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OSCILLATORY BEHAVIORS IN INITIAL FILM BOILING: IMPLICATIONS ON THE TRIGGERABILITY OF SINGLE DROPLET VAPOR EXPLOSIONS

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A transient one-dimensional film boiling model was developed to study the film boiling dynamics that would occur when a hot spherical droplet is immersed in cold liquid. The focus of this study was to investigate the effects of noncondensible gas, liquid temperature, droplet temperature, and ambient pressure on film boiling during the initial growth phase. The results indicate that the film generally stablizes with more noncondensible gas present, higher liquid and lower droplet temperature. Small ambient pressurizations cause violent fluctuations of the film pressure while higher ambient pressure suppresses these oscillations. These qualitative behavior of film boiling around hot spherical droplet suggests that the spontaneous triggering of small-scale single droplet vapor explosions is led by the oscillatory characteristics of vapor film in its initial growth phase.

Key Words: Film Boiling, Oscillatory Behaviors, Single Droplet Vapor Explosions Triggerability

NOMENCLATURE

C : Noncondensible gas constant
c_p : Specific heat at constant pressure
d : Diameter of spherical droplet
G : Universal gas constant
h : Enthalpy
h_{fg} : Latent heat of vaporization of cold liquid
k : Thermal conductivity
m : Mass
P : Pressure
P_{co} : Saturation pressure of T_{co}
q'' : Heat transfer rate per unit area
R : Radius of spherical droplet
Re : Reynolds number
r : Radial coordinate
T : Temperature
T_{co} : Temperature of vapor-liquid interface at the liquid side
T_{vs} : Temperature of vapor-liquid interface at the vapor side
t : Time
u : Radial velocity of liquid at vapor-liquid interface
V : Volume
W : Mechanical work of film formation

Greek Symbols

α : Thermal diffusivity
β : Accommodation coefficient
γ : Specific heat ratio of gas
δ : Film thickness
ε : Emissivity of hot spherical droplet
θ : Surface tension
λ : Thermal boundary layer thickness
μ : Dynamic viscosity
ρ : Density
σ : Stefan-Boltzman constnat

Superscripts

$*$: Normalised variable

Subscripts

b : Base-line parameter
c : Cold liquid
f : Film
h : Hot droplet
v : Vapor
g : Noncondensible gas
g_o : Nocondensible gas at intial state

1. INTRODUCTION

Film boiling is a prerequisite for the initiation of vapor explosion which is defined as a rapid evaporation of cold liquid due to heat input from a hot molten material. Only when there is an insulating vapor film is there enough time to mix the hot and cold components without a premature rapid heat transfer taking place.

Only a limited number of analytical attempts to simulate vapor film dynamics have been reported. Bromley(1950) first developed a steady state analytical model of film boiling on vertical walls. On a heated, horizontal wall, bubbles detach themselves at the top of the film and rise as a consequence of the fluid instability, corresponding to Rayleigh-Taylor instability(Taylor, 1950). On the basis of this concept, Berenson(1961) developed a steady state film boiling model on horizontal surface. Transient film boiling on a horizontal wire has been considered by Pitts et al.(1968) and Wehmeyer and Jackson(1972). Wehmeyer and Jackson have indicated that approximately 1 ms was required for a clear vapor film to form.

Transient film boiling around a sphere in its initial growth period was first studied by Kazimi(1973). He investigated the

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dynamic behavior of a vapor film growing at the surface of a hot sphere which has been suddenly immersed in a cold liquid. Corradini (1981) subsequently investigated the growth and collapse of vapor film and the effects of initial and boundary conditions. For both studies, calculations were able to be done up to only a few milliseconds, which is too short to investigate the characteristics of film boiling dynamics. Kim and Corradini(1984) studied the behaviors of vapor film around hot droplet based on experimental data of Nelson and Duda(1981). However their model somewhat underestimated the oscillatory behaviors of vapor film.

In this study a transient one-dimensional film boiling model was developed to investigate the film boiling dynamics with implication on the triggering characteristics of small-scale single droplet vapor explosions. The vapor film behavior was studied as a function of initial hot droplet-liquid conditions. For the application of the model, Nelson and Duda's single droplet injection experiments(1981, 1982) were chosen among the numerous experiments performed owing to the availability of the data over a wide range of initial conditions.

