Phase transition model of water flow irradiated by high-energy laser in a chamber

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In the absorption chamber of a high-energy laser energy meter, water is directly used as an absorbing medium and the interaction of the high-power laser and the water flow can produce a variety of physical phenomena such as phase transitions. The unit difference method is adopted to deduce the phase transition model for water flow irradiated by a high-energy laser. In addition, the model is simulated and verified through experiments. Among them, the experimental verification uses the photographic method, shooting the distribution and the form of the air mass of water flow in different operating conditions, which are compared with the simulation results. The research shows that it is achievable to reduce the intensity of the phase transition by increasing the water flow, reducing the power intensity of the beam, shortening the distance the beam covers, reducing the initial water temperature or adopting a shorter wavelength laser. The study's results will provide the reference for the design of a water-direct-absorption-type high-energy laser energy meter as well as an analysis of the interaction processes of other similar high-power lasers and water flow.

Keywords: phase transition, high-energy laser, water flow, photographic method

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1. Introduction

In the high-energy laser (HEL) energy test, under most circumstances, a complete-absorbing-type energy meter is adopted to achieve the purpose of accurately measuring the laser energy in the measurement. The energy-measuring equipment usually belongs to the calorimetric type, and can absorb most of the injected energy.[1–6] In order to improve the system's measuring capability, water is directly taken as an absorbing medium and energy carrier, so as to greatly enhance the system's measuring capability. However, the HEL has high power and large energy, and interacts with water flow, so this process of interaction may lead to the phase transition of the water flow[7] and the generation of a phase transition will have great influence on the internal pressure in the absorption chamber and therefore measurement accuracy.[8] At present, there is no literature relevant to this research, so it is of important practical significance to carry out research of the phase transition model of the water flow in the absorption chamber. In addition, the interaction process of the laser and water flow is very complicated, involving lots of knowledge such as optics, thermotics and fluid mechanics. First of all, the problem of water flow and bubble-s backscatter of the laser has been studied in many literatures[9–11] in detail, so this paper does not analyze it any further. According to the characteristics of laser transmission in water, this paper uses the unit difference method, taking the laser coverage as the object of research, to deduce the water phase transition model under the action of the laser. In order to reduce the amount of calculation, the whole deduction was focused on a super-Gaussian circular beam, and similar methods can be used for the beam with other shapes and distributions. In addition, it simulates the above models and verifies through experiment. Since the temperature distribution of the water flow and the form of the air mass in the chamber can not be directly measured, photographic methods are used in the experiments to study them. The distributions and forms of the air mass of water flow in different operating conditions are shot, which are compared with the simulation results. Both of them have good consistency, which has verified the correctness of this model.

2. Theoretical analysis

In the HEL energy meter, the absorption chamber is sealed by a quartz window, and HEL can travel through it into the water. The sectional view of the absorption chamber is shown in Fig. 1.

The mechanisms of the heat exchange between laser and water flow are very different to traditional mechanisms. In the traditional processes, the surface of a piece of solid material is often irradiated by a laser and the temperature of the material will quickly rise. When water or another liquid flows along the back of the material, heat exchange will occur and the temperature of the water flow will increase. If the power

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intensity of the laser is high enough, the phase transition will occur on the back surface of the material. Different phase transition models such as pool boiling models,[12,13] heat transfer enhancement models,[14–16] microchannel boiling models,[17] and so on have been studied. In these traditional models there is a common point that a laser can not directly react with water flow, as a result, convection is the main mode for heat exchange. Since the above process in which the bubbles are produced is often very slow, the microcosmic processes always have great effects on the phase transition model. However, when water flow is directly irradiated by HEL, the process of heat exchange is almost instantaneously completed. Therefore, the effects by convection and the microcosmic processes can be ignored, and the model will be greatly simplified. Since there is almost no literature relevant to the model at present, it can be studied by deducing the temperature field and the surplus temperature of the water flow in the chamber, then the intensity of the phase transition can be decided by the surplus temperature. The temperature field is studied using the unit difference method in which the laser coverage is divided into many small parts, and the incremental energy in each part is calculated when the laser power and the velocity of the water flow is known.

