REGENERATIVE ELECTRICAL GAS HEATER FOR GDL

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The heat exchange and behavior of some structural elements of the heater under natural operational conditions of the GDL are investigated.

One of the basic problems determining the working characteristics of gasdynamic lasers (GDL) is the creation of an efficient and reliable gas heater. The most diverse types of heaters are currently used in GDL setups, for example, combustion chambers, plasmatrons, shock tubes, electrical explosions in a closed chamber, resistive electrical heaters for direct heating, regenerative gas heaters operating on the combustion products, etc. [1-9]. The use of different types of heaters in GDL is described, for example, in [10, 11].

In what follows, we present the results of one of the stages of the work on the development of a regenerative electrical gas heater with a heat-storing packing in the form of spheres and the results of the selection of materials for the main elements and parts of the heater and of investigations of the heater as part of a continuous gasdynamic CO_2 laser are discussed. The use of the selected gas heater in the experimental GDL setup, in principle, permits performing multifactor optimization of GDL, since in the experiment, it is easy to guarantee optimal values of parameters determining the efficiency of the GDL (for example, the gas temperature), for any fixed composition of the working gas mixture.

1. Calculation of Heat Exchange. Calculations were performed in order to select the design and the structural elements of the gas heater for the following working conditions: composition of the working gas mixture (vol. %), (40-90%) N_2 + (0-45%)He + (10-20%)CO_2 + (0-3%)H_2O; gas temperature in cylinders, 300°K; gas pressure in the heater, $(5\text{-}25) \cdot 10^5$ Pa; maximum temperature of the gas mixture at the outlet from the heater, 1673°K; flow rate of gas mixture through the heater (1-6 kg/sec); quasicontinuous working regime of the heater; duration of the pulse of gas mixture transmitted through the heater with given flow rate, (0.3-5) sec; pulse repetition frequency, 1 pulse/h; time for preparing the heater for operation, 3 h.

The solution of the problem of the temperature distribution in the packing and in the gas, in general, presents serious mathematical difficulties, since it involves the integration of a strongly nonlinear system of partial differential equations. In solving this temperature problem, the following assumptions were made:

a) The packing consists of separate spherical bodies, each of which is located under identical heat-exchange conditions;

b) the temperature of the packing is assumed to be constant over the radius and equal to the temperature at the lining packing interface;

c) the packing is separated vertically into several identical sections and it is assumed that the initial temperature of the spherical bodies changes abruptly at the boundary of the sections.

Let us examine a spherical body with some initial temperature, which is assumed to be constant on the given section of the packing. Over the course of the pulse, it is washed by the gas mixture with a constant, for the given section, temperature. It is necessary to find the temperature distribution inside the sphere at any time and the heat flow rate under the condition that the temperature at any point of the sphere is a function of time and of the radius.

The last condition corresponds to uniform cooling of the sphere along the surface, for which the isothermal surfaces are concentric spheres (symmetrical problem). A problem formulated in this manner is solved in [12].

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TABLE 1. Results of Tests for Thermal Strength

Specimen material	Diameter, m	Test conditions, °K	Number of heat exchanges	Result of tests
Al_2O_3	0,022	1773 (in water)	1	Network of cracks
ZrC	0,026	1373 (in water)	7	Breakup into pieces
Siliconized graphite	0,010	773 (in water)	10	Network and breakup are absent

In solving the strength problem, the case of central symmetry was examined using the basic equations of thermoelasticity in spherical coordinates [13].

Maximum stresses of 0.9 and 27 kg/mm^2 were obtained from the equations of equilibrium for graphite and aluminum oxide, respectively. Comparison of these quantities with the permissible stresses shows that this stress level is not dangerous for graphite, while fracture will occur in aluminum oxide spheres.

The aerodynamic problem for the case of gas flow through a layer of granulated solid matter (packing) was calculated according to [14].

2. Experimental. Reliable operation of the gas heater is in many respects determined by the reliability of the packing elements and other structural details, their ability to operate for a long time under the conditions of high temperatures and considerable dynamic and thermal loads and in a corrosive medium.

2.1. Thermal Strength of Heater Parts. Under the working conditions, the initial heat flow with cooling of the packing elements by the gas mixture constitutes $2.4 \cdot 10^6$ W/m^2. Under such thermal operational conditions, the maximum stretching stresses (due to temperature drops) appear on the surface of the specimen. In this case, specimens usually fracture with the appearance of a network of cracks on the surface (in addition, in a single test, as a rule, complete breakup into pieces was not observed). However, with cyclical repetition of the heat exchange, cracks can grow in the body of the specimens and, as a result, the specimen can break up completely into pieces. To check these assumptions, we performed laboratory tests of specimens, in which the working conditions were simulated, first of all, by retaining the values of the initial heat flow and, second, the specimens were cooled in order to create a stressed state in the body of the specimen equivalent to the working regime.

