Advanced Journal of Physics Research and Applications

Review Article

High Power/Energy Optics Based on Liquid Alkali Metals -

Victor V. Apollonov*

AM Prokhorov GPI RAS, Vavilov str. 38, Moscow, 119991, Russia

***Address for Correspondence:** Victor V. Apollonov, AM Prokhorov GPI RAS, Vavilov str. 38, Moscow, 119991, Russia, E-mail: vapollo@kapella.gpi.ru

Submitted: 13 April 2021; **Approved:** 19 April 2021; **Published:** 20 April 2021

Cite this article: Apollonov VV. High Power/Energy Optics Based on Liquid Alkali Metals. Adv J Phys Res Appl. 2021 April 20;1(1): 011-014.

INTRODUCTION

Prospects of utilising Liquid Alkali Metal (LAM) coolants in the area of High Power/Energy Optics (HP/EO) suggested by us [1-5] were determined by the possibility of achieving a high heat transfer coefficient in the porous structure due to a favourable combination of thermo-physical properties of LAM. This allowed one to lessen the requirements to the thermal conductivity of the porous structure material, which opened up the possibility of using new structural materials with a low thermal expansion coefficient and thermal conductivity in reflectors. The most particular interest was the employment of eutectic alloys of LAM with low melting points in HP/EO.

Consider some results of theoretical and experimental investigations of heat and thermal deformation characteristics of HP/EO cooled by the eutectic alloy Na–K. As part of earlier assumptions the heat transfer equation can be written as

$$\frac{d^2t}{dx^2} = \frac{h_e}{\lambda} S_V (t - t_T), \tag{1}$$

Where h_e is the heat transfer coefficient between the porous structure material and the coolant. Due to the lack of published data on the heat transfer of LAM in porous structures, the lower bounds of heat transfer coefficient were estimated by using the known data on the heat transfer of LAM coolants in triangular arrays of nuclear reactor fuel elements [6]. To calculate the heat transfer of LAM in the nuclear fuel assemblies, use was made of the relations:

in densely packed structures (*s*/*d*=1)

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{lam}} + 0.0408\left(1 - 1/\sqrt{1.24\varepsilon + 1.15}\right)\mathrm{Pe}^{0.65}; \tag{2}$$

in not densely packed structures (1.0<*s*/*d*<1.2)

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{lam}} + \frac{3.67}{90(s/d)^2}\left\{1 - \left[\frac{1}{\left[(s/d)^{30} - 1\right]/6 + \sqrt{1.24\varepsilon + 1.15}}\right]\mathrm{Pe}^{m_1}\right\}; \tag{3}$$

in not densely packed structures (1.2<*s*/*d*<2)

$$\mathrm{Nu} = \mathrm{Nu}_{\mathrm{lam}} + 3.67\mathrm{Pe}^{m_2}/90(s/d)^2. \tag{4}$$

Here, $m_1 = 0.56 + 0.19 s/d - 0.1/(s/d)^{80}$; Pe is the Péclet number;

$$\mathrm{Nu}_{\mathrm{lam}} = \left[7.55\left(\frac{s}{d} - \frac{6.3}{(s/d)^{17(s/d)(s/d-0.81)}}\right)\right]\left[1 - \frac{3.6}{(s/d)^{20}(1 + 2.5\varepsilon^{0.86}) + 3.2}\right]$$

is the Nusselt number for the laminar flow; *s*/*d* is the relative spacing of the fuel elements in the array; and $\varepsilon = \lambda_{\mathrm{st}}/\lambda_{\mathrm{T}}$ is the ratio of the thermal conductivity of the fuel element cladding material to the thermal conductivity of the coolant. The relations (7) are valid for $\varepsilon > 0.01$ and $1 \le \mathrm{Pe} \le 4000$.

Assuming that the hydraulic diameter of the array of the fuel elements corresponds to the hydraulic diameter of the HP/EO porous structure $(d_s = d_p)$, and the diameter of a set of rods – to the wire diameter (for metal-fibrous porous structures), we can obtain the dependence $d_s = d_m \Pi_V / (1 - \Pi_V)$ for felt porous structures.