2. FORMULATION OF THE MODEL

The model is of a spherical droplet immersed in a large volume of cold liquid, Fig. 1. This picture is quite characteristic of the small scale single droplet experiments. The growth of the vapor film is governed by the applied ambient pressure and the heat transfer rates across the hot droplet-vapor and vapor-liquid interfaces.

2.1 Basic Assumptions

In formulating the model, the following assumptions were made :

(1) The droplet-liquid system is spherically symmetric.

(2) All the vapor produced is retained in the film around the droplet.

(3) The pressure in the film is spatially uniform.

(4) The vapor and other gases, if any, in the film are considered to be perfect gases.

(5) The liquid and the vapor are at thermodynamic nonequilibrium at the vapor-liquid interface.

(6) The cold liquid and hot spherical droplet if molten are considered to be incompressible.

(7) The thermophysical properties are considered to be constant except the latent heat of liquid and the density of gas/vapor mixtures.

The assumption of spherical symmetry implies that the variations of film thickness is small compared to the droplet radius. In Nelson and Duda's experiments observations indicated the roughly spherical symmetry of the droplet and the retention of all the vapor produced around the droplet until the initiation of vapor explosions.

The vapor in the film may be treated as perfect gases at the mean temperature of the vapor as long as the critical point of the cold liquid is avoided.

Initial gaseous film comprises both the gas generated at the surface of the droplet due to chemical reaction as well as the gas swept into the cold liquid as the hot droplet immersed. In the model, only the gas swept into the liquid is considered. There is no experimental data on the thickness of the gaseous film, although the film was visually observed with a thickness less than the droplet radius in the experiments. The thickness of this film is treated parametrically in the subsequent calculations.

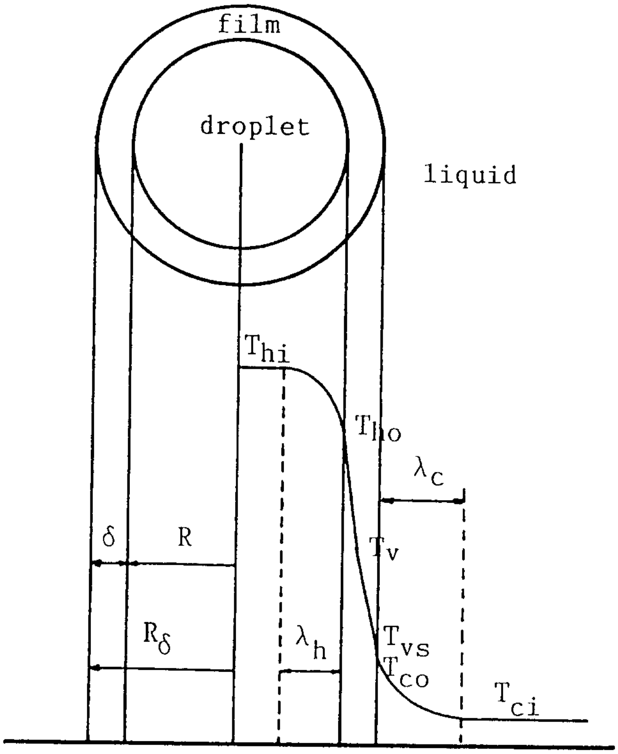


Fig. 1 Schematic diagram of film boiling model

The liquid and vapor are consideredd to be at non-equilibrium at the film-liquid interface. Therefore the pressure of the vapor is no longer the saturation pressure of the vapor-liquid interface temperature because of the transient nature of the vapor dynamics.

Since the film pressure undergoes severe fluctuations under certain conditions, the latent heat of vaporization of liquid is given as a function of the saturation temperature of the vapor-liquid interface at liquid side. The other properties do not change very much during the short times of interest(less than 100 milliseconds).

2.2 Mathematical Formulations

The dynamics of film boiling process was modeled by writing a momentum equation for film dynamics and energy equations for each region of the system (hot droplet, liquid vapor, and liquid) and linking each region by the appropriate boundary conditions. The integral approach was used for the energy equations in each region where the differential equation was integratd over the region and a temperature profile was assumed. This approach transformed the partial differential equations into ordinary differential equations with time as the independent variable.

