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Chapter 9

DEVELOPMENT OF METHODS OF COOLING LIQUID PROPELLANT ROCKET ENGINES (ZhRDs), 1903-1970*

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The question about the development of methods of cooling liquid propellant rocket engines until recently has remained virtually undiscussed in historical technical literature. The only exception is a report by I. Sänger-Bredt and R. Engel [28], in which, however, the study of this problem was limited to a narrow chronological framework (1926-1942), and also focuses only on two countries: Austria and Germany. There is no doubt that the successes of specialists in these countries in the resolution of the problem of ZhRD cooling were considerable, just as it is difficult to doubt the essential successes which occurred in the resolution of this problem in the U.S.S.R. and the U.S.A.. Obviously, an investigation of the development of methods of cooling should be continued, extending it to works carried out in the U.S.S.R. and the U.S.A., and also deepening the analysis for the purpose of establishing those laws inherent in the development of methods of cooling in each individual country, and also in all countries as a whole.

This investigation is also necessary because inaccuracies frequently appear in the literature, especially relative to priorities in the area of research on the cooling of ZhRDs. The statement of D. Sutton, made in work [14] in the chapter devoted to a brief historical survey of the development of ZhRD, serves as an example of this. Sutton wrote: "Oberth in his 1923 work *A Rocket to Interplanetary Space* proposed the first self-cooled engine, i.e., an engine equipped with a coolant jacket within which the fuel circulated prior to its injection" [14, p. 25].

But the idea of external regenerative (flow) cooling was for the first time expressed not by Oberth, but by K. E. Tsiolkovskiy, who in 1903 wrote: "Hydrogen and oxygen in the liquid state before entering the gun (combustion chamber - G. S.) will pass through a special jacket along its surface and will cool it, and they themselves will be heated and then already to enter the gun and be detonated" [2, p. 34].

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Certain authors, without denying the priority of Tsiolkovskiy in his statement of this idea, nevertheless indicate an incorrect date for this statement. For example, in a note to the above-indicated phrase of D. Sutton, the editorial board of the "Foreign Language" publishing house in the Russian translation of his book [ll], observed: "The author (i.e. Sutton - G. S.), speaking about the work of Oberth . . . , allows an inaccuracy. A self-cooled rocket engine, i.e., *a regeneratively cooled engine was proposed by K. E. Tsiolkovskiy in 1915*" [11, p. 36] (our emphasis - G. S.)

Inaccuracies consisting of the incorrect date of one event or another are very wide-spread, and they frequently include simultaneous disproof of one assertion or another. For example, the authors of work [28], emphasizing the priority of K. E. Tsiolkovskiy in expressing the idea about external regenerative cooling, nevertheless consider the date of the appearance of the latter to be 1928 [28, p. 244], which automatically leads to a priority in this question for R. H. Goddard, who expressed this idea (and even made an attempt at its practical realization) in 1922 [23, pp. 506-507].

The appearance in the literature of the inaccuracies is frequently caused by inaccurate reproduction of the text of the work of pioneers in rocket engineering in contemporary republications of their works. As an example, the collected works of K. E. Tsiolkovskiy, released by the Publishing House of the AN U.S.S.R. in 1954, in the article "The Investigation of Outer Space by Reactive Devices" for some reason or other omitted the above paragraph, which contained the idea of the scientist about external dynamic regenerative cooling (see [1, p. 80]).

The results of a study of ideas about the cooling of ZhRDs, expressed by pioneers of rocket engineering up to 1930 appear in Table 1, where the asterisk [x] indicates the appropriate priorities. The following two observations should be made regarding this table:

1. It is evident from the table that the first idea about external dynamic regenerative cooling was contained in the working notebooks of S. S. Nezhdanovskiy. However, his writings were not published at that time and became known only in the mid 1950s; consequently, there is no foundation for considering that Nezhdanovskiy has priority in the statement of this idea.
2. It also follows from the table that K. E. Tsiolkovskiy was the first to propose a method of ablation cooling. However, this proposition was expressed by the scientist in primitive form--he indicated only one side of the mechanism of this cooling: the partial ablation and carrying-off of the heat-shielding material, and said nothing about the absorption of heat by the sublimating material.