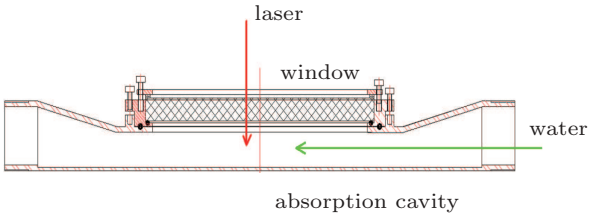


Fig. 1. (color online) Schematic diagram of the absorption chamber.

When parallel light is transmitted uniformly in a body of water, its permeation power P_t and incident power P_0 satisfy the following relationship:[18,19]

$$P_t = P_0 e^{-kZ}, \tag{1}$$

where k refers to the attenuation coefficient, and Z refers to the distance of the laser in the transmission of the water body. From Eq. (1), it can be seen that the laser absorption in the water belongs to volume absorption, so its boiling should take place in three-dimensional space. There are many factors influencing the flow boiling model, including the initial power density of the laser, the characteristics of the water body scattering the laser forward and backward, the shape of the pipe line, the flow velocity, the flow position, the shape of the light spot and the initial temperature of the water flow.[20] In order to establish the above phase transition model, all the above factors need to be considered. According to the characteristic that the shape of a strong laser spot is usually a hollow ring,[21,22] this paper will take a circular light spot as the object of research, and the analysis of another shape of light spot is similar to that of a circular light spot, referring to the related method of a circular light spot. Therefore, the circular center is taken as the origin, the surface where the circular ring is located is the XY direction, the direction of water flow is the same as that of the Y direction, and the incident direction of light is that of the Z direction. The coordinate system is established, the whole circular ring is taken as the object of research, and the whole area is divided into several equal parts, the schematic diagram for the horizontal unit distribution is shown in Fig. 2.

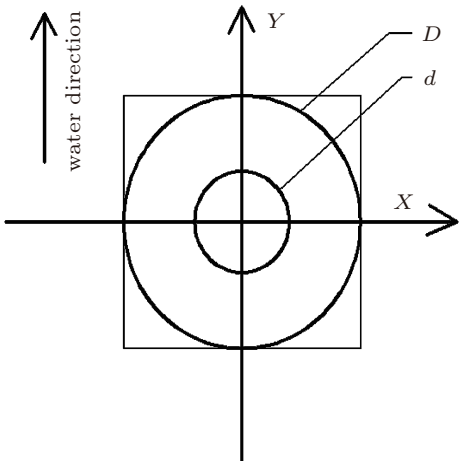


Fig. 2. Water unit distribution of the XY direction.

In the area in Fig. 2, the diameter of the inner circle is set as d, the diameter of the outer circle is set as D, the step length of the XY direction is taken as l, and the step length of the Z direction is l'. The cross section of the whole light spot can be divided into an $m \times m$ matrix, along the Z direction, it can be divided into n columns. The flow velocity is $v(X,Y,Z)$, the density is ρ, the specific heat is c, the average power of the laser is P_a, the power at the point (X,Y,Z) is $P(X,Y,Z)$, and the area of the light spot is S. After each unit moves the distance of l, its temperature is increased by ΔT. The action time of water flow and the laser is very short, at the same time, the speed of boiling heat transfer is far more than that of convectional heat transfer, so in the area of the phase transition, the influence of the convection of the water flow is negligible. The following formula can be obtained through the conservation of energy:

$$\rho l^2 l' c \Delta T = P(X,Y,Z) l / v(X,Y,Z). \tag{2}$$

Most strong lasers are super-Gaussian beams, so they are approximately taken as flat-topped beams.[23,24] In order to reduce the calculated amount, here the influence of the non-uniform distribution of the light spot can be neglected. Meanwhile, considering that the transmission characteristics of the laser in water is exponential decay, the attenuation factor is set

as γ (its size is relevant to the light wavelength and the characteristics of water), the correction factor of forward scattering is $c_{\rm f}$, the correction factor of backscattering is $c_{\rm b}$, and the expression for $P(X,Y,Z)$ can be obtained

$$P(X,Y,Z) = \frac{P_{\rm a}}{S} l^2 \gamma c_{\rm f} c_{\rm b}. \tag{3}$$

The expression for the attenuation factors γ and S are

$$S = \frac{\pi}{4}(D^2 - d^2), \tag{4}$$

$$\gamma = {\rm e}^{-kz} - {\rm e}^{-kz'}. \tag{5}$$

By substituting Eqs. (4) and (5) into Eq. (3), we can obtain

$$P(X,Y,Z) = \frac{4P_{\rm a} l^2 c_{\rm f} c_{\rm b}}{\pi(D^2 - d^2)}({\rm e}^{-kz} - {\rm e}^{-kz'}). \tag{6}$$