The momentum equation for film growth was modeled by the Rayleigh equation that includes the effects of viscosity and surface tension in a spherically symmetric system (Rayleigh, 1917).

$$\frac{du}{dt}=\frac{1}{R_\delta}\left[\frac{P_f-P_\infty-\dfrac{2\theta_c}{R_\delta}-\dfrac{4\mu_c}{R_\delta}u}{\rho_c}-\frac{3}{2}u^2\right] \tag{1}$$

The ambient pressure during the growth of the vapor film was held constant.

The evaporation or condensation rate was obtained from a kinetic theory of gas model under the non-equilibrium assumption at the vapor-liquid interface(Schrage, 1953).

$$\frac{dm_v}{dt}=4\pi R_\delta^2\beta\sqrt{\frac{M}{2\pi G}}\left[\frac{P_{co}}{\sqrt{T_{co}}}-\frac{P_v}{\sqrt{T_{vs}}}\right] \tag{2}$$

where the accommodation coefficient, β, varying from 0.01 to 1.0 depending upon the conditions of the interface(Schrage, 1953, Lednovich and Fenn, 1977, Maa, 1970). In the application of the model to the iron oxide-water system the accommodation coefficient is assumed to be 0.1.

The velocity of the vapor-liquid interface is different from the velocity of liquid because of the evaporation or condensation of the vapor, which causes additional interface movement. Therefore the velocity is given as

$$\frac{dR_\delta}{dt}=U+\frac{dm_v/dt}{4\pi R_\delta^2\rho_c} \tag{3}$$

The heat transfer in spherical droplet is governed by Fourier's conduction equation.

$$\frac{\alpha_h}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial}{\partial r}T_h(r,t)\right]=\frac{\partial}{\partial t}T_h(r,t) \tag{4}$$

To transform the partial differential equation to an ordinary differential equation, equation (4) is integrated from $r=0$ to $r=R$. However, for short times, the droplet behaves as a semi-infinite mass because the thermal wave may have not penetrated to the center of the droplet. Therefore, for the interest of analysis the droplet is treated as a semi-infinite mass and integrated from $r=R-\lambda_h$ to $r=R$,

$$\alpha_h\int_{R-\lambda_h(t)}^{R}d\left[r^2\frac{\partial}{\partial r}T_h(r,t)\right]=\int_{R-\lambda_h(t)}^{R}\frac{\partial}{\partial t}[T_h(r,t)]dr \tag{5}$$

A quadratic temperature profile within the thermally active region is assumed for the boundary conditions of

$$T_h(R-\lambda_h,t)=T_{hi}(t) \tag{6.1}$$

$$T_h(R,t)=T_{ho}(t) \tag{6.2}$$

$$\left.\frac{\partial T_h(r,t)}{\partial r}\right|_{r=R-\lambda_h}=0 \tag{6.3}$$

Then the temperature profile within the thermally active region becomes

$$T_h(r,t)=T_{hi}+(T_{ho}-T_{hi})\left[1-\frac{R-r}{\lambda_h}\right]^2 \tag{7}$$

When this is substituted into equation (5), the result is

$$\begin{aligned}\left[\frac{1}{6}-\frac{1}{6}\left(\frac{\lambda_h}{R}\right)+\frac{1}{20}\left(\frac{\lambda_h}{R}\right)^2\right]\frac{d\lambda_h}{dt}&=\frac{\alpha_h}{\lambda_h}+\frac{\lambda_h}{2(T_{hi}-T_{ho})}\\&\times\left[\frac{1}{3}-\frac{1}{6}\left(\frac{\lambda_h}{R}\right)+\frac{1}{30}\left(\frac{\lambda_h}{R}\right)^2\right]\frac{dT_{ho}}{dt}\end{aligned} \tag{8}$$

The energy equation for the liquid is similar to equation (4) except that a radial convective term is included to account for the movement of the film and the subsequent movement of the liquid.

