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Research Paper

# Planar laser-induced fluorescence diagnostics of water droplets heating and evaporation at high-temperature

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## HIGHLIGHTS

- Temperature field in the water droplet is highly non-homogeneous during the heating.
- PLIF allows observing temperature fields in droplets even at high air temperatures.
- Maximum temperature differential from the droplet surface to centre can achieve 30–40 °C.
- Nonlinear evaporation rate dependences are plotted for the main parameters.
- Water evaporation rate increases dozens of times during the droplet heating.

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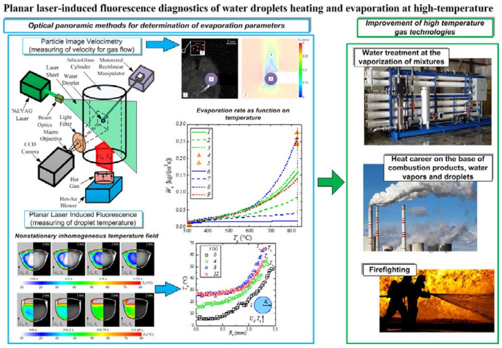
## GRAPHICAL ABSTRACT



## ABSTRACT

Gas-steam-droplet technologies are widely used in systems operating at high temperatures ranging between 400 and 2000 °C, namely: fire-fighting systems, thermal fluid cleaning, fuel compounding, industrial waste gasification and evaporation systems for advanced fuel components, cleaning of thermally loaded surfaces of power equipment, *etc.* System parameters are usually selected empirically *via* multiple tests and continuous trial operation of appropriate units, aggregates, assemblies, and installations. This situation is caused by insufficient basic knowledge of conditions and parameters of high-temperature (over 500 °C) heating and evaporation of water and water-based emulsions, solutions, and slurries. Limited information is available regarding the evaporation rates dependent on the temperature of gaseous medium. Consequently, the up-to-date evaporation models allow the researchers to achieve adequate values (in good agreement with the experiment) of evaporation rates at air temperatures not exceeding 300–400 °C. The paper presents a set of experiments on water droplets with the size ranging from 1 to 2 mm, which is used to create the information database on high-temperature evaporation parameters. The approach to measuring the evaporation rate involves observation of the droplet size or more exactly its mean radius, and recording the time of its existence. A high-speed video camera and Tema Automotive software with different tracking algorithms are used for experimental observations. During gas heating, the distribution of highly non-homogeneous and non-steady temperature field in evaporating water droplets is detected by the hardware and software cross-correlation system and Planar Laser-induced Fluorescence optical diagnostics. Instantaneous and medium evaporation rates are computed for the whole period of the droplet lifetime. Highly nonlinear evaporation rate dependences are suggested for gas temperatures and the water droplet surface, size, and time of gas heating. Approximate relationships are described for the prediction of evaporation rates depending on the basic parameters. The evaporation rate is shown to increase several-fold during the heating of a water droplet

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## Nomenclature

| | |
|---|---|
| $m$ | weight of water droplet, g |
| $R_{\text{d}}$ | water droplet radius, mm |
| $R_{\text{d}}^*$ | droplet radius during evaporation, mm |
| $S$ | conventional surface area of the droplet, m$^2$ |
| $t$ | time, s |
| $t_{\text{d}}$ | droplet lifetime (time of complete evaporation), s |
| $t_{\text{d}}^*$ | droplet lifetime within $R_{\text{d}}$–$R_{\text{d}}^*$ range, s |
| $t_{\text{h}}$ | droplet heating time, s |
| $T_{\text{a}}$ | air temperature, °C |
| $T_{\text{d}}$ | droplet temperature, °C |
| $T_{\text{s}}$ | surface temperature of the droplet, °C |
| $U_{\text{a}}$ | air velocity, m/s |
| $V_{\text{d}}$ | droplet volume, μL |
| $W_{\text{e}}$ | mean evaporation rate, kg/(m$^2$s) |
| $W_{\text{ei}}$ | instantaneous evaporation rate, kg/(m$^2$s) |
| $x$, $y$ | horizontal and vertical coordinates, mm |
| $\alpha$ | relative luminosity of Rhodamine B, brightness units |
| $\rho_{\text{d}}$ | water density, kg/m$^3$ |
| $Nu$ | Nusselt number |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |

