International Journal of Thermal Sciences 127 (2018) 360–372

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Vaporization of water droplets with non-metallic inclusions of different sizes in a high-temperature gas

Jean Claude Legros[1], Olga Lutoshkina[1], Maxim Piskunov[1,*]

National Research Tomsk Polytechnic University, Institute of Power Engineering, 30, Lenin Avenue, Tomsk, 634050, Russia

A R T I C L E I N F O

Keywords:
Evaporation
Boiling
Phase transformation
Fluid
Water droplet
Solids
Graphite

A B S T R A C T

Experimental research on mechanisms of vapor production by boiling and evaporation was carried out on heterogeneous droplets of water containing graphite particles of different sizes and concentrations, heated by high-temperature environment (up to about 1373 K). Different steps have been observed, such as free surface evaporation of the droplet, bubbles boiling at the *solid inclusion/liquid* interface, the explosive disintegration of a drop into a cluster of small droplets and efficient evaporation of the produced smaller droplets. We proposed the conditions for the appearance of this explosive breakup of droplets. The present paper reports that the addition of small graphite particles into heterogeneous droplets can reduce their lifetimes by about 50% in this type of high-temperature environment. Moreover, this facilitated the explosive breakup of droplets, allowing intense vaporization. This behavior led us to make the hypothesis that an insulating layer of vapor appears at the outside droplet surface and at the interface between the solid inclusions and the droplet. Measurements on the explosive breakup of heterogeneous water droplets have allowed establishing an increase of the evaporation surface area by almost fifteen times, as compared to the initial surface of droplets. However, when using graphite suspension, the measured increase of the evaporation surface was not larger than threefold. The evaporation surface area during the explosive breakup of water-graphite suspensions was 5.4 smaller as compared to water without impurities. We reported on the reasons for the above differences. The results are useful for developing technologies of fire extinguishing by using water sprays containing non-metallic solids. Practical implementation of the explosive breakup of heterogeneous droplets can eventually permit extinguishing fire on larger areas with an identical water load.

1. Introduction

1.1. Role of heterogeneous liquid droplets

To date, most of the mechanisms of liquid vaporization under different conditions of heat exchange are known, e.g. evaporation from a free surface, bubble and film boiling. Each of them is very complex and characterized by particular features and behavior: different rates of vapor production and heating of surface liquid layer, convection current in this layer, position of *liquid/gas* interface, extreme conditions of processes implementation, durations of processes, etc. [1–10]. Onset, growth, departure and movement of bubbles (for example, [11–15]) are usually followed by intensive evaporation from a free surface, this problem has some common points with investigation of leading mechanism of vaporization under various conditions of heat exchange that takes place at interfaces. It is important to study the necessary and sufficient conditions for intensification of vaporization, and the growth and departure of bubbles, to determine the vapor formation rate and the influence of internal and external factors, namely temperature and pressure of environment, conditions of heat exchange, properties of liquid and vapor. Some particular accent has to be put on the impacts of convection, conduction and radiation at the *liquid/gas* interface.

These problems are of prime importance for the widely used heterogeneous liquids (emulsions and suspensions) [16–20]. The heterogeneous, two-phase and multi-phase gas-vapor-droplet fluxes are extensively developed during the recent years [21–25]. The study of vaporization under high temperature of gas environment (more than 600 K) is also of high interest. Particularly, it yields the development of some useful applications (for example, thermal and flame cleaning of liquids, defrosting of granular media by gas-vapor-droplet fluxes, cleaning of surfaces of power production equipment by gas-droplet mixtures, polydisperse fire extinguishing). The description of vaporization mechanisms of liquid droplets with solid inclusions (foreign particles) in high-temperature gas is not yet totally completed. In the

* Corresponding author.
E-mail address: piskunovmv@tpu.ru (M. Piskunov).
[1] https://hmtslab.wixsite.com/hmtslab.

https://doi.org/10.1016/j.ijthermalsci.2018.02.011
Received 2 November 2017; Received in revised form 17 January 2018; Accepted 8 February 2018
1290-0729/

recent years, experimental researches were carried out [25–27] on vaporization of heterogeneous water droplets (with non-metallic and metallic inclusions) moving through high-temperature gas (more than 1000 K). Liquid evaporation rates, including the influence of inclusions (size, shape) in the droplets, the initial droplet states, gas temperature and rates of the different vaporization steps were determined [25–27]. Carbon and aluminum particles were added to water droplets to intensify liquid evaporation [25–27]. It was reasonable to think about using this effect for improving the way to extinguish large fires [25]. Different mechanisms contribute to this improvement by decreasing temperatures and reducing the concentrations of air in the fire zone by massive water vapor formation. Such mechanisms as energy absorption due to the high enthalpy of vaporization of water, the replacement of air by water vapor and the decrease of temperatures in fire zones were observed.

The advanced practical applications based on heating-up and evaporation of heterogeneous droplets of suspensions and emulsions are extremely numerous: firefighting, thermal or flame water cleaning from unspecified impurities, pulverization of slurry and emulsified fuels in combustion chambers, and others; these practical applications are discussed in detail in Refs. [28–31]. To date, the scientific community is largely successful in studying a mechanism of these processes for emulsion droplets and two-component (two-fluid) droplets (for example, [32–35]. A considerably less number of studies is published for suspension droplets. This is due to difficulties of suspension droplet generation, recording of their heating-up, evaporation, boiling, and breakup (disintegration). The attempts to investigate a mechanism of these processes for suspensions were made in Refs. [25–27] on the example of single droplets containing one inclusion.