$$\frac{\partial T_c}{\partial t}+\frac{\partial r}{\partial t}\ \frac{\partial T_c}{\partial r}=\frac{\alpha_c}{r^2}\left[\frac{\partial}{\partial r}\left(r^2\frac{\partial T_c}{\partial r}\right)\right]+kQ''_{rad} \tag{9}$$

where the last term in the right side is the effect of radiative heat flux deposited in the thermally active region of liquid, and is considered as volumetric energy generation within and without thermal boundary layer. Constant k is a function of the temperature of droplet and the depth of thermally active region in cold liquid. The liquid is assumed to be semi-infinite and again a quadratic temperature profile is assumed in the liquid thermal boundary layer. Boundary conditions are

$$T_c(R_\delta+\lambda_c,t)=T_{ci}(t) \tag{10.1}$$

$$T_c(R_\delta,t)=T_{co}(t) \tag{10.2}$$

$$\left.\frac{\partial T_c(r,t)}{\partial r}\right|_{r=R_\delta+\lambda_c}=0 \tag{10.3}$$

The temperature profile within the thermally active region of the liquid becomes

$$T_c(r,t)=T_{ci}+(T_{co}-T_{ci})\left[1-\frac{r-R_\delta}{\lambda_c}\right]^2 \tag{11}$$

By substituting equation (11) into equation (9) and integrating from $r=R_\delta$ to $r=R_\delta+\lambda_c$, the resulting equation is

$$\begin{aligned}\left[\frac{1}{6}+\frac{1}{6}\left(\frac{\lambda_c}{R_\delta}\right)+\frac{1}{20}\left(\frac{\lambda_c}{R_\delta}\right)^2\right]\frac{d\lambda_c}{dt}&=\frac{\alpha_c}{\lambda_c}\\&+\frac{kR^2\varepsilon\sigma T_{ho}^4}{2R_\delta^2\rho_c C_{pc}(T_{co}-T_{ci})}+\frac{1}{2}u\\&+\frac{\lambda_c}{2(T_{ci}-T_{co})}\left[\frac{1}{3}+\frac{1}{6}\left(\frac{\lambda_c}{R_\delta}\right)+\frac{1}{30}\left(\frac{\lambda_c}{R_\delta}\right)^2\right]\frac{dT_{co}}{dt}\\&-\left[\frac{1}{2}+\frac{1}{3}\left(\frac{\lambda_c}{R_\delta}\right)+\frac{1}{12}\left(\frac{\lambda_c}{R_\delta}\right)^2\right]\frac{dR_\delta}{dt}\end{aligned} \tag{12}$$

Using a lumped parameter energy equation for the film, energy conservation equation is given as

$$\begin{aligned}&\frac{d}{dt}(m_v h_v+m_g h_g)\\&\quad=Q_v+V_f\frac{dP_f}{dt}+\frac{dm_v}{dt}[h_{fg}+c_{pv}(T_{vs}-T_{co})]\end{aligned} \tag{13}$$

where

$$Q_v=4\pi R^2\frac{2k_v}{\delta}(T_{ho}-T_v)-4\pi R_\delta^2\frac{2k_v}{\delta}(T_v-T_{vs}) \tag{14}$$

Enthalpy of the vapor can be expressed as

$$h_v(T_v,P_v)=c_{pv}(T_v-T_{co})+h_{fg}+c_{pc}(T_{co}-T_{ref}) \tag{15}$$

Another relation between the rate of change of T_{ho} and λ_h is obtained from the continuity of heat flux at the droplet-vapor interface given as

$$\frac{2k_h}{\lambda_h}(T_{hi}-T_{ho})-\varepsilon\sigma T_{ho}^4=\frac{2k_v}{\delta}(T_{ho}-T_v) \tag{16}$$

At the vapor-liquid interface the balance equations of total energy flow are satisfied from the kinetic theory of gases.

$$\frac{2k_v}{\delta}(T_v-T_{vs})$$

$$+\beta\sqrt{\frac{M}{2\pi G}}\left(\frac{P_v}{\sqrt{T_{vs}}}-\frac{P_{co}}{\sqrt{T_{co}}}\right)[h_{fg}+c_{pv}(T_{vs}-T_{co})]$$
$$=\beta\sqrt{\frac{M}{2\pi \mathrm{G}}}\left[\frac{P_v}{\sqrt{T_{vs}}}\{h_{fg}+c_{pv}(T_{vs}-T_{co})\}-\frac{P_{co}}{\sqrt{T_{co}}}h_{fg}\right]$$
$$=q_c'' \qquad (17,\ 18)$$

The heat transfer rate in the liquid was determined from the assumed temperature profile.

$$q_c''=\frac{2k_c}{\lambda_c}(T_{co}-T_{ci}) \qquad (19)$$

However the growth of the thermal boundary layer thickness is limited due to the motion of droplet as it immerses in cold liquid.

