AN OVERVIEW ON THE DESIGN VARIANTS FOR ORGANIZATION OF THE LIQUID FILM COOLING IN LPRE COMBUSTION CHAMBERS

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Abstract. New technologies always create a trend to modernize and improve existing designs with new opportunities. At present, additive technologies have one of the most significant development rates among other manufacturing technologies. For modern liquid-propellant rocket engines, there is also a general trend towards increasing the efficiency of engines, finding new technological solutions that make it possible to simplify manufacturing technology, reduce technological costs and increase reliability. In this paper, known design solutions which employ film cooling for thermal protection of the walls of the engine chamber are considered. The main ways of organizing internal cooling are analyzed, the main mechanisms that define the thermal protection of the walls of the LRE chamber are considered. An overview of the existing design variants of devices which organize internal film cooling is given. The design solutions for film cooling of both the list of the real engines RD-105, RD-106, RD-0110, RD-115, RD-119 and known patent solutions are considered. The main features of such devices are shown and the influence of some design differences on the efficiency of the film cooling is analyzed. The main characteristics defining the efficiency of the device for film cooling are given. A review and analysis of the implemented design solutions for film cooling showed that the most efficient designs use the following elements, such as a gas-dynamic redan, a profiled wall of the predetermined space, and various types of inlet and outlet slots. Each design decision is based on the results of experimental testing of the engine. All these elements of film cooling design are very dependent on the accuracy of the manufacturing technology. Capabilities of additive manufacturing allow it possible to create new designs with stable geometric characteristics in the form of a single part. The paper considers the options for applying the SLM additive manufacturing technology to create the design of the film cooling rings for liquid-propellant rocket engines.

Keywords: ADDITIVE MANUFACTURING, SELECTIVE LASER MELTING, LRPE COMBUSTION CHAMBER, HYDRAULIC CHANNELS, FILM COOLING, FILM COOLING DESIGN, FILM COOLING DESIGN FEATURES, FILM COOLING DESIGN REVIEW, RD-0110, RD-105, RD-106, RD-115, RD-119.

ОГЛЯД ВАРІАНТІВ КОНСТРУКЦІЙ, ЯКІ РЕАЛІЗУЮТЬ ВНУТРІШНЄ РІДІННЕ ЗАВІСНЕ ОХОЛОДЖЕННЯ КАМЕР РРД

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Анотація. Нові технології завжди створюють тренд з модернізації та вдосконалення існуючих конструкцій з урахуванням нових можливостей. Значний розвиток зараз відбувається у сфері адитивних технологій. Для сучасних РРД також існує згустка тенденцій до підвищення ефективності двигунів, знаходження нових технологічних рішень, які дозволяють спростити технологію виготовлення, зменшити технологічні витрати та підвищити надійність. У цій роботі розглянути конструктивні рішення, що забезпечують теплоозахист стінок камер двигунів за рахунок створення завісного охолодження. Проаналізовано основні способи організації внутрішнього охолодження, розглянуто основні механізми, що становлять теплоозахист стінок камер РРД. Наведено огляд існуючих варіантів пристроїв для організації внутрішнього завісного охолодження. Розглянуто конструктивні рішення завісного охолодження як реальних двигунів РД-105, РД-106, РД-0110, РД-115, РД-119 так і патентні рішення. Показано основні особливості таких пристроїв та проаналізовано вплив деяких конструктивних відмінностей на ефективність роботи завісів. Наведено основні характеристики, що відображають ефективність роботи пристрою для організації завісного охолодження. Огляд та аналіз реалізованих конструктивних рішень завісного охолодження показав, що для найефективніших конструкцій використовують такі конструкційні елементи: газодинамічний редан, профільований стінку зареданого простору та різні види вхідних та вихідних щілин. Кожне конструкторське рішення ґрунтується на результатах експериментального відпрацювання двигуна. Всі ці конструктивні елементи завісного охолодження сильно залежать від точності технології виготовлення. Можливості адитивного виробництва дозволяють створювати нові конструкції із більш стабільними геометричними характеристиками у вигляді однієї деталі. В роботі розглянуто варіанти застосування технології адитивного виробництва SLM для створення конструкції поясу завісного охолодження РРД. Ключові слова: АДИТИВНІ ТЕХНОЛОГІЇ, SELECTIVE LASER MELTING, КАМЕРА ЖРД, ГІДРАВЛІЧНІ ТРАКТИ, ЗАВІСНЕ ОХОЛОДЖЕННЯ, КОНСТРУКЦІЯ ЗАВІСНОГО ОХОЛОДЖЕННЯ,
Introduction