Tests performed by cooling a preheated specimen in water with a temperature drop of not less than 773°K satisfy these conditions. The results of the tests are presented in Table 1.

The experimental data confirmed the initial assumption concerning the behavior of materials under working conditions and made it possible to select the most stable structural material: siliconized graphite.

2.2. Compatibility of the Heater Materials with Carbon and Nitrogen. A thermodynamic estimate of the possibility of the occurrence of reactions in the contact zone of a number of materials used in the heater with carbon in an inert medium and nitrogen showed that for aluminum oxide, the weight can change due to reduction at temperatures above 1800°K, while nitriding of carbide compositions can occur only at temperatures above 2000°K. To confirm these results, we performed experiments, whose results agree satisfactorily with the thermodynamic estimates. The temperature in the contact zone $Al_2O_3 + CuAl_2O_3 + SiC$ in any medium should not exceed 1750°K. An increase in temperature is accompanied by reduction and sublimation of aluminum. Zirconium carbide in a medium of technical-grade nitrogen is quite capable of working for a long time at temperatures of 2300°K and above. Graphite, saturated with silicon carbide, practically does not interact with technical-grade nitrogen.

The thermodynamic estimates and the experiments performed showed that the most promising materials for making heaters, from the point of view of interaction with carbon and nitrogen, are zirconium carbide and graphite saturated with silicon carbide.

2.3. Compatibility of the Heater Materials with the Gas Mixture at Working Temperatures under Static Conditions. The heaters, packing, and lining were tested. Structural elements made of graphite, siliconized graphite, aluminum oxide, tungsten, lightweight chamotte, lightweight corundum, and others were used. The working mixture consisted of 90% N_2 and 10% CO_2. The working temperature was 1623-2323°K. Positive results under the given conditions were obtained with structural elements consisting of siliconized graphite and thermal insulation materials consisting of lightweight corundum.

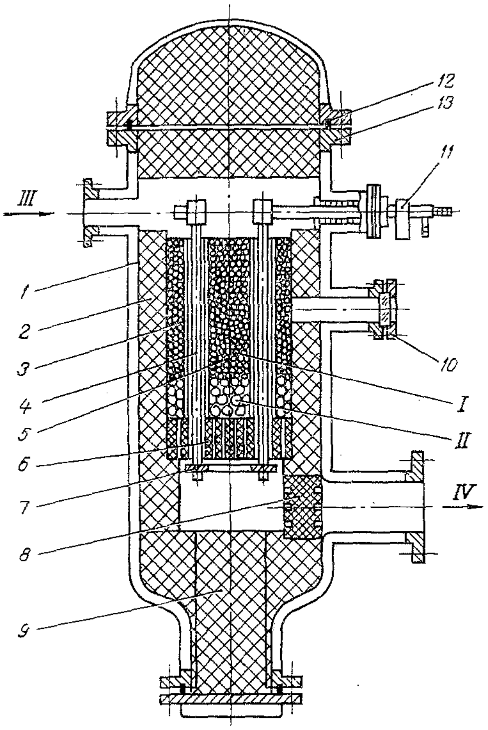

Fig. 1. Diagram of heater: 1) housing; 2) lining; 3) separating pipes; 4) rods-heaters; 5) packing; 6) grid; 7) graphite ring; 8) filter; 9, 13) thermal insulation; 10) viewing window; 11) input current lead; 12) upper cover; I, II) diameter of sphere 0.012 and 0.025 m; III) gas inlet; and, IV) gas outlet.

2.4. Compatibility of the Working Mixture with the Structural Materials of the Heater in the Flow. Specimens consisting of ÉG-0 graphite and siliconized graphite were tested. The temperature of the specimens was 1800-2000°K, the composition of the working mixture was 85% N_2 + 15% CO_2, the flow rate was 30 m/sec, the pressure was $20 \cdot 10^5$ Pa, and the duration of a single test was 300 sec. The ability of the materials to withstand corrosion-erosion was determined from the change in weight of the specimen. The best results on the compatibility of the working mixture with the structural materials were obtained in tests of materials consisting of siliconized graphite.

The calculations and experiments permitted developing an experimental design of a regenerative electrical gas heater with packing consisting of siliconized graphite spheres of lightweight corundum linining, and siliconized graphite heater elements.

The gas heater permitted solving completely most of the problems arising in the design and operation of heater setups for GDL.

