

NOTICE

**CERTAIN DATA
CONTAINED IN THIS
DOCUMENT MAY BE
DIFFICULT TO READ
IN MICROFICHE
PRODUCTS.**

CONF-901007--12

UCRL-CR--103908

DE91 000947

DEC 1 8 1990

AN APPROXIMATE METHOD FOR ANALYZING TRANSIENT CONDENSATION ON SPRAY IN HYLIFE-II

Robert Y. Bai and Virgil E. Schrock
Department of Nuclear Engineering
University of California at Berkeley
Berkeley, CA 94720
(415) 642-6431

Paper Proposed for
the Ninth Topical Meeting on Technology of
Fusion Energy

October 7-11, 1990, Oak Brook, IL

Work performed under the auspices of the U.S. Department of Energy
by the Lawrence Livermore National Laboratory under contract W-7405-
Eng-48

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

Work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract number W-7405-ENG-48.

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

AN APPROXIMATE METHOD FOR ANALYZING TRANSIENT CONDENSATION ON SPRAY IN HYLIFE - II

R.Y. BAI and V.E. SCHROCK
Department of Nuclear Engineering
University of California at Berkeley
Berkeley, CA 94720
(415) 642-6431

ABSTRACT

The HYLIFE - II conceptual design calls for analysis of highly transient condensation on droplets to achieve a rapidly decaying pressure field. Drops exposed to the required transient vapor pressure field are first heated by condensation but later begin to reevaporate after the vapor temperature falls below the drop surface temperature. An approximate method of analysis has been developed based on the assumption that the thermal resistance is concentrated in the liquid. The time dependent boundary condition is treated via the Duhamel integral for the pure conduction model. The resulting Nusselt number is enhanced to account for convection within the drop and then used to predict the drop mean temperature history. Many histories are considered to determine the spray rate necessary to achieve the required complete condensation.

INTRODUCTION

An ICF (inertial confinement fusion) power plant basically consists of three parts: (1) a primary energy source (called the driver) which can either be a laser or ion beam, (2) a reactor chamber (also called vacuum chamber or target chamber) where the thermonuclear reaction ($D + T \rightarrow He + n + 17.6$ Mev) occurs, and (3) an energy removal and conversion system to produce electrical power.

After a thermonuclear microexplosion, typically 32% of the energy is carried by X-rays and energetic debris and the remainder by neutrons. The energy radiates in every direction inside the cavity, finding a place for final deposition. Hence the prevention of the damaging effects of the neutrons, x-rays and debris represents a primary technical concern in the design of an ICF reactor. In order to protect the structural wall of the reactor through its lifetime, a scheme has been proposed in the HYLIFE-II design which consists of a curtain of liquid Flibe jets for neutron absorption and blast

attenuation coupled with cool Flibe liquid spray for condensation of vaporized Flibe. Since liquid Flibe has the effect of absorbing and attenuating the high energy residuals, it forms one of the main attractions in the HYLIFE-II design. And in the HYLIFE-II the aim is to take the advantage of better safety characteristics of liquid Flibe compared to the liquid lithium of the HYLIFE-I design. The X-ray energy is deposited in a thin layer of the Flibe curtain at the surface exposed to the microexplosion. This results in sudden evaporation, dissociation and ionization of a considerable amount of Flibe liquid. Most of the plasma is very energetic and implodes onto the site of the microexplosion. A small fraction of the mass evaporated is less energetic and is dispersed within the chamber volume raising the pressure significantly. The imploded gaseous material has an average internal energy far in excess of the saturated vapor state. Much of the excess energy is expected to be rapidly transferred to the Flibe curtain by radiation and convection causing additional material to be vaporized. The total amount of vapor generated can only be found from a detailed analysis of these complex processes. For a conservative estimate we assume that all the X-ray energy is eventually present as internal energy of saturated Flibe vapor filling the entire reactor chamber. This is conservative because some sensible heating of the Flibe curtain is caused by X-ray energy via subsequent heat transfer processes. However, this heating leaves a protective thermal boundary layer on the curtain surface such that they do not aid in the condensation process. Continuous Flibe spray is to be provided into the annulus between the curtain and the vessel wall, adequate to handle the entire condensation process.