Modern rocket engine chambers are subjected to high requirements for ensuring high performance along with the maximum reduction in the cost of the production process. This, in turn, leads to the necessity of creation of extreme conditions for LPRE operation process: the materials used often operate in the range of extreme temperatures and pressures. The described approach determines the need of application of the list of the special means aimed at the creation of the reliable thermal protection system of the engine chamber walls. LPRE cooling system organization is one of the most important tasks while designing of the engine and its solution is the key to the successful operation of the product in conditions of extreme temperatures and pressures, typical for rocket engines. Often, the engine’s cooling scheme determines a major part of the engine design. Moreover, some of the components of the cooling system require a significant amount of the experimental study, which is inevitably followed with technological and manufacturing complexity. There are several means of the cooling schemes known organization for LPRE: external, internal, radiation, ablative, thermal coating, heat capacity and combined cooling (two or more types) [1, 2, 3]. In turn, it is not typical for LPRE design to employ only one of the described cooling types. For instance, combined cooling which includes external regenerative and internal film cooling is widespread in liquid rocket engines. The application of this system allows to ensure high performance with relatively low specific impulse losses together with decreasing of the thermal loads on the chamber design which increases engine life. Furthermore, liquid film cooling exerts protective effect on the chamber wall preventing erosion from a high temperature combustion product to occur. Such protective effect takes place even at small thickness of the liquid film. [3] In turn, although the refusal to apply internal cooling leads to an increase in the performance of the engine [1, 2, 3, 4, 5], it is often closely associated with significant difficulties. For instance, it is possible to exclude the inner cooling system by applying cryogenic component as a coolant. [6]. Such component has a number of advantages. For example, a significant temperature gradient from the heated wall to the coolant, a high temperature for the start of thermal catalytic decomposition, a possibility of creating such conditions under which the cooler would be in a supercritical state, which means that there is no phase boundary. However, designing such system is difficult due to several reasons: dependencies used to calculate a heat transfer coefficient to hydrocarbon coolers are very different from more complex cryogenic ones; the lack of reliable data on the thermodynamic properties of cryogenic components used in LRE cooling conditions, which, as a result, leads to a significant amount of fire testing, decreases the overall cost efficiency and increases time to create an engine design. A large number of studies devoted to attempts to predict the influence of the design features of film cooling devices on the efficiency of their operation [7, 8, 9, 10]. The application of the inner liquid film cooling along with external regenerative cooling using hydrocarbon fuels has become a widespread in LPRE combustion chambers design [4]. There is a great number of experimental data as well as semiempirical dependencies which allow to reliably predict the coolant parameters [1, 2, 3, 11, 12]. This approach has a number of obvious advantages in the highly competitive market of the modern aerospace industry. It allows to decrease designing time of high-efficient LPRE, and to decrease the amount of the fire testing.

There is another approach which allows to increase the rocket engines production efficiency along with enhancing its reliability. It consists in application of additive technologies for LPRE manufacturing. Thus, there is a number of works in which the possibility of creating the hydraulic channels, creating complex structure elements and manufacturing of the experimental film cooling rings using SLM-technology is considered [13,
14, 15, 16]. Studies show that there is a possibility to adapt design features of LPREs to additive manufacturing requirements. The work on production of models of film cooling rings is also successful. The manufactured rings have a number of advantages compared to similar ones made using conventional means of manufacturing in the aerospace industry. The main advantage of additive manufacturing is the possibility of manufacturing of complex multi-element designs as one single piece with stable geometric characteristics, which meet the requirements for repeatability of hydraulic characteristics, and also provides uniform distribution of liquid along the perimeter of the hot-gas wall in a wide range of component flow rates [14].

In this paper, the main features, as well as design options for the implementation of liquid film cooling rings are considered. It is known that the application of the liquid film cooling is more efficient compared to the gaseous film cooling [1]. In addition, it is a design which influences the efficiency of the film cooling unit and which often determines the technological complexity of the unit. Therefore, it is important to consider the available options for the designs of film cooling rings, the features of their application in the LPRE chambers, as well as the options for manufacturing of film cooling rings using additive technologies.

**Formulation of the research problem**

To consider the main means and principles of the film cooling organization for LPRE combustion chambers. To give an overview of the existing film cooling designs as well as modern patented solutions. To consider the possibility of the application of the SLM-technology for film cooling rings manufacturing.