3. Gas Heater Setup. According to its principle of operation, the heater (Fig. 1) is a regenerative heater, in which the working gas mixture is heated to the required temperature, passing through the layer of packing. The packing is first heated by an electrical heater consisting of six rods, insulated from the packing by dividing pipes. The external casing of the heater consists of a cylindrical, steel, water-cooled housing, which contains the inlet and outlet pipes, sockets for the viewing hole, six sockets for introducing current, a lower mounting socket, and the top cover.

The housing contains the following: lining, packing, heating rods, a base grid, filter, current input leads. The packing, heating rods, separating pipes, and base grids were made of siliconized graphite and placed in the central cavity of the thermally insulated lining.

The top ends of the heating rods are clamped into the water cooled current input; their lower ends, passing through the bearing grid, are connected with the "zero" graphite ring with graphite screws. The mounted heater was degassed at a packing temperature of 1373°K and a pressure of 13.3 Pa. Further testing of the heater was connected together with the gasdynamic laser.

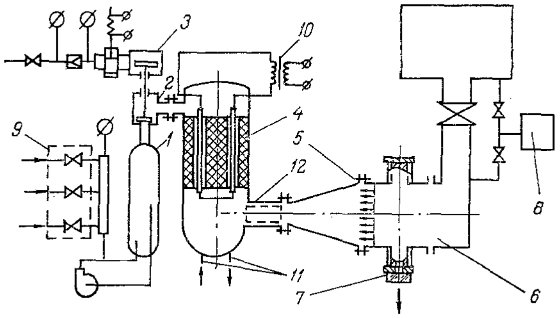

Fig. 2. Diagram of setup: 1) feeder mixing tank; 2) connecting mainline; 3) shutoff valve; 4) gas heater; 5) 100-blade nozzle unit; 6) working channel; 7) optical cavity; 8) vacuum system; 9) gas ramp; 10) power supply system for heater; 11) water cooling system; 12) filter.

4. Results of Tests of the Gas Heater in the GDL Setup. The GDL setup (Fig. 2) consists of a wind tunnel with quasistationary action with the gas exhausted into an evacuated volume. The nozzle block of the GDL consists of 100 shaped flat nozzle blades with expansion of 20 and a critical section with a height of 0.5×10^{-3} m (the total area of the critical section is 2.5×10^{-3} m^2).

A stable optical cavity was formed by a concave nontransmitting copper mirror (d = 0.060 m) and a semitransparent output mirror (d = 0.060 m, transmission 20%). We measured the temperature of the packing with an optical pyrometer and tungsten–rhenium thermometers, placed inside the packing at different depths $(50\text{–}235) \cdot 10^{-3}$ m. We measured the temperature of the gas mixture with tungsten–rhenium thermometers with readout on an oscillograph. The pressure was measured with the help of MDD gauges. For the tests, the heater in the GDL setup was operated in a regime that guaranteed heating of the gas mixture to the maximum possible temperature (i.e., 1250°K). The tests of the heater showed good agreement between the experimental results and the calculations. In the experiments, in which the average temperature of the packing, measured by the pyrometer and several thermometers, equaled 1400°K, the average gas temperature was 1200°K. This is essentially the computed value of the gas temperature – 1250°K.

The low value of the measured gas temperature compared with the computed value is explained by the fact that the measuring thermocouples were placed in the nozzle block at a distance of 1.5 m from the packing and this section was not thermally insulated from the surrounding medium.

To check the strength characteristics of the packing materials experimentally, the computed data for the permissible stress levels in the elements were confirmed. The calculations showed that the maximum stresses arising in graphite spherical elements reach $\sigma_{\max} = 9 \cdot 10^6$ N/m^2 and $\sigma_{\max} = 270 \cdot 10^6$ N/m^2 in the Al_2O_3 elements, while the permissible stresses for elements made of these materials are, respectively, $[\sigma]_{\mathrm{per}} = 11 \cdot 10^6$ N/m^2 for graphite and $[\sigma]_{\mathrm{per}} = 2.9 \cdot 10^6$ N/m^2 for Al_2O_3.

From a comparison of the computed quantities with the permissible stresses, it is evident that for graphite this stress level should not be dangerous, while fracturing should be observed in aluminum oxide spheres. After several tens of hot shots, no microcracks were observed on the siliconized graphite spheres, while the Al_2O_3 spheres fractured.

The tests performed showed that erosion of structural materials, operating under the conditions of high temperatures ($T \geq 1700$°K), high gas flow velocities ($W \geq 50$ m/sec), high thermal stresses, and high chemical activity of the working medium, is an important factor, determining to a large extent the working capacity of the gas heaters, which cannot be neglected in designing GDL setups. The experimental confirmation of the computed aerodynamic quantities is shown in Table 2.

