Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Evaluation, boiling and explosive breakup of oil–water emulsion drops under intense radiant heating

Pavel A. Strizhak[a], *Maxim V. Piskunov*[a,*], *Roman S. Volkov*[a], *Jean C. Legros*[a,b]

[a] *National Research Tomsk Polytechnic University, 30, Lenin Avenue, 634050 Tomsk, Russia*
[b] *Euro Heat Pipes SA, Rue de l'Industrie 24, B1400 Nivelles, Belgium*

ARTICLE INFO

Article history:
Received 1 March 2017
Received in revised form 3 July 2017
Accepted 6 September 2017
Available online 18 September 2017

Keywords:
Oil–water emulsion
Drop
Evaporation rate
Explosive breakup
Drop fragmentation
High radiant heat fluxes

ABSTRACT

An experimental study on conditions and main characteristics for high-temperature (more than 700 K) evaporation of oil–water drops is presented. The high-temperature water purification from impurities can be the main practical application of research results. Thus, the heating of drops is implemented by the two typical schemes: on a massive substrate (the heating conditions are similar to those achieved in a heating chamber) and in a flow of the heated air. In the latter case, the heating conditions correspond to those attained while moving water drops with impurities in a counter high-temperature gaseous flow in the process of water purification. Evaporation time and rate as functions of heating temperature and conditions for the heat energy supply to an emulsion drop are illustrated. The influence of oil product concentration in an emulsion drop on evaporation characteristics is discussed. The conditions for intensive flash boiling of an emulsion drop and its explosive breakup (fragmentation) with formation of the fine droplets cloud are pointed out. High radiant heat fluxes required in the boundary layer of a drop for intensive flash boiling and explosive breakup of drops with further formation of the fine aerosol. The fundamental differences between flash boiling and explosive breakup of an emulsion drop when heated on a substrate and in a flow of the heated air are described. The main prospects for the development of the high-temperature water purification technology are detailed taking into account the fast emulsion drop breakup investigated in the paper.

1. Introduction

The role of water in human life and activities is surely high. Water is applied in almost all technological processes, particularly, in fuel technologies, power engineering, and systems of cooling and heating, washing, blowdown, cleaning, defrosting and others. Water is utilised as a raw material for industrial applications, because numerous chemical elements are contained in salt water of lakes and seas, as well as in ground water. To be noticed is that the sector of industry uses far more water than takes it from water sources (oceans, seas, rivers, lakes), because water supplied from water sources is multiply used (i.e. recycling water supply). A part of water volume is consumed by evaporation and filtration, and these losses are necessary to compensate. Under such conditions, the role of industrial and waste waters is extremely high due to the limited content of fresh water on earth (International Energy Agency, 2014; Romero-Pareja et al., 2017; Vysokomornaya et al., 2015).

Nowadays, the large group of methods and technologies is applied to purify water from various anthropogenic emissions and impurities. In particular, it is possible to distinguish the following (Esakkimuthu et al., 2014; Hosseini-Bandegharaei et al., 2014; Liu et al., 2017; Moreira et al., 2017; Tiwari and Sahu, 2017; Zhang et al., 2016): flame (burning), thermal (evaporating), chemical (coagulation, adsorption, floatation, extraction, ion exchange, cristallisation, oxidation, inactivation), strati-

* *Corresponding author.*
E-mail address: piskunovmv@tpu.ru (M.V. Piskunov).
http://dx.doi.org/10.1016/j.cherd.2017.09.008
0263-8762/

Nomenclature

A^d	Ash content, %
d	Middle diameter of droplet, mm
$d_{01}\ldots d_{04}$	Diameters of droplet in different directions, mm
C	Heat capacity, J/(kg K)
C_g	Heat capacity of gas, J/(kg K)
K	Kutateladze criterion
p	Probability
Q_e	Heat of evaporation, MJ/kg
Q_c	Combustion heat, MJ/kg
$Q_{(conv)}$	Convective heat flux, W/m^2
$Q_{(cond)}$	Conductive heat flux, W/m^2
$Q_{(rad)}$	Radiant heat flux, W/m^2
$Q_{(sum)}$	Total heat flux, W/m^2
R_d	Radius of an oil–water emulsion drop, mm
S_0	Initial evaporation surface area, mm^2
S	Total evaporation surface area, mm^2
t	Time, s
t_e	Lifetime of an oil–water emulsion drop, s
T_b	Temperature of boiling, K
T_f	Flash point, K
T_{ign}	Ignition temperature, K
T_g	Temperature of substrate/air flow, K
T_m	Temperature of the metallic substrate, K
T_s	Temperature of droplet surface, K
ΔT	Overheating, K
U_g	Air flow rate, m/s
W_e	Evaporation rate, kg/(m^2 s)
W^a	Moisture content, %

