

**Analysis of possible methods  
of oxygen-kerosene LPE improvement  
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## **Introduction**

The emerging commercial trend in space exploration has set new requirements for propulsion units (PU). The main requirements include higher reliability and low cost of PUs while maintaining (or improving) the existing level of energy-mass perfection.

When present-day oxygen-kerosene engines were designed the main criterion was energy-mass perfection, that is why they do not fully meet the new requirements that are set nowadays.

The energy-mass perfection of existing PUs was achieved by:

- use of LPE schemes with afterburning of oxidizing generator gas
- higher pressure in the combustion chamber
- higher temperature of turbine energy carrier
- higher rotation speed of the turbopump unit (TPU).

All these factors limit reliability of the PU and increase its cost.

For instance, higher levels of pressure in the combustion chamber (~25 MPa), when its fire wall is cooled by kerosene, jeopardizes its reliability; while curtain cooling (composed of three to four curtain belts) not only obviously reduces reliability but decreases specific thrust impulse of the PU as well.

Using oxidizing generator gas means running the risk of ignition of engine gas duct elements, especially when maximum permissible (for resistance of turbine blades material to oxidizing medium) temperatures of gas generator are reached.

Higher rotation speed of the turbopump unit (especially when shaft power is more than 50-60 MW) cause high levels of engine vibration. This is the reason why provision of guaranteed life for

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the feeding system becomes problematical.

It is quite obvious that in order to achieve one hundred percent reliability one must pay a price. One only hopes that this task is not accomplished at the expense of the level of perfection of present-day LPEs.

This work provides analysis of the possible solution for this difficult technical problem featuring examples of three types of oxygen-kerosene engines [1] (see Table 1).

Table 1

<b>Engine No.</b>	<b>1</b>	<b>2</b>	<b>3</b>
Engine purpose	Boost unit	Stage II of carrier vehicle	Stage I of carrier vehicle
Thrust in vacuum (kN)	80	833,6	2092
Thrust on Earth (kN)	-	830,93	1922
Specific impulse in vacuum (m/s)	3444,0	3414,6	3316,6
Specific impulse on Earth (m/s)	-	3403,7	3046,9
Pressure in combustion chamber (MPa)	7,0	16,28	24,52
Proportion of components	2,6	2,6	2,63
Pressure at nozzle exit section (Pa)	$2,8 \cdot 10^3$	$0,12 \cdot 10^5$	$0,76 \cdot 10^5$
Geometric grade of nozzle expansion	180	100	36,87
Mass (kg)	230	1190	2200
Specific impulse coefficient	0,931	0,937	0,942

## 1. Definition of research objective.

1.1. The main objective of this work is to analyze failure possibilities for curtain cooling of LOX/kerosene LPE combustion chambers (ПГ-1). Traditionally such engines are kerosene cooled. When combustion chamber pressure is higher than 5÷6 MPa simple regenerative cooling is not enough to protect the fire surface of the combustion chamber wall from high temperatures. Therefore several belts of liquid cooling are used to provide reliable cooling. Liquid curtains (~ 3% of total consumption) make up a wall layer with fuel excess and reduce the wall temperature to an acceptable level, but also cause additional losses in specific thrust impulse of the engine. LPE designers have accepted these losses because curtain cooling

allowed them to increase pressure in the combustion chamber and thus improve engine mass specifications. To evaluate characteristic reserves related to rejecting curtain cooling let us analyze the example of an 80 kN thrust engine (see Table 1, engine No.1). If we ignore the temperature of the fire wall, the extreme capacity of this engine's scheme permits to raise pressure in the combustion chamber up to 19,5 MPa instead of 7 MPa, while leaving pressure at nozzle exit section and other conditions unchanged. This would give us an increase in specific thrust impulse of  $\sim 159,4$  m/s ( $\sim 16,2$  s). This gain is not only explained by elimination of losses caused by curtain cooling, but also by the possibility to step up the geometric grade of nozzle expansion because of smaller throat section of the nozzle and fixed diameter of the nozzle exit section.

1.2. Kerosene has poor cooling characteristics. That is why if we attempt to make a combustion chamber with regenerative cooling, we need a more efficient coolant (than kerosene).

This can be oxygen (the second component of an oxygen-kerosene LPE) whose cooling characteristics are better than those of kerosene, or another special component. Generally this third component is not necessarily used for combustion, it can only be applied in the autonomous cooling circuit of the combustion chamber.

