Flow field analysis of the rod amplifier with water thermal recovery system

Zhiyuan Ren (任志远)* and Jianqiang Zhu (朱健强)

Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

*Corresponding author: renzhiyuan@siom.ac.cn

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The flow field of thermal recovery system in the rod amplifier has significant influence on the laser beam quality. The flow field of the thermal recovery system depends on the inlet and outlet angles of water. Based on the flow field distribution of the direct-flow type for the thermal recovery system, we develop the optimum inlet and outlet angles of the thermal recovery system to the rod amplifier, which enhances the uniformity of the flow field and heat exchange efficiency of the thermal recovery system.

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High-power laser facilities, rod amplifier as an essential amplifying unit is widely used in the study of inertial confinement fusion system[1]. In high-power laser system of the Shenguang-II, the rod amplifier with flash lamp pumped longitudinally is enclosed in a quartz tube with the cooling medium. But due to the difference between the pump and laser photon energies termed quantum defect heating and broad spectral distribution of the pump source caused a certain amount of background absorption by the laser host material. Most of the energy of flash lamp converted to heat deposition in the rod amplifier[2–4]. This leads to stress birefringence and the thermal lens effect in rod amplifier, and even causes crack in rod amplifier. In order to eliminate the adverse effect of temperature gradient on the rod amplifier, it is vitally necessary to conduct effective cooling in rod amplifier[5,6]. It is a rapid and energy saving cooling method with water in the thermal recovery system of the rod amplifier. Owing to the influences of the angle of inlet and outlet of cooling water and gravity itself, pressure distribution of the cooling water in rod amplifier system is not uniform. This results in bubble in the thermal recovery system which degrades the beam quality. With the evolution of bubble, there is even cavitation phenomenon that damages the surface of the rod amplifier. We conducted numerical simulation of flow field on the water-cooled thermal recovery system in rod amplifier and presented the optimum inlet and outlet angles of the thermal recovery system.

The flow field of thermal recovery system in rod amplifier depends mainly on the velocity of the fluid and inlet and outlet angles of the thermal recovery system (Fig. 1).

Flow field distribution of the water between the quartz tube and the laser rod mainly depends on the type of the split ring. There are three types of split ring as shown in Fig. 2. The axis of the hole in the split ring is parallel to the axis of the laser rod and perpendicular to the radial direction of the laser rod in the direct-flow split ring individually. The axis of the hole is at 45° angle to the axial and radial directions of the laser rod in the inclined flow split ring. The axis of the hole is at 45° angle to the axial direction and perpendicular to the radial direction of the laser rod in the swirl-flow split ring. We built the computational fluid dynamics (CFD) models with three types of the split rings to obtain the flow field of the thermal recovery system of the rod amplifier.

We defined the problem based on different types of split rings as shown in Fig. 2. The numerical simulation model consists of water in the hole of the split ring and the space between quartz tube and laser rod. To simplify the numerical simulation, we make some assumptions as follows: 1) the inlet velocity of the water is 15 kg/s, and the water is incompressible, 2) the thermal characteristic and the density of the water are in steady state, and 3) normal acceleration of gravity is constant and should not be neglected.

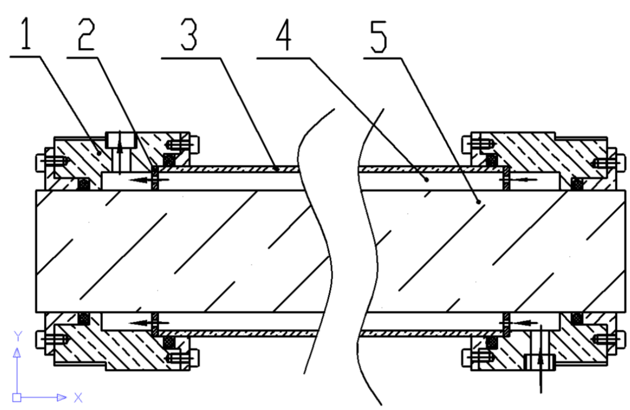

Fig. 1. Sectional drawing of rod amplifier. 1 – sealing boot; 2 – split ring; 3 – quartz tube; 4 – water; and 5 – laser rod.

