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Thermal transients during the evaporation of a spherical liquid drop

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ABSTRACT

This work is centered upon the thermal transients taking place during the evaporation of a spherical drop of a pure liquid suspended in a gaseous environment. Based on mass and energy conservation equations, a so-called complete model is developed considering quasi-steady diffusive and Stefan convective transports in the non-isothermal gas phase, and unsteady conduction in the liquid drop. A simplified version of the complete model, the so-called quasi-homogeneous model, is developed using an asymptotic analysis in the limit of small thermal homogenization time in the drop compared to the total drop evaporation time. The models enable highlighting the role of two dimensionless numbers, $\mathcal{R}$ and $\mathcal{H}$, characterizing the two thermal transients of the problem: the thermal relaxation transient of the drop interfacial temperature and the thermal homogenization transient of the drop. The values of these two dimensionless numbers are provided for several liquids and their dependence on the evaporation conditions is discussed. It is shown that, when an accurate evaluation of the drop evaporation time is required by the considered application, the use of a fully quasi-steady model should be restricted to systems presenting small values of $\mathcal{R}$ compared to one (at least an order of magnitude smaller) and $\mathcal{H} < 1$. For other systems, it appears necessary to use the complete model or the quasi-homogeneous model. A simple formula is proposed to evaluate the relative difference between the drop evaporation times predicted by the complete model and by the fully quasi-steady model. When an accurate evaluation of the time evolution of the drop temperature field is required by the considered application, it appears to be necessary to use the complete model, whatever the system considered in this work. Indeed, the thermal transients can generally take an important part of the drop evaporation time and large temperature gradients can develop in the drop. The use of the complete model reveals that three different types of dynamics can be observed when a drop evaporates, depending on the relative values of three temperatures: the initial drop temperature, the dew point temperature of the gas far from the drop and the established interfacial temperature (*i.e.* the drop interfacial temperature calculated using a fully quasi-steady model).

1. Introduction

Maxwell, in 1877 [1], proposed the first mathematical model describing the evaporation of a spherical liquid drop suspended in a gaseous environment. The problem stated by Maxwell concerns a simplified system composed of isothermal liquid and gas phases, at fully quasi-steady state, and with a purely diffusive evaporation flux. Subsequent works published in various research fields (combustion, sprays, powders, crystallization...) tried to describe more realistic systems by relaxing Maxwell's hypotheses. The aerosol physicist Fuchs [2] introduced, in 1959, a convective evaporation flux due to Stefan flow in the Maxwell's model. At the same time, models including thermal transients in the drop were developed in the aerospace and combustion sectors [3–9]. In 1975, Hubbard et al. [10] proposed a model taking into account thermal gradients in the liquid and gas phases. Such a model posed the question of considering homogeneous liquid and gas physicochemical properties. Subsequent other works analyzed the validity of Maxwell's assumptions for the modeling of drop evaporation [11–14]. However, in all of the works mentioned above, the results are presented for specific practical studied cases, where the components of the system, the gas composition and temperature and/or the pressure are set. In contrast, in one of our previous works [15] and in the present paper, a comprehensive analysis of the evaporation of a suspended spherical drop of a pure liquid in a gas phase is proposed, considering various liquids and a wide range of gas compositions and temperatures.

In our aforementioned previous work [15], based on mass and energy balance equations, a fully quasi-steady model (with all relevant time scales being much smaller than the evaporation time) has been developed, including diffusive and convective transports,

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Notations

Roman symbols

Bi	Biot number, –
c	molar density or concentration, mol/m^3
C_p^*	heat capacity, J/(mol K)
$\mathcal{C}_p$	reduced heat capacity, –
D_{va}	diffusion coefficient of vapor in air, m^2/s
$\mathcal{H}$	thermal homogenization number, –
j^*	local molar evaporation flux, mol/(m^2 s)
L	reduced latent heat of vaporization, –
$\mathcal{L}^*$	latent heat of vaporization, J/mol
Le	Lewis number, –
$\mathcal{M}$	reduced molar mass, –
$\widehat{M}$	molar mass, kg/mol
P	pressure, Pa
r	radial coordinate, m
R	drop radius, m
$\mathcal{R}$	thermal relaxation number, –
$\widehat{R}$	universal gas constant, J/(mol K)
St	Stefan number, –
t	time, s
T	temperature, K
u	mass-averaged velocity of the gas mixture, m/s
u^*	molar-averaged velocity of the gas mixture, m/s
V	volume, m^3
X	mole fraction of vapor in the gas phase, –