In addition, equation (6) is substituted into Eq. (2); at the same time, if the flow velocity $v(X,Y,Z)$ is substituted by the average velocity v, after sorting out, the expression for ΔT is shown as

$$\Delta T = \frac{4P_{\rm a} l c_{\rm f} c_{\rm b}}{\pi \rho v c l'(D^2 - d^2)}({\rm e}^{-kz} - {\rm e}^{-kz'}). \tag{7}$$

In essence, studying the boiling state means studying the surplus temperature of the liquid, equal to the difference between the substance's temperature and liquid saturated temperature, and its expression is shown as[25,26]

$$\Delta T_{\rm e} = T_{\rm s} - T_{\rm sat}, \tag{8}$$

where $\Delta T_{\rm e}$ refers to the surplus temperature; $T_{\rm s}$ refers to the water temperature; $T_{\rm sat}$ refers to the water-saturated temperature. According to different surplus temperatures, boiling can be divided into four modes. From low temperature to high temperature, the requirements for the saturated temperature are natural convection boiling, nucleate boiling, change boiling and film boiling respectively, and the critical values of these temperature are 0 °C, 5 °C, 30 °C, and 120 °C respectively. The initial temperature of water flow is T_0

$$T_{\rm s} = T_0 + \Delta T n_{\rm l}, \tag{9}$$

where $n_{\rm l}$ refers to the effective unit number of laser irradiation. Equations (7) and (8) are substituted into Eq. (9)

$$\Delta T_{\rm e} = T_0 + \frac{4P_{\rm a} l c_{\rm f} c_{\rm b}}{\pi \rho v c l'(D^2 - d^2)}({\rm e}^{-kz} - {\rm e}^{-kz'}) n_{\rm l} - T_{\rm sat}. \tag{10}$$

In a free position of the whole area, the surplus temperature $\Delta T_{\rm e}(X,Y,Z)$ is

$$\Delta T_{\rm e}(X,Y,Z) = T_0 + \sum_{g=-m/2}^{Y} b_{\rm g} \frac{4P_{\rm a} l c_{\rm f} c_{\rm b}}{\pi \rho v c l'(D^2 - d^2)}({\rm e}^{-kz} - {\rm e}^{-kz'}) - T_{\rm sat}. \tag{11}$$

In the formula, the expression of $b_{\rm g}$ is shown to be

$$\begin{aligned} &b_{\rm g} = 0, \quad \sqrt{X^2 + Y^2} > D \quad \text{or} \quad \sqrt{X^2 + Y^2} < d, \\ &b_{\rm g} = 1, \quad d < \sqrt{X^2 + Y^2} < D'. \end{aligned} \tag{12}$$

Other models for different shapes of light spot are similar to those in Eq. (11). Take the circular solid light spot as an example. This time, $d = 0$ and the conditions of Eq. (12) remain unchanged. For a hollow square light spot, it is fine to only change the expression of the area in Eq. (11) and the conditions in Eq. (12). For an unevenly distributed and irregular light spot, under the circumstance of a given distribution, a similar method can be used. For the light intensity at each point, the boiling models are computed respectively, except that the computational process is more complicated than the above process. In order to better illustrate this point, the super-Gaussian circular beam is still taken as the main object of research.

3. Simulations of the phase transition

Equation (11) is the expression for the forced boiling model. According to this expression, a little surplus temperature can be obtained randomly, thus according to the critical temperature, the boiling model and state can be identified. According to a set of data, the distribution of surplus temperature is simulated. The laser is set as a super-Gaussian beam, the whole light spot is distributed evenly, $D = 20$ mm, $d = 8$ mm, $T_0 = 20$ °C, $l = 0.2$ mm, $l' = 0.1$ mm, $\rho = 1000$ kg/m^3, $c = 4.2$ kJ/(kg·°C), $k = 1.6$ cm^{-1} ($\lambda = 1.315$ μm), $T_{\rm sat} = 100$ °C, $v = 0.045$ m/s, $P_{\rm a} = 3$ kW, and the influence of forward and backward scattering is neglected. The surplus temperature distribution can then be obtained in the whole area. Figure 3 shows the surplus temperature distribution of the $Z = 0$ direction, namely, the surplus temperature distribution on the boundary of the light spot and the water. Figure 4 gives the surplus temperature distribution of the $Y = D/2$ direction of water flow, namely, the surplus temperature distribution of the cross section of the water flow on the edge of the light spot.

