



A comprehensive analysis of the evaporation of a liquid spherical drop



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ABSTRACT

In this paper, a new comprehensive analysis of a suspended drop of a pure liquid evaporating into air is presented. Based on mass and energy conservation equations, a quasi-steady model is developed including diffusive and convective transports, and considering the non-isothermia of the gas phase. The main original feature of this simple analytical model lies in the consideration of the local dependence of the physico-chemical properties of the gas on the gas temperature, which has a significant influence on the evaporation process at high temperatures. The influence of the atmospheric conditions on the interfacial evaporation flux, molar fraction and temperature is investigated. Simplified versions of the model are developed to highlight the key mechanisms governing the evaporation process. For the conditions considered in this work, the convective transport appears to be opposed to the evaporation process leading to a decrease of the evaporation flux. However, this effect is relatively limited, the Péclet numbers happening to be small. In addition, the gas isothermia assumption never appears to be valid here, even at room temperature, due to the large temperature gradient that develops in the gas phase. These two conclusions are explained by the fact that heat transfer from the gas to the liquid appears to be the step limiting the evaporation process. Regardless of the complexity of the developed model, yet excluding extremely small droplets, the square of the drop radius decreases linearly over time (R^2 law). The assumptions of the model are rigorously discussed and general criteria are established, independently of the liquid–gas couple considered.

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1. Introduction

Drop evaporation is crucial for a wide range of applications such as spray drying, spray cooling, fire suppression, combustion, crystallization, painting, medical aerosols or prevention of aircraft icing. Consequently, a substantial effort has been performed to model this process and the corresponding literature is abundant. The recent reviews of Sazhin in 2006 [1] and Zhifu et al. [2] in 2013 summarize the different, more or less complex approaches that have been developed until now. These papers highlight the need for a simple analytical model that quantitatively describes drop evaporation. Indeed, even the evaporation of a suspended drop involves complex phenomena: phase change coupled with heat and mass transfers. The heat is transferred by conduction and convection between the surrounding gas and the drop interface, while the vapor is transported away from the interface by diffusion and convection.

The first analytical model of a spherical drop evaporation was developed by Maxwell in 1877 [3]. Maxwell described the evaporation of a drop in an infinite and uniform medium assuming that

the process is quasi-stationary, isothermal (in the liquid and gas phases) and exclusively controlled by the vapor diffusion. Fuchs, in 1959, completed Maxwell's model taking into account the Stefan flow, *i.e.*, a bulk flow motion induced by the evaporation at the drop surface and going away from the drop [4]. Recently, more complete analytical models of drop evaporation have been proposed. Farshid Chini and Amirfazli [5] developed an analytical transient convecto-diffusive model in which the liquid and gas phases are considered isothermal. Without the consideration of the energy conservation equation in their model, their investigation is restricted to the case of evaporation at room temperature. Tonini and Cossali [6] proposed an analytical convecto-diffusive model based on the solution of species, momentum and energy conservation equations. They investigated the validity of the isothermal gas assumption and concluded that for high molar mass species and high evaporation rate, the gas temperature gradient must be considered. They especially focused on the characterization of the flow field in the gas phase.

In this paper, a new comprehensive analysis of a suspended drop of a pure liquid evaporating into air is presented. Based on mass and energy conservation equations, a quasi-steady model is developed including diffusive and convective transports, and considering the non-isothermia of the gas phase. The main original

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Nomenclature

Roman symbols

c	molar concentration, mol/m ³
C_p^*	heat capacity, J/(mol K)
D_{va}	diffusion coefficient of vapor in air, m ² /s
j	local mass evaporation flux, kg/(m ² s)
j^*	local molar evaporation flux, mol/(m ² s)
\mathcal{J}^*	global molar evaporation flux, mol/s
\mathcal{L}^*	latent heat of evaporation, J/mol
L_e	Lewis number, -
M	molar mass, kg/mol
P	pressure, Pa
P_e	Péclet number, -
$P_{sat}(T)$	saturation pressure of the liquid at temperature T , Pa
r	radial coordinate, m
R	drop radius, m
\bar{R}	universal gas constant, J/(mol K)
\mathcal{R}	resistance, (m s)/mol
S_n	Sutherland coefficient of species n , K
T	temperature, K
u	mass averaged velocity of the gas mixture, m/s
u^*	molar averaged velocity of the gas mixture, m/s
v	diffusion volume, cm ³ /mol
V	volume, m ³
X	mole fraction of vapor in the gas phase, -

