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CHOICE OF HEAT-TRANSFER AGENT FOR HEAT PIPES OPERATING IN THE TEMPERATURE RANGE 300-500°C

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The authors analyze possible heat-transfer agents for heat pipes operating within the structural members of a gas-turbine motor. The authors have examined silicone liquids, for which they present thermophysical properties and the results of heat-pipe tests.

A number of plant and equipment items operate under complex thermal conditions. For example, most elements of a gas-turbine motor (GTM) are under high thermal load, where the thermal stresses arising in the members decrease the operating potential and degrade the economics of the motor. One can reduce the thermal stresses by using heat pipes or by including structural members operating on the heat-pipe principle.

The main problem in making such members is to choose a nontoxic, explosion-proof, noncorrosive heat-transfer agent capable of operating at temperatures of 300-500°C. To bring a GTM rapidly to operation from startup and provide flexibility of a system based on the heat-pipe principle, the agent should have a low melting temperature and remain in liquid form at a temperature of −50°C. From the viewpoint of structural strength at low mass, the vapor pressure should not exceed 5-7 kg/cm^2 at a temperature of 500°C.

The choice of agent is made difficult because this temperature range is not suited to heat-pipe operation, due to a limited choice of working liquids. Practically a single substance is used, mercury, which has a number of negative factors (toxicity, corrosive to steel structures, high specific gravity, low wettability of metal surfaces).

Analysis of existing high-temperature heat-transfer agents has shown that the above requirements can be satisfied by silicone oils. These are colorless liquids, insoluble in water, but soluble in aromatic hydrocarbons and alcohols [1, 2]. They are nontoxic, free of explosion hazard, and chemically inert. Their most valuable technical properties are the low freezing temperatures (−70 to −140°C), the low dependence of viscosity on temperature, the low saturated vapor pressure, the good stability towards irradiation, and the high dielectric properties. The thermophysical properties of silicones are shown in Table 1.

It was noted in [1, 2] that silicones can be used at temperatures up to 250-300°C in air, and it was recommended that they be used only in the form of nonboiling liquids, since silicone vapors are unstable and decompose rapidly. However, taking into account the specific operating conditions in heat pipes (absence of oxygen, increased pressure, and the short period where the agent is vaporized), one can propose the possible use of silicone oils as heat-transfer agents in heat pipes at temperatures up to 500°C. To check this experimentally, we tested nine silicone oils whose thermophysical properties are given in Table 1. The capabilities of the silicone oil agents were determined from the characteristics of heat pipes filled with the test liquids.

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TABLE 1. Thermophysical Properties of Silicones

Heat transfer agent	Temperature, °C		$\nu \cdot 10^6$, m^2/sec	ρ, kg/m^3	c_p, kJ/kg·deg	λ, W/m·deg
	melting	boiling*	at 20°C			
SOA-1	— 70	$\frac{360}{0{,}2}$	60—100	1070	1,42—2,00	0,140
SOA-2	— 60	$\frac{185—250}{1—3}$	42—48	970—1180	1,86	0,147
SOA-3	— 60	$\frac{250}{1—3}$	200—500	990—1020	1,85	0,163
SOA-4	— 40	$\frac{430—460}{760}$	70	1100	1,59	0,128
SOA-5	— 30	$\frac{420—450}{760}$	200	1100	1,59	0,128
SOA-6	— 0	$\frac{400—430}{760}$	80 (+50°)	1100	1,59	0,128
SOA-7	— 20	$\frac{400—450}{760}$	700	1100	—	0,128
SOA-8	— 55	$\frac{233—241}{1—2}$	54	1021	—	—
SOA-9	—100	$\frac{112{,}5}{20}$	2,2—2,5	870	1,63	0,167

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*The denominator of the fraction gives the pressure in torr.

We prepared and tested eight heat pipes with identical geometry of the body and the capillary structure. The heat-pipe body was of stainless steel of internal diameter 8 mm, wall thickness δ = 0.5 mm, and length l_p = 150 mm. The capillary structure was made of two layers of woven mesh with a cell gap of 0.075 mm. The mesh material was 1Kh18N9T. The heat-pipe designation corresponds to the liquid number in Table 1.

The heat was supplied to the heat-pipe evaporator zone of length 70 mm by means of an electrical heater. Heat was removed in the condenser zone of length 70 mm by air cooling. The slope of the pipe axis to the horizontal was 45°.