In such a circuit, heat generated in the combustion chamber is transferred by a third component (coolant) to LOx in a special heat exchanger. A separate pump provides circulation of the third component. The following substances can be used as an autonomous coolant: hydrogen, oxygen, water, methane, ammonia, water-ammonia mixture, helium; all of these have significantly better cooling properties than kerosene.

Further articles of this work explain different variations of curtainless combustion chamber cooling using new schematic engine solutions, and offer numerical analyses of their efficiency.

All calculations were performed with the software complex AnaSyn – system designed for multifunctional computer modeling of LPEs [2] developed at Keldysh Center.

1.3. Mass characteristics of the new engine scheme were based on the following assumptions:

- mass of combustion chamber is proportional to the area of its side surface;
- mass of the turbopump unit (TPU) is proportional to the square root of its capacity;





2.2. Results of calculations for transfer of the 60 kN thrust engine cooling are shown in Fig. 3.

Oxygen cooling has permitted:

- 1) Regenerative cooling of combustion chamber and nozzle.
- 2) To raise pressure in the combustion chamber from 7 MPa to 10 MPa.

At the same time the temperature of the gas-side wall near the throat section does not exceed 850°K. Calculations assumed that without curtain cooling the specific thrust impulse coefficient can reach the value of  $\varphi = 0.951$ .

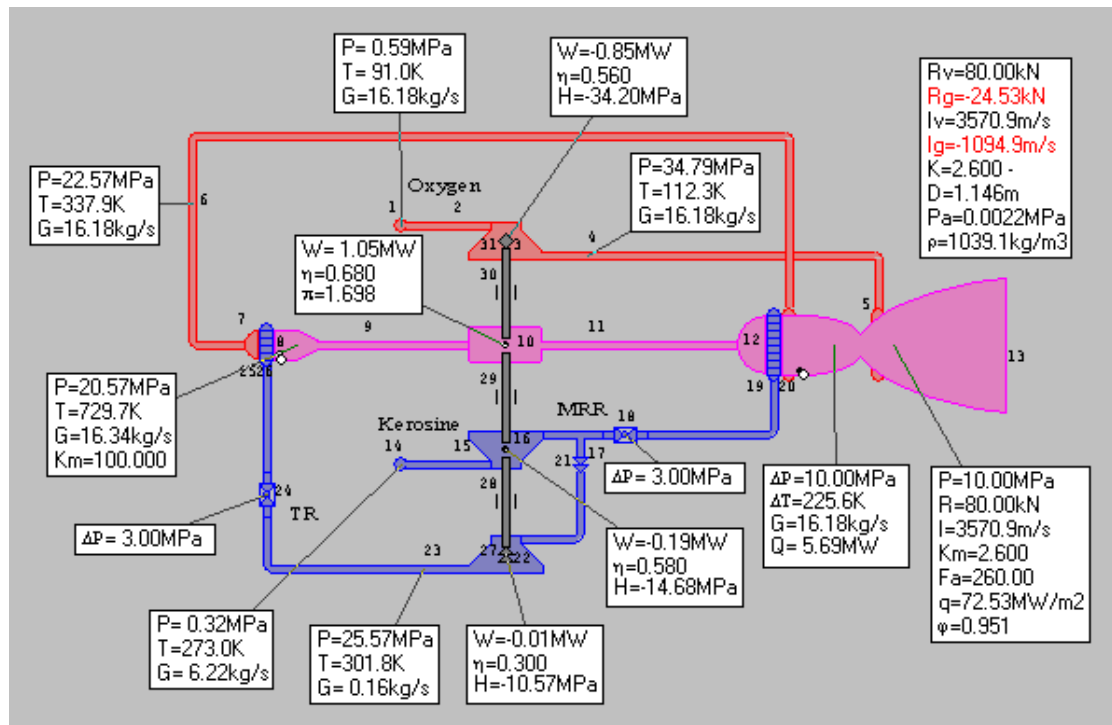


Fig. 3

By comparing results in Fig 2 and Fig 3, we see that introduction of oxygen cooling of the engine permits to raise the specific thrust impulse by  $\Delta I = 3570.9 - 3443.9 \approx 127 \text{ m/s}$  ( $\sim 13 \text{ m/s}$ ). The efficiency of this technical solution is justified by the fact that its implementation doesn't require large expenses or new technological solutions. The only problematic question is high temperatures in the cooling duct  $\approx 673 \text{ K}$  ( $400^\circ \text{C}$ ). Taking into account that oxygen is a very active chemical element one could fear ignition of cooper under these conditions, although experimental data certifies that threshold values of this temperature are much higher.

