Combustion-driven gas-dynamic CO$_2$-laser on the basis of modern aviation engines

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Abstract. Combination of combustion-driven gas-dynamic lasers with gas-turbine turbojet and turbo-shaft engines has been considered. Development of aviation technologies has been analyzed. Output performance of a laser taking air from modern helicopter and airplane engines taking into account ensuring exhaust of spent active medium into the ambient atmosphere has been determined. The application of penetration cooling of the laser nozzle bank blades has been evaluated.

1. Introduction
Combustion-driven gas-dynamic CO$_2$ lasers were developed and studied in the 1960-70s. They achieved high specific energy values. Transformation of the active medium accumulated energy into the laser radiation took place as a result of exothermic reactions of burning of hydrocarbon fuels with oxygen-containing oxidizers and supersonic acceleration of the obtained combustion products using nozzle banks without additional supply of energy.

The diagram of combustion-driven CO$_2$-GDL is presented in figure 1. CO$_2$-GDL consists of: a component storage and supply system (CSSS); a gas generator, where a gas mixture with high temperature and pressure is created; the nozzle bank, where the mixture is quickly cooled with gas-dynamic expansion in the supersonic nozzles; a laser chamber; an optical cavity and a supersonic diffuser ensuring exhaust of the used gas mixture to the environment. The nozzle bank usually consists of a great number of flat nozzles.

The gas mixture coming to the laser chamber must contain CO$_2$ and N$_2$ molecules, as well as a certain quantity of H$_2$O. Such composition of the medium is dictated by the specifics of the energy exchange process taking place in the active medium. To ensure the laser generation conditions, the flow in the laser chamber must have a static temperature of about 300K and the pressure of several dozens torrs.

In its essence, GDL is a thermal machine, the same as an aircraft engine. Both appliances use the combustion products of hydrocarbon fuel with compressed air for their operation.

The application of CO$_2$-GDL based on gas-turbine engine (GTE) has a number of advantages. Air, the basic component by mass (over 95%) to create the active medium of the laser, is taken from the
atmosphere and compressed to the required pressure level in the engine compressor. This allows the component storage system to be greatly reduced, as the mobile storage includes the fuel only, whose share in the total consumption does not exceed 5%.

Figure 1. The diagram of combustion-driven CO₂-GDL.

Ideas of combining the GDL with gas-turbine engines have existed long ago, both in Russia and abroad. There are the Russian and foreign patents for implementation of GDL into the aircraft engine [1-5]. In the end of the 1970s the world first ground-based gas-dynamic laser with air bleed from the aircraft engine P-38-300 operating uninterruptedly for a long time [6] was created in Russia (Former SU) under the guidance of Academician O.N. Favorskiy. The reached power was about 180 kW.

The basic parameters of combustion-driven GDL have an optimal values in terms of maximum output power, and they are in the range of 25-45 bars by pressure and in the range of 1,500-1,900K by temperature of combustion products before the nozzle bank.

Over the time of development of aircraft engines from the 1950s to the 2010s the characteristics of the engines affecting the output parameters of the gas-dynamic laser were greatly improved, such as: pressure after the last stage of the high pressure compressor and operating temperature in the combustion chamber of the engine. Figure 2 shows the tendencies of growth of one of the basic parameters of the engine (a compression ratio) over the entire history of development of Russian aircraft engine building. The data are taken from the work [7] for turbojet engines (TJE) for subsonic and supersonic combat, transport and civil airplanes and for turbo-shaft engines (TSE) for helicopters.

Figure 2. Development of turbojet engines for airplanes and turbo-shaft engines for helicopters by compression ratio.

The development of the temperature level of operability of cast heat-resistant alloys [8] and the use of cooling systems of gas-turbine engine blades [9] allows the temperature of the gases and, respectively, the characteristics of the engines to be increased. A steady growth of the compression ratio to the levels of 30-35 and the temperature level of operability of materials to the temperatures of 1,473-1,523K, as well as an increase in operating temperature of gas to 2,200K can be traced. Besides, modern cooling systems allow the difference between the gas and blade wall temperatures to be significantly increased to the values of 800K.
When choosing the structural design of GDL operating on the base of GTE, various types of take-offs from an engine are possible: air bleed, gas or power takeoffs. All three methods lead to a decrease in the design characteristics of the engine and change the design. However, in terms of minimizing the engine design change and optimal laser parameters (maximal power at minimal weight and size), an air bleed method looks preferable, which is discussed below.

2. Determining GDL output performance for helicopter and airplane engines

The choice of CO$_2$-GDL parameters, providing the maximum specific power, is based on the analysis of energy and gas dynamic characteristics, as well as taking into account design considerations.

The main determining parameters of the laser are:

- gas medium stagnation parameters (temperature and pressure in the high pressure (HP) chamber);
- total mass flow rate and ratio of components;
- parameters of the nozzle bank (nozzle expansion ratio, throat height h*, blade height).

**Pressure in the HP chamber.** Pressure before the nozzle bank should be sufficiently high in order to ensure the exhaust of the used gas mixture to the atmosphere, and to achieve the efficient output performance. In case of air bleed, the pressure in HP chamber is limited by pressure after the engine compressor.