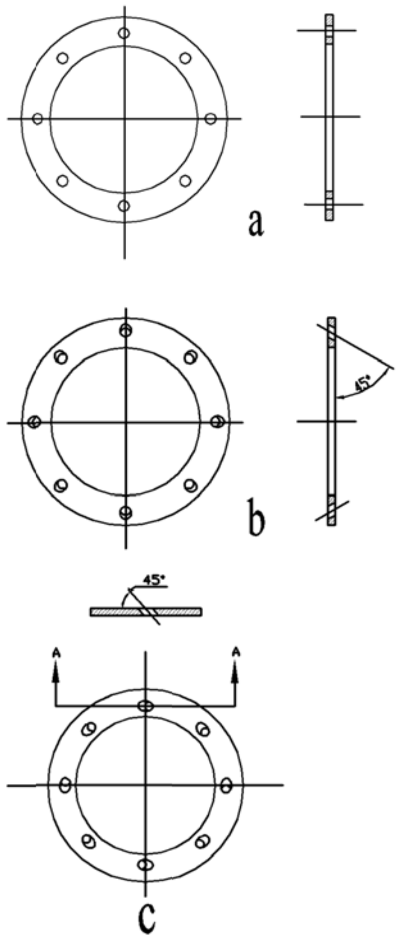

Fig. 2. Three types of the split rings: (a) direct-flow split ring, (b) inclined flow split ring, and (c) swirl-flow split ring.

The flow field of the thermal recovery system was meshed with the commercial code GAMBIT. We conducted three grid independent tests to obtain a nearly grid-independent solution. In these tests, the difference in the overall pressure loss between the three grid systems is around 1.5% with 132524, 325458, and 1358814 cells that were adopted for the calculation of the entire simulation model.

The continuity equation is

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho u_i)=0, \qquad (1)$$

where ρ is density of the water, u_i (i = 1, 2, and 3) is the velocity of the water, and x_i (i = 1, 2, and 3) is the distance from the inlet.

The momentum equation is

$$\rho\frac{\mathrm{D}u_i}{\mathrm{D}t}=-\frac{\partial p}{\partial x_i}+ \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] +\frac{\partial}{\partial x_j}\left(-\rho\overline{u_i'u_j'}\right), \qquad (2)$$

$$-\rho\overline{u_i'u_j'}=\mu_t\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)- \frac{2}{3}(\rho k+\mu_t\frac{\partial u_i}{\partial x_i})\delta_{ij}, \qquad (3)$$

where μ_t is the eddy diffusion coefficient and p is the pressure of the water.

The turbulent model used re-normalization group $k-\xi$ model. Turbulent kinetic energy equation (k equation) for the turbulent in the mode is

$$\rho\frac{\mathrm{D}k}{\mathrm{D}t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] +G_k+G_b-\rho\varepsilon-Y_M, \qquad (4)$$

where G_k is the turbulent kinetic energy caused by mean velocity, G_b is the turbulent kinetic energy caused by buoyancy, and Y_M is the pulsation rate coefficient.

Pulsation rate equation (ξ equation) in the mode is

$$\rho\frac{\mathrm{D}\varepsilon}{\mathrm{D}t}=\frac{\partial}{\partial x_i}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial x_i}\right]+ C_{1\varepsilon}\frac{\varepsilon}{k}(G_k+C_{3\varepsilon}G_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}, \qquad (5)$$

where $C_{1\varepsilon}$= 1.44 $C_{2\varepsilon}$ = 1.92, $C_{3\varepsilon}$ = 0.9, σ_k= 1.0, and σ_ε = 1.3.

Based on the three types of split rings in the thermal recovery system for the rod amplifier, we obtained the flow field of the thermal recovery system.

The water sprays through the direct-flow split ring over the surface of laser rod. The pressure contour and the streamline of the water over the laser rod are shown in Fig. 3.