1.2. Mechanisms of vaporization of heterogeneous liquid droplets

The experiments [25–27] discovered that mechanisms of vaporization in systems of *heterogeneous liquid droplet – high-temperature gas* are complex and include not only vapor formation at the outside surface of droplet but also at the inside interface (*liquid/solid*). These processes can lead to the droplet breakup. If the heating-up times are short, then the effects will correspond to explosive droplet disintegration. These effects can improve the efficiency of a fire extinguishing system [25]. Studies were initiated to investigate this effect by using a single water droplet with a similar-sized solid, nontransparent inclusion and a high-temperature gas environment (more than 500 K). Additionally, to enhance heat transfer in the system under consideration, the addition of small graphite inclusions can be potentially effective.

In the general case, surface structure, i.e. the morphology of matters or various artificially created enhancers, e.g. surface roughness, plays one of the key roles during the heat exchange between the liquid and the solid surface. Quite a few experimental and theoretical investigations are performed within this fundamental thermophysical concept. Note that these investigations involve a practical application in power engineering and other fields. As an example, we present several review articles [36–38].

It is necessary to make a point of studies of high-porous surfaces, foam materials [39]. Often, in studies similar to [39], the following statement is mentioned as one of the key conclusions. During the nucleation, formation and evolution of bubbles at a heat-exchange surface, the size of pores on this surface plays rather a critical role. Moreover, a smaller size of pores of matters facilitates the vaporization on its surface and enhances boiling, e.g. during pool boiling.

1.3. Aim and tasks of the present research

The present work develops the research [27] on conditions for intensive vaporization at inside and outside interfaces. In Ref. [27], we performed the experiments with 5 μl, 10 μl and 15 μl water droplets containing 2 mm, 3 mm and 4 mm graphite inclusions of different shapes. As a result, the main features of evaporation and boiling of such droplets were investigated. Moreover, we revealed the phenomenon of explosive breakup of the heterogeneous water droplet, when heated. This physical phenomenon is a new one and can be primarily useful when developing the technologies of fire extinguishing. The explosive breakup occurs due to the intensive formation of vapors at *solid/liquid* interface inside the heterogeneous droplet. Using a high-speed video registration tool, we showed that the mechanism of explosive breakup of water film around the inclusion is due to the increase in vapor pressure inside the droplet compared to the pressure of the liquid film. The bubbles of vapor were formed on the surface of the inclusion, coalesced and grew rapidly until the formation of one whole bubble with a size that exceeded the size of the inclusion. In the experiments [27], the explosive breakup was possible for different volumes of water droplets and sizes of inclusions. The main condition for explosive breakup of a heterogeneous water droplet was the heat supply during a short period of time sufficient for warming up the water film and inclusion. The time until the explosive breakup was 2–3 s. If the explosive breakup did not happen during this time, then it was unlikely to ever take place during further heating [27]. In this paper, the important and interesting point was to perform the experimental analysis of conditions for the heat transfer enhancement in the system of *heterogeneous water droplet – high-temperature gas environment* for various sizes and concentrations of graphite inclusions. In this case, the heterogeneous droplet contained several small inclusions and one large inclusion. We believe that the obtained results will considerably expand the experimental base of the given line of research, as well as contribute to the development of the existing models of heat and mass transfer at high temperatures of gas environment.

The aim of the present work is to define conditions for vaporization of heterogeneous water droplets containing solids of different sizes and concentrations.

2. Experimental setup and methods

2.1. Rationale for choosing research methods

In the research, the heterogeneous droplets of suspensions dangling at the end of a holder made of the material with low thermal conductivity. This is a popular approach to the detailed research of thermophysical and physicochemical characteristics for unsteady processes of heat transfer at interfacial boundaries during high-temperature heating [40–43]. It is obvious that static conditions for a droplet dangling in a flow impose some restrictions when analyzing forces of inertia and aerodynamic drag in the system as well as the influence of the holder on heat exchange peculiarities. Nevertheless, in case of a falling heterogeneous droplet it is quite difficult to make firm conclusions, for instance, about the behavior of evaporation at interfacial boundaries.

Among the reasons for these difficulties were the continuous movement of the solid particles inside the liquid droplets and, consequently, internal interfacial boundaries (Fig. 1).

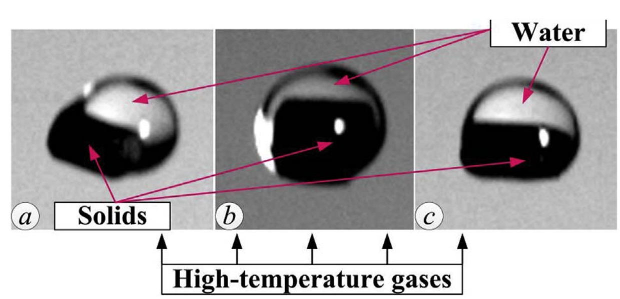

Fig. 1. Typical photographs of water drops containing inclusions in the form of (a) cylinder, (b) cube, and (c) parallelepiped during their motion through high-temperature gases [44].