Preliminary tests of the heat pipes showed that pipes Nos. 5-8 did not meet the given operating conditions, and they were eliminated from further tests. Pipes Nos. 5-7, filled with agents (silicone oil agent, SOA) SOA-5, SOA-6, and SOA-7, operated well at evaporator temperatures less than 350°C. At evaporator temperature T_{ev} = 360°C carbonizing of the capillary structure occurred and the heat pipe became inoperable.

With pipe No. 8, filled with agent SOA-8, we reached an evaporator temperature of T_{ev} = 350°C. Later this pipe disintegrated.

Figures 1 and 2 show the test results for pipes Nos. 1-4, filled with SOA-1, -2, -3, and -4, respectively. The ordinate shows the heat flux per unit cross section of the pipe vapor channel, q, W/cm^2, and the abscissa shows the temperature drop, ΔT, °C, along the pipe at the external body surface.

At evaporator temperature T_{ev} = 400°C (Fig. 1a) the best heat-transfer capability is shown by pipe No. 4. For a temperature drop along the pipe of ΔT = 110°C it transfers a heat flux of q = 150 W/cm^2. At increased temperature T_{ev} > 400°C carbonization of the capillary structure occurred in pipe No. 4, after 2 h of operation. Pipes Nos. 1-3 operated reliably at evaporator temperature T_{ev} = 500°C (Fig. 1b), and pipe No. 2 showed the best heat-transfer capability. Pipe No. 3 had a capability less by a factor of 5-10 than pipe No. 2. Incidently, the viscosity of SOA-3 is less by a factor of 5-10 than that of SOA-2 at 20°C. It should be noted that pipe No. 3 operated stably at evaporator temperature T_{ev} = 600°C.

Of the agents examined for use in heat pipes operating in elements of a GTM, we can recommend SOA-1 and SOA-2, for which the heat-pipe characteristics are shown in Fig. 2.

According to [3], silicone oils can operate at a temperature of 350°C for up to 1000 h. The present authors investigated operation of SOA-9 for 250 h in four thermal siphons of

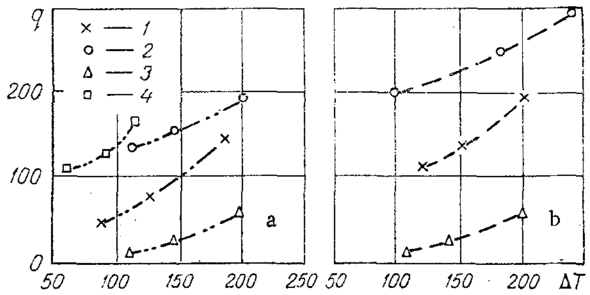

Fig. 1. Results of heat-pipe tests (pipes Nos. 1-4) at evaporator temperature of (a) 400 and (b) 500°C.

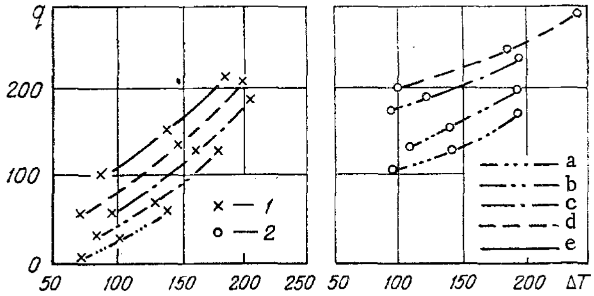

Fig. 2. Results of tests on heat pipes Nos. 1 and 2 at evaporator temperature 350°C (a), 400 (b), 450 (c), 500 (d), 530°C (e).

diameter 8 mm and length 150 mm in a vertical position with evaporator temperatures of 520, 515, 510, and 475°C, where the internal surfaces of siphons Nos. 2-4 were passivated prior to filling. At the end of the tests the siphons were opened, and chromatographic analysis showed that the original liquid (silicone polymer) had decomposed to the extent 98, 54.9, 54.6, and 49.7%, respectively. Here the temperature drop over the siphon was 64.0, 30.2, 26.7, and 8.3%, respectively, compared with the original values.

Thus, heat pipes with silicone oils have shown satisfactory operation in the temperature range 300-500°C. In theory, the liquids examined can be used from −70 to 500°C, since they have freezing temperature as low as −70°C.

NOTATION

q, heat flux transferred by a pipe per unit area of cross section, W/cm^2; ΔT, temperature drop along the pipe, °C.

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