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Instantaneous heat transfer for large drops levitating over a hot surface

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A B S T R A C T

The paper deals with the process of evaporation of large water drops with the initial mass of 1 g deposited on a hot surface, the temperature of which is higher than Leidenfrost point. The behavior of water drops was examined at the test stand, at which three independent measurement paths were available, namely those of instantaneous mass measurements, temperature recording and sequential recording of the thermal field of the drop upper surface. Thus obtained sets of drop mass, drop temperature, and its area size, for pre-defined temperature of the heating cylinder having a great thermal capacity, were used to compute instantaneous values of the heat transfer coefficient. The methodology of investigations was discussed in detail. Measurement uncertainties were analysed using the total differential method. On the basis of thermographic images, recorded with a thermovision camera, of the drop upper surfaces, substantial thermal diversity of drops was found. The difference between the maximum and minimum temperatures periodically amounts to above 9 °C, and standard deviation from the area of their upper surfaces amounts even to 2 °C. Measured instantaneous values of the heat transfer coefficient were approximated with a power function, dependent on the heating surface temperature and a momentary drop size. This relation was selected in accordance with the developed approximation procedure, at the imposed condition of the minimum of the mean square error. Consequently, a constant value of exponent and a dependence on the heating wall temperature were obtained. It was shown that values of measured and approximated heat transfer coefficients are contained in the interval defined by the value of the relative error ranging from −13% to +9%. An approximation of the perpendicular projection of the drop area in the form of polynomial is proposed. Under these assumptions, an analytical solution to the energy balance equation is given. Exemplary computations provided in the study indicate a very good effectiveness of the proposed method.

1. Introduction

A demand for modern thermal devices that are characterised by small size and high cooling or heating power resulted in a markedly increased interest in heat transfer enhancement. The most effective ways of approaching this issue is to apply phase change phenomena. Advancement in such technologies came as a spin-off from space exploration and nuclear power plants, a rapid development of which started in the middle of the twentieth century. Despite intensive research into the subject, sufficiently accurate schemes necessary to design efficient cooling systems have not been developed. It is also true about very large scale integration electronic devices [1], in which in addition to the dispersion of high density heat fluxes, a constant temperature and the lowest possible noise level are also required [2].

Nuclear power plants consume large amounts of water, even twice as much as conventional power stations of the same capacity [3]. That creates a demand for innovative cooling technologies based on two phase mixtures. In study [4], it was found that the droplets Sauter mean diameter could decrease when the liquid flows through the grid spacer, which results in an increase in interfacial heat transfer surface area. The change in various flow conditions, namely vapor injection velocity, heater temperature, droplet size, and droplet flow rate inside a heated rod bundle was experimentally investigated in [5].

Understanding the phenomenon of evaporating droplet is very important for such devices as diesel engines [6,7], liquid–fuel rocket engines, aircraft jet engines and industrial furnaces. Improvements in efficiency and power output as well as reliability and durability depend on efficient cooling systems. From a variety of cooling technologies discussed in [8,9], droplet injection to maximise the cooling surface [10] may be effectively applied.

Two-phase water droplets-gas flows are also found in high temperature gas flow cooling [11], heat recovery in ventilation [12], air

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Nomenclature

A	area of drop projection on hot surface
a	polynomial coefficient
b	coefficient of the Maclaurin series
C_θ	coefficient defined in the text
c_p	specific heat
h_{fg}	enthalpy of vaporisation
M	mass flux
m	mass
n	exponent
T	temperature
t	time

Greek symbols

α	heat transfer coefficient
δ	relative error
θ	temperature above saturation

Subscripts

0	initial
d	drop
s	saturation
w	heating surface

humidifying and drying in evaporation chambers of air conditioning systems [13], humidification process in spray towers [14], draft cooling towers [15], evaporation in fire [16], and two-phase closed systems in heat pipes where liquid and gas phases are close to the saturation equilibrium state [17] and heat transfer limitation is reached [18,19].