Analysis revealed a frequency law in the development of methods for the cooling of ZhRDs that consists of certain technical solutions used at the early (lowest) levels of development of engines, which, after a certain break in time, again begin to be used at a higher scientific-technical level (or at the highest level). Work on transpiration cooling serves as an example of this. It is known that the first experimental ZhRD with this cooling was prepared and tested by Goddard in 1930 [25, p. 13]. However, the tests ended unsuccessfully, and neither Goddard himself nor other researchers used this method for a long time.

Table 1

Method of Cooling and Heat Shielding	Use of Refractory Materials	Use of Materials with High Thermal Conductivity	External Regenerative Dynamic Cooling	Indep. Cooling	Capacitative Cooling by Liquid	Internal Cooling	Ablation Cooling	Transpiration Cooling
Author 1. S.S. Nezhdanovskiy	(Ref. 10) pp64, 130 1893		(Ref. 10) p221 1894					
2. K.E. Tsiolkovskiy	(Ref. 2) p33 (*) 1903	(Ref. 3) p211 1926	(Ref. 2) p34 (*) 1903	(Ref. 2) p33 (*) 1903	(Ref. 2) p33 (*) 1903		(Ref. 2) p33 (*) 1903	
3. H. Oberth	(Ref. 22) p65 1923	(Ref. 22) p65 (*) 1923	(Ref. 22) p66 1923			(Ref. 22) pp53-54 1923		
4. Yu. V. Kondratyuk	(Ref. 5) p550 1929		(Ref. 5) p550 1929					
5. R.H. Goddard	(Ref. 24) p479 (Ref. 23) p499 1921		(Ref. 23) pp506-507 1922-1923	(Ref. 23) pp506-507 1922-1923		(Ref. 23) pp506-507* 1922-1923		

(*) Priority in Statement of the Idea.
(Ref.) Literature where the priority is described; see Reference section at the end of this paper.

As shown in work [26], in the mid 1940s the American firm Aerojet carried out research on an oxygen-hydrogen ZhRD. During this research, attempts to use transpiration cooling were again made; moreover, instead of the porous ceramic materials utilized by Goddard, porous metals began to be used. But this was also curtailed. A new attempt to prepare an engine with transpiration cooling was undertaken at the firm Pratt & Whitney in the beginning of the 1960s [15], and at the beginning of the 1970s one such engine of this firm gave substantial competition to the engine of the firm Rocketdyne in competition for the best design of a ZhRD for the Space Shuttle [16].

Other examples may be cited. In 1934, I. Sänger created a number of experimental engines, with combustion chambers prepared from spirally wound tubes [28, pp. 233-236]; tubular designs at that time did not receive wide acceptance. In the mid 1950s, on the ZhRD for Navaho II, the use of tubular designs was adopted again [17 p. 95], although already at a higher level: The tubes, arranged around the circumference of the chamber, had variable cross sections and were bent in accordance with the profile of the chamber and nozzle.

Besides repetition at the highest and lowest level, repetition occurred at identical stages in the development of cooling for ZhRDs. For example, after the first preliminary experiments that used the most diverse propellant components, in approximately 1932-1933, the majority of engines already worked on hydrocarbon fuel (gasoline or kerosene in combination with liquid oxygen).*

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* The exceptions were only V. P. Glushko's engines which worked on kerosene and nitric acid.

Beginning in 1933, researchers in different countries, independently of each other, began to use a less caloric mixture of propellant--an aqueous solution of alcohol and liquid oxygen. This transition was made in 1933 by specialists in Germany and the U.S.S.R. (GIRD [Group for the Study of Jet Propulsion]), and in 1935 by specialists of the American Rocket Society.