**Solution of the problem**

The principle of operation of liquid film cooling of the LPRE combustion chambers is considered below. It should be noted that almost the whole process of heat transfer between the hot combustion products and the engine hot-gas wall occurs in the thin layer of gas lying near the wall called the boundary-layer. That is why it is important to “saturate” the boundary layer with the component. With this purpose, a part of the component progresses on the hot-gas wall of the chamber and nozzle with low velocity. As a result of the interaction with the main flow, the liquid tightens to the surface of the inner wall, takes the heat flow rate and vaporizes forming low-temperature gas layer near the wall. Due to the weak transverse mixing, such a layer retains its efficiency over a considerable distance. The scheme of the liquid film cooling operation is shown in Figure 1. There are many works that consider the possibility of theoretical evaluation of the film cooling efficiency [1, 4, 7, 8, 9, 10]. However, in practice, from 30 to 70% depends on the design features of the cooling unit [1, 12, 17].

![Figure 1 – Liquid film cooling operational concept](image)

The application of the film cooling is known for the LPRE design of the A-4 rocket. Several rows of holes were made in the chamber hot-gas wall. The component is fed to the wall through holes made in the form of discrete jets. The rows were located at a considerable distance relative to each other and are shown in Figure 2.
The main disadvantages of the discrete-jet method of supplying a film coolant:

– significant uneven distribution of the component. This in turn leads to the development of the large scale nonuniformity of the coolant which can be the reason of the occurrence of local overheated areas.

– film coolant entrainment before its full atomization and vaporization while the jet-formed component movement along the chamber hot-gas wall.

The described disadvantages significantly reduce the effectiveness of the operation of film cooling unit. The boundary layer increases which demands the increased coolant flow rate supply.

It is possible for LPRE design to use more than one film cooling ring. Study results on the influence of the number of film cooling rings on the specific impulse loss are described in patent [29]. Meanwhile, with other things being equal, the application of two-three film cooling rings is more effective. It is known that in RD-170 and RD-180 combustion chambers designs, three film cooling rings are used [24, 25]. The mass flow rate of the component for the inner cooling, typically lies between 1.5...2.5% to 6...8% with respect to the total mass flow rate. This roughly corresponds to a specific mass flow from 5...6 to 20...25 g/(cm·s), i.e. a component mass flow per 1 cm of the perimeter of the chamber where the film cooling ring is located [17]. Also, in the work [29], calculation and experimental dependencies are given for choosing the geometric parameters of the elements of different film cooling designs.

The simplest design of the film cooling ring is shown in the Figure 3 [4, 17, 19]. A small collector is made in the chamber housing which is a part of the cooling channel. The firing cavity is connected with the inner collector with holes, shown in the cross-section A–A. The outlet of the holes is located in a small cavity on the hot-gas wall of the chamber which is called a film cooling collector. The collector is used for better liquid film formation and even component distribution around the chamber perimeter. Despite the relative simplicity, this design has a number of disadvantages: the flow rate of the component is mainly determined by the technological accuracy of the holes [18], and it is also impossible to control the uniformity of the liquid pressure distribution in the internal collector of the cooling duct. In addition, the liquid film in the outlet collector of the film cooling ring is subjected to intense blurring, especially if the ring is located in the fuel combustion zone, which inevitably leads to a decrease in the efficiency of the ring operation, which is accompanied by losses in the specific impulse. Such rings have not found wide application in the known LRE chambers.

There is a design variant of the film cooling ring with an independent component inlet (see Fig. 4) [4, 19]. In this case, the component inlet collector is not connected to the cooling duct, and the component is supplied through a separate pipeline. Figure b) shows an embodiment of a film cooling ring with a ledge covering it. The ledge forms a ring redan, which prevents the liquid film in the outlet collector from blurring.
There is a known scheme of the autonomous component inlet to the film cooling ring [4, 19]. A cooling component is taken from a mixing head area, then goes through the pipeline to the inlet collector of the ring (see Figure 5). The installed orifice regulates the mass flow rate of the component to the film cooling ring. The bypass of the component in the cooling duct is organized by a special collector.

The design of the film cooling rings of the real engines is considered below. The design of the autonomous film cooling ring is shown in the Figure 6.

The changeable orifice is installed in the inlet manifold. The cooling duct is formed by the inner and outer shells, with corrugated spacers between them. The corrugations are brazed between the shells. The component of
the ring is given a tangential velocity by holes made with an angle to the camera axis. The additional shell is installed to ensure the protection of the liquid film in the outlet collector of the ring. The shell is welded to the hot-gas wall of the chamber.