Considering the fact that TPU capacity grows 1.625 times, one can expect an 8 kg increase in the mass of the new scheme TPU. At the same time increase in combustion chamber pressure (at fixed nozzle section diameter of 1.146 m) has not change the side surface of the combustion chamber significantly, therefore the mass of an oxygen-cooled engine is roughly 6 kg more than the mass of the basic configuration. A 13 s thrust impulse increase raises the mass of payload (P/L) at the geosynchronous orbit by approximately 195kg.

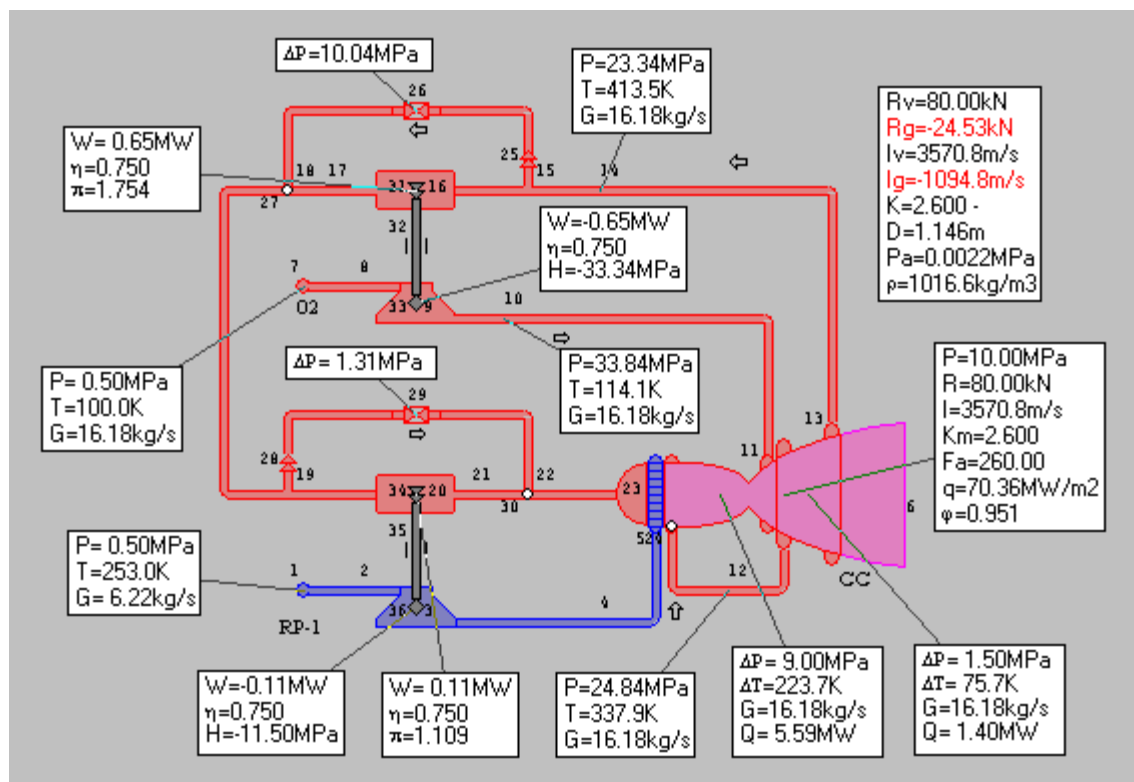
2.3. The high oxygen pressure at the cooling duct exit and high consumption of oxygen permit consideration of a non-generator LPE scheme with oxygen gasified in the cooling duct as turbine working fluid (Fig. 4). The same mode of combustion chamber as the one shown in Fig. 3 has been implemented for the non-generator 80 kN thrust LPE.

Advantages of this scheme are rather obvious and show higher reliability if compared to the scheme in Fig. 3 because:

- no gas generator is present
- the temperature of the turbine working fluid is lower  $\sim 413^{\circ}\text{K}$  ( $140^{\circ}\text{C}$ ).

Estimation shows that mass characteristics of this engine scheme are 10 kg lower than of the basic variant. Therefore this engine scheme can provide an increase in payload mass on the geosynchronous orbit of  $\sim 205$  kg.

Fig. 4



2.4. Possibility of further perfection of the oxygen-kerosene LPE employ use of a third component as coolant. A possible scheme of such LPE is shown in Fig. 5.

