Experimental investigation of the effect of laser radiation on evaporation of a liquid

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Abstract. To study the process of model liquid (ML) evaporation under laser irradiation, two experimental samples (ES) in the form of ML reservoirs have been developed: an experimental reservoir with transparent walls, ES1, and an experimental reservoir of metal ES2, as a prototype of a future porous structure.

The processes of ML evaporation under constant and discrete laser radiation (LR) of different power were studied.

The program and methodology of experiments were developed and preliminary results of ML evaporation processes were obtained, including: current mass and temperature for ES1, ES2.

The advantage of the discrete mode of exposure LR over constant mode of LR is shown. In the discrete mode of LR at a distance of 10 mm between the focus of LR and the surface of ES2 at a power of LR of 60 W evaporated ML by 4% more than at constant LR, and at a power of LR of 90 W evaporated ML by 22% more than at constant LR.

1. Introduction

The process of liquid evaporation from various porous materials is often investigated, e.g. during drying of rocket fuel tanks [1], in microthermal tubes [2], during drying of coal [3], construction materials [4], products [5], etc. There are various methods of liquid evaporation from porous materials, for example, based on the convective influence of thermal gas flows [4], electromagnetic influence using emitters with different power and frequency of radiation [6], including lasers [7].

In [6], an interconnected electromagnetic model and a model of heat transfer in a multiphase porous medium for microwave heating of coal were developed. Microwave heating is realized by converting electromagnetic energy into thermal energy [8], and the ability of the material to absorb microwave energy and convert it into thermal energy depends on the dielectric constant [9]. Studies have shown that absorption of microwave radiation by coal causes a significant redistribution of the electromagnetic field in the resonator, forming regions of high and low energies. Water evaporation and surface convection of heat have a strong influence on the thermal emission of coal, in which the temperature increases nonlinearly because the dielectric properties of coal constantly change during microwave heating. However, these studies do not consider metallic porous materials.

In [10] the process of liquid evaporation in a microchannel at LR is considered. The process under study is characterized by inhomogeneity of the temperature field at the liquid-gas-porous material interface and, as a consequence, non-uniformity of liquid evaporation, which affects thermocapillary convection, which may differ from convection caused by a source of uniform heating or spontaneous evaporation. The results of a numerical study of liquid evaporation in a microchannel under infrared laser influence [10] showed that the heat transfer coefficient at the interface decreases with increasing laser heating time because the increased vapor pressure in the gas phase prevents liquid evaporation. In addition, the evaporation rate increases with increasing laser power and decreasing humidity.
Existing studies of the influence of LR on the evaporation of liquid in the microchannel are focused on the steady-state of the evaporation process of the liquid column. The parameters of heat and mass transfer process at the convection of liquid column in a microchannel under conditions of discrete LR mode are not considered.

2. Problem statement
Research of influence of LR on the process of evaporation of ML from ES1, ES2 includes the solution of the following tasks:

- justification of parameters of ES1, ES2 including material;
- development of the experimental research program and methodology;
- obtaining experimental dependences of the change in the ML mass and temperature on the LR parameters (power, location of the laser focus relative to the surface of the ES) in ES1, ES2.

3. Justification of ES parameters
At the consideration stage of the study two variants of ES are considered:

- ES1 (Figure 1a) main purpose for analysis of ML dynamics under influence of LR with different parameters, has transparent walls with a thickness of 0.5 mm, material is plastic;
- ES2 (Figure 1b) main purpose is to conduct preliminary experiments, including debugging of technology of LR impact on ML, the metal structure of ES, to study heat and mass transfer process at various modes of LR impact on ML; is made of an alloy belonging to Al-Mg-Mn system. To conduct preliminary experiments, a cavity with a diameter of 12 mm with a converging taper at the bottom was made on the ES. In addition, the initial level of the ML coincides with the surface of ES1 and facilitates the process of adjusting the focus of the laser beam relative to the initial position of the ML surface.

Further research suggests a sequential complication of ES, for example, ES3 (Figure 1c) is a simplified porous metal structure, which is a complication of ES1, including 20 model pores, evenly distributed over the surface of the plate, the pore diameter is 1 mm. ES4 (Figure 1d) is a porous metallic structure, which is a complication of ES3, manufactured by additive technologies, the porosity of such a sample will have a random character. At the final stage, a fragment of the power rod of the fuel tank shell of the launch vehicle with a microcrack will play the role of ES5 (Figure 1e).

4. Program and methodology of experimental research. Metrological support
In order to solve these problems, an experimental stand was created, which makes it possible to conduct experimental studies of the process of liquid evaporation under laser influence. The scheme of the experimental stand is shown in Figure 2.
To conduct experimental studies, two ES were developed in the form of reservoirs with ML:
1. ES1 in the form of an experimental container with transparent walls (Figure 1a) made of plastic, to determine the dynamics of bubbles in the ML, the depth of LR in the ML, and to develop the technology of LR influence on the ML.
2. ES2 as an experimental reservoir of metal with one hole (Figure 1b), as a prototype of the future porous structure.

