Optics & Laser Technology 67 (2015) 65–71

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Heat exchange model in absorption chamber of water-direct-absorption-typed laser energy meter

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ARTICLE INFO

Article history:
Received 15 November 2013
Received in revised form
27 June 2014
Accepted 30 September 2014
Available online 23 October 2014

Keywords:
Heat exchange
Laser energy meter
Absorption cavity

ABSTRACT

The interaction between laser and water flow is very complicated in the absorption chamber of a high energy laser (HEL) energy meter which directly uses water as an absorbing medium. Therefore, the heat exchange model cannot be studied through traditional methods, but it is the most important factor to improve heat exchange efficiency in the absorption chamber. After the exchanges of heat and mass were deeply analyzed, experimental study and numerical fitting were brought out. The original testing data of laser power and water flow temperature at one moment were utilized to calculate those at the next moment, and then the calculated temperature curve was compared with the measured one. If the two curves matched well, the corresponding coefficient was obtained. Meanwhile, numerous experiments were performed to study the effects of laser power, duration, focal spot scale, and water flow rate on heat exchange coefficient. In addition, the relationship between water phase change and heat exchange was analyzed. The heat exchange coefficient was increased by optimizing the construction of the absorption chamber or increasing water flow rate. The results provide the reference for design of water-direct-absorption-typed HEL energy meters, as well as for analysis of the interaction between other similar lasers and water flow.

1. Introduction

In high energy laser (HEL) energy test, a complete-absorption-type energy meter is adopted in most circumstances for accurate measurement of laser energy. This type of energy measuring equipment usually belongs to the calorimetric type and absorbs most of the incident laser [1–4]. The power of HEL is usually above 10 kW and its energy is above 10 kJ [5]; however, sometimes its power may even reach MW and its energy may achieve dozens MJ. Most high power HEL which can be Nd:YAG, chemical oxygen iodien laser (COIL), DF, fiber laser, etc. is long pulse laser. Since these lasers are designed to destroy almost anything in the beam path, successfully measuring their power output is a difficult job [6]. In order to improve the system's testing capability, water is directly used as an absorbing medium and energy carrier. It is the key task to improve the heat exchange efficiency in the absorption chamber. However, the interaction between laser and water flow is very complicated, involving numerous knowledge of optics, thermotics, fluid mechanics and so on. No literature is relevant to this research, and it is impossible to study the heat exchange model in an absorption chamber with traditional methods. Therefore, in this paper, an indirect way by experiments and numerical fitting was carried out. The fitted water-flow temperature was compared with the measured one to obtain the corresponding heat exchange coefficient. Based on this, numerous experiments are performed to study the effects of some parameters (e.g. laser power, duration, focal spot scale, and flow rate) on heat exchange coefficient. In addition, water phase change in the absorption chamber by laser can greatly affect the water flow field and heat exchange, and thereby the relationship between water phase change and heat exchange should be analyzed. The construction of the absorption chamber was optimized and improved to reduce the degree of phase change and increase the water speed, and the effects were tested.

2. Basic principles

First, the basic principles of a water-direct-absorption-type (WDA) laser energy meter will be briefly introduced. When laser energy is

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http://dx.doi.org/10.1016/j.optlastec.2014.09.015
0030-3992/

injected into the water flow, it is absorbed by the water in the absorption chamber. Then the temperature of water flow increases rapidly and water flow carries the thermal energy away from the chamber. The injected laser energy can be calculated by measuring the mass of water flow, the temperature difference between inflow and outflow, and the specific heat of water [7].

The measuring diagram of the WDA-typed HEL energy meter is shown in Fig. 1.

It is assumed that with respect to the energy of water at 0 °C, the measured energy from a temperature sensor at the cold water end or at the hot water end is E_1 and E_2 respectively. The energy E which is absorbed for water temperature rise can be expressed as follows [8,9]:

$$E = E_2 - E_1 = \iint_{m_2} c_w T(m_2) dT dm - \iint_{m_1} c_w T(m_1) dT dm \quad (1)$$

where c_w is the specific heat of water; m_2 and m_1 are the masses of outflow and inflow respectively; $T(m_2)$ and $T(m_1)$ are the temperatures of water outflow and inflow respectively.

According to Eq. (1) only heat loss between temperature sensors at the entrance and temperature sensors at the exit has effects on the accuracy of the result. The average temperature rise of the water in the absorption cavity, energy-integral time, the mass and the surface area of the absorption cavity are dominated to minimize the heat loss. In addition, the pipes are made of PVC plastic material, and the absorption cavity, pipes are sealed to decreased convection. As a result, the heat loss by conduction, thermal radiation and convection are estimated to be less than 0.4% of the incident laser energy, and the effects on heat loss by conduction, thermal radiation and convection are always ignored in engineering.