Figures 1 and 2 show the results of numerical calculations of thermal deformation characteristics of the HPO cooled by the eutectic coolant Na–K. It was assumed that the porous structures of the reflectors were made of molybdenum and invar felt. The mean diameter of the felt and the bulk porosity of the structure varied within $d_s = d_m \Pi_V / (1 - \Pi_V)$ μm and $0.1 \le \Pi_V \le 0.9$. The curves in figure 1 and 2 are the envelopes of the thermal deformation characteristics of the HP/EO family and plotted at a constant pressure drop of the coolant and a maximum temperature of the cooling surface equal to 100 °C.

One can see from figure 1 that the deformation of the optical surface in the region of the coolant outlet, calculated with account for its heating in the porous structure, substantially exceeds the deformation in the region of the coolant inlet $\left(W_2^* > W_1^*\right)$. The maximum power densities of the heat flux (not a laser light flux) for the HP/EO in question are as follows: $q_1 > 20$ kW cm^{-2} in the region of the coolant inlet and $q_1 = 6.6$ kW cm^{-2}; in this case, $W_2^* = 0.3$ μm. The minimum deformation W_2^* in the region of the coolant outflow at a power density of 4.2 kW cm^{-2} is 0.12 μm, which is significantly lower than the optical damage threshold of the HPO for CO_2 and HF/DF lasers.

Analysis of the data in figure 2 shows that the use of porous structures made of materials with a low thermal expansion coefficient (invar fibres) allows one to significantly (approximately by 3–4 times) reduce thermal deformations of the mirror surface both in the region of the coolant inlet and outlet in the case of LAM cooling. Thus, the maximum thermal loads, experimentally allocated from the mirror surface, exceeded 10 kW cm^{-2}. The experimentally measured thermal deformations of HP/EO made of invar fibres in the region of minimum deformations were less than 0.5 μm.

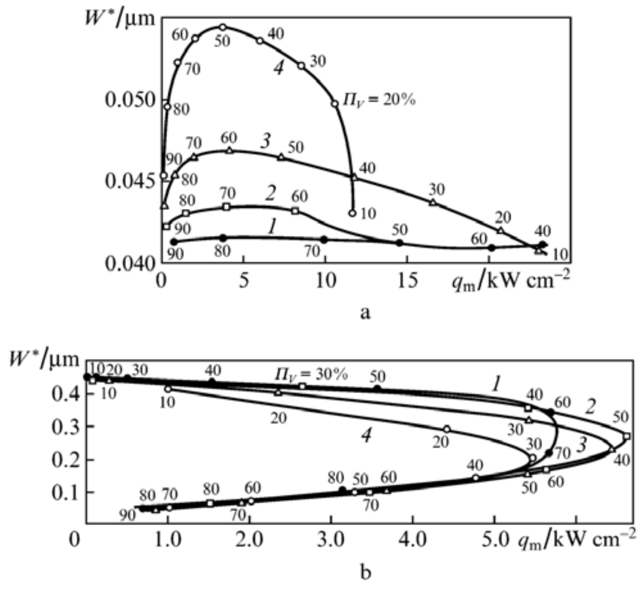

Figure 1: Nomo grams of thermal deformation characteristics of HP/EO based on metal-fibrous porous structures made of molybdenum, which are cooled by a Na−K coolant in the regions of its inlet (a) and outlet (b) at (1) 20, (2) 50, (3) 100 and (4) 200 .

It should be noted that the results presented in figure 1 and 2 clearly show that liquid metals are very promising for HP/EO cooling. Such cooling in combination with porous structures made of materials with relatively low coefficients of thermal expansion opens up fundamentally new possibilities for creating a class of very precise HP/EO with a high optical damage threshold.

Today, due to the accumulation of experimental data on convective heat transfer and hydrodynamics in porous structures, such structures are widely used in space instrumentation and nuclear power systems exposed to high radiation doses. Due to the structural features, metal porous structures have no blind pores, which eliminates unwanted thermal processes. They provide good permeability, high thermo-physical characteristics, ability to use HP/EO at a boiling point of working fluids in heated regions, high heat transfer rates and high limiting values of critical heat fluxes. Metal porous structures exhibit good physical-mechanical and performance characteristics. Metallurgical production technology ensures their stability and reproducibility, long service life, and high reliability. One of the first mirrors based on porous structures [7-10] is shown in figure 3.

