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Forced convective cooling of a high-power solid-state laser slab

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Abstract

A cooling system utilizing the concept of forced convection has been devised to cool the slab of a high-power solid-state laser. Numerical studies were conducted to investigate the thermal effect of the slab cooled by water flowing in a narrow channel. Numerical simulations were performed for Reynolds numbers between 500 and 8000. The calculation results show that for fixed Reynolds number, when the channel height is reduced, the local Nusselt number decreases while the local heat transfer coefficient increases. The maximum thermal stress occurs at the pumped surface in contact with the water coolant, and its location moves from the upstream end to the center of the pumped surface with increasing the Reynolds number and/or reducing the channel height. For fixed Reynolds number with fixed channel height, both the highest temperature and the maximum thermal stress increase with increasing the thermal load, but they increase in a different manner—the former increases linearly while the latter increases more quickly for greater thermal load. The maximum permissible thermal load increases with increasing the Reynolds number and/or reducing the channel height. Such thermal load is decided by the limit temperature for small Reynolds number and/or small channel height case but by the limit thermal stress for large Reynolds number and large channel height case.

Keywords: Laser cooling; Forced convection; Narrow channel; Thermal effect

1. Introduction

When a laser operates, it is inevitable that a significant part of the pump light is converted to heat, causing additional stress and strain. Thermal heating is becoming one of the major limiting factors in scaling the power of a high-power solid-state laser. To reduce the thermal effect, such a laser must be cooled efficiently.

Studies on laser cooling were conducted by several researchers. Weber et al. [1] studied and compared four different methods for cooling the high-power end-pumped laser, they concluded that cooling with composite rods was the best choice for the laser applications. Xie et al. [2] simulated and obtained the optimum convective heat transfer coefficient and coolant flow rate based on an ideal one-dimensional model. Brown [3] studied the cooling characteristics of high-power diode-pumped lasers, with a special emphasis on the effects of the thermophysical and mechanical properties of the laser slab, he reported that consideration of the temperature-dependency for thermal conductivity and thermal expansion coefficient would lead to non-quadratic transverse temperature profiles and over-predicted stress components as compared with that by the traditional linear theory. Mudge et al. [4] also reported results on the thermal stresses in a centrally cooled slab based on the finite-element analysis. It is useful to note that all the researches introduced above were based on the uniform heat transfer coefficient model.

We have recently devised a system that utilizes forced convection of water flowing in a narrow channel to cool the side-pumped high-power solid-state laser. Fig. 1 schematically shows the concept of this cooling scheme.

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Nomenclature

A	pumped surface area of the laser slab, m^2
b	length of the laser slab, m
c	channel spacing, m
d	thickness of the laser slab, m
D_h	hydraulic diameter of the channel, m
E	Young's modulus, Pa
h	heat transfer coefficient, $W/(m^2\ k)$
L	width of the laser slab, m
Nu	Nusselt number
Pr	Prandtl number
q	heat flux, W/m^2
Q	thermal load, W
Re	Reynolds number
T	temperature, K
x, y	coordinate, m
x^*	dimensionless axial distance defined by Eq. (20)

Greek symbols

a_a	absorption coefficient, m^{-1}
a_e	thermal expansion coefficient, K^{-1}
η	fluid dynamic viscosity coefficient, kg/(m s)
λ	conductivity, W/(m K)
v	Poisson ratio; kinematic fluid viscosity coefficient, m^2/s
σ	thermal stress, Pa
$\dot{\Phi}$	heat source, W/m^3

Subscripts

avg	average
b	bulk
f	fluid
i	inlet
s	solid
x, x^*	local
w	wall

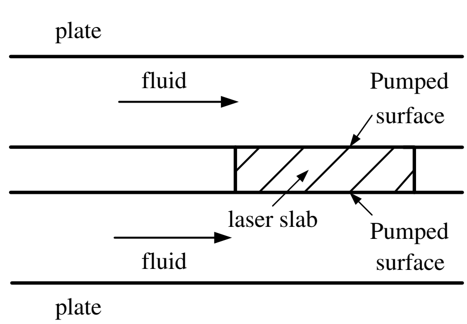

Fig. 1. Laser slab cooling scheme.

Water flows over the laser slab and cools it, yielding a conjugate heat transfer problem for fluid flow in one side heated parallel plates within the thermal entrance region. A narrow channel is adopted because it can provide a high heat transfer coefficient due to the small size effect. Guo and Li [5] divided the physical mechanisms for the size effects on the micro/mini-channel flow and heat transfer into two classifications: (1) the fluid rarefaction effect occurs when the continuum assumption breaks down as the characteristic length of the flow becomes comparable to the mean free path of the molecules, and (2) variations of the predominant factors influence the relative importance of various phenomena on the flow and heat transfer as the characteristic length decreases, even if the continuum assumption is still valid. The size effect in the present case certainly belongs to the second classification.

It is known that the convective heat transfer coefficient is an important parameter in the thermal design for the laser slab cooling. The convective heat transfer coefficient in the present case varies along the fluid flow direction; this non-uniformity will certainly affect the temperature distribution field and consequently the thermal stress in the slab. The laser will not work properly unless the temperature and thermal stress of the laser slab are maintained under certain levels, this limits the power of the laser. The primary objective of the present research is to numerically study the thermal effect of the laser slab cooled by water flowing in a narrow channel and determine the maximum permissible thermal loads for various conditions.

2. Computational details

2.1. Problem description

Consider the conjugate problem for the laser slab cooling system shown in Fig. 1. Because of the symmetry in geometry, it is reasonable to consider only half of Fig. 1 system. Fig. 2 defines the problem as well as some key geometric variables. The coordinate system is also depicted in the figure. The slab is made of Nd:YAG crystal, it has a length of b and a thickness of d, while the water flow passage, which is formed by the laser slab and the insulating plates, has a spacing of c. As indicated by Fig. 2, water flows through the channel and