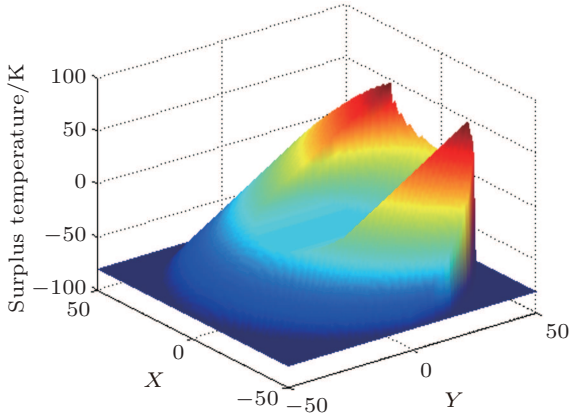


Fig. 3. (color online) Surplus temperature distribution of the $Z = 0$ direction.

From Fig. 3, it can be seen that in the Y direction (i.e., the direction of the water flow), the surplus temperature is increased gradually, and reaches the critical values of boiling at different levels, and the degree of boiling is increased rapidly. In the $Y = D/2$ direction, the degree of boiling increases to a maximum. At the same time, a peak takes shape on both sides of the $X = 0$ direction respectively, the boiling is increased to a maximum near the top of the peak. Two peaks are distributed in the shape of the sector, and are bilaterally symmetrical in the X direction, the center is located at $X = \pm D/2$, and the two peaks are equal. As for the above simulation data, it can be seen that near the above two peaks, the surplus temperature is more than 0 °C, the natural convection boiling starts to occur, and gradually increases to nucleate boiling and changes boiling. At the peak point, the surplus temperature $\Delta T_e = 82$ °C.

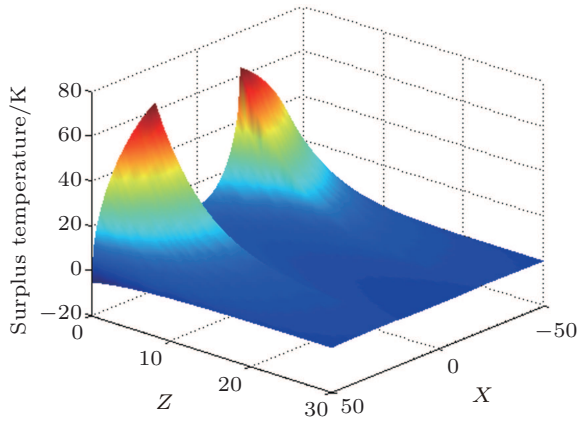


Fig. 4. (color online) Surplus temperature distribution of the $Y = D/2$ direction.

From Fig. 4, it can be seen that in the incident direction of the beam, the boiling degree in the incident plane closest to the light (as shown at $Z = 0$) is the strongest, its surplus temperature is the same as that at the peak point in Fig. 3, and its form is still a bimodel type. In the transmission direction of light, the surplus temperature is reduced rapidly. Finally, it reaches the boiling critical value. With the decrease of boiling, the convection is increased gradually, and eventually the surplus temperature is completely displaced by a two-phase flow. According to the above model, the surplus temperature at each point can be computed. Combined with the critical value, the state can be obtained, and then the flow state can be obtained in the whole area.

For a solid circular light spot, the parameters are set to be the same as those of the above circular light spot (except that the inner diameter is 0), the surplus temperature distribution can be computed in the $Z = 0$ direction, namely, the surplus temperature distribution on the boundary of the light spot and water flow, as shown in Fig. 5. Apart from that the circular light spot forms two peaks, the solid light spot only forms one peak.

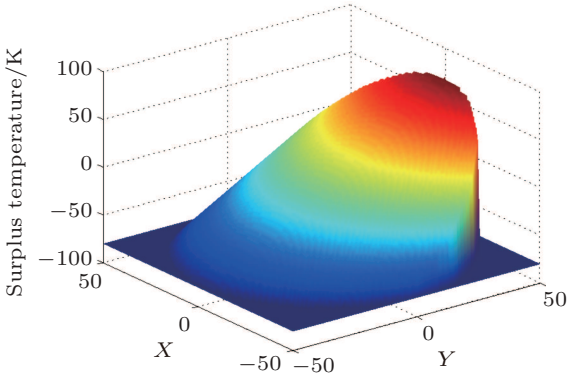


Fig. 5. (color online) Surplus temperature distribution of the $Z = 0$ direction.

