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On the Rayleigh–Taylor instability for confined liquid films with injection through the bounding surfaces

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Abstract

An experimental and numerical investigation has been conducted to evaluate the hydrodynamic characteristics of a thin liquid film bounded by a downward-facing flat wall through which the liquid is continually injected. Both horizontal and inclined surfaces have been examined. The effect of different parameters, namely, the film thickness, liquid injection velocity, inclination angle and liquid properties on liquid film behavior have been examined. Non-intrusive optical techniques have been used to follow the transient evolution of the film free surface. Specifically, the frequency of droplet detachment, the size of the detached droplets, and the penetration depth prior to droplet detachment have been measured. These data have been compared against predictions of a mechanistic numerical model based on the level contour reconstruction front tracking method. The numerical model predictions are in good agreement with the experimental data.

Keywords: Rayleigh–Taylor instability; Liquid film stability; Interface morphology; Numerical front tracking

1. Introduction

More than a century ago, Lord Rayleigh studied the stability of a density interface subject to a constant gravitational acceleration. Taylor extended Rayleigh's analysis to consider density interfaces subject to arbitrary accelerations. Here, we consider the case of Rayleigh–Taylor instability when a heavy immiscible fluid is situated above a light fluid under the influence of gravity. Under such conditions, the density interface becomes unstable for certain perturbation wavelengths; these perturbations evolve into bubbles of light fluid and spikes of heavy fluid that penetrate into the heavy and light fluids, respectively [1]. This phenomenon has been the subject of numerous experimental and numerical studies because of its fundamental importance in a variety of practical applications (see Ref. [2] for a recent summary of the literature).

Our interest in this problem derives from our work on first wall protection for inertial fusion reactors. Among the proposed wall protection schemes for such reactors is the ‘‘porous wetted wall'' concept, originally proposed by Los Alamos in 1972 [3,4], and later adopted by several conceptual reactor designs [5–10]. In a typical rendition of such a design [5], a thin (0.4–0.6 mm) film of liquid lead is permitted to form on the inner surface of the reactor cavity by continually injecting the liquid lead through the porous silicon carbide first wall (Fig. 1). The X-rays and ions produced by the exploding targets at the center of the reactor cavity deposit their energy in the thin liquid lead film and the vapor cloud produced by lead evaporation, thereby protecting the underlying silicon carbide first wall. Recondensation of the vapor cloud allows the energy absorbed in the film to be recovered prior to the next target explosion, albeit over a longer time period, hence limiting first wall heating and thermal stress.

The hydrodynamics of the porous wetted wall protection scheme, as applied to the downward-facing upper surface of the inertial fusion reactor cavity (Fig. 1), can be

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Nomenclature

A	surface area, m^2
D	equivalent diameter, m
g	gravitational acceleration, m/s^2
h_0	liquid film mean thickness, m
I	indicator heaviside function
l	length scale, $(\sigma/[g(\rho_L - \rho_G)])^{1/2}$, m
$\mathbf{n}$	unit vector normal to the interface
p	non-dimensional pressure
P_0	pressure scale, $\rho_L U_0^2$, N/m^2
Q	volume flow rate, m^3/s
Re	Reynolds number, $\rho_L l U_0/\mu_L$
T	temperature, K
t	non-dimensional time
t_0	time scale, l/U_0, s
$\mathbf{u}$	non-dimensional fluid velocity vector
U_0	velocity scale, $(gl)^{1/2}$, m/s
u, v, w	fluid velocity components in Cartesian coordinates, m/s
We	Weber number, $\rho_L l U_0^2/\sigma$
$\mathbf{x}$	non-dimensional position vector
x, y, z	Cartesian coordinates, m
z_0	initial liquid film thickness, m

Greek symbols

δ	Dirac delta function
ε_s	amplitude of initial perturbation, m
θ	inclination angle, degrees
κ	twice the mean interface curvature
μ	dynamic viscosity, N s/m^2
μ^*	dynamic viscosity ratio, μ_G/μ_L
ρ	density, kg/m^3
ρ^*	density ratio, ρ_G/ρ_L
σ	surface tension, N/m; standard deviation, s

Subscripts

f	quantity at interface
G	gas phase
L	liquid phase

Superscripts

*	property ratio or non-dimensional quantity
+	non-dimensional quantity

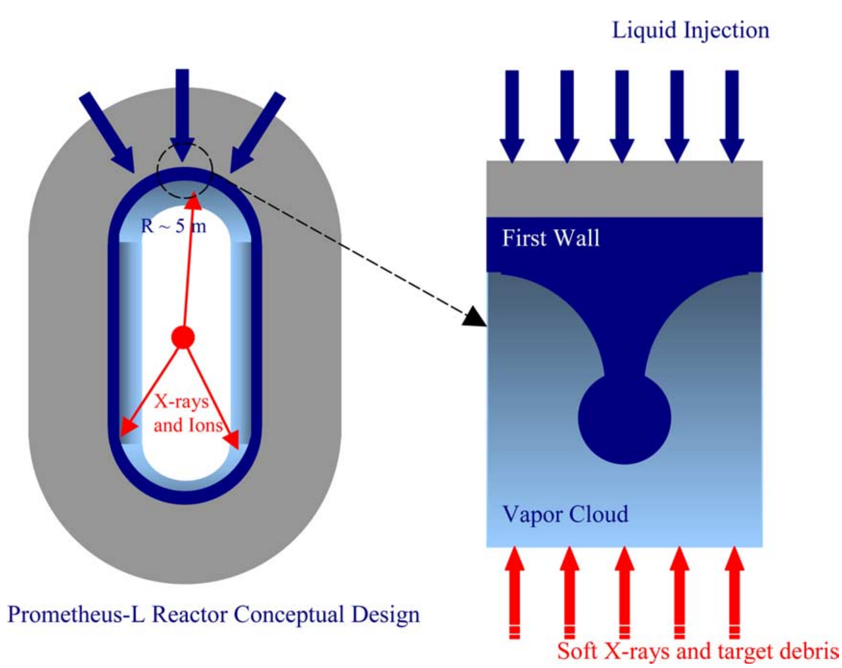

Fig. 1. Schematic illustration of the proposed thin liquid film protection scheme for the inertial fusion energy IFE system.

viewed as a variation of the Rayleigh–Taylor (henceforth RT) instability problem. Numerous experimental and theoretical studies of the RT instability have been reported in the literature; however, no work has heretofore been reported on the evolution and stability of thin liquid films on downward-facing surfaces with liquid injection through the wall. To this end, an experimental and numerical investigation has been conducted to examine the hydrodynamics of thin liquid films formed on horizontal and inclined downward-facing surfaces of a porous wall with continuous liquid injection normal to the surface. The objective is to determine the effect of different parameters, namely