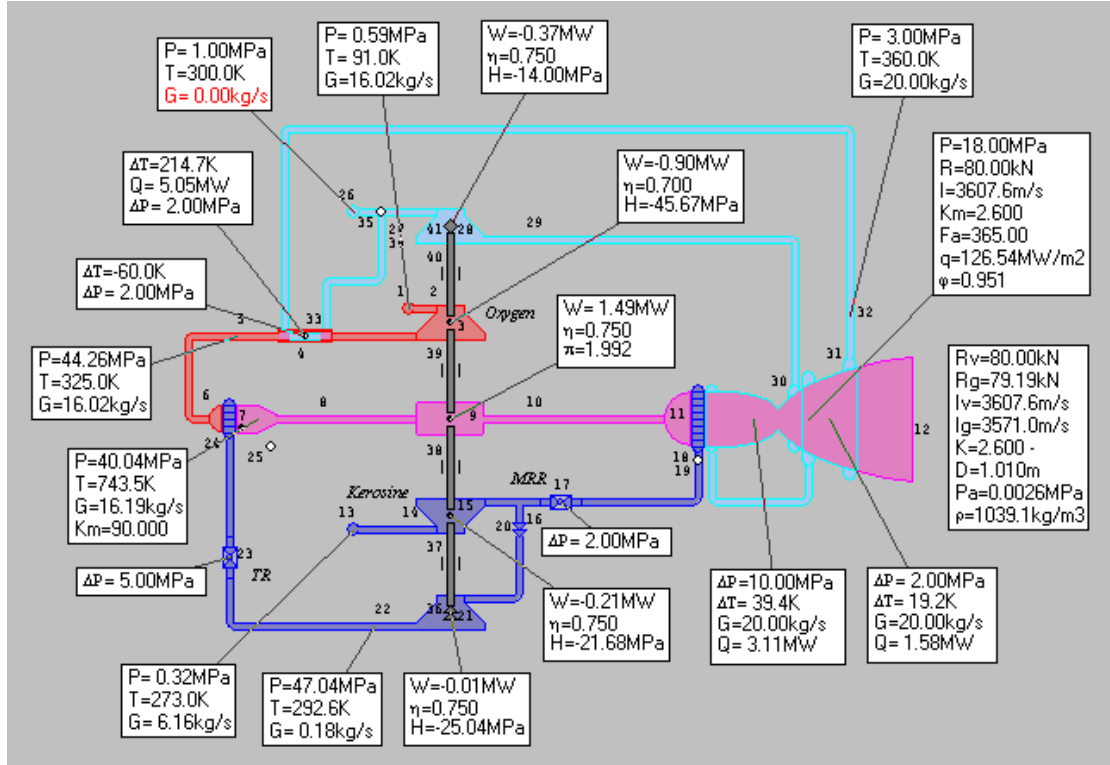


Fig. 5

Its characteristic properties are:

1) Closed water cooling circuit of the combustion chamber circulation of water within the cooling circuit is provided by a pump (28). Heat from combustion chamber is transferred to liquid oxygen in the heat-exchanger (Assemblies 4 and 28 in Fig 5).

2) Oxygen is gasified in the heat exchanger and reaches the temperature of  $\sim 325^\circ\text{K}$ , that is why the gas generator (7) works on gaseous oxygen and liquid kerosene.

3) The combustion chamber works on gaseous oxygen and liquid kerosene.

Results of energy coordination of parameters of such LPE scheme are shown in Fig. 5.

Serviceability of this scheme is defined by the following requirements:

- 1) Water in the cooling duct must not boil;
- 2) Water after the heat exchanger must not freeze;

3) Extreme capacity of the scheme is determined by available capacity of the turbine, considering the required capacity for rotation of the water pump.

In order to meet the first two requirements, the circuit must be filled with water at 300°K (27°C) and pressure of 10 MPa. When water heats up in the cooling duct and reaches 360°K, a pressure of 10 MPa at the exit of the cooling duct prevents cooling.

In the heat exchanger water must be cooled to 300°K (60°C) and oxygen must be heated at the same time from 91°K to 325°K (by 215°C).

Available capacity of the turbine at generator gas temperature of ~ 743°K permits a pressure of ~ 18 MPa in the combustion chamber.

Required water flow rate in the cooling circuit is 20 kg/s. Implementation of this scheme has allowed a raise of the specific thrust impulse of the basic variant by 175.4 m/s (~ 18 s).

Mass characteristics of the scheme:

- TPU mass is 18 kg more than the mass of the basic variant;
- combustion chamber mass is 13 kg less than the mass of the basic variant;
- gas generator mass is ~ 10 kg;
- heat exchanger mass is ~ 45 kg.

This means that the mass of the engine is 50 kg more than the mass of the basic variant of the engine. Considering these values, the mass of payload that this engine can insert into the orbit is increased by ~ 230 kg.