Repetition at the identical stage of development occurred in the postwar years upon transition to the use of so-called connected designs of combustion chambers, which was realized independently in the U.S.S.R. and the U.S.A.; in the 1960s-1970s milled chamber designs were adopted in these countries.

In all these examples it is not difficult to detect the manifestation of repetition of one technical solution or another. Speaking of repetition, we compared the development to date at different levels--highest and lowest--and at the same level but in different countries, of one and the same element of technical equipment.

In the process of development, however, another form of repetition, which we will call "conditional repetition," occurs. Its special feature consists in the the development of technology seemingly repeating an idea expressed earlier. In other words, this form of repetition is detected during the comparison of some heterogeneous phenomena: ideas, a spiritual phenomenon--and technology, a material phenomenon. But material by no means can identically repeat the spiritual, therefore we call this repetition conditional.

In the development of methods of cooling ZhRDs, this form of repetition is encountered very frequently. Here are some examples:

1. Almost all the methods of cooling proposed by K. E. Tsiolkovskiy found their practical realization during later creation of the rocket engine.
2. In 1934, I. Sänger expressed the idea about cooling by deposition [28, p. 231], while in the 1960s this idea was in practice realized in the U.S.A. on the ZhRD of the rocket "Agena" [18, 19].
3. K. E. Tsiolkovskiy in work [3] considered the advisability of engine cooling by heat transfer from the hotter spots of the chamber to the cooler ones with the aid of thermal conductivity [3, p. 211]. This idea underwent further development (it was repeated) on the American engine "Durain" and on one of the engines of the space vehicle "Mariner 71" [12, pp. 28-44]. The combustion chamber and nozzle of these engines were made from a high-heat-conducting alloy of beryllium. The chamber was curtain cooled near the wall, heat from the uncooled nozzle was removed partially by emission into space, and partially by thermal conductivity to the "cold" sections of the combustion chamber.

Analysis of conditional repetition makes it possible to conclude that methods of rocket cooling used until the mid 1960s were developed in essence within the framework of ideas expressed by pioneers of rocket engineering, and only in the last 10-15 years have some new methods begun to be used, such as cooling with the aid of thermal tubes, intensification of heat emission due to roughness and curvature of coolant passage, and certain others.

The research of F. A. Tsander, who at the end of the 1920s attempted to develop a procedure for calculation of heat transfer in a ZhRD [4], occupies a special position among the work of the pioneers of rocket engineering. He calculated the heat-transfer coefficient from the combustion products to the wall of the engine and from the wall to the cooling fluid using one and the same empirical formula obtained for the developed boundary layer of water in a tube:

[Equation missing in original document]

where U has the dimensionality of meters/second.

Calculations according to this formula, however, gave essential errors, since it was obtained for conditions that differed markedly from the conditions that actually occurred in rocket engines, and also due to the absence at that time of scientific premises for determining the thermophysical parameters of combustion products at high temperatures, and the unsuccessful method that Tsander used to calculate the change in properties of combustion products throughout the boundary layer.

Calculations show that using the procedure proposed by Tsander, the velocity of the coolant is almost 20 times less than that which is required in actuality. Of course, with such errors the results of the calculations became the source of errors and were not able to serve as a basis for the design of cooling systems. At the same time, the calculations made by Tsander and his associates had positive value, since they allowed others to compose general ideas about the nature of heat-flow distribution along the wall of the engine and to understand the interconnection of the parameters which affect heat transfer in liquid propellant rocket engines.

The works of F. A. Tsander marked the beginning of the more than twenty-year period of development of procedures for heat transfer in engine nozzles based on empirical formulas; moreover, by the end of the 1940s, formulas were utilized intended for calculations of heat transfer in various kinds of industrial installations, i.e., for conditions which differed sharply from the conditions which also occurred in rocket engines*; from the end of the 1940s to the mid 1950s attempts were made to obtain calculation formulas for the transonic flow of gas in tubes or nozzles with low expansion (see, for example: [8, 27, 29]). In 1950, V. M. Iyevlev [7] (U.S.S.R.), and then in the mid 1950s M. Sibulkin [20] and D. Bartz [21] (U.S.A.), obtained the first procedures based on a solution of the equations of the turbulent boundary layer typical of the ZhRD.

