For instance, the paper [6] considers the efficiency of film cooling in a rocket engine (RE) working on $H_2(g) + O_2(l)$ mixture. Gaseous hydrogen was used as a coolant.

The paper discusses the influence of the following factors on the film cooling efficiency:

1) relative mass loading of the injection and main flows M determined by the relation

$$M = \frac{\rho_2 u_2}{\rho_\infty u_\infty}, \tag{4}$$

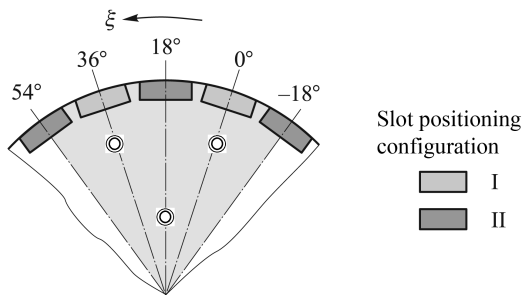


Fig. 1. Positioning configuration of the coolant supply slot [6]

where ρ_2 and ρ_∞ are densities of the coolant and the main flow; u_2 and u_∞ are feed velocities of the coolant and the main flow;

- 2) pressure in the combustion chamber;
- 3) design and position of the slot.

The study results show that the greater M is, the higher the film cooling efficiency becomes, while pressure influences the cooling efficiency insignificantly.

To study the influence of the slot position on the cooling efficiency, two position configurations of the coolant supply slot were used (Fig. 1).

The first slot positioning configuration corresponds to the angles $\xi = 0^\circ$ and 36° . The slot is located directly behind the external coaxial spray injector in the injection triangle. The second slot positioning configuration corresponds to the angles $\xi = -18^\circ, 18^\circ$ and 54° , when the slot is located between the external coaxial spray injectors in the injection triangle. The research demonstrated that the film cooling efficiency was considerably higher for the second configuration, with slots located between the injectors. This is caused by the reduced washout of the flow, going out of the film slot, with the exhaust from the periphery injectors.

To study the effect of the slot design on the film cooling efficiency, the slots with the height $s = 0.25$ and 0.4 mm were used. The results of the experiments show that there is no correlation between the film cooling efficiency and the height of the slot.

The paper [7] is of considerable interest as it describes the subsonic and supersonic gas films experiments, which were conducted using the LTRE powered by kerosene + O_2 (g) fuel components. The paper analyzes the impact of the following factors on the film cooling efficiency:

- 1) film arrangement method;
- 2) coolant relative mass flow rate $\overline{\dot{m}}_f$, which is determined as

$$\overline{\dot{m}}_f = \dot{m}_f / \dot{m}_\Sigma, \quad (5)$$

where \dot{m}_f is the component flow rate to the film, \dot{m}_Σ is the total flow rate of the components, going through the chamber;

- 3) a type of film gas.

To study the effect of the film arrangement method, the cooling gas was injected by four different injection methods forming so called radial and tangential films either with or without gas swirl (Fig. 2). The radial nonswirling film was obtained by injecting the coolant through 12 holes evenly distributed around the circumference in the direction from the periphery to the chamber axis at the right angle to the wall being cooled (Fig. 2, *a*).

The cooling gas was injected into the radial swirling film tangentially to the combustion chamber internal surface through 12 holes evenly positioned around the circumference (Fig. 2, *b*).

The tangential swirling and nonswirling films differ from the radial ones in having an additional spacer ring that deflects the coolant flow in the direction of the main flow and directs it along the combustion chamber wall. The spacer ring is shown with a dashed line in Fig. 2, *a*.