Parameters of ML, ES1, ES2, laser beam trajectories:
1. ML
1.1 Initial temperature of ML: 26-30 °C.
1.2 Type of ML: distilled water.
2. ES:
2.1 ES1 - transparent glass, polystyrene material, diameter 55 mm, depth 65 mm, the initial mass of the ML is 100 g (Figure 1a).
2.2 ES2 - metal plate with one hole, material aluminum d16t, diameter 12 mm, the initial mass of ML 0.3 g.; cone depth 4.5 mm. (Figure 1b).

Trajectory and mode of the laser beam influence on the ML:
3.1 Along the spiral from the edge of the hole to the center of the ML mirror at the initial spiral diameter of 10 mm (constant mode) (Figure 3a);
3.2 Along the spiral from the edge of the hole to the center of the ML mirror at the initial diameter of the spiral 4 mm (constant mode) (Figure 3b);
3.3 Along the circle with a diameter of 4 mm (discrete mode) (Figure 3c).
3.4 Experiment time: in constant mode - 15 s; in discrete mode LR - 26 s.
3.5 LR power: 30; 60; 90 W for ES1, ES2.
3.6 Distance from the edge of the laser head to the initial surface of ML: 8; 10; 14 mm.
3.7 Temperature of the LR at the point of contact with the ML ~ 1890 °C.
Figure 3. Trajectory of movement and mode of action of LR on a mirror of ML: a) along with a spiral from the edge of a mirror of ML to the center of a mirror of ML at the initial diameter of a spiral 10 mm (constant mode); b) along a spiral from the edge of a mirror of ML to the center of a mirror of ML at the initial diameter of a spiral 4 mm (constant mode); c) along a circle with diameter 4 mm (discrete mode)

The following are used as measured parameters and metrological equipment:
– the mass of the liquid (laboratory scales VM510DM-II with a measurement error of ± 0.005 g);
– ML temperature (temperature meter with a thermocouple, measurement error ± 1.5 °C).

The technique for carrying out the main experiments consists in parametric LR on the ML located in the ES and measuring the mass and temperature of the evaporated ML.

According to the scheme of the experimental stand shown in Figure 2, ES is set on the laboratory scales 2 and in the reservoir of ES is poured ML 3. The mass of ML 3 is determined by the readings of the laboratory scales 2. Thermocouple 4 is lowered into ML 3 and the temperature of the ML is determined using a temperature meter 5. The head of the laser transmitter 6 is set over the surface of an ML at the chosen distance 8; 10 or 14 mm from the initial surface of an ML at a constant laser focus point of 10 mm. SF-1410 is used as a laser machine tool 7. In the program of the laser machine tool 7, the power of LR radiation (30; 60; 90 W) and the trajectory of movement of the head of the laser transmitter 6 taking into account the speed and time of LR are set (Figure 3). The process of ML evaporation is recorded using a video camera 8.

During the experiments with ES1 the LR power of 60 W is set, the trajectory of LR movement along the spiral from the edge of the ML mirror to the center of the ML mirror at the initial spiral diameter of 10 mm, and a constant mode of LR (Figure 3a).

Experiments with ES2 are carried out at LR power of 30, 60, 90 W, trajectory of LR movement along the spiral from the edge of the ML mirror to the center of the ML mirror at the initial spiral diameter of 4 mm; 10 mm, constant and discrete modes of LR (Figure 3a, 3b, 3c).

Fig. 4 shows the experimental stand with ES1.

![Figure 4. Experimental stand with ES1 (transparent glass)](image)

In Figure 5 shows the experimental stand with ES2.
5. Preliminary results of experimental studies

As a result of the experiments with ES1 and ES2, the dependences of changes in the mass and temperature of the ML on the power of the LR, the operating modes of the LR, and the distance from the edge of the laser head to the initial surface of the ML were obtained.

Figure 6 shows the dependence of changes in ML mass in ES1 at LR power of 60 W and distance from the edge of the laser head to the initial surface of ML 8; 10 and 14 mm under conditions of constant influence of LR on ML.

![Figure 6. Change of ML mass in ES1 at constant LR power of 60 W and distance from the edge of the laser head to the initial surface of the ML: 1 – 8 mm; 2 – 10 mm; 3 – 14 mm](image)

Figure 7 shows the dependence of changes in ML mass in ES2 on LR power at distances from the edge of the laser head to the initial surface of the ML of 8; 10 and 14 mm under conditions of constant exposure to LR on the ML.
Figure 7. Variation of ML mass in ES2 under constant LR with power: 1 – 30 W (10 mm from the initial ML surface); 2 – 30 W (8 mm from the initial ML surface); 3 – 30 W (14 mm from the initial ML surface); 4 – 60 W (10 mm from the initial ML surface); 5 – 60 W (8 mm from the initial surface of ML); 6 – 60 W (14 mm from the initial surface of ML); 7 – 90 W (10 mm from the initial surface of ML); 8 – 90 W (8 mm from the initial surface of ML); 9 – 90 W (14 mm from the initial surface of ML).