Fig. 2 shows the schematic structure of an absorption cavity. It is made of stainless steel, and contains an entrance on the bottom and an exit on the top, which are connected to the pipeline. A quartz window is mounted on its front surface. Laser enters the water flow through the window and is absorbed by water flow. Since laser absorption in water varies greatly by wavelength, the thickness of the water should be adjusted to ensure almost all of the incident laser energy is absorbed by the water flow. According to the Lambert–Beer law 99.4% of the incident laser energy ($\lambda = 1.319$ μm) is already absorbed by water whose thickness is only 3 cm, and above 99.9% laser energy ($\lambda = 10.6$ μm) is absorbed by water whose thickness is only 0.1 cm. So in this paper Nd:YAG whose wavelength is 1.319 μm was adopted. The research of the heat exchange model relies on the temperature sensors installed in its entrance and exit.

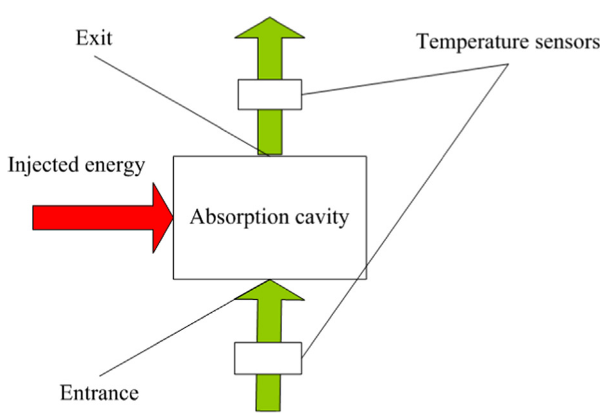

Fig. 1. Measuring diagram of WDA-typed HEL energy meter.

Since the absorption cavity is sealed, the vapor cannot escape, which prevents the energy consumed by the phase change of water from loss. The water is transformed into vapor by irradiation of high power density laser, and then the vapor is transformed into water with normal temperature water. Since the energy is conserved during the above processes, the effects of the phase change of the water can be eliminated after the vapor is completely transformed into water.

3. Heat exchange model

3.1. Theoretical analysis

The interaction between laser and water flow is very complex. On one hand, the state of the flow field affects the absorption and transmission of laser beam. On the other hand, the laser sharply increases the temperature of water flow, thereby changing the phase of water flow [8,9]. In reverse, it affects the state of the flow field. It is difficult to fully understand this process by using the existing techniques. From the perspective of application, the problems will be greatly simplified by only studying the final thermal efficiency and not limiting to the original complicated process.

First, starting with the process of water flow in the absorption cavity, after the water flow enters the cavity from the entrance, a part of the water flow will be mixed with the water remaining in the cavity, and then flow through the laser irradiation area. In this area, water temperature rises rapidly, and the phase of partial water flow is changed. At the same time, water flow is mingled with phase-changed gas. After water flows through the laser irradiation area, heat quickly exchanges between water and phase-changed gas because the average temperature of water flow is far lower than that of phase-changed gas. When the quantity of gas-released heat is more than the phase-changed heat, vapor is re-inverted into water, and then the water retained between water flows as well as between water flow and the absorption cavity still exchanges the heat. Finally, a large proportion of energy is retained in the cavity, and only a fraction flows out of the cavity. The whole process is shown in Fig. 3.

Fig. 3 clearly shows that the whole heat exchange and mass exchange process runs all the time through the absorption cavity, including the transformation of water flow into vapor and vapor into water flow. In order to clarify the model and efficiency of heat exchange in the cavity, we should obtain the temperature difference before and after water flows into the cavity, as well as the laser energy injected into the cavity. Through analyzing the relationship between flow energy increment, injected laser energy and stored

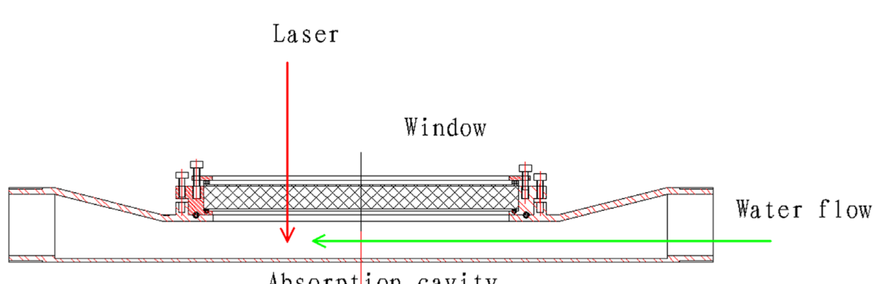

Fig. 2. Schematic structure of the absorption cavity.