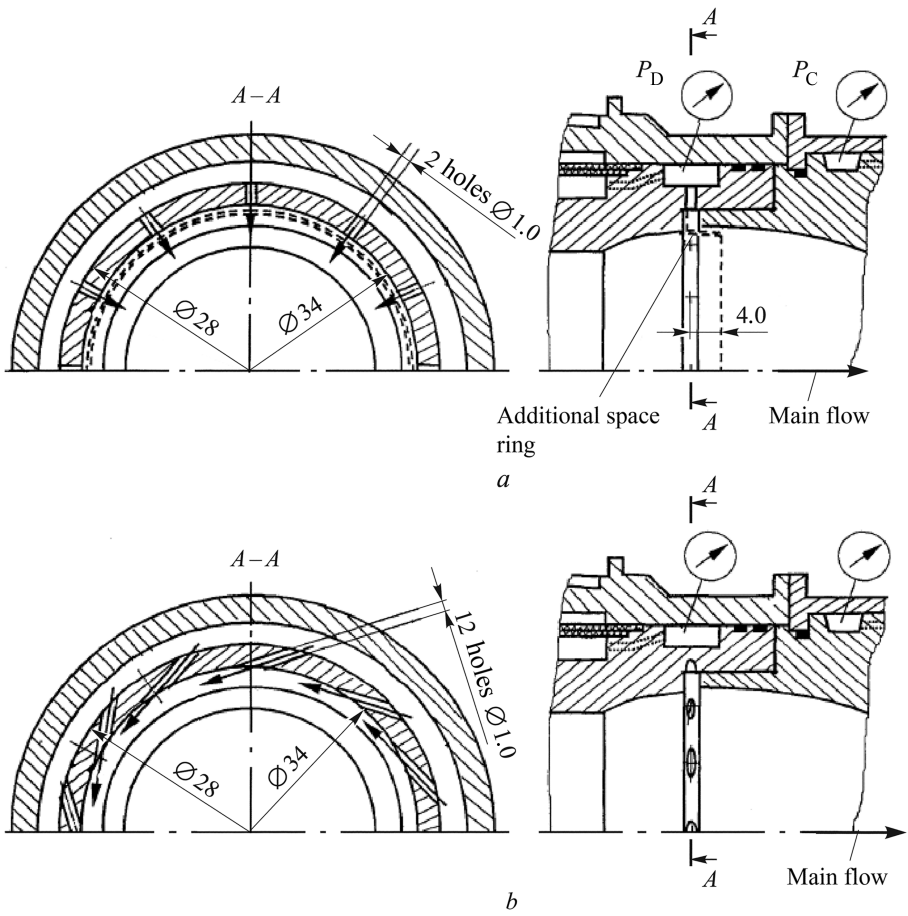


Fig. 2. Film arrangement methods [7]:
a – radial nonswirling film, *b* – radial swirling film

According to the experimental data, the swirling films have higher cooling efficiency compared to the nonswirling ones, with comparatively low relative flow rates of cooling gas to the film ($\overline{m}_f = 0.236$) which is of pragmatic interest with regard to the cost efficiency.

It could be related to the fact that the centrifugal force pushes the film flow to the wall and prevents its premature washout by the main flow combustion products.

In order to study the coolant type influence on the cooling efficiency, gaseous oxygen and nitrogen were used as film gas in [7]. With the nonswirling films, the cooling efficiency does not depend on the type of film gas, whereas swirling films have higher efficiency with a nitrogen injection than with an oxygen one. The author attributes this fact to a fraction of the injected oxygen being involved into the combustion process. However, as it was mentioned earlier, the centrifugal force emerging with the swirling flow should also be taken into account, this force prevents the film from mixing with the main flow in different ways. That is why, when using gases with various physical properties, such as density, viscosity, heat capacity, and thermal conductivity, the difference in their efficiency as films can be attributed to the difference in both heat-mass transfer and mass transfer conditions, with all other conditions being equal.

Another subject in [7] was the influence of coolant relative mass flow-rate on the gas film efficiency: the greater the flow-rate is, the higher the efficiency becomes.

The experiments in [8] were aimed at establishing how the film slot positioning affected the cooling efficiency. The testing facility was a rocket engine working on $\text{CH}_4(\text{g}) + \text{O}_2(\text{l})$ propellant combination. Gaseous methane was used as a coolant.

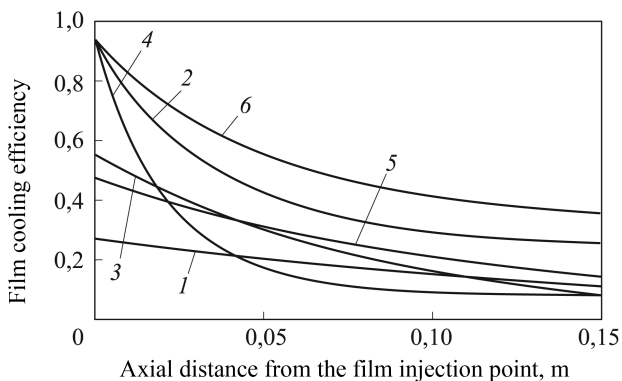
Similar to [6] the research was done for two film slot positioning configurations: in the first configuration the slot was located directly behind the external coaxial spray injector, in the second configuration the slots were located between the injectors.

The experimental data confirmed that the film slot positioning influenced the film cooling efficiency considerably. Thus, the slot positioned between the periphery injectors is the most favorable one in terms of cooling the combustion chamber walls. The authors attribute it to the superposition of the adjacent flows, which create a layer of a cold film fuel component preventing the wall from being heated by the exhaust products coming from the injector located between these slots.

