Heat and mass transfer are in the interaction of multi-pulsed spray with vertical surfaces in the regime of evaporative cooling

P N Karpov¹, A D Nazarov¹, A F Serov¹,², V I Terekhov¹,²

¹Kutateladze Institute of Thermophysics, Siberian Branch of the RAS
Russia, 630090 Novosibirsk, Ac. Lavrentieva ave., 1
²Novosibirsk State Technical University
Russia, 630073 Novosibirsk, K. Markska ave., 20

Abstract. Sprays with a periodic supply drop phase have great opportunities to control the processes of heat transfer. We can achieve optimal evaporative modes of cooling by changing the pulse duration and the repetition frequency while minimizing flow of the liquid phase. Experimental data of investigation of local heat transfer for poorly heated large surface obtained on the original stand with multi nozzle managed the irrigation system impact of the gas-droplet flow present in this work. Researches on the contribution to the intensification of spray options were conducted. Also the growth rate was integral and local heat. Information instantaneous distribution of the heat flux in the description of the processes have helped us. Managed to describe two basic modes of heat transfer: Mode "insular" foil cooling and thick foil with forming of streams. Capacitive sensors allow to monitor the dynamics of the foil thickness, the birth-belt flow, forming and the evolution of waves generated by "bombing" the surface with the droplets.

1. Introduction

Trend of developing miniature electronics dictates the demand for the new ways of removing high heat fluxes from small heat exchanging surfaces, and this can be ensured only by maintaining the admissible operating temperatures of equipment and instruments by the new active cooling systems. Controlled local cooling by the single pulses of a gas-droplet flow, working at film and evaporative cooling is one of the most effective options for increasing heat transfer from selected power electronic components. The modern electronic components operate in temperature range of up to 100°C, which defines the requirements for the working liquid flows (solid film, island coating, rivulets or drops).

It is known that when cooling the low-temperature surface, the temperature gradient at the liquid-solid surface interface plays a major role in heat transfer due to the Marangoni effect [1] because a significant contribution to heat transfer intensification is made by thermo-capillary convection due to evaporative cooling on a moving film - dry surface boundary.

According to the studies, development of island film cooling is observed on the surface, when tangential forces and local surface tension coefficient arise at insufficient wetting, resulting in shear film flows and dry spot formation, local film areas, rivulets and droplets. The conditions of forming a thin evaporating film with microthickness along the contact line allow maintenance of a high heat transfer rate.
2. Experimental apparatus and instrumentation

The experimental setup is a multifunctional device. It consists of: programmable multi-jet source of a pulsed gas-droplet flow (pulse injector), automatic calorimeter with removable heat exchanger, automated system of registering the gas-droplet flow parameters, including original capacitive sensors for detecting the thickness and velocity of waves on the liquid film, as well as gradient sensors of the local heat flux [2]. The applied integral method of heat transfer registration allowed us to record the dependence of heat transfer on the regime of gas-droplet flow formation, its intensity, characteristics of roughness the heat exchanging surface and other design features of the cooled body.

The controlled source of the gas-droplet jet is formed via the off-duty factor: droplet flow and continuous gas flow. The programmable multi-jet source of the pulsed gas-droplet flow is designed in the form of a two-chamber unit: for air and water. On the flat part of the source, there are 16 individually controllable liquid injectors in the form of 4 × 4 matrix with a spacing of 30 mm. The liquid nozzle is a sprayer of four nozzles with 125-μm diameter, switched-on by a solenoid valve. On the same surface, there are 25 gas nozzles with the outlet diameter of 0.35 mm around the liquid nozzle, which form the impinging multi-jet air flow. These investigation results relate to the regime, when the heat exchanger surface is normal to the gas-droplet flow and vertical relative to the horizon.

The scheme of formation of the wall liquid and air flow is shown in Figure 1.

![Figure 1. Schematic of experimental setup](image)

Distilled water is used as the working liquids. To monitor the process of the near-wall film formation on the heat exchanger surface, we have determined the regime, when the impinging multi-jet gas-droplet flow forms a liquid film on the entire surface of heat exchanger. These regime allows observation of hydrodynamics and heat transfer in the central and peripheral areas of the near-wall flow of cooling liquid in the regime of conditionally single pulse, when the film with characteristic currents in specific zones of the surface is formed at the moment of irrigation by the droplet flow. The film evaporates partially or completely in-between the pulses. The above regime relates to cooling by conditionally single pulse.