Greek symbols

α	thermal diffusivity, m ² /s
λ	thermal conductivity, W/(m K)

Φ	dimensionless quantity; see Eq. (12)
μ	dynamic viscosity, Pa s
θ	temperature difference $T_\infty - T_i$, K
ρ	density, kg/m ³
σ	surface tension, N/m
τ_{ev}	evaporation time, s
τ_D	mass diffusion time, s
τ_{th}	thermal diffusion time, s

Subscripts

a	air
b	boiling
g	gas phase
i	drop interface
eth	ethanol
ℓ	liquid
m	mass
n	subscript referring to the species n
t	time
th	thermal
v	vapor
w	water
∞	far from the drop

feature of this simple analytical model lies in the consideration of the local dependence of the physico-chemical properties of the gas with the gas temperature. This aspect is neglected in all the previous models available in literature, to the best of our knowledge. The model allows to deeply investigate the impact of the surrounding atmospheric conditions on the drop evaporation. Simplified versions of the model are developed in order to highlight the key mechanisms governing the evaporation process. A simplified model in particular allows defining resistances to the evaporation from which the limiting mechanism of the evaporation process can be identified. The assumptions of the model are rigorously discussed and general criteria are established independently of the liquid–gas couple considered. The model proposed here appears to be valid under a large variety of conditions of practical interest. Most of the results presented in this paper are obtained for a water drop. However, to extend the investigation, ethanol is also considered.

2. Statement of the problem

2.1. System description and assumptions

The system considered here is a suspended spherical drop of a pure liquid (subscript ℓ) evaporating into an air–vapor mixture (subscripts a and v , respectively). This system is schematically represented in Fig. 1. Gravity is neglected. The problem is approached with a molar formulation (instead of a massic approach as done in [6]) and solved in spherical coordinates. Due to the symmetry in polar and azimuthal directions, the problem description can be simplified and restrained to the radial coordinate r . The gas phase (indicated by the subscript g) is assumed to be an ideal mixture of ideal gases. Therefore, the total gas pressure is expressed by the Dalton's law, $P_g = P_v + P_a$, with $P_n = c_n \bar{R} T$ (with $n = g, v$ or a).

The gas molar concentration is $c_g = c_v + c_a$. The total gas pressure is considered to be constant and equal to the atmospheric pressure in all the examples considered in this work. The validity of this assumption is discussed in Section 3.1.3. Radiative heat transfer is neglected. This evaporation problem is then solved by the expression of the heat and mass transfers in the gas phase. Diffusive and convective heat and mass transports are taken into account, but the system is considered to be quasi-steady in both phases at the time scale of drop evaporation. This implies in particular an isothermal drop with an established temperature. The validity of this quasi-steady approximation is discussed later through the examination of the characteristic times of the system (Section 3.1.2). The liquid–gas interface is considered at local equilibrium; *i.e.*, the gas phase is saturated with vapor at the drop

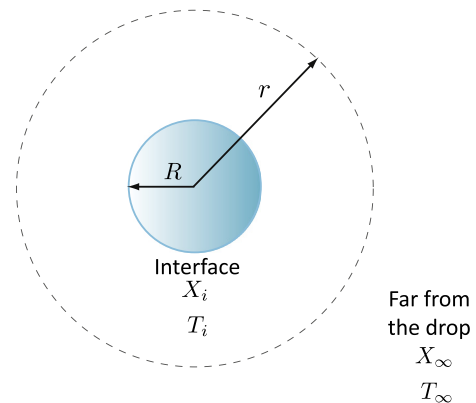


Fig. 1. Schematic representation of a drop surrounded by air. T_i, T_∞ and X_i, X_∞ are the temperature and the mole fraction of vapor at the drop interface ($r = R$) and far from the drop ($r = \infty$), respectively.

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