The influence of the mass flow-rate on the film cooling efficiency was also considered in [9]. The object of the research was RE working on kerosene + $\text{O}_2(\text{g})$ propellant combination. Gaseous nitrogen N_2 and kerosene were used as a coolant. The study was conducted at the chamber

Fig. 3. Influence of coolant mass flow-rate on film cooling efficiency [9]:

1, 3 and 5 – nitrogen, $m_f = 6, 11$ and 15% ; 2, 4 and 6 – kerosene, $m_f = 9, 5$ and 14% respectively



pressure $p_k = 2$ MPa and the constant mixture ratio $K_m = 3.2$. The value of the coolant relative mass flow-rate \bar{m}_f varied from 0.05 to 0.15. The results prove that the higher the coolant relative mass flow-rate is, the higher the film cooling efficiency becomes. With the distance from the coolant injection point increasing, the cooling efficiency gradually decreases (Fig. 3)

Special attention should be paid to [10]. This paper considers the thermal state of the RE combustion chamber walls working on gaseous $\text{CH}_4 + \text{O}_2$, $\text{H}_2 + \text{O}_2$, and $\text{CO} + \text{O}_2$ propellant combination. Such engines feature a new cooling method, so called “vortex cooling”. The method is essentially the following: the whole amount of oxidizer used as a coolant is fed into the combustion chamber not via a mixing unit but through cyclonic ports located in the cylindrical axisymmetric segment of the chamber. This cyclic injection results in forming a coolant vortex along the combustion chamber wall, which restrains the combustion within the chamber core unit, thus reducing the heat transfer to the wall surfaces. In its turn, the fuel is injected via a mixing unit and is entrapped into the oxidant vortex flow in the chamber, forming an internal vortex where the combustion occurs. The general layout of this engine is shown in Fig. 4.

A transparent acrylic segment of the combustion chamber was used to visualize the flow for this cooling method during the hot starts. Fig. 5 presents an image of the cylindrical combustion chamber in the process of $\text{H}_2 + \text{O}_2$ combustion with $K_m = 6$ mixing ratio and $p_k \approx 0.9186$ MPa chamber pressure. Information for the scale: the external diameter of the chamber acrylic segment is 0.09 m.

According to Fig. 5 the combustion zone is restricted within the chamber internal area, a ring of cold gas separates the wall inner surface from the combustion zone.

A series of two-second hot starts was performed. The test results show a high efficiency of engines performance. For instance, for the $\text{H}_2 + \text{O}_2$ rocket engine specific impulse constituted 97 % of the one theoretically possible

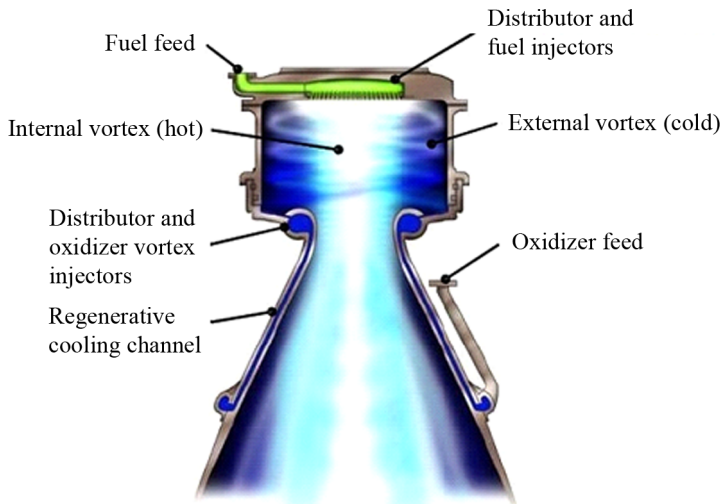


Fig. 4. Rocket engine with vortex cooling [10]

(calculated with the help of CEA-2000 software), for $\text{CH}_4 + \text{O}_2$ – 98 %, for $\text{CO} + \text{O}_2$ – 86 %. Furthermore, the temperature of the chamber wall increased by 2... 8 °C compared to the initial temperature for the $\text{H}_2 + \text{O}_2$ rocket engine.

The potential of this chamber arrangement method is evident; however, the experimental data in [10] are insufficient to draw conclusions about the thermal efficiency of this cooling method. Duration of LTRE hot tests is not enough to determine both the combustion efficiency and a specific impulse. It does not provide adequate information on the stationary thermal state of the combustion chamber wall as well.