For all the efficiency that this variant of LRE schematic solution offers, it has one significant draw back, namely that water may freeze in the cooling duct when the engine is in space.

Taking this into account, water must be contained in a separate thermal insulating tank and fed into the cooling duct before each start of the engine, and after each stop of the engine water must be drained from the duct.

Considering this, a more efficient coolant for this type of engines could be ammonia, whose freezing temperature is  $-60^{\circ}\text{C}$ .

### **3. Results of calculations and their analysis for an 830 kN thrust engine**

3.1. The following sections of this paper analyze the feasibility of using an autonomous cooling circuit for engines with different thrust characteristics.

Greater engine thrust values cause greater heat capacity, which is transferred from the combustion chamber to the coolant, and consequently require bigger heat exchangers. The purpose of this section is to determine a compromise between increase in specific thrust impulse and greater engine mass when using an autonomous cooling circuit. Methodically, the problem is solved in the same way as for 80 kN thrust engines.

According to the most efficient scheme: on autonomous water-cooling circuit.

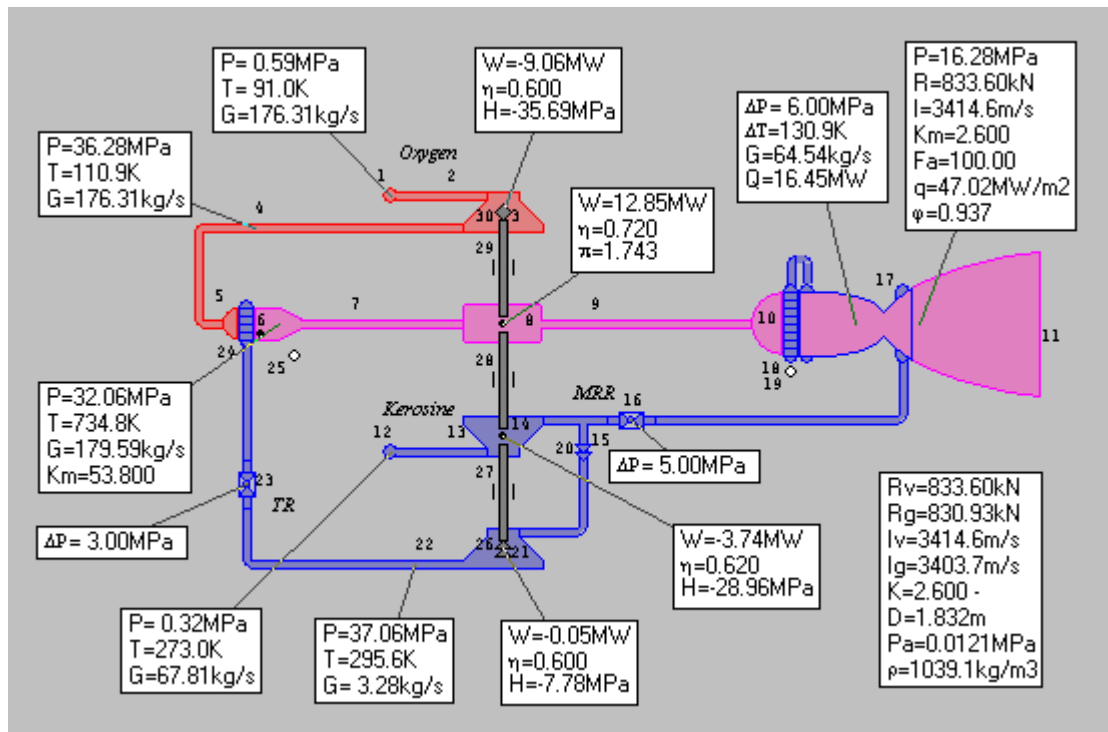


Fig. 6

Fig. 6 shows the scheme of the basic variant of a 833.6 kN thrust engine. This is the scheme of an LPE with afterburning of oxidizing generator gas. The combustion chamber is kerosene cooled. Pressure in the combustion chamber is 16.28 MPa. Approximate value of the coefficient of specific thrust impulse is  $\phi_l \approx 0.937$ . Low value of the coefficient of specific thrust impulse is caused by curtain cooling of the combustion chamber fire wall by kerosene. The feed system is a single shaft system, turbine capacity is 12.85 MW. Generator gas temperature is:  $\sim 735^\circ\text{K}$ . Area of combustion chamber side surface and nozzle is  $8.8 \text{ m}^2$ , total heat pick-up equals, 16.45 MW. Pressure at nozzle section equal 0.012 MPa at geometric grade of nozzle expansion is:  $\sim 100$ .