The film pressure is determined from Dalton's law of partial pressure;

$$P_f=P_v+P_g \qquad (20)$$

From the ideal gas assumption for the vapor, partial pressure of the vapor is given as

$$P_v=\frac{m_v G_v T_v}{V_f} \qquad (21)$$

Assuming that the noncondensible gas may be treated isentropically, the gas partial pressure at any time becomes

$$P_g=P_{go}\left(\frac{V_{go}}{V_f}\right)^{\gamma} \qquad (22)$$

Initial noncondensible gas film thickness is considered to be some fraction of the boundary layer thickness of the flow over sphere, and is assumed as

$$\delta_g=Cd(Re_d)^{-1/2} \qquad (23)$$

where noncondensible gas constant C is parameterized in numerical experiments.

2.3 Method of Solutions

Equations (1), (2), (3), (8), (12), (13), (16), (17), and (18) constitute a set of non-linear first order differential equations in the nine time-dependent variables R_s, u, m_v, T_v, T_{co}, T_{vs}, T_{ho}, λ_h, and λ_c.

By successive substitutions among nine equations, the time rate of change for each variable, Y_i, can be expressed in the form

$$\frac{dY_i}{dt}=F_i(Y_j: j=1,2,\cdots,9) \quad i=1,2,\cdots,9 \qquad (24)$$

A simultaneous solution of the equations in the form of equation (24) has been obtained by numerical integration. One step Runge-Kutta-Merson technique(Lance, 1960) which is a modification of 4th order Runge-Kutta integration is used.

Due to numerical integration technique, analytic solutions suitable for an initial small period of time was used to start the numerical integration. The initial time solutions assumed the followings:

(1) The vapor film thickness is initially the diameter of critical nucleation embryo for homogeneous nucleation (Cole, 1979).

(2) The film pressure is initially at the ambient pressure. The resultant film behavior to the assumed starting values seemed to be insensitive as long as the starting values satisfy the overall initial energy balance.

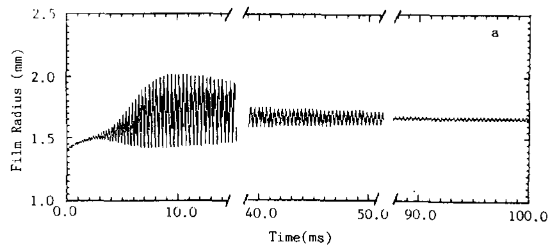
3. APPLICATIONS OF THE MODEL: RESULTS AND DISCUSSIONS

The model developed has been applied to the growth phase of the film around a molten iron oxide droplet in water under various contitions. The initial conditions in the experiments performed by Nelson and Duda(1981) were used as basic parameters for the applications (Table 1).

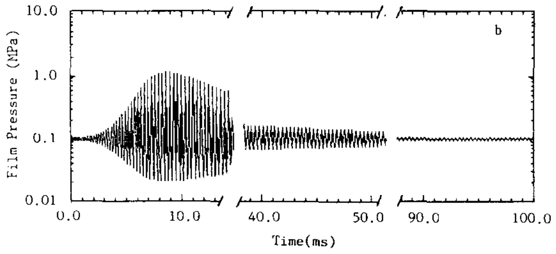
In all cases the rapid vaporization results in a pressure rise in the film which accelerates the film-liquid interface outward as shown in Fig. 2(a) and 2(b). However, the outward motion of the interface continues beyond the equilibrium position, at which the film pressure is equal to the ambient pressure. Thus the film pressure falls below the ambient pressure leading to a deceleration of the interface. The movement of film-liquid interface is then reversed and the film starts to collapse. The continued evaporation in the film leads to a second pressure rise in the collapsing film. The cycle of growth and partial collapse is repeated with increasing amplitude of pressure fluctuation until it reaches its maximum value. Then the pressure fluctuation and the vapor film oscillation decreases slowly, which seems to enter its quasi-steady state. The amplitude and frequency of the film oscillation during the growth phase strongly depend on the initial conditions.