In droplet evaporation discussed above, an interaction with solid surface is a common issue. At sufficiently high temperatures, vapor created on the droplet surface nearest to the wall produces a lubrication layer, from which the droplet is suspended. That is known as the Leidenfrost effect [20]. At surface temperatures above the Leidenfrost point, the droplet levitates on a thin vapor layer through which heat is transferred. The Leidenfrost temperature may be determined from a droplet evaporation curve, where the droplet lifetime is plotted versus wall superheat. At that temperature, the vapor layer prevents any significant contact between the droplet and the surface, and the droplet evaporation time reaches its maximum. In the literature, different values for that point are given. In [21], large variations in the Leidenfrost temperature for water are discussed. It is found that the differences result from droplet size and its mass, method of deposition, subcooling, the heating surface thermal properties, its condition, ambient pressure, and liquid purity. The complexity of the phenomenon therefore requires detailed investigations into the impact of separate factors on the droplet evaporation.

Wettability of the surface is one of the most important parameters affecting the process of heat transfer. In [22,23], a change in evaporation characteristics of water droplets on hydrophobic and hydrophilic surfaces is discussed. The evaporation is strongly dependent on convection. The air motion modifies the mass transfer and thermal parameters of the boundary layer with the corresponding change in the droplet shape [24]. The coupling between the droplet shape and the applied electric field may produce internal droplet flow, which decreases heat transfer [25]. Evolution of the thermal and internal flow coexisting with evaporation is also discussed in [26]. It is concluded that the evaporation rate is not a constant value. It depends on the energy balance of latent and sensible heat. An interaction with the hot surface may change the evaporation significantly. When a droplet is deposited onto a hot surface, heat is transferred from the solid and consumed to heat up a fluid and to change phase from liquid to gas. At a sufficiently high surface temperature, a stable vapor layer is created and heat transfer is reduced. The dependence of the rate of evaporation on droplet shape and size are studied numerically in [27,28]. The evaporation rates of small droplets of different diameters located on a horizontal surface are studied in [29], where a faster evaporation of small droplets is investigated experimentally. Vaporisation and chemical conversion are simulated for different ambient conditions in [30].

Evaporation of the droplets is studied in many areas of technology. Various investigations conducted into the subject focus on the physics of the phenomenon, which depends strongly on the liquid and its components, thermal and flow conditions, interaction with the surface, etc. Although the problem has been thoroughly analysed, the mechanisms of evaporation are still not fully clear.

The present paper examines the behavior of a large single drop levitating over a hot surface, unsteady mass of the drop, and heat transfer. For the sake of the experiment, it was necessary to develop specific methodology based on measurement uncertainty. The outcome of the experimental investigations is provided in the form of changes in the drop weight, on the basis of which instantaneous heat transfer coefficient is determined.

2. Test facility

Fig. 1 shows a diagram of the research stand, the main element of which is a cooper heating cylinder, 3.5 cm in diameter. It upper surface is shaped like a bowl having a very large radius of curvature. Support for the heating system, additionally installed, allows its independent levelling, which facilitates stable drop depositing. ~300 W heater was wrapped on the cylinder lateral side. The desirable temperature of the system was obtained by setting the voltage from the autotransformer directly connected to the mains. The voltmeter in the electrical circuit was used to roughly measure the voltage supplied. The parameter that was precisely controlled was the heating surface temperature. For temperature control, a K-type coat thermocouple, 0.5 mm in diameter, was soldered in the opening drilled in the bottom. The weld was located just beneath the surface and the thermocouple leads were connected to

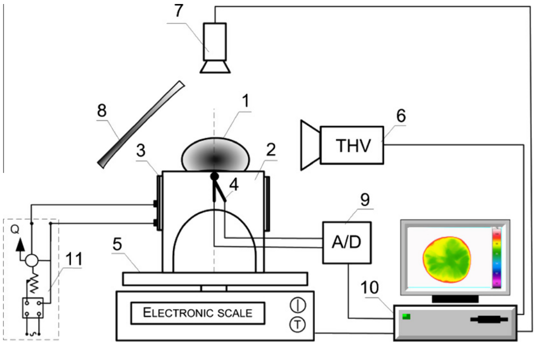

Fig. 1. Diagram of the test apparatus: 1 – droplet of water, 2 – copper cylinder, 3 – wrapped heater, 4 – thermocouple, 5 – electronic scales, 6 – infrared camera, 7 – digital camera, 8 – mirror, 9 – A/D signal processing system, 10 – computer, 11 – electric power supply unit (autotransformer).