**Design of film cooling with inner ring**

The design of a single-slot film cooling ring [26] is known, in which the disadvantages inherent in slotted film cooling rings with a redan are eliminated. There is a wide problem of the blurring of the liquid film in slot film cooling rings design. The redan itself protrudes relative to the inner surface of the chamber, forming a rather small gap (see Fig. 4), which is very difficult to manufacture, and the geometric dimensions of the formed gap can change their value when the unit goes through autonomous strength, hydraulic and fire tests. As a result, this can lead to a change in the gap between the redan and the chamber wall, which negatively affects the distribution of the liquid film along the perimeter which in turn, leads to local blurring of the film and, as a result, to the local overheating of the wall.

**Design of the liquid film cooling ring of RD-0110 engine [20]**

The design of the film cooling ring of the RD-0110 chamber is known. Figure 8. Its cooling component is kerosene. This type of the film cooling ring is related to the autonomous ones. The component is supplied through the inlet pipe to the inlet manifold.

![Figure 8 – Film cooling ring design of the RD-0110 engine](image)

The hot-gas cavity of the chamber is connected with the outlet collector of the ring with tangential holes and the outlet slot. The tangential holes ensure swirling of the component which positively influences on the sustainability of the liquid film. The cooling duct is formed by the inner and outer shells, with corrugated spacers between them. The corrugates are connected with the inner and outer shells with brazing.

However, the reviewed design variants have disadvantages. Less favorable conditions for regenerative cooling arise inside the cooling channels before the ring; the stagnation area of the component flow takes place due to the specific features of the carryover manifold which leads to the poorer cooling of the chamber walls and may result in local chamber wall overheating. Moreover, the manifold
features contribute to increasing pressure drop inside the cooling channels.

**Design of the film cooling ring with horizontal channels of the component carryover [4, 19]**

The film cooling ring design which is shown in the Figure 9, partially solves the mentioned problem.

The component inside the cooling duct does not change its direction while moving inside the jacket. As a result, the hydraulic losses decrease and conditions of the reliable cooling is maintained: the stagnation area of the component flow does not take place which prevents chamber wall from overheating. However, the application of such design of the film cooling rings is complicated for high-thrust engines. As the flow rate to the ring increases, it is also necessary to increase the inlet collector of the ring to ensure conditions for a uniform supply of the component around the entire perimeter of the chamber. In this case, for the high-thrust engines, double-slotted rings are usually used (see Fig. 10).

**Design of the double-slotted liquid film cooling ring of RD-115 engine [4, 19]**

![Figure 9 – Film cooling ring design with horizontal transfer of the component](image)

![Figure 10 – Film cooling ring design of the RD-115 engine](image)

The known design represents film cooling ring of the RD-115 chamber. Both slots are performed identically, the coolant fuel is supplied through the holes A and ring slot B through special inclined grooves for liquid swirling. Further, through the collector C, it flows through the tangential holes into the collectors D and E and then through two slots along the tangential notches, having obtained the necessary swirl, it reaches the wall and is evenly distributed over it, forming a thin and stable protective film of the liquid. It is noteworthy that the flow rate through the slot located downstream of the gas flow is twice as high as the flow rate through the upper slot. The film cooling rings have a brazed copper part located from the hot-side to improve cooling conditions. The flow rate of the component is adjusted by changing the screws shown in Figure 10.

**Design of the double-slotted liquid film cooling ring of RD-119 engine [4, 19]**

The design of the film cooling ring consists of power rings, a ring insert, a fuel
bypass manifold and four fittings for supplying the component to the ring. The ring insert has the system of tangential holes, which provide the swirl of the component at the outlet slots and is shown in the Figure 11.

Figure 11 – Film cooling ring design of the RD-119 engine

The inner part of the ring insert is presented by the copper ring, brazed with the titan ring. With the aim of even distribution of the flow as well as even the velocity of the flow along the chamber perimeter, inclined grooves are performed inside the slots.

Application of the additive manufacturing for increase in effectiveness of the film cooling rings

Application of the additive manufacturing is a relatively new means of parts production [21, 22, 23]. One of the popular types of additive manufacturing in rocketry is SLM (Selective Laser Melting which operation principle lies in layer-by-layer melting of the metallic powder in an inert gas environment.

Previously, the authors carried out research to study the possibility of using SLM technology to create various elements of hydraulic channels: regenerative LPRE cooling jackets, orifices, elements of tangential holes, and film cooling rings. As a result of the study, the margins of the applicability of the SLM technology in terms of LPRE were determined and the possibility of the manufacturing of the film cooling rings was confirmed. The study allowed to emphasize several obvious advantages such as: the design simplicity, acceptable repeatability of the hydraulic characteristics of the obtained parts as well as the repeatability of the geometric characteristics, which positively influences on the reliability and manufacturability of the part. The obtained parts do not require additional machining and can keep its performance in a vast range of the mass flow rates.