The new areas of research, which have been successfully investigated together with LAM cooling, include the study of organic liquids boiling on the surfaces of porous structures with their hydrodynamic characteristics taken into account. The study of the influence of these characteristics on the contact thermal resistance between the porous and solid layers and the study of heat transfer during condensation of liquids on the working surfaces of porous structures were investigated as well. It should be noted that our investigations of heat transfer in porous structures made it possible to develop the technological basis for creating a series of water-cooled and LAM - cooled HE/PO for lasers by employing the chemical etching of metal foils with subsequent soldering to fabricate a multilayer heat exchanger with a moderate degree of development of the heat exchange porous surface [11-14].

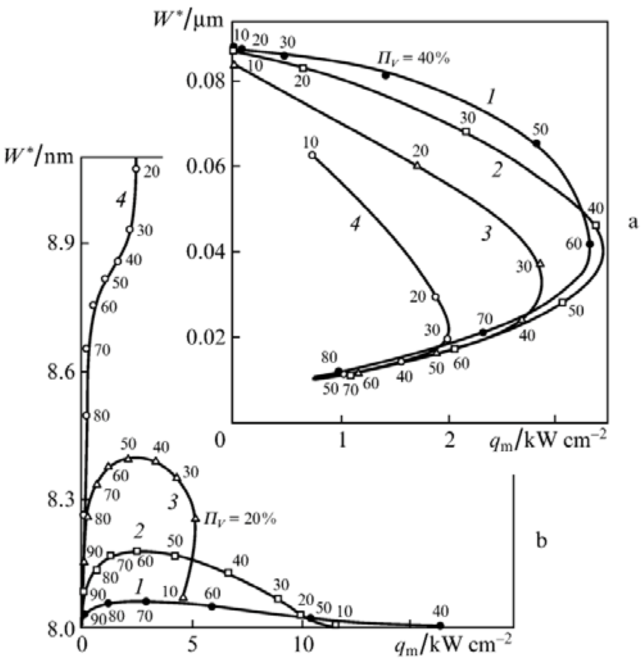

Figure 2: Nomo grams of thermal deformation characteristics of HP/EO based on metal-fibrous porous structures made of invar, which are cooled by a Na−K coolant in the regions of its inlet (a) and outlet (b) at d_m = (1) 20, (2) 50, (3) 100 and (4) 200 μm.

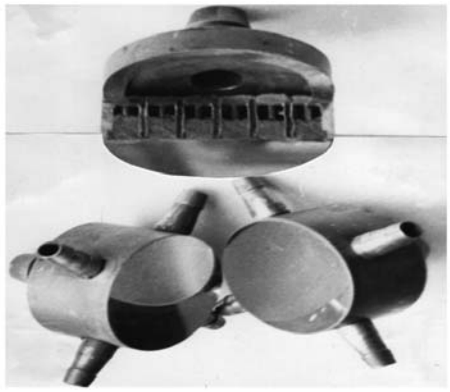

Figure 3: First cooled HP/EO elements with a powder based porous structure.

CONCLUSION

Further increase in the optical damage threshold of a mirror surfaces of HP/EO based on porous and microcapillar structures is possible when LAM and their alloys are used as the coolants. Prospects of utilising LAM coolants in HP/EO were determined by the possibility of achieving a high heat transfer coefficient in the porous structure due to a favourable combination of thermo-physical properties of liquid alkali metals. The particular interest of the employment of eutectic alloys of LAM with low melting temperature in the case of HP/EO had been confirmed theoretically and experimentally. Extraordinary high importance results of experimental investigations of thermal deformation characteristics of HP/EO cooled by the eutectic alloy Na–K had been achieved and demonstrated for the case of MW scale lasers [15-17]. According to our experimental tests and expectations the heat flux with a power density up to 30 kW cm^{-2} can be evacuated from the optical (heat exchange LD matrix) surface.

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