*Abbreviations*

| | |
|---|---|
| IPI | Interferometric Particle Imagine |
| PIV | Particle Image Velocimetry |
| PLIF | Planar Laser Induced Fluorescence |
| PTV | Particle Tracking Velocimetry |
| SP | Shadow Photography |

in a high-temperature gaseous medium. The experimental data are described most accurately by exponential dependences of water evaporation rate versus the airflow temperature and velocity. This result makes it possible to predict the corresponding highly nonlinear dependences of evaporation rate versus the density of convective heat flux and the overall thermal conditions in the industrial chambers, evaporators, heat exchangers, etc. The mathematical expressions obtained can be used to identify the effective conditions of water droplet heating in a large group of high-temperatures applications as well as for developing high-temperature liquid evaporation models.

## 1. Introduction

The up-to-date models of heat and mass transfer that describe gas heating and evaporation of fluids, water in particular, are based on hypotheses and concepts developed by Spalding [1], Fuchs [2], Ranz and Marshall [3] a long time ago. The development of these concepts during the past 30 years [4–11] has allowed researchers to derive a group of approximate relationships that determine the correlation of Nusselt number *vs.* Reynolds and Prandtl numbers, namely $Nu = f(Pr, Re)$. Traditionally, these equations are used in modeling processes of heat and mass exchange and phase transformations at the air/water interface. Vysokomornaya et al. [12] determined the limitations of this approach, which cannot provide a satisfactory agreement between theoretical and experimental results on the parameters of water evaporation. They highlighted the problem of reproducing high-temperature evaporation conditions (over 500 °C) with the use of diffusion and kinetic models and traditional empirical expressions of $Nu = f(Pr, Re)$. Results obtained in [12] show that the agreement between experimental and theoretical predictions (the difference is 10–15%) on the evaporation rates is rather satisfactory when using $Nu = f(Pr, Re)$ correlation within the moderate air temperatures (under 300 °C), while at temperatures over 500 °C, this difference is several times higher. The authors [12] developed a hypothesis that at high air temperatures, a central role in high-temperature evaporation belongs to the formation of non-homogeneous and non-steady temperature field of evaporating water droplets, a buffer vapor film near the droplet surface, conditions of conductive, convective and radiative heat transfer at the interface of two media [12,13] and molecular changes in optical properties of water [14,15].

From [11], we conclude that for many years it has been relevant to construct dependences between integral characteristics of evaporation (in particular, vaporization mass rate) of emulsions, solutions, and slurries as well as the droplet ambient temperature or the heat flux. The calculation of evaporation rate constants was also important as well as the achievement of reliable experimental findings for gas-steam-droplet processes occurring at temperatures higher than 500 °C. This importance is conditioned by the temperature range, which corresponds to a wide spectrum of promising applications such as thermal or flame cleaning of fluids; multiphase flue gas heaters, water steam and droplets; firefighting; cleaning of thermally loaded surfaces of power equipment, contact heat exchangers for power systems, *etc.* Solid particles in drop and gas flows substantially intensify phase transformations and convection processes in heterogeneous multiphase systems [16]. Hence, the development of science-based concepts and process models of the droplet phase transfer at high gas temperatures will assist in solving many problems of heat and mass exchange arising in these systems.

Kuznetsov et al. [17] have developed an approach to the evaluation of the droplet evaporation rates in a high-temperature-controlled gaseous medium. This approach involves tracking the air/water interface and provides high-speed measurements of the droplet evaporation rates at gas temperatures ranging from 250 to 700 °C and higher. However, in order for the classical vaporization concepts to be met, it is important to measure the surface temperature of the droplet and droplet temperature fields. The internal temperature distribution can be highly non-homogeneous and non-steady during the intensive gas heating. There is a lack of the experimental methods for determination of the internal temperature due to its high rate change, observed, in particular, during the intensive droplet heating. Even special miniature (0.1 mm junction) and fast response (less than 1 °C) thermocouples do not provide reliable measurements of the droplet temperature fields due to their thermal conductivity affecting the droplet heating. In particular, it was shown in [18] that during the initial warm-up phase, the holder (rod or thermocouple) takes heat from the droplet surface, and during the final stage, the situ-