On the one hand, the pressure gradient is uniform and the pressure decreases gradually in the inlet area. On the other hand, the pressure gradient over the surface of the laser rod turns to be nonuniformed from the middle of the laser rod, and there is obvious pressure fluctuation on the outlet area over the surface of the laser rod. Such pressure fluctuations lead to turbulences over the surface of outlet area in the laser rod as shown in Fig. 3. The water stream breaks up into turbulence, the excess energy is absorbed by the turbulent eddies and this energy is irrecoverable. The bubbles appear

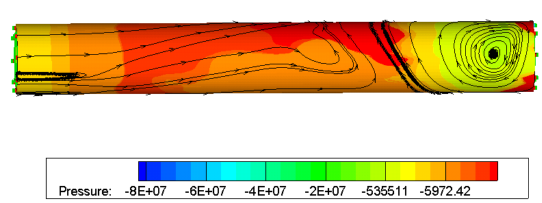

Fig. 3. Pressure contour of laser rod with direct-flow split ring.

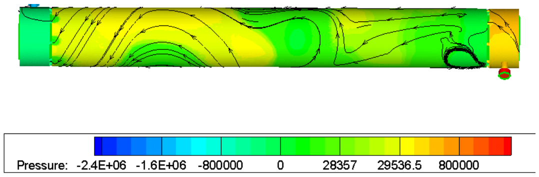

Fig. 4. Pressure contour of laser rod with inclined flow split ring.

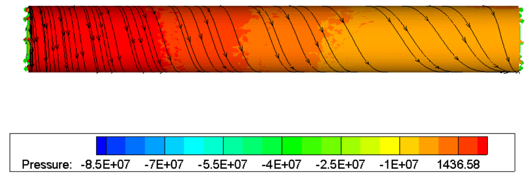

Fig. 5. Pressure contour of laser rod with swirl-flow split ring.

when the pressure fluctuation is violent. The thermal recovery efficiency of the rod amplifier and pumped efficiency of the flash lamp degrades when bubbles appear in the cooling water.

In order to accelerate the thermal recovery efficiency of rod amplifier, the axis of inclined flow split ring is at 45° to the axial and radial of the laser rod individually. In such inlet scheme of the cooling water, because velocity of water has a perpendicular component, it is equivalent of spray over the surface of laser rod. This has positive impact on the thermal recovery efficiency in the inlet area of the laser rod. The pressure contour and the streamline of water are as shown in Fig. 4.

There are two obvious turbulent eddies located in the inlet and outlet areas. The turbulent eddy in the inlet area is caused by the gravity of the water and the inclined angle of the inlet flow. Due to the perpendicular component of the velocity, the velocity of the water decreases more quickly than the velocity of the direct flow. Because of the effect of the gravity of the water and the interaction between the axial component and radial component of the velocity of the inclined flow, the bubble appears with revolution of the turbulent eddy in the thermal recovery system. The turbulent eddy of even the bubble is not acceptable for the pumped efficiency and thermal recovery time.

In the swirl-flow split ring, the axis of the hole is at 45° angle to the axial direction and perpendicular to the radial direction of the laser rod. The pressure contour and streamline for the water through the split ring in the thermal recovery system are shown in Fig. 5. The swirl component of velocity eliminates the effect of gravity of the water, there is no turbulent eddy over the whole thermal recovery system of the rod amplifier.

The pressure gradient of the water along the surface of the laser rod is uniform in this cooling scheme. And the streamline of the velocity swirls along the axis of the laser rod. There is no turbulent eddy in whole thermal recovery system. It is an optimized cooling scheme for the thermal recovery system of the rod amplifier with swirl-flow split ring.

In conclusion, we obtain the flow field distribution with three types of split rings in the thermal recovery system based on CFD technology. Because of the gravity of water with direct-flow split ring in the thermal recovery system and the radial component of velocity of the water with inclined flow split ring in the thermal recovery system, respectively, there is turbulent eddy over the surface of the laser rod consequently. The swirl flow is established along the surface of the laser rod with swirl-flow split ring in the thermal recovery system, which makes the pressure gradient contour uniform and avoids the bubble in the thermal recovery system. It enhances the pumped efficiency and improves the heat transfer coefficient with swirl-flow split ring in the thermal recovery system.

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