4. Experimental verification

According to the above model, the experimental research has been conducted, using a relatively uniform hollow laser beam to irradiate water flow. The average power of the laser is 3 kW, the wavelength is 1.315 μm, the external diameter of the light spot is 20 mm, the inner diameter is 8 mm, the speed of the water flow is 0.045 m/s, the pressure is one atmosphere, and the water temperature is the normal temperature. When the laser injects the water, the camera is used to record the boiling state of the water flow, in comparison with the simulated results. The boiling image and the region covered by bubbles in the simulations are shown in Fig. 4.

As shown in Fig. 6, water flows from bottom to top, corresponding to the Y direction in Fig. 3. From Fig. 6, it can be seen that the boiling rate and distribution are consistent with the simulated results in Fig. 3. As shown in the figure, the central region is hollow, and there is an air mass on each side (two elliptic internal area as shown in the figure), which is formed by water vapor generated by the boiling. In the upper-end area of light spot, the quantity of air mass is up to a maximum. The air mass forms two peaks respectively, corresponding to the two peaks of surplus temperature in Fig. 3. These two peaks are symmetrically distributed roughly in the shape of a fan, and the right peak is larger than the left one. Their forms are basically in line with those of the two peaks in Fig. 3.

The above-mentioned laser power and other states remain unchanged. The water flow is adjusted, so that the velocity can be increased to 0.09 m/s. At this moment, the boiling image is shown in Fig. 7 (as shown in the figure, the red spot is caused by the reflection of a 0.6328-μm guiding light). It can be seen that the distribution is basically the same as that in Fig. 6, except that the density and volume of the bubble mass are decreased, in good consistency with the simulated results.

A solid beam is used to repeat the above experiment, and the power of the light beam and other parameters are the same as the above-mentioned conditions. At the moment, the boiling image is shown in Fig. 8.

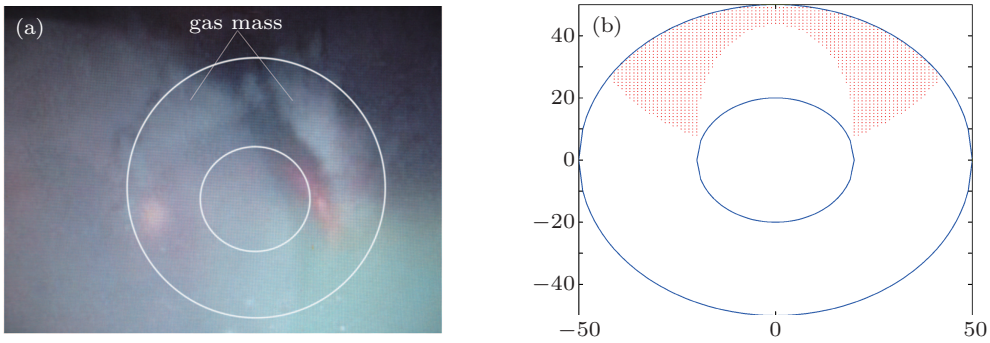


Fig. 6. (color online) The comparison of boiling image 1 and the regions covered by bubbles in the simulations, $v = 0.045$ m/s. (a) Boiling image: the two circles represent the edge of the laser beam. (b) The simulation result: the two circles are the borders of the laser beam, the region with red dots is covered by bubbles in the simulations.

It can be seen that the form is in good consistency with the simulated results in Fig. 5, only forming a model air mass. Thus it further proves the correctness of the above model.

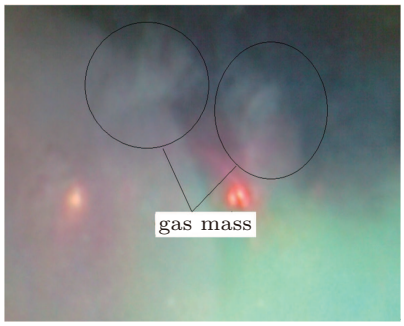


Fig. 7. (color online) Water boiling image 2 by laser, $v = 0.09$ m/s.