The influence of the coolant injection angle on the film cooling efficiency was studied in [11–14] (Fig. 6, *b*). The results of the experiments indicate that the increase of the coolant injection angle results in decreasing the cooling efficiency, with its dropping to the minimum during the radial injection. This can be attributed to the film being washed out by the main flow because of different flow directions and rates.

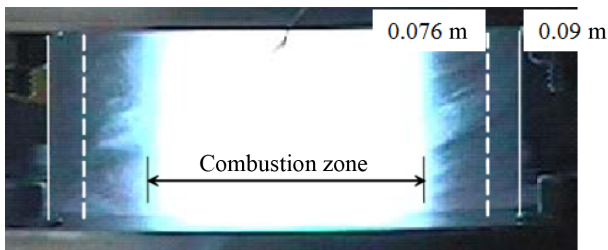


Fig. 5. Image of the combustion zone limited by the internal vortex [10]

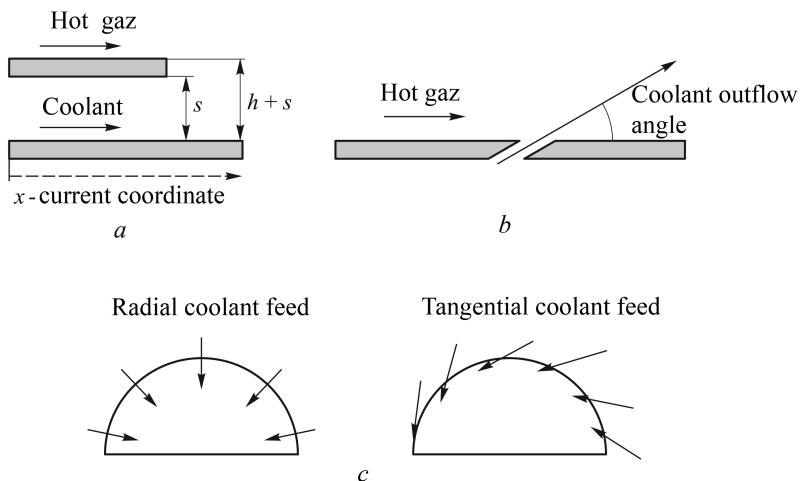


Fig. 6. Coolant injection methods layout:

a – slot height and slot wall thickness, *b* – coolant outflow angle; *c* – radial and tangential coolant feed

The influence of the coolant turbulence in the slot and the main flow was analyzed in [15, 16]. Changing the coolant turbulence intensity in the slot from 5.5 % to 9.5 % slightly affects the film cooling efficiency [15], while reducing the main flow turbulence intensity from 3.2 % to 22 % decreases film cooling efficiency considerably [16]. The results of this research can be limitedly applied to LTRE, since nitrogen at approximately 810 K was used as the main flow; its temperature was significantly lower than the ones in the LTRE combustion chambers.

It should be noted that the specialized thermoanemometric equipment is required for conducting an accurate experiment, which is intended to determine the film turbulence influence on its efficiency. However, there are certain constraints which do not allow using it for studying the LTRE combustion chamber processes [17]. These constraints include: a very high temperature in the RE combustion chamber, a rapidly changing flow under testing, sophisticated equipment installation in the combustion chamber, discontinuity of the natural flow due to the probe, and a high cost of the equipment.

As a result, the efficiency of the film cooling is influenced by a whole set of factors. The main factors include:

1) cooling system design and the coolant injection method: the slot height s (Fig. 6, *a*); wall thickness above the slot h (Fig. 6, *a*); a cooling gas output angle (Fig. 6, *b*); the radial or tangential injection of the cooling component (Fig. 6, *c*), film slots positioning relative to the injectors;

2) film characteristics: coolant mass flow-rate or relative mass flow-rate; coolant chemical composition; coolant temperature; cooling gas flow turbulence level;

3) combustion chamber process characteristics: pressure; main flow temperature; main flow turbulence intensity; boundary layer thickness;

4) parameters of the film and main flow combined: relative mass loading of the injected and the main flow M .

It should also be noted that some of these factors are studied quite well, while others require the further study.

The following guidelines with regard to the film cooling of the LTRE combustion chamber can be given:

1) relative mass loading of the injected and the main flows M should be close to a unity;

2) the coolant should be injected along the combustion chamber wall (the coolant injection angle equals zero);

3) coolant injection slots should be positioned between the periphery injectors;

4) the main flow should be organized so that it was maximally laminar (the main flow turbulence intensity should be as low as possible).

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