



Assessment of evaporation equilibrium and stability concerning an acoustically excited drop in combustion products



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ABSTRACT

The evaporation of drops in a sound field has been the subject of numerous studies aimed at determining its role in combustion instability. The models generally assume local equilibrium evaporation at the interface. We determine here the conditions of validity of this assumption, without calling into question other a priori assumptions of the classical model, in particular spherically symmetric quasi-steady evolution in the gas phase and liquid phase thermal unsteadiness with pure heat conduction.

Another possible phenomenon concerns the differential recoil of the vapor. In the case of rapid evaporation, a pressure difference appears between both sides of the interface, even if the latter is plane. This pressure difference, usually neglected, is proportional to the square of speed and the resulting force is oriented toward the denser fluid, i.e. the liquid. A very fast evaporation may even cause local deformation, i.e. Hickman instability. The stability condition concerning this phenomenon has also been determined.

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1. Introduction

The evaporation of drops in an acoustic field has been the subject of many studies aimed at determining its role in combustion instability. The models generally assume local evaporation equilibrium at the interface. We want to determine here the conditions of validity of this assumption, without questioning the other a priori assumptions of the classical model, in particular: spherical symmetry, quasi-stationary evolution in the gas phase and thermal unsteadiness of the liquid phase with pure heat conduction [1,2].

The local evaporation equilibrium is characterized by the equality of chemical potentials of the constituent of the drop in liquid and vapor phases,

$$\mu_{FL} = \mu_{FV} \quad (1)$$

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Nomenclature

a, b, c	constant coefficients	x, y, z	Cartesian coordinates
A, B	thermodynamic coefficients in the transfer function	Z	transfer function of the fed oscillating droplet
B_M, B_T	Spalding parameters for mass and temperature	$\alpha, \alpha_v, \alpha_c$	evaporation–condensation, vaporization, condensation coefficients respectively
c_p	specific heat at constant pressure	$\bar{\alpha}$	coefficient of the transfer function of the fed oscillating droplet
C	combustion chamber level	$-\beta_L$	thermal gradient in a liquid boundary layer
d	droplet diameter	δ	thickness of a boundary layer (δ for the vapor side, δ_L for the liquid one)
Da	Damköhler parameter	λ	heat conductivity
$E(u, \theta)$	function $E(u, \theta) = 1 - (1 + i)\sqrt{3u/2\theta} \coth[(1 + i)\sqrt{3u/2\theta}]$	$\eta(x, y, t)$	function describing a disturbed surface $z = \eta(x, y, t)$, the reference value being zero
g	thermodynamic potential per unit mass, gravitational acceleration	κ	heat diffusivity
G	gas phase	μ	dynamic viscosity; thermodynamic potential per mole $\mu = \mathcal{M}g$
h	liquid height	μ_j	chemical potential of species j
H	container height	ν	quantity equal to: $(1 + i)\sqrt{3u/2\theta}$
Hi	Hickman number	$\bar{\Pi}$	tensor of viscous pressures
k	heat conductivity	θ	ratio $\bar{\tau}_v/\bar{\tau}_T$
l	latent heat per unit mass	Θ	reduced temperature
L	liquid phase; phenomenological coefficient for near-equilibrium evaporation–condensation mass	ρ, ρ_L	gas and liquid densities
M	mass	σ	surface tension
\mathcal{M}	molar mass	τ	characteristic time; τ_{vap} for evaporation–condensation; τ_{mec} mechanical time
\dot{m}	unit mass flow rate	τ_{excit}	period of an oscillating disturbance
\dot{M}	mass flow rate for an evaporating droplet	$\tau_T, \bar{\tau}_T$	characteristic times for heat diffusion respectively in the gas, $\tau_T = \delta^2/\kappa$ and in the liquid, $\bar{\tau}_T = \bar{r}_S^2/\kappa_L$
N	response factor $N = \bar{\alpha}\mathfrak{N}(Z)$	$\bar{\tau}_v$	mean residence time of the injected liquid for a fed drop; equal to the lifetime τ_{life} of the free droplet
$\bar{\mathbf{N}}$	unit normal at a point of an interface; quantity $\bar{\mathbf{v}} \cdot \bar{\mathbf{N}}$ being the average normal curvature	ω	pulsation of an oscillating wave
p	thermodynamic pressure	ξ	reduced radius $\xi = r/\bar{r}_S$
p_{sat}	saturation pressure	ζ_T	reduced variable $\zeta_T = \dot{M}c_p/4\pi kr$
q_T	coefficient equal to $\tau_T/6\pi\bar{\tau}_T$	*	reference conditions
r	gas constant per unit mass $r = R/\mathcal{M}$	–	the liquid side of the interface
\bar{r}_S	mean radius of the fed droplet	+	the vapor side of the interface
R	universal gas constant	//	tangentially to the interface
S	interface level; cross section area	⊥	normally to the interface
T	temperature in K		
u	reduced pulsation: $u = 3\omega\bar{\tau}_v$		
V	speed		
$\bar{\mathbf{v}}$	fluid velocity		
$\bar{\mathbf{w}}$	interfacial velocity		
We	Weber number: $We = \rho(V_G - V_L)^2/\sigma$		

In the case of *local evaporation non-equilibrium*, the equality of chemical potentials is no more guaranteed and the mass flow rate of vaporization is a function of their difference. According to Bond and Struchtrup [3], in the case of a pure substance, the rate of evaporation can be written:

$$\dot{m} = \left(\frac{\mathcal{M}}{2\pi R} \right)^{1/2} \left(\alpha_v \frac{p_{\text{sat}}}{(T_S)^{1/2}} - \alpha_c \frac{p^+}{(T^+)^{1/2}} \right) \quad (2)$$

with two different coefficients α_v, α_c , respectively for evaporation and condensation, \mathcal{M} the molar mass, R the universal gas constant, p_{sat} the saturation vapor pressure at the temperature $T^- = T_S$ of the liquid surface, T^+, p^+ corresponding to the gas. Coefficient values α_v, α_c become equal when one tends towards equilibrium: $\alpha_v = \alpha_c = \alpha$.

Another phenomenon can occur during very fast evaporation, changing the shape of the liquid–vapor interface. It is called the *vapor recoil* (see Appendix A.1). It can be explained by the momentum balance at the interface and results in a force acting towards the densest fluid, i.e. the liquid.

The case of vacuum evaporation, which results in surface deformation, has been particularly studied by Palmer [4], who found the stability limit of the phenomenon. This is the *Hickman instability* [5] (see Appendix A.2).

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