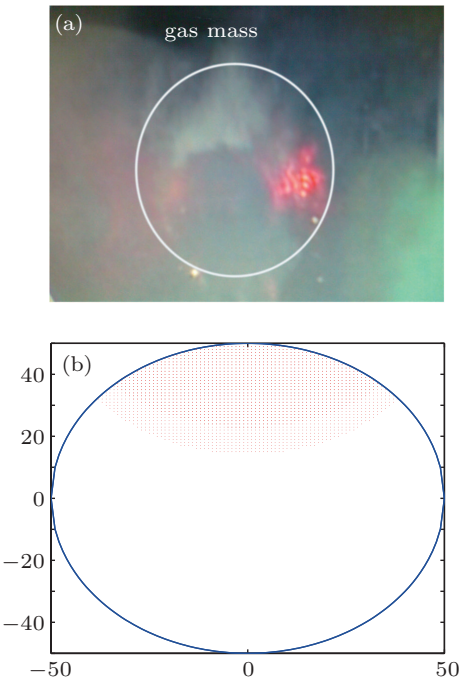


Fig. 8. (color online) The comparison of boiling image 3 and the regions covered by bubbles in the simulations, $v = 0.045$ m/s. (a) Boiling image: the circle represents the edge of the laser beam. (b) The simulation result: the circle is the border of the laser beam, the region with red dots is covered by bubbles in the simulations.

5. Discussion

5.1. Effects of the wavelength of the laser on the phase transition model

Since laser wavelength has a great effect on the attenuation coefficient k in Eq. (1), the absorption depth of the water flow can be varied with laser wavelength λ. The longer the wavelength is, the faster the laser energy is absorbed. Typical transmittance curves for different laser wavelengths ($\lambda = 1.064$ μm, $\alpha = 0.347$ cm^{-1}, $\lambda = 1.315$ μm, $\alpha = 1.7$ cm^{-1} and $\lambda = 10.6$ μm, $\alpha = 800$ cm^{-1}) are shown in Fig. 9. Figure 9 shows that 99.4% of the incident laser energy ($\lambda = 1.315$ μm) is already absorbed by water with a thickness of only 3 cm, and above 99.9% laser energy ($\lambda = 10.6$ μm) is absorbed by water with a thickness of only 0.1 cm.[27] Therefore, the phase transition of the water flow irradiated by CO_2 laser can be much stronger than other shorter wavelength lasers.

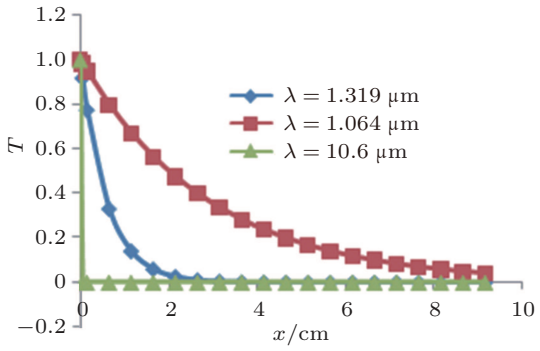


Fig. 9. (color online) The relation between laser transmittance and propagation length for different laser wavelengths.

5.2. Comparisons between the new model and the old one

According to the experiments and simulations we can see that the new model and the old one have both similarities and differences. First, parameters such as heat flux density/laser power density, the water saturated temperature, water velocity/water flux have great effects on both the models. In order to decrease the phase transition, the laser power density should be reduced or the water saturated temperature should

be increased, and the goal can also be reached if water velocity is improved. However the effects of water velocity are much more important in the new model than in the old model.

Obviously, laser wavelength and the material of the window are very important in the new model. The relationship between the laser wavelength and the new model is given in Section 5.1. Besides, the laser must pass through the window before it reaches the water flow, and a lot of energy may be reflected and absorbed by the window. Physical properties and the roughness of the surface have a small effect on the new model, however, it is very important for the old model. In some cases, the surface is roughened to increase the amount of water transformed into gas.

5.3. Limitations of the new model

Since the interaction of the laser and the water flow is very complex, in the theoretical analysis and simulation above many approximation methods are adopted to simplify the problem. However, it will decrease the reliability and accuracy of the model. Scattering and backscattering will increase the region irradiated and decrease the power intensity. Bubbles will increase energy loss and pressure in the chamber, and the water saturated temperature will change with the pressure. Turbulence of the water flow may affect the phase transition model, too. These problems should be studied in future work to improve the new phase transition model.