Table 1 Base-line parameters used in applications

Droplet radius	1.4㎜
Droplet temperature	2233K
Droplet atmosphere	Air
Droplet fall velocity in water	0.2m/s
Water temperature	300K
Ambient pressure	0.1MPa
Noncondensible gas constant	0.01



(a) Film radius as a function of time



(b) Film pressure as a function of time

Fig. 2 Film radius and pressure during initial film boiling phase under base-line conditions

An indication of the oscillatory behavior or the violence of film growth and collapse might be the mechanical work of film formation or the potential energy of the film given as

$$W = V_{f,\max}|\Delta P| \tag{25}$$

where $V_{f,\max}$ is the maximum volume of the film during the growth period and ΔP is the difference of film and ambient pressure which might be considered as the driving force for film collapse. This work represents the potential energy of the liquid at the instant of maximum film size which can be equated to the kinetic energy of the liquid when the film collapses.

The effects of the initial conditions on the characteristics of film boiling, the oscillatory behavior of initial film growth phase, have been reviewed in terms of normalized mechanical work of film formation defined as

$$W^* = \frac{W}{W_b} \tag{26}$$

where W_b is the mechanical work of film formation under base-line conditions.

Normalized initial conditions, i.e. droplet temperature, cold liquid temperature and ambient pressure are equated as

$$T_{hi}^* = \frac{T_{hi} - T_{sat}}{T_{hi,b} - T_{sat}} \tag{27-1}$$

$$T_{ci}^* = \frac{T_{sat} - T_{ci}}{T_{sat} - T_{ci,b}} \tag{27-2}$$

$$P_\infty^* = \frac{P_\infty}{P_{\infty,b}} \tag{27-3}$$

3.1 Effects of Noncondensible Gas

The influence of initial noncondensible gas on the film growth is significant. The oscillations of film were diminished enormously with an increase of the initial noncondensible gas film thickness due to the retardation of heat transfer across the film and its damping effect on pressure fluctuations. And so does the mechanical work of film formation as shown in Fig. 3. The result suggests that the occurrence of spontaneous triggering of the single droplet vapor explosions at a lower drop fall height can be explained by a smaller amount of noncondensible gas ; the lower drop fall height reduces the entry Reynolds number and therefore the amount of noncondensible gas entrained in the film causing larger film and pressure oscillations, film collapse, and triggering of vapor explosions.

3.2 Effects of Droplet Temperature

With the increase of the initial droplet temperature, the film radius oscillations have larger amplitude and remain over longer time period. The film thickness also grows faster and larger with the droplet temperature. The mechanical work of film formation increases almost linearly with droplet temperature as shown in Fig. 4. Bjornard et al. (1974) reported the increase of the amplitude and frequencies of pressure oscillations with droplet temperature in their experiments of molten tin droplet in water pool($t < 60$ms). This is in qualitative agreement with the current model. In contrast, experimental observations (Nelson and Duda, 1982) indicated the decrease in the maximum pressure generated during vapor explosions with the increase in melt temperature above a certain peak point. However these results are to be understood in terms of the violent generation of noncondensible gas, probably from the oxidation of iron by the steam, at higher melt temperature.

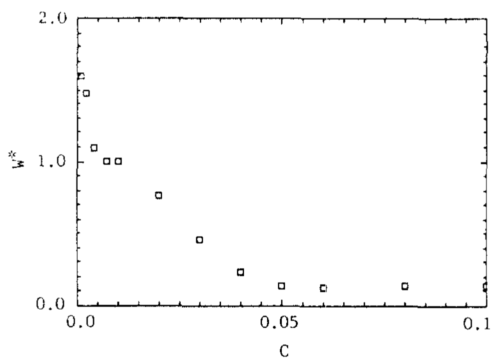


Fig. 3 Mechanical work of film formation as a function of initial noncondensible gas constant