Greek symbols

α	thermal diffusivity, m^2/s
β	accommodation coefficient, –
Δ	difference, –
ϵ	relative difference, –
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3
τ	dimensionless time, –

Subscripts

0	initial conditions
a	air
b	boiling
crit	critical
dp	dew point
ev	evaporation
g	gas phase
hom	thermal homogenization
he	heat exchange
i	drop interface
ℓ	liquid
m	mass
rel	thermal relaxation
qs	quasi-steady
t	time
v	vapor
∞	far from the drop

Superscripts

max	maximum

and considering the non-isothermia of the gas phase. The main original feature of this simple model lied in the consideration of the local dependence on the temperature of the physicochemical properties of the gas. It appeared that this inhomogeneity of the gas physicochemical properties can have a significant influence on the evaporation rate, especially at high ambient temperatures. Simplified versions of the model were developed in order to highlight the key mechanisms governing the evaporation process. Concerning heat transfer, the model highlighted that a gas isothermia assumption never appears to be valid for the considered conditions, even at room temperature, due to the large temperature gradient that develops in the gas phase. The assumptions of the model were rigorously discussed and general criteria were established, independently of the liquid–gas couple considered. It appeared that considering drop isothermia with an established drop temperature (*i.e.* the drop temperature calculated using a fully quasi-steady model) remained the most dubious assumption. Therefore, in the continuity of this previous work, the present paper focuses on the thermal transients within a drop during its evaporation.

When evaporating into a gas, a drop is initially subject to two simultaneous thermal transients. One thermal transient is the thermal relaxation transient of the drop interfacial temperature which corresponds to the change of the drop interfacial temperature from its initial value to its established value, *i.e.* the drop interfacial temperature calculated using a fully quasi-steady model. The duration of this thermal relaxation transient is called the thermal relaxation time of the drop. The other initial thermal transient corresponds to the thermal homogenization of the drop. This transient is hereafter referred to as the thermal homogenization transient and its duration is called the thermal homogenization time of the drop. Regarding these two transients, different degrees of simplification are encountered in the models of drop evaporation proposed in the literature. The simplest models are fully quasi-steady models, considering a drop of constant and uniform temperature [1,2]. Some authors looked at the temperature distribution inside a drop of constant interfacial temperature [5]. Other authors took into account the thermal relaxation transient but consider a homogeneous temperature inside the drop [3,7,13] to simplify their model. Finally, the most complete models consider both thermal transients [6,8–11]. According to different authors, the thermal transients occurring during the evaporation of a drop are damped in less than 10% [7,9] or 20% [8] of the drop lifetime. Results presented in these papers also showed that the evaporation time can be underestimated when the thermal transients are not considered. For instance, considering the evaporation of a homogeneous drop of hydrocarbons, Williams et al. [3] showed that neglecting the thermal relaxation transient can lead to an underestimation of the evaporation time by up to 20%. In contrast, Law et al. [9] concluded that the evaporation time of an octane drop is only slightly underestimated when the thermal transients are not considered in a model of its evaporation. No author mentioned that the evaporation time could be overestimated by neglecting the thermal transients in a model. Moreover, in these different works, no criteria was proposed to enable predicting easily whether or not the thermal transients should be considered in a model of an evaporating drop, depending on the considered case. Therefore, a wider point of view about the thermal transients occurring during the evaporation of a liquid drop is needed, in order to fully analyze their influence on the evaporation process of the drop. Such a study implies a comprehensive analysis of the involved physical phenomena and of their mathematical formulation.

In this work, we propose a model of a spherical drop evaporation taking into account both thermal transients in the drop.