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Optimization design of water-cooled mirror for low thermal deformation

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HIGHLIGHTS

- A novel structure of mirror layer for water-cooled mirror is proposed.
- The novel structure improve the magnitude and uniformity of thermal deformation.
- Inlet/outlet arrangement impact heat performance, stiffness, thermal deformation.
- Effective design must provide both effective heat dissipation and enough stiffness.
- Re ≈ 1000 is figured out to be optimal hydraulic conditions for working parameters.

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ABSTRACT

A novel structure of mirror layer for water-cooled mirror is proposed in this paper. Numerical simulations are carried out to compare the performance between the novel and conventional structure by examining four types of flow passage configuration and inlet/outlet arrangement. The analyses are based on computations of fluid-solid conjugated heat transfer. Advantages and limitations of each design are evaluated by analyzing the temperature rise, temperature uniformity, thermal deformation and deformation uniformity of the mirror surface. It is concluded that the novel structure of mirror layer shows steady improvement in both magnitude and uniformity of the thermal deformation. An effective design for water-cooled mirror must provide effective heat dissipation and ensure enough stiffness for the mirror layer at the same time. The configuration locating bent channels in the center and keeping the inlet/outlet away from the center is beneficial to water-cooled mirror, as it enhances heat dissipation and ensures stiffness. The average Reynolds number around 1000 is figured out to be optimal hydraulic conditions for different designs of water-cooled mirrors.

1. Introduction

High power lasers are widely used in the fields of military application and industrial production. The thermally induced deformation of laser mirror degrades the quality of the laser beam drastically and leads to a large focus spot for remote transmission [1–4]. With the increase of laser power and working time, this problem becomes more serious. To solve the problem, researchers have presented the water-cooled mirror to keep the thermal deformation within a certain range by reducing thermal effect [5–14].

Water-cooled mirror employing microchannel heat sink helps to decrease the temperature rise by transferring the absorbed heat to coolant. The thermal deformation of water-cooled mirror is associated with several factors, including the coating quality of mirror surface, substructure material [5,6], operation conditions [7], profiles of thermal load [8], and the internal structure of laser mirror (heat sink) [9]. Among these factors, the internal structure is most likely to be optimized based on the existing technology. Since it is quite laborious and expensive to manufacture and test such water-cooled mirrors, modeling approach is an alternative way for the structure optimization of water-cooled mirrors.

A mathematical model of the steady-state heat transfer of water-cooled laser mirror was developed by Zhernovyi et al. [10] to investigate the influence of the illumination nonuniformity and the reflector thickness on the effective heat transfer coefficient. Ach et al. [11] simulated the thermal deformation of different copper

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Nomenclature

a	width of channel, mm
b	depth of channel, mm
c	separating of channel, mm
A	area, mm^2
C_p	specific heat, J/kg K
d	thermal deformation, μm
D	diameter, mm
D_m	diameter of mirror layer, mm
D_h	hydraulic diameter, mm
H_l	minimum thickness of mirror layer, mm
E	Young's modulus, N/m^2
FoM	figure of merit
G	shear modulus
k	thermal conductivity, W/m K
n	number
m	mass flow rate, kg/s
p	pressure drop, Pa
P	power, W
q_a	absorbed heat flux, W/m^2
q_{total}	total heat transfer rate, W
Q	flow rate, mL/s
R	radial distance from the center of laser beam, mm
R_i	radius of the laser irradiation area, mm
Re_{ave}	average Reynolds number in channel
T	temperature, K
T_a	ambient temperature, K
$\vec{V}$	fluid velocity vector
v_{in}	inlet velocity, m/s
x, y, z	Cartesian coordinates
xy,yz,xz	axial plane
Greek symbols	
α_T	thermal expansion coefficients, 10^{-6}/K
ρ	density, kg/m^3
υ	Poisson's ratio
μ	viscosity of liquid, Pa s
η_a	heat absorptivity
η_{pump}	pump efficiency
ε	normal strain
σ	normal stress
σ_d	standard deviation of thermal deformation
σ_T	standard deviation of temperature
τ	shear strain
γ	shear stress
Δ	differential
λ	laser wavelength
Subscripts	
s	solid
f	fluid
l	laser beam
ch	outlet
in	inlet
out	outlet
max	maximum
min	minimum
ave	average
pump	pumping power

mirrors for infrared laser beams by using the finite element method (FEM), concluding that the least deformation could be achieved by designing a set of straight cooling channels and a stiff body. Zhu et al. [12] numerically studied the structure parameter of microchannel water-cooled copper mirror, and found that cooling area played the most significant role. Besides, Cao et al. [13] and Hu [14] analyzed the microchannel water-cooled silicon mirror as a function of microchannel geometry, including laser intensity, channel width, channel depth, fin width and cross-section shape.

In the above modeling studies, the phenomena of fluid flow and conjugated heat transfer on the interface were simplified to be a homogeneous process, by loading a constant heat transfer coefficient on the interface. This simplification may lead to great discrepancy between predictions and facts since the heat transfer performance in channel shows different properties along the flow direction, especially when flow passage and hydraulic diameter are short [15,16]. Furthermore, the local heat transfer coefficient in each channel is uneven for different inlet/outlet arrangements and flow passage configurations [17,18]. Therefore, these modeling studies also may ignore the impact of non-uniform cooling on the temperature distribution. Besides, the previous studies almost focused on the parameter optimization of the channel layer, ignoring the mirror layer and chamber layer. However, the inlet/outlet arrangement in the chamber layer has significant impact on fluid field, the consequent heat performance and the rigidity of mirror body. Moreover, the research with respect to the optimization of mirror layer for water-cooled mirror has not been studied yet. In fact, the authors have successfully fabricated the microchannel heat sink on the back of silicon mirror by direct laser sintering [19], which makes the design of silicon water-cooled mirror more flexible.

This work aims to provide design recommendations and optimal working parameters for water-cooled mirror, by means of investigating the working characteristics of water-cooled mirror with different internal designs. Two types of mirror layer are designed, i.e. the conventional design named equal thickness structure and the novel design named unequal thickness structure. Each type of mirror layer is examined with four designs of channel layer and chamber layer. The temperature information of water-cooled mirror is acquired by solving the 3D finite volume model of fluid flow and heat transfer equations. Then, the obtained temperature fields are coupled to the finite element model of the mirror body for solving the thermoplastic equation [20]. Details of temperature rise, temperature uniformity, pressure drop, thermal deformation and deformation uniformity are analyzed to evaluate the performance of each design and figure out the optimal working parameters.

2. Description of numerical simulation

Eight designs of water-cooled mirror are presented in Fig. 1 (only configurations of fluid part are presented). All designs are classified into four groups, namely group A, B, C and D, respectively. Each group includes two types of sub-model, for example, group A includes A-I and A-II. Green and red arrows (in the web version) indicate the inlets and outlets, respectively.

2.1. Physical models

The flow passage configuration and inlet/outlet arrangement of A-I and A-II are shown in Fig. 1a and b, respectively. The geometric parameters of A-I and A-II are exhibited in Fig. 2a and b,