Figure 8 shows the change in ML temperature in ES2 when the laser head is positioned 10 mm away from the initial surface of the ML and the power of the constant LR is 30; 60; 90 W.
Figure 8. Variation of ML temperature in ES2 at the location of the laser head from the initial surface of ML at the distance of 10 mm and constant LR power: 1 – 30 W; 2 – 60 W; 3 – 90 W

In Figure 9 the dependence of change of ML mass in ES2 at the location of the laser head from the initial surface of ML at a distance of 10 mm and power of discrete LR of 30; 60; 90 W is presented.

Figure 9. Variation of ML mass in ES2 at the location of the laser head from the initial surface of ML at a distance of 10 mm and discrete LR power: 1 – 30 W; 2 – 60 W; 3 – 90 W
6. Discussion

Figure 7 shows that when the LR power is increased from 30 to 60 and 90 W at a distance of 10 mm from the edge of the laser head to the initial surface of the ML (curves 1; 4; 7), the mass of the residual liquid on ES2 after 15 s of LR is 0.244 g, 0.171 g and 0.161 g, respectively. The average evaporation rate of the liquid is 3.73*10^{-3} g/s at 30 W, 8.6*10^{-3} g/s at 60 W, and 9.27*10^{-3} g/s at 90 W.

When the distance from the edge of the laser head to the initial surface of the ML is reduced by 2 mm (Figure 7, curves 2; 5; 8), the mass of the remaining fluid on the ES2 is 0.250 g/s at 30 W; 60 W - 0.187 g/s; 90 W - 0.173 g/s. Consequently, decreasing the distance from the edge of the laser head to the initial surface of the ML leads to a decrease in the liquid evaporation rate at 30 W by 10.6%, at 60 W by 12%, at 90 W by 8.6%.

When the distance from the edge of the laser head to the initial surface of ML is increased by 4 mm (Figure 7, curves 3; 6; 9) the mass of the remaining liquid on ES2 is at 30 W - 0.227 g; 60 W - 0.140 g; 90 W - 0.130 g. At the same time, the liquid evaporation rate, relative to the first option of laser head location from the initial liquid surface of 10 mm, increases by 30% at 30 W; by 24% at 60 W; by 22% at 90 W. Since the laser beam has the form of a convergent and divergent cone from the focal point of the laser beam, increasing the distance from the edge of the laser head to the initial surface of the ML increases the area of the laser beam effect on the liquid. Consequently, the optimal distance from the edge of the laser head to the initial surface of the liquid is 14 mm, at which the evaporation rate of ML is maximal.

The fluctuating nature of the curves in Figures 6-9 is explained by the non-uniformity of liquid evaporation, due to liquid movement and formation of vapor bubbles in the liquid volume.

Figure 8 shows a sharp increase in liquid temperature from the initial moment of time to 6 seconds of the experiment. From 6 seconds to 15 seconds the liquid temperature is almost constant. When the laser power is increased from 30 W to 60 W the liquid temperature increases by 15%, from 30 W to 90 W by 52%.

The mass of vaporized ML in ES1 at LR power of 60 W (constant mode) and distance from the edge of the laser head to the initial surface of ML of 8 mm is 0.038 g, 10 mm - 0.067 g, 14 mm - 0.093 g, (Figure 6). In a similar mode of LR on the surface of ML located in ES2 the amount of ML evaporated more (Figure 7) than in ES1 (Figure 6): 8 mm - 0.113 g, 10 mm - 0.129 g, 14 mm - 0.160 g. This is due to the fact that LR passes through the ML and heats the pore walls of ES2. Thus, the ML heats up and evaporates from the LR and from the walls of the pore of ES2. In ES1 the LR does not reach the walls of ES1 and a significant part of the thermal energy is spent on heating the ML at the depth of ES1 without boiling, which is associated with a large mass of stirring of the ML.

When the LR is discrete (Figure 9) and the laser head is located 10 mm away from the initial surface of the ML, the mass of the remaining ML at ES2 is: at 30 W power - 0.255 g; 60 W - 0.164 g; 90 W - 0.126 g. Comparative analysis of the remaining mass of ML under discrete (Figure 9) and constant (Figure 7) LR modes showed that under discrete LR, the ML evaporated more by 4% at 60 W and by 22% at 90 W. At 30 W LR power, ML vaporized equally in discrete and constant LR modes.

7. Conclusion

1. A physical model of the process of liquid evaporation from ES during LR has been developed.
2. Experimental stand for research of LR effect on ML and developed program and technique of experimental studies of ES vaporization process at laser radiation power of 30; 60 and 90 W and location of laser head from ES surface at constant and discrete LR.
3. Preliminary results of the ML evaporation process were obtained, including current mass and temperature of the liquid in EL as well as preliminary results of numerical simulation of the simplified physical-mathematical model.
4. Advantages of the discrete mode of LR over the constant mode were shown, in particular, by the mass of the evaporated ML at a distance of 10 mm between the focus of LR and the surface of ES2 by 4% at a power of LI 60 W and by 22% at a power of 90 W.
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