3.2. According to the recommendations indicated in section 3 of this paper the basic variant of the engine is updated as follows (see Fig.7):

- curtain cooling of the combustion chamber is replaced;
- fuel (kerosene) bypasses the cooling duct and is fed directly into the head;
- combustion chamber is cooled by water looped in a closed thermal cycle (heat regeneration) by the pump and the heat exchanger.

Extreme capacity of this system has been estimated by the maximum pressure in the combustion chamber, which can reach  $P_a=0,012$  MPa and provide reliable thermal condition of combustion chamber fire wall.

Results of calculations are shown in Fig. 7.

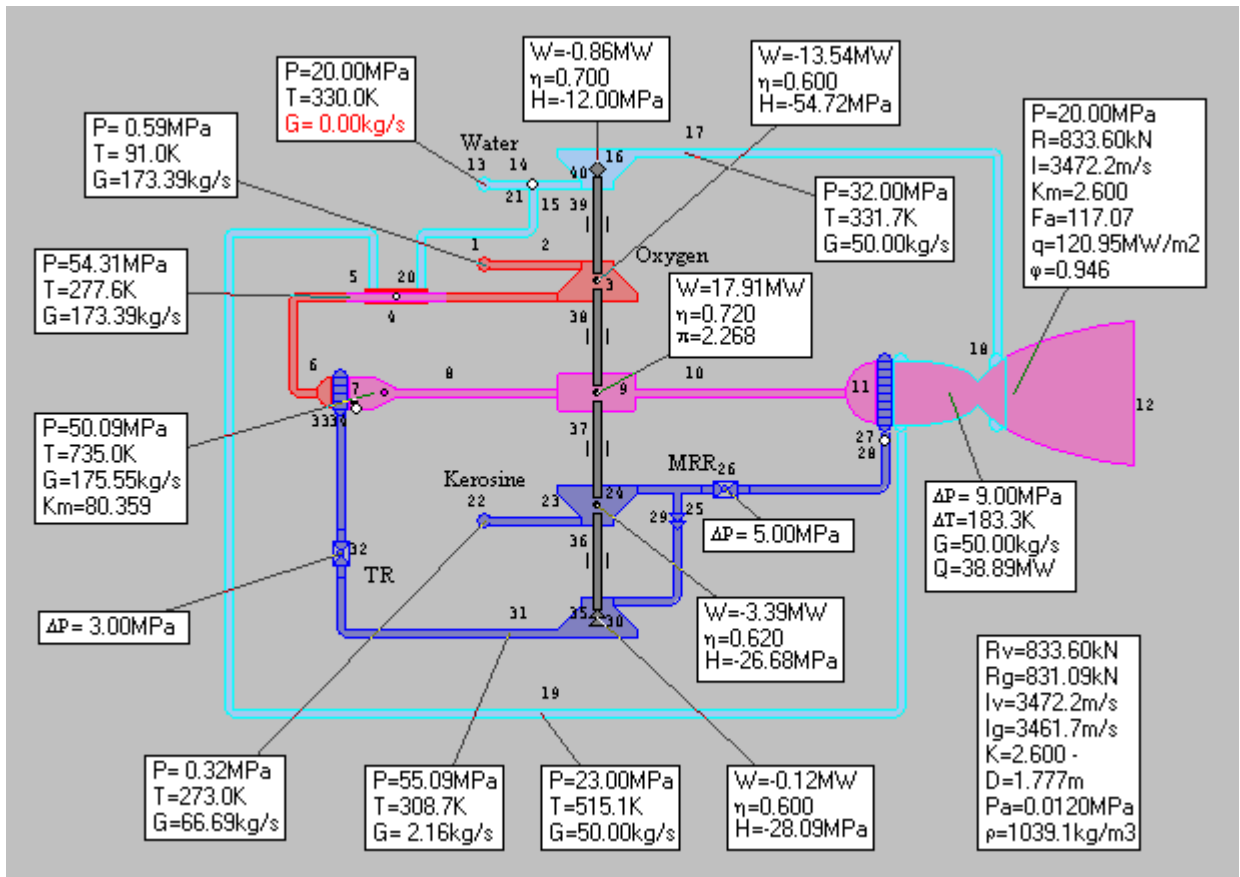


Fig. 7

The combustion chamber pressure has been raised to 20 MPa, as can be seen. Specific thrust impulse increased by  $\sim 57.6$  m/s (or 5.87 s), and engine mass for the new scheme increased by 128 kg (or which  $\sim 110$  kg is the weight of the heat exchanger).