**Temperature in the HP chamber.** The store of vibrational energy grows with an increase of gas temperature; however, the static temperature of the gas medium in the laser chamber should be about 300...350 K to ensure the laser generation conditions, i.e. with the fixed Mach number of the flow there is a limit for stagnation temperature (temperature in the HP chamber).

**Total mass flow rate and ratio of components.** Total mass flow rate of the fuel components is determined by the air flow rate that can be taken from the engine compressor.

**Parameters of the nozzle bank.** The nozzle bank is a key element determining the properties of the active medium: the gain and optical homogeneity of the active medium in the resonator zone. To keep the maximum vibrational energy, the length of the nozzle along the flow should be small enough. On the other hand, to ensure homogeneity and temperature of gas at the resonator input, the nozzle profile must correspond to several gas-dynamic requirements, and ensure the technological ability of manufacturing a great number of identical nozzle blades.

**Nozzle expansion ratio** is determined from the evaluation of the parameters of a supersonic exhaust diffuser at the given flow total pressure and at the condition of ensuring pressure at the output over 1 bar.

**Nozzle throat height** should be as low as possible. It is necessary to take into account a number of limiting factors: thermal deformation of the nozzle blades and changes in geometric dimensions, the growth of the boundary layer on the walls of the nozzles, as well as technological capabilities of manufacturing. Taking these factors into account leads to the height of the critical section of the nozzle $h^* = 0.3$ mm.

**Nozzle blade height** is chosen taking into account the requirements for the output aperture (which is determined by the height of the nozzle block) in terms of further transformation in the laser beam formation and transmission system, the requirements to an optimal magnification of resonator and a restriction by mirror damage threshold.

Thus, the choice of the parameters of CO$_2$-GDL operating on the basis of aircraft engines is reduced to determining the fuel components ratio ensuring optimal temperature in the HP chamber, with the existing restrictions for pressure, nozzle expansion ratio, throat height h$^*$ and blade height.

It is obvious that specific power and output power of the laser depend directly on the air pressure behind the GTE compressor and the flow of the air which can be taken off from the compressor without significant degradation of the engine performances. To analyze the feasibility of a gas-dynamic laser based on aircraft GTE and determine its output performance, an airplane engine AL-31F developed in A. Lyulki Experimental Design Bureau and a helicopter turbo-shaft engine VK-3000V developed in JSC «UEC-Klimov» were chosen. The basic characteristics of the engines are given in Table 1 [7].
Table 1. Basic characteristics of aircraft engines.

| Engine   | Temperature in gas generator $T_g$, K | Compressor pressure ratio $\pi_c$ | Air flow $G_A$, kg/sec |
|----------|-------------------------------------|----------------------------------|------------------------|
| AL-31F   | 1,690                               | 24                               | 118                    |
| VK-3000V | 1,510                               | 17                               | 9.2                    |

As a result of evaluation of the main determining parameters (taking into account the restrictions by pressure and temperature) the initial data for the energy estimation of the laser based on the considered engines were determined. At that, the engine parameters correspond to the sea level operating conditions. The initial data are given in Table 2.

Table 2. Main laser parameters for considered engines.

| Engine | Air flow, kg/s | Pressure in HP chamber, bars | Throat height ($h^*$), mm | Mach number at nozzle exit | Blade height, mm |
|--------|----------------|-------------------------------|---------------------------|---------------------------|-----------------|
| 2x(AL-31F) | 11.8          | 24                            | 0.3                       | 5                         | 150             |
| 2x(VK-3000V) | 1.84         | 17                            | 0.3                       | 4.6                       | 75              |

It is considered in estimation for AL-31F that the air bleed to the laser is carried out from the GTE compressor in the amount of 5 and 10% from the engine total mass flow rate for aircraft and helicopter engines correspondingly. A mixture «kerosene+air» is considered as a fuel composition for the laser taking into account the air compression ratio. The ratio of components of the fuel is a varied parameter.

The energy estimation is made for a stable single-pass resonator with the height and length of the mirrors corresponding to the height of the blade of the nozzle bank and with the optimal transmission factor of a semitransparent mirror. As a result of the estimation the geometric parameters and output power of the laser are determined in operation from two engines. The estimation results are presented in figures 3 and 4 as dependences of the output power and specific power on the oxidizer excess coefficient (ratio of the laser fuel components).

![Figure 3. Output performance of GDL based on two airplane engines AL-31F.](image)

![Figure 4. Output performance of GDL based on two helicopter engines VK-3000V.](image)
The performed estimations show that when using two airplane high-compression engines and high air mass flow rate even when taking 5% only, the laser power of about 80 kW in the uncooled nozzle bank (the temperature in the HP chamber of the laser not exceeding 1.500 K) can be obtained. It can be seen that the power peak is achieved at a temperature in the HP chamber of about 2,000 K, i.e. when using cooled nozzle blades, the output power can be increased to 135 kW.