The development of methods of cooling had a very strong effect on the development of rocket engines. Analysis shows that practically every 10-15 years in the development of rocket engines there appears a limitation caused by the difficulty of resolving cooling problems.

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* In 1936, under the direction of M. K. Tikhonravov, an attempt was made in the U.S.S.R. to create a procedure for calculating heat transfer in rocket engines [9]. A fundamental difference in this procedure from that proposed by Tsander involved taking into account the radiant component of the heat flux. However, the calculation of this flow was done using formulas intended for industrial installations, i.e., for temperatures and pressures of the gas mixture substantially lower than those that occur in an engine chamber.

In the 1930s this limitation occurred because researchers in different countries could not find an expedient design concept of a cooling system that made possible stationary heat removal from the engine wall. Without dwelling in detail on the proofs of this position, let us merely note that the problem was solved at the end of the 1930s in the U.S.S.R. by using both propellant components for external dynamic cooling of the combustion chamber and nozzle, and also in Germany by using a combination of internal and external regenerative cooling. In the U.S.A. this problem was solved somewhat later, apparently after American specialists had become familiar with German rocket engineering.

In the first postwar years, development of ZhRDs appeared limited by the impossibility of simultaneously satisfying the contradictory requirements of strength and heat transfer in the design of combustion chambers. To put it briefly, the essence of this limitation consisted of the following: With an increase in the pressure and temperature of gases in the engine chamber, the heat flux through the cooled chamber fire wall increased. To avoid destruction of the wall through overheating, it was necessary to make it thinner, but then it did not withstand the pressure [6, p. 27].

In the U.S.S.R. this problem in essence was solved by A. I. Isayev. In 1946 he developed and tested chambers in which the inner and outer shells were interconnected by spot welding through intermediate longitudinal bands along the entire surface [13, p. 97].

In the U.S.A. this contradiction was resolved in the mid 1950s by introducing tubular designs for combustion chambers. The first engine of this design was the ZhRD for Navaho II.

Toward the end of the 1950s and the beginning of the 1960s, conditions again appeared to limit increasing pressure in the combustion chamber of open-loop engines. These limitations involved the unacceptably high amounts of propellant lost driving the turbopump unit with a pressure increase in the chamber of more than 90 atm (abs.). The problem could be solved by turning to closed-loop engines in which the gas exhausted from the turbine is recirculated in the main chamber. In this scheme, losses in driving the turbopump are virtually nonexistent, and the possibility arises of raising the pressure in the chamber to several hundred atmospheres.

But complex problems of heat transfer lay in the path of achieving this pressure. Then-existing tubular and other chamber designs with very high heat-transfer rates were ineffective. In the U.S.A., the problem of cooling engines with high pressures was solved at the beginning of the 1960s. The solution was found in the use of so-called milled chambers, used on the engines of the Space Shuttle.

In the U.S.S.R. the first experimental closed-loop engine was developed and tested in 1958-1959 [6, p. 33]. Such an engine is installed, for example, on the Proton carrier rocket that has been making space voyages since 1965 [6, p. 71].

With the creation of engines with high combustion chamber pressure (approximately 200 atm.), researchers again discovered limitations on heat transfer which made difficult any increases in the pressure and temperature of the combustion products. This constraint essentially involved the high complexity of further decreasing the thickness of the fire wall, and overcoming this difficulty will require serious design and technological measures.*

At present, unfortunately, it is difficult to draw an unambiguous conclusion about the prospects for further developments to resolve the cooling problem. Supposedly, improvements can be achieved through the use of new materials, and also by more active research on the parameters of the boundary layer of combustion products.

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* At the firm "Pratt & Whitney," this problem was solved with the aid of transpiration cooling.

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