Results of estimation of the new 830 kN thrust LPE variant's energy efficiency for use of the engine is part of the second stage propulsion system on a launch vehicle have been obtained from calculations for insertion of P/L into the near earth orbit. Increase in payload mass of  $\sim 500$  kg.

Comments of the previous section regarding the possibility of water freezing in space is less significant for this engine class because the engine starts once after the first stage of the launch vehicle.

#### 4. Results of calculations and their analysis for on 2010 kN thrust engine.

4.1. The basic variant of a 2090 kN thrust engine is shown in Fig. 8. This engine has been designed according to the scheme of afterburning of oxidizing generator gas. Pressure in the combustion chamber is 24.52 MPa. Approximate value of the coefficient of specific thrust impulse is  $\varphi_I \approx 0.947$ . Percentage of kerosene employed for curtain cooling is 1.37 % of the total consumption. Generator gas temperature is 823<sup>0</sup>K, turbopump unit capacity is:  $\sim 44.58$  MW. Heat capacity transferred by kerosene is 36.13 MW. Engine mass is:  $\sim 2200$  kg.

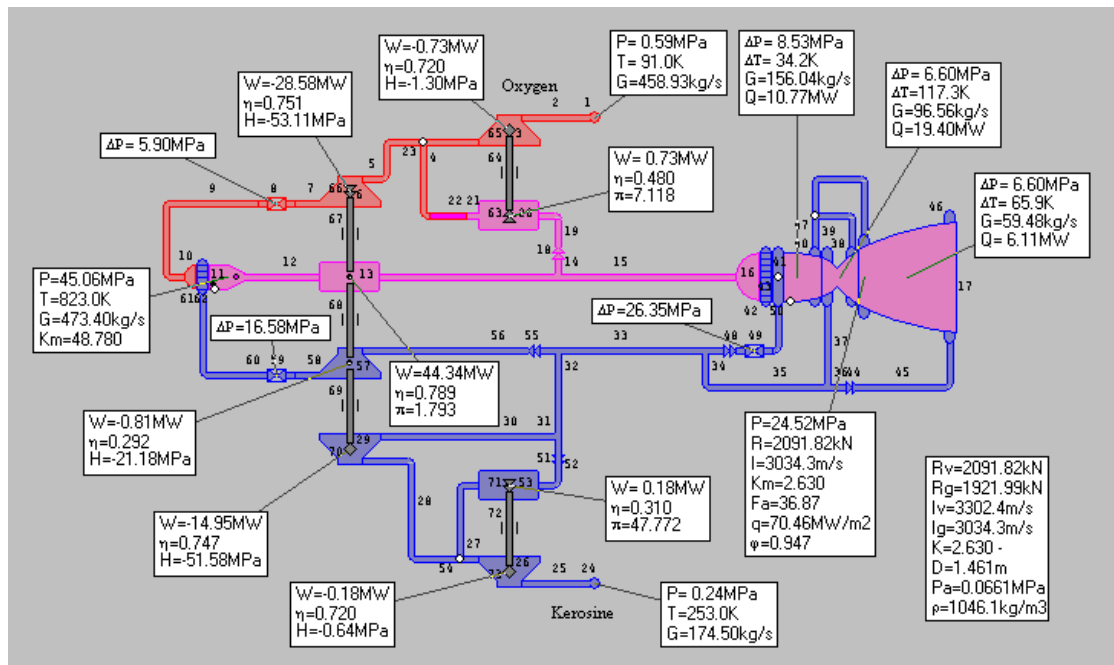


Fig. 8

4.2. Transformation of basic engine variant scheme is done with a closed circuit at combustion chamber water cooling, as shown in Fig.9.