For two helicopter engines that have a significantly lower compression ratio and a significantly lower air mass flow rate, the power not exceeding 10 kW can be achieved.

It can be seen that specific power grows with an increase in the Mach number of the flow in the laser chamber. The highest permissible Mach number, however, is limited by a possibility to ensure the exhaust of the used active medium into the environment. The higher Mach number, the higher the pressure in the HP chamber of the laser should be. That is, the increase in specific power can be achieved by increasing the air compression ratio in the GTE compressor.

3. Evaluation of the application of transpiration cooling of GDL nozzle bank blades

The use of cooling blades in GDL allows increasing the operating temperature in HP chamber, and, correspondingly, increasing the specific power and output power of the laser by 60...70% compared to uncooled blades. One of the promising methods of laser nozzle blade cooling is transpiration cooling. In this case in the most thermally loaded part of the blade (from the beginning of subsonic part to nozzle throat section, figure 5), a porous layer is installed through which the cooling medium is forced. It cools the blade and creates a barrier curtain along the wall. The compressed air from the engine compressor can be used as the cooling medium.

Currently, there are several known transpiration cooling schemes: Lamilloy (Allison Transmission), Transplay (Rolls-Royce), Supercooling (Pratt & Whitney). In Russia similar works were carried out in VIAM (All-Russian Research Institute of Aircraft Materials). The first original design was constructed jointly with Bauman Moscow State Technical University and was named «Vikhrepor» [10]. The USA has a patent [11] according to which the blades with transpiration cooling system are fabricated from an intermetallide alloy by an additive technology.

Transpiration cooling and the thermal state of the blade were numerically investigated in a CFD-package in a two-dimensional setting on the element of symmetry (figure 5).

![Figure 5. Computational model – symmetry element.](image)

The simulation was performed by solving Reynolds equations in a stationary arrangement using a turbulence model – k-omega SST. The simulation was made on a mesh with a characteristic size of 0.01 mm. At the inlet to the computational region the mass flow rate of combustion products with stagnation temperature of 2,121K was specified. The reduced air mass flow rate for cooling was 15% of the total mass flow rate of air to burn.

The porous layer in the model was described by the Darcy law which is a part, as an additional member, of an equation for pulses of a liquid medium. The thermal state of the porous medium was described by an equilibrium single-temperature model. Heat propagation in the porous matrix is determined by the conductive part of the energy equation, in which the effective value of the thermal conductivity ratio determined through porosity of the medium was used. The porous medium grain diameter was specified to 40 µm, porosity was set to 0.25. The permeability of the porous layer was determined by the Kozeny-Carman equation.

On the surfaces of the internal channels the condition of convective cooling by the medium with temperature of about 700K (compressed air) was specified. The heat-transfer coefficient in the inner
channels of nozzle blade was evaluated by criterion dependences and was equal to about 1,000 W/m²/K.

Figure 6 shows the distribution of oxygen volume ratio of in the porous layer and gas domain. The formation of a barrier curtain along the nozzle blade surface can be seen due to oxygen distribution. This also shows that the distance between the channels, supplying air to the porous wall, influences the flow in the porous layer.

Figure 6. Volume ratio of oxygen.

Figure 7 shows the calculated distribution of temperature in the blade volume.

Figure 7. Temperature field in the blade volume.

The maximum temperature of the blade in the throat section region is 1,200-1,225°C, which corresponds to the temperature level of operability of modern heat-resistant cast alloys.

4. Summary
It can be concluded that at the moment the existing level of technology development allows implementation of combining the combustion-driven gas-dynamic laser with aircraft engines in relation not only to the gas turbine engines with big mass flow rate, but also to the engines whose mass flow rate are relatively small, for example, to helicopter engines.

References
[1] Bushman B B 1995 Patent US No. US005384802A/ № 5384802; field 20.10.1992; publ. 24.01.1995.
[2] Smith E A 1987 Patent US No. US4713823; field 27.09.1985; publ.15.12.1987.
[3] Hill R J, Jewell N T 1975 Patent US No. US3899749; field 07.18.1972; publ. 08.12.1975.
[4] Perelshtein B H 2014 Patent RF No. RU2516985; field 14.02.2013; publ. 27.05.2014.
[5] Vovk M Yu, Marchukov Y U, Petrienko V G and Perelshtein B H 2016 Patent RF No. RU2587509; field 04.07.2015; publ. 20.06.2016.
[6] Gubarev V 2017 J. V Mire Nauki (Russian ed. of Sci. American J.) 11 110-15.
[7] Fomin A 2006 Take-off Magazine 4 7-29.
[8] Kablov Ye N, Lomberg B S and Osppenikova O G 2012 The Krylya Rodiny (Wings of Motherland) magazine 3–4 34–8.
[9] Gerasimov V V 2016 Proc. of VIAM: Electr. Sci. J. 10 3-28.
[10] Bratukhin G A 1997 Patent RF No. RU2078946; field 22.03.1994; publ. 10.05.1997.
[11] Deckard C R 1994 Patent US No. US5312584; field 18.02.1992; publ. 05.17.1994.