Greek

α	Heat exchange coefficient, W/(m^2 K)
ε_d	Emissivity factor for an emulsion drop
ε_g	Emissivity factor for a gas
ε_m	Emissivity factor for the metallic substrate
γ	Volume concentration of an oil product in the emulsion, %
λ_d	Heat conductivity of an emulsion drop, W/(m K)
λ_g	Heat conductivity of a gas, W/(m K)
λ_o	Heat conductivity of an oil product, W/(m K)
λ_w	Heat conductivity of water, W/(m K)
ν	Kinematic viscosity, m^2/s
ν_g	Kinematic viscosity of gas, m^2/s
ρ	Density, kg/m^3
ρ_g	Gas density, kg/m^3
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
Nu_g	Nusselt number
Pr_g	Prandtl number
Re_g	Reynolds number

fying (gravity sedimentation, filtering), biological (biofilters, aerotanks, oxidation ponds) and membrane technologies. However, most of the focus is on high-temperature methods (flame and thermal) of water purification, because provide removing the wide group of impurities and components (Vysokomornaya et al., 2015). Traditional disadvantages of such group of the methods include the repeated cyclic supply of water into heating chambers and high costs associated with the significant fuel consumption and the long duration of purification processes. The reason for this is that traditionally the empirical approaches are applied to regulate water purification systems functioning, as a rule, in the range from 700 K to 1200 K. The usage of such ineffective approaches is due to the deficiency of experimental data on the high-temperature evaporation of water both with various impurities and without them. Consequently, there are no models for an adequate prediction of evaporation rates of corresponding fluids, emulsions, suspensions and solutions.

Modern concepts of the water drop evaporation under conditions typical for high-temperature water purification technologies arose based on works by Ranz and Marshall (1952), Fuchs (1959), Spalding (1955), Yuen and Chen (1978), Renksizbulut and Yuen (1983), Kutateladze (1979), Labuntsov and Yagov (2000), Terekhov et al. (2010), Avdeev and Zudin (2012), and others. This works rely on rather complex experimental investigations that contributed to develop a group of adequate physical and mathematical models of vaporization. The most of such models rests on Hertz-Knudsen law (Kutateladze, 1979; Labuntsov and Yagov, 2000) describing highly nonlinear evaporation rate function of both a temperature and a vapour concentration gradient. Such functions have the particular importance at high temperatures of the outside environment.

Research work (Vysokomornaya et al., 2016a) reports the analysis of temperature ranges of using models (Avdeev and Zudin, 2012; Fuchs, 1959; Kutateladze, 1979; Labuntsov and Yagov, 2000; Ranz and Marshall, 1952; Renksizbulut and Yuen, 1983; Spalding, 1955; Terekhov et al., 2010; Yuen and Chen, 1978) for the adequate prediction of evaporation rates of water drops in the heated gaseous flow. Moreover, this paper states the range of the gas medium temperature variation (as high as 700 K), in which the known evaporation models (Avdeev and Zudin, 2012; Fuchs, 1959; Kutateladze, 1979; Labuntsov and Yagov, 2000; Ranz and Marshall, 1952; Renksizbulut and Yuen, 1983; Spalding, 1955; Terekhov et al., 2010; Yuen and Chen, 1978) allow the adequate prediction of evaporation rates. Importantly, paper (Vysokomornaya et al., 2016a) presents the temperature range (more than 1000 K), in which the correct simulation of experimental evaporation rates is possible to provide only taking into account convective, conductive and radiant heat transfer, as well as radiation of a gaseous medium. The results from the performed analysis contribute to update the modern concepts on the high-temperature evaporation of liquids, emulsions, solutions and suspensions, and to develop potentially advanced gas–vapour–droplet technologies: thermal cleaning, fuel systems, fire suppression, heat carriers and others. However, an application of research results (Avdeev and Zudin, 2012; Fuchs, 1959; Kutateladze, 1979; Labuntsov and Yagov, 2000; Ranz and Marshall, 1952; Renksizbulut and Yuen, 1983; Spalding, 1955; Terekhov et al., 2010; Vysokomornaya et al., 2016a; Yuen and Chen, 1978) can be only indirect (i.e. by approximation, extrapolation and interpolation), because up to date, there are no experimental data on evaporation characteristics of water emulsions with different impurity concentrations under high temperatures. Until recently, such the situation can be explained by lack of the necessary experimental equipment and the research techniques.

During last 5–7 years, the meaningful progress was reached in developing optical techniques for two-phase flow diagnostics, cross-correlation systems, high-speed videocameras, tracking systems and special purpose software. By using such the systems, an experimental research of the evaporation of liquids, emulsions, solutions and suspensions becomes possible even under high temperatures. Papers (Kuznetsov et al., 2015; Vysokomornaya et al., 2016a) present evaporation rates of water without impurities at temperatures of a gaseous area up to 1100 K. Studies (Volkov et al., 2016; Vysokomornaya et al., 2016b) aim to investigate an influence of solid nontransparent particles on water suspension evaporation process. However, an influence of liquid impurities is poorly investigated. Therefore, to use research results in the high-temperature water cleaning it is expedient to carry out experiments to measure evaporation rates of emulsions based on water with typical impurities. Liquid impurities (water pollutants) are the main components of the typical emulsified and slurry fuels (International Energy Agency, 2014; Romero-Pareja et al., 2017; Vysokomornaya et al., 2015). Consequently, experimental investigations on the evaporation of drops of emulsions and suspensions based on water with the controlled content of oil products, combustible and flammable liquids are extremely urgent.