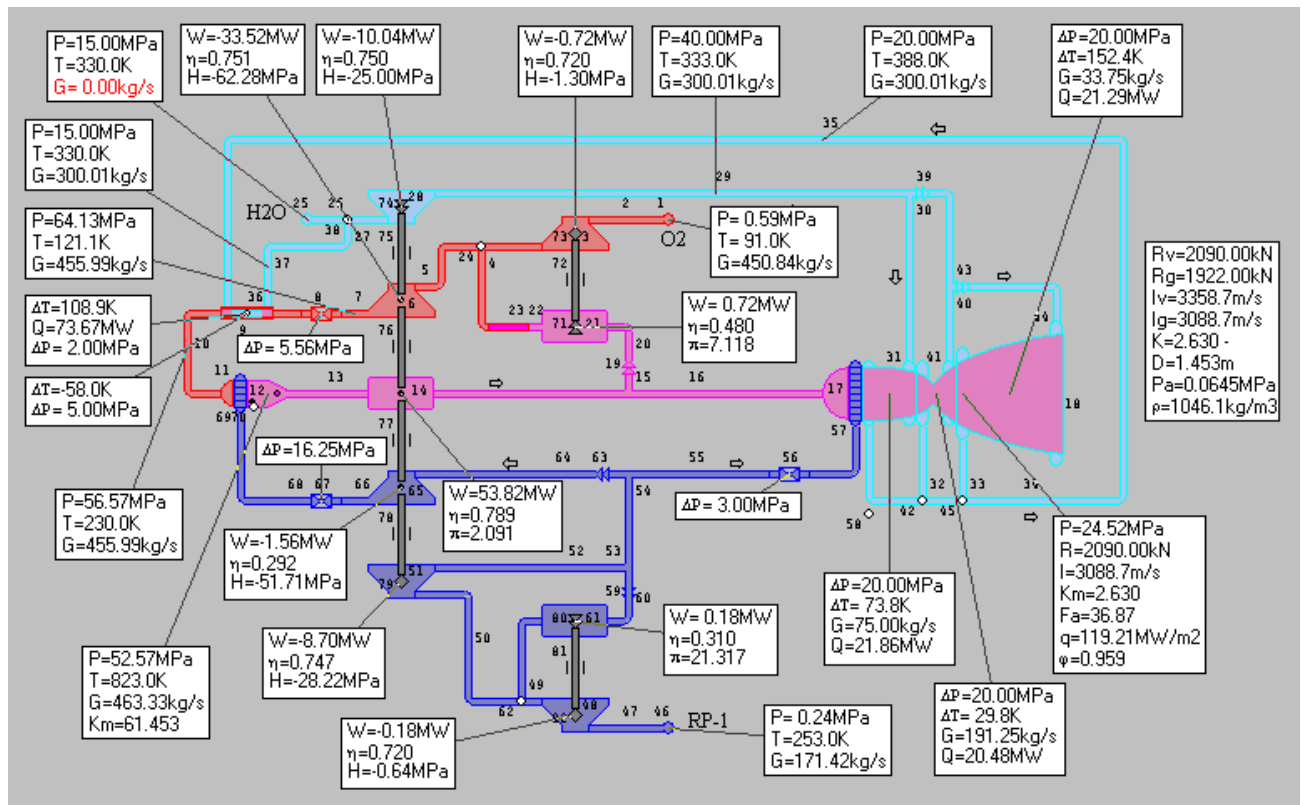


Fig. 9

Transfer to water cooling increases the vacuum specific thrust impulse by 41.8 m/s (~ 4.26 s). However, the capacity of the turbine is increased to 63.8 MW and the TPU mass increased by 16 kg, if compared with the basic variant. If the heat exchanger mass is ~ 180 kg, the total mass increase of the new scheme equals 196 kg.

Estimation results of energy efficiency of the new 2090 kN thrust LPE variant when used in the first stage propulsion system of a launch vehicle were obtained from calculations for insertion of payload into a near earth orbit.

Expected increase in P/L mass due to oxygen-kerosene LPE of the new scheme type as part of the first stage on a 2-stage launch vehicle can come to ~ 160 kg.

There are no problems associated with using water as cooling on this engine class. The cooling circuit can be filled with water before launch from the launch pad water systems.

## **Conclusion**

1. Perfection possibilities of modern oxygen-kerosene LPE in terms of improvement of energy end better reliability have been analyzed.
2. It has been demonstrated that the transfer of a 80 kN thrust engine into engine permits:
  - to reject curtain cooling of combustion chambers and to raise the specific thrust impulse by 127m/s (13 s);
  - to implement a non-generator LPE scheme with gaseous oxygen actuation of the pre-chamber turbine.
3. In terms updating, the new scheme of LPE with closed autonomous cooling circuit for the combustion chamber with a third component – water.

The proposed scheme works for engines with dimensions: 80 kN, 800 kN, 2000 kN , and permits a raise of the specific thrust impulse accordingly by: 175.4 m/s (18 s), 57.6 m/s (5.87 s), 41.8 m/s (4.26 s).

## **Acknowledgements**

The authors are grateful to the employees of Keldysh Research Center E. A. Gosudarev and I. O. Eliseev for fruitful discussions of work results and estimation of ballistic efficiency of the new LPE schemes.

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