3. Results and discussion

The aim of this work is studying the processes of intensification of heat transfer from the heat-loaded surface at pulse irrigation by conditionally single multi-jet droplet flows. The short-term operation of all liquid nozzles with the ratio of period between pulses to duration of the droplet flow pulse higher
than 20 is considered as a single pulse. The original programmable device forming the multi-jet pulse
gas-droplet flows allows us to set the initial conditions of the cooling spray in a wide range.

![Relative ripple amplitude](image)

**Figure 2.** Instantaneous value of droplet flow density near the heat exchanging surface.

Formation of the multi-jet flame is studied insufficiently, at first, it was necessary to obtain data on
distribution and behavior of the droplet train during target bombing. The effect of the co-current air
flow on distribution of the droplet flow density in the drift space and over the flow cross-section near
the cooled surface was studied (Figure 2). The data showed that the droplet mixture flame in the co-
current air flow has more uniform distribution of the droplet flow density over the cross-section and
droplet grouping along the velocity vector, which result in more effective cooling (~ 3 times). During
the movement of a droplet train in the air flow, the large droplets group, forming a denser “head” of a
pulse, which provides intensive “turbulization” of the formed film.

The next stage of research was data obtaining on the values of local and integral heat transfer
coefficients at irrigation by conditionally single pulses of the droplet-air mixture. Capabilities of the
programmable multi-jet source allowed us to form a thin liquid film on the surface of the heat-loaded
surface. The main condition was “conditional singleness of a pulse”. Figure 3 shows the dependence
of heat transfer obtained with the help of the local heat flux sensor. The peak corresponds to maximal
heat transfer. When the bulk liquid is deposited on the surface, formed liquid film heating is observed
(horizontal shelf), then there is uniform evaporation of the heated liquid film. The abrupt peak in the
diagram corresponds by its time to the “end” of the droplet train. It is also possible to observe
contribution of the secondary droplets to the process of heat entrainment from the surface.

In all experiments, the pulse duration was constant and equal to 4 ms. Repetition rate varied under the
condition that the preceding pulse had no effect on the subsequent one (complete evaporation of all
liquid film from the surface). The data on the values of heat transfer coefficients are shown in Table 1.
Figure 3. Heat flux density obtained by the local heat flux probe

Table 1. Effectiveness of the spray

| F (Hz) | \( r, (g \cdot m^{-2} \cdot s^{-1}) \) | \( h, (W \cdot m^{-2} \cdot K^{-1}) \) | \( \eta \) |
|--------|---------------------------------|---------------------------------|--------|
| 0.25   | 1.4                             | 269.1                           | 0.96   |
| 1      | 3.6                             | 446.8                           | 0.87   |
| 2      | 5.9                             | 596.4                           | 0.81   |
| 4      | 10.7                            | 795.5                           | 0.75   |
| 6      | 16.2                            | 888.4                           | 0.69   |

\[ \eta = \frac{q}{m \cdot \left( C_p \cdot (T_w - T_s) + r \right)} \]

where \( q \) is the heat flux density (W/m²), \( m \) is the specific mass flow rate (kg/m² s), \( C_p \) is the specific heat capacity (J/kg K), \( T_w \) and \( T_s \) are the temperatures of the heat-exchanging surface and liquid (K), and \( r \) is the latent heat of vaporization of liquid phase (J/kg). Data in the Table show that at frequency \( F = 0.25 \) Hz, the most effective heat removal is observed.

4. Conclusions

It has been experimentally shown that the intensification of heat transfer is due to the contribution of evaporative cooling by primary and secondary drops on dry sections of the surface of the heat exchanger in the intervals between the impulses of the liquid. The increase in pulse duration at a constant frequency of the pulses of the liquid phase in the gas-droplet flow leads to the fact that the fraction of the evaporation process decreases and in heat exchange the main mechanism is the transfer of thermal energy to the liquid film. Under such conditions, the heat transfer coefficient of the pulsed gas-droplet flow is comparable with the coefficient of heat transfer during drip irrigation.
5. References
[1] Gatapova E, Kabov O, Marchuk I 2004 Technical Physics Letters 30 418—421
[2] Nazarov A, Serov A, Bodrov M 2010 Technical Physics 80 724-727
[3] Pedersen C 1970 Int. J. Heat Mass Transfer 13 369-381

Acknowledgments
The work was financially supported by the grant of Russian President NSh-8780.2016.8