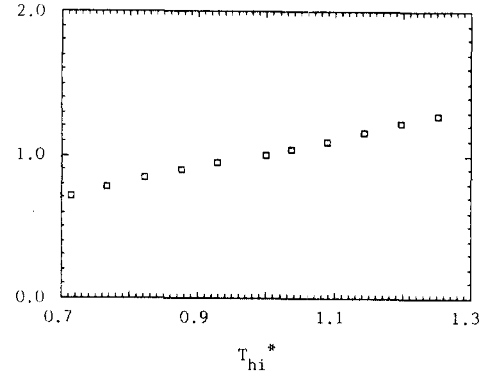


Fig. 4 Mechanical work of film formation as a function of iron oxide droplet temperature

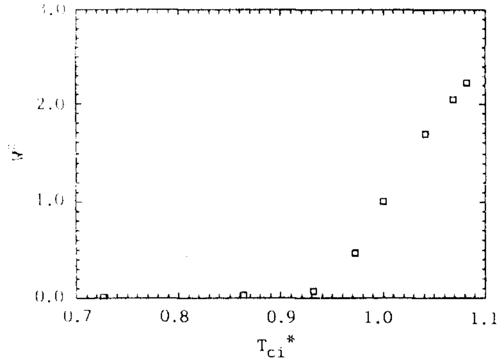


Fig. 5 Mechanical work of film formation as a function of water pool temperature

3.3 Effects of Liquid Temperature

The oscillatory behavior of the film pressure is damped quickly when water temperature is increased (Fig. 5). The reason for the damped oscillation at lower subcooling is the continuous and higher evaporation of cold liquid which tends to prevent the film pressure falling below the ambient pressure. Thus lower water subcooling makes film collapse more difficult due to these effects on forming a more stable and thicker film around the droplet. Board et al.(1971) reported an increase in the frequency of the growing film oscillations as

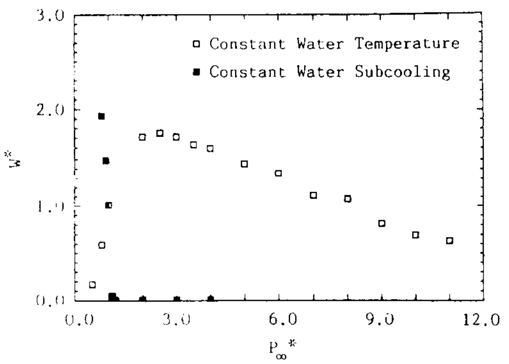


Fig. 6 Mechanical work of film formation as a function of ambient pressure

water subcooling increases. This also is in agreement with the current model.

3.4 Effects of Ambient Pressure

The duration of film pressure fluctuations becomes shorter as ambient pressure increases. Also the time required to reach maximum film pressure and the period of oscillations decrease with ambient pressure. The effects of ambient pressure on the mechanical work of film formation are shown in Fig. 6.

For the constant water temperature, the maximum pressure generated in the film increases sharply for the small ambient pressurizations, which results in the abrupt increase in the mechanical work of film formation even the maximum size of film reduces with ambient pressure. However further increase in ambient pressure leads the work to reach its peak and then decreases relatively slowly.

At constant water subcooling, the oscillation of the film pressure has a smaller amplitude and damped quickly at higher ambient pressure. Higher ambient pressure suppresses the oscillation of the film and higher water temperature induces easier vaporization leading to more stable film. Therefore lower water subcooling seems to be one of the significant factors inhibiting the initiation of vapor explosions due to their stablizing effects.

In some aspects these film behaviors agree qualitatively with the experimental observations that small increase in ambient pressure leads to the easier initiation of vapor explosions, i.e. low triggering pressure required to initiate vapor explosions in Nelson and Duda's experiments(1982).

4. CONCLUSIONS

The conclusion on this study is that a simple model of film boiling dynamics can qualitatively predict the triggering characteristics of small-scale single droplet vapor explosions in terms of the oscillatory behaviors in initial film boiling, i. e, mechanical work of film formation.

The initial noncondensible gas film thickness and liquid temperature have consistent and predictable effects on film growth by diminishing the oscillations of film pressure. Stable growth of film boiling is disturbed at higher droplet temperature with linearly increasing mechanical work of film formation. Ambient pressure affects film behavior depending upon the magnitude of pressurization, and results in the most violent pressure oscillation at a certain intermediate ambient pressure. However, the influence of any one parameter on the film boiling can be suppressed or enhanced by varying another parameter; they are closely interrelated to each other.

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