Thus, it is necessary to consider the known variants of the SLM-manufactured film cooling rings.

Design of the film cooling ring, manufactured with additive technologies [27]

The know patented solution represents a single-part additively manufactured design of the film cooling ring.

Figure 12 – Additively manufactured film cooling ring design with individual jets

The design is a one-piece printed part with an inlet pipe 1, a component supply manifold 2, partitions between the component supply manifolds and the film cooling ring inlet manifold 3, bypass holes 4, a ring inlet manifold 5 and component supply holes to the hot-gas wall 6. The obvious advantages of this design are its simplicity and reliability. However, the inlet liquid on the hot-gas wall of the engine chamber does not have a swirl relative to the axis of the chamber, as well as the ring collector, in which a liquid film would form. The component flow entering the chamber wall remains in the form of discrete jets, which negatively affects the efficiency of the ring.

Design of the film cooling ring, manufactured with additive technologies [28]

This patented solution represents additively manufactured film cooling ring and is shown in the Figure 13. The design is a one-piece printed part and consists of a component inlet pipe 1, a leveling baffle 2, component
outlet holes 3, a primary mixing manifold 4 and a secondary mixing manifold 5. This patented solution represents additively manufactured film cooling ring and is shown in the Figure 13.

![Figure 13 – Additively manufactured film cooling ring design with inclined exit channels](image)

This patented solution represents additively manufactured film cooling ring and is shown in the Figure 13. The design is a one-piece printed part and consists of a component inlet pipe 1, a leveling baffle 2, component outlet holes 3, a primary mixing manifold 4 and a secondary mixing manifold 5.

The advantages of this design are its simplicity and reliability. In order to increase efficiency of the film cooling rings, the outlet holes may have the incline with respect to the chamber axis which would give a swirl component to the coolant flow and as a result would increase the effectiveness of the ring. However, the design does not include an outlet ring collector for liquid film formation along with the redan for additional liquid film protection from the harsh combustion products influence.

**Scientific novelty**

The scientific novelty of the article lies in the identification and justification of the ways of improvement of liquid film cooling rings design of the liquid rocket engines and formulates the requirements, which must be met in case of SLM manufacturing technology application.

**Conclusions**

The principle of operation and design solutions for LPRE liquid film cooling are considered. The application of the described cooling technique reduces the thermal load on the hot-gas wall of the chamber, and also has a protective effect, preventing the erosive effect of the hot gas flow on the chamber wall, which has a positive effect on the overall reliability of the product. The design of the film cooling ring has a direct impact on the efficiency of its operation. Therefore, it is possible to put forward a number of mandatory requirements for the rings, namely:

- the design of the film cooling ring should ensure the most uniform distribution of the component flow rate along the perimeter of the chamber section at the location of the unit;
- the component at the outlet of the assembly must form a formed film of liquid, stable over a length sufficient to ensure the greatest possible efficiency of the assembly;
- the design of the film cooling ring must ensure the absence of large discrete-jets of the component on the chamber hot-gas wall;
- the component film at the outlet of the film cooling ring should be formed as thin as possible;
- the design of the film cooling ring must ensure the continuous outflow of combustion products to prevent local blurring of the coolant liquid film.

The main types of film cooling rings design are considered, taking into account the above requirements to one degree or another. It should be noted that the manufacture of the rings using conventional means of manufacturing used in the industry is inevitably associated with inaccuracies in manufacturing. Under the requirement of providing a uniform gap between the redan and the hot-gas wall, the value of the required executable size may lay within the manufacturing tolerance. In turn, the deviation of the gap directly affects the uniformity of the liquid distribution in the outlet section of the film cooling ring. Therefore, measures to improve the efficiency of the film cooling rings, as well as options for the implementation of film cooling rings using additive technologies were considered. The application of additive technology methods, in particular, the SLM method, has significant potential. The considered options for the implementation of film cooling rings, as well as previous experimental work, confirm both the possibility of adapting existing technical
solutions and creating unique designs of film cooling rings that reliably operate under liquid-propellant rocket engine conditions produced by the new technology.

References


26. Inner cooling ring of a combustion chamber of a liquid-propelled rocket engine [Text]: pat. UA 45465 C2 Ukraine: MPK6 F02K9/00, 9/64.


28. Integrated liquid film cooling structure of thrust chamber [Text]: pat. CN211202146U China, IPC F02K9/64.


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