6. Conclusion

In a high-energy laser energy test, the method of directly using water as an absorbing medium has significant advantages, but the presence of water and a laser in the absorption chamber is complicated, as absorption, scattering, phase transition and heat exchange, mass transfer, and other physical processes occur. The process of the phase transition of water flow has great impacts on the use of the system and measurement accuracy, so this paper further studies the phase transition model. Based on the detailed deduction of the measurement model, this paper adopts the unit difference method, taking the laser coverage as the object of research, to deduce the water phase transition model under the action of the laser. In addition, it simulates the above models and verifies through the experiment. Among them, the experimental verification uses the photographic method, shooting the distribution and form of the air mass of water flow in different operating conditions, which are compared with the simulation results, and both have good consistency.

The research shows that it is achievable to reduce the strength of the phase transition by increasing the water flow, reducing the power intensity of the beam, shortening the distance the beam covers, reducing the initial water temperature, or adopting a shorter wavelength laser. Therefore, the corresponding methods can be applied to decrease the phase transition during the design of the laser energy meter. In order to further grasp this physical process and its influence, future studies are required to seek more perfect simulation and experimental conditions, to achieve better results. The above phase transition model can be promoted in similar situations with other high-power lasers and water flow.

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References

[1] Su Y and Wan M 2004 *High-Energy Laser System* (Beijing: National Defense Industry Press) p. 320
[2] Smith R L and Russell T W 1972 *IEEE Trans. Instrum. Measurement* **IM21** 434
[3] Johnson E J 1997 *Appl. Opt.* **16** 2315
[4] Li G P, Wang L and Yang Z J 2004 *Acta Photon. Sin.* **34** 1111
[5] Thomas R S 1991 *IEEE* **CH2940-5** 227
[6] Wei J F, Zhang K, Qian S S and Zhou S 2007 *High Power Laser and Particle Beams* **19** 1105
[7] Sonic R K, Mandloie V K and Pote M B 2007 *Opt. Laser Technol.* **39** 198
[8] Wei J F, Sun L Q and Zhang K 2013 *Meas. Sci. Technol.* **24** 055103
[9] Li L, Gao Z Y and Wang X 2003 *Transactions of Beijing Institute of Technology* **23** 489
[10] Maffion R A, Dana D R and Honey R C 1991 *SPIE* **1537** 182
[11] Swartz B A and Cummings J D 1991 *SPIE* **1537** 50
[12] Xiao B Q, Wang Z C, Jiang G P and Chen L X 2009 *Acta Phys. Sin.* **58** 2523 (in Chinese)
[13] Zeng J B, Li L J, Liao Q and Jiang F M 2011 *Acta Phys. Sin.* **60** 66401 (in Chinese)
[14] Xiao B Q, Fan J T, Jiang G P and Chen L X 2012 *Acta Phys. Sin.* **61** 154401 (in Chinese)
[15] Zhou X F and Gao L 2007 *Chin. Phys.* **16** 2028
[16] Xiao B Q 2013 *Chin. Phys. B* **22** 14402
[17] Chun T L and Chin P 2009 *Journal of Micromechanics and Microengineering* **19** 55013
[18] Li T Z 1998 *Appl. Opt.* **19** 19
[19] Schippnick P F 1990 *SPIE* **302** 1247
[20] Zhou Y L, Sun B and Chen T K 2002 *Chin. J. Nuclear Sci. Eng.* **22** 218
[21] Zhang S, Li J Q and Zhang B 2008 *Acta Photon. Sin.* **37** 888
[22] Zheng R L and Liu J 2002 *Acta Photon. Sin.* **31** 482
[23] Qing Y S and Lü B D 2001 *High Power Laser and Particle Beams* **13** 677
[24] Luo S R, Lü B D and Zhang B 2000 *Acta Photon. Sin.* **10** 1215
[25] Vanstralen 1979 *Boiling Phenoena* (New York: McGraw-Hill/Hemisphere) p. 412
[26] Butterworth D T 1977 *Two-phase Flow and Heat Transfer* (London: Oxford University Press) p. 245
[27] Wei J F, Sun L Q and Zhang K 2013 *Appl. Phys. B* **110** 574