The underestimation of the pressure (compared with the computed values) at the heater outlet is explained by the fact that the computed value of P_{out} determined the pressure loss only over the height of the packing, while the experimental value included, in addition, the pressure loss in the shutoff valve and at the inlet to the packing, since the pressure gauge was placed in front of the cutoff valve.

Laser radiation was generated with laser beam output onto a target in two experiments. The power level was ~1000 W. Optimization of the laser energy was not performed in these experiments. After several hot shots, the materials carried away by the gas from the apparatus were removed from the packing and studied by methods of chemical, x-ray, and metallographic analysis.

TABLE 2. Computed and Experimental Values of the Pressure in the Heater

Pressure in heater $P \cdot 10^{-5}$ Pa		
at the inlet (expt.)	at the outlet (calc.)	at the outlet (expt.)
7,2	6,0	5,5
7,2	6,0	5,5
8,5	5,3	4,5

TABLE 3. Results of Chemical and X-Ray Analysis of Erosion Products

Chemical analysis (wt. %)					Phase analysis (vol. %)			
C_{total}	Al	Fe	Si_{total}	O_2	C	Al_2O_3	SiC	SiO_2
45—50	13	0,2	20	22—17	80	5,0	8,0	6,0

The metallographic analysis established that the samples contain three fractions of material: pieces of graphite; fine crumbs of the lightweight material, and silicon oxide particles. The particle sizes varied from fractions of a millimeter up to several millimeters. The data obtained from the chemical and x-ray analysis are presented in Table 3.

During the operation of the heater, erosion of the thermally insulated lightweight material, consisting of aluminum oxide, was also observed. The appearance of SiO_2 particles is related with the evaporation of the excess silicon from the packing spheres and its oxidation by the components of the working body.

The tests that were performed demonstrated the promise and the interesting, for practical applications, possibilities of the selected working scheme of a gasdynamic laser utilizing thermal energy storage. The experimental results permitted formulating the requirements for further improvement of the structural materials.

LITERATURE CITED

1. E. F. Gerey, "Gas dynamic laser," Laser Focus," 6, No. 12, 61-66 (1970).
2. R. A. Meinzer, "Investigation of CW GDL," AIAA J., 10, No. 4, 41-49 (1972).
3. S. B. Goryachev, B. A. Tikhonov, and V. F. Sharkov, "Results of experiments on gasdynamic CO_2 laser," Kvantovaya Elektron., 6, No. 8, 1775-1776 (1979).
4. A. P. Dronov, A. S. D'yakov, E. M. Kudryavtsev, and N. I. Sobolev, "Gasdynamic CO_2 laser with efflux of working mixture, heated in a shock tube, through a slit," Pis'ma Zh. Eksp. Teor. Fiz., 11, No. 11, 516-519 (1970).
5. V. N. Kroshk, R. I. Soloukhin, and N. A. Fomin, "Effect of the composition and temperature on the efficiency of excitation and inversion of a mixture in a sonic flow," Fiz. Goreniya Vzryva, 10, No. 4, 473-485 (1974).
6. B. A. Vyskubenko, E. T. Demenyuk, and A. D. Eremin, "Gasdynamic CO_2 laser with gas heated by an electrical explosion," Kvantovaya Elektron., 5, No. 10, 2154-2161 (1978).
7. G. V. Abrosimov, A. A. Vedenov, and A. F. Vitshas, "Generation of intense infrared radiation in a gasdynamic CO_2 laser near threshold temperatures for thermoemission," Teplofiz. Vys. Temp., 13, No. 4, 865-867 (1975).
8. G.M. Klepach, V. A. Konakh, V. A. Soldatov, and V. F. Sharkov, "Experimental and theoretical investigation of CO_2 gasdynamic laser with a closed loop," Kvantovaya Elektron., 6, No. 4, 1171-1175 (1979).
9. V. S. Makeev, L. N. Semenychev, V. N. Khromylev, et al., "Regenerative type gas heater," Inventor's Certificate No. 481143, Byull. Izobret., No. 30 (1975).
10. S. A. Losev, Gas Dynamic Lasers [Russian translation], Mir, Moscow (1977).
11. D. Anderson, Gas Dynamic Lasers. Introduction [Russian translation], Mir, Moscow (1979).
12. A. V. Lykov, Theory of Heat Conduction [in Russian], Vysshaya Shkola, Moscow (1967).
13. H. Parkus, Nonsteady State Temperature Stresses [in Russian], Fizmatgiz, Moscow.
14. J. Perry, Chemical Engineering Handbook [Russian translation], Vol. 1, Khimiya, Moscow (1969).