The condensation in the HYLIFE-II is a highly transient process. After the explosion of a fuel pellet, a vapor pressure of hundreds of MPa builds up at the center of the cavity. On the other hand, to create the beam path for the next laser beam (ion beam) bombardment, the pressure has to be lowered to 10 Pa (0.1 Pa). The whole condensation process is to be completed in tens of

milliseconds for a repetition rate of several Hertz. It is the extreme change in vapor pressure required that characterizes this transient condensation process.

The approximate method adopted to estimate the condensation in HYLIFE-II consists of assuming that the surfaces of droplets are always at the saturation temperature corresponding to the instantaneous vapor pressure. This is equivalent to assuming that all the thermal resistance is on the liquid side of the interface. Because the problem is one of time dependent boundary condition we find it convenient to use the Duhamel superposition integral with the fundamental solution for a step change in vapor pressure (surface temperature) to calculate the thermal history of an individual droplet of any specified size exposed to the transient vapor pressure (assumed exponentially decaying in time in this analysis). We have the pure conduction model for the fundamental solution. Hijikata¹ has done numerical calculations for the high Peclet number case which show that the convection induced by Hill's vortex and surface oscillations enhance the pure conduction transient Nusselt number for the step forcing function by a factor of about ten. His calculations were verified by experiments. Our approach then, is to use the Duhamel superposition integral to obtain the transient heat transfer coefficient for exponentially decaying surface temperature for pure conduction. The heat transfer coefficient is then enhanced by Hijikata's factor and the result used in an ordinary differential equation to obtain the time dependence of the average temperature of the drop. This procedure is only approximate because exact numerical calculation would show that the enhancement factor may be time dependent when the time constant for exponential decay of surface temperature is smaller than the characteristic time constants of the convective processes. (Clift, et al.² show also that for moderate Peclet numbers the conduction and convection effects may combine to produce oscillation in the Nusselt number, even for the step forcing function case.) The resulting enhanced Nusselt number is then used to predict the drop mean temperature history. Many histories are considered to determine the spray rate necessary to achieve the required condensation.

ENERGY ABSORBED BY A SINGLE DROPLET

The fundamental transient conduction solution is found for a step change boundary condition based on the following assumptions:

- (1). The droplet is initially at uniform temperature

T_0 , where $T_0 < T_{sat}$

- (2). At time $t = 0$ the surface temperature jumps to and remains at T_{sat} .
- (3). Neglect the thermal resistance of condensate and neglect change in the droplet size.
- (4). Neglect the internal convection.
- (5). Neglect distortions of droplet shape.

The transient conduction equation is

$$\frac{\partial \theta}{\partial t} = \frac{\alpha}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial \theta}{\partial r} \right) \quad (1)$$

where

$$\theta(r, t) = T(r, t) - T_0$$

and

$$\alpha = \frac{k}{\rho c_p}$$

is the thermal diffusivity. The corresponding initial and boundary conditions are

$$\theta(r, 0) = 0,$$

$$\theta(R, t) = \theta_{sat}(t) = T_{sat} - T_0$$

$$\frac{\partial \theta(0, t)}{\partial r} = 0$$

The solution of this problem is given by Carslaw and Jaeger [3]

$$\begin{aligned} \psi(r, t) &= \frac{T(r, t) - T_0}{T_{sat} - T_0} \\ &= 1 + \frac{2R}{r} \sum_{n=1}^{\infty} \frac{(-1)^n}{\lambda_n} e^{-\lambda_n^2 Fo} \sin\left(\frac{\lambda_n r}{R}\right) \end{aligned} \quad (2)$$

where eigenvalues $\lambda_n = n\pi$, and Fourier modulus $Fo = \alpha t/R^2$.

The surface temperature difference of the droplet (above the initial drop temperature) is assumed to be exponentially decaying with time

$$\theta_{sat}(t) = \Theta e^{-t/\tau_0} \quad (3)$$

where Θ is the step temperature rise at $t = 0$. By Duhamel's theorem³, we can find the solution for the time dependent surface temperature. The integral theorem is

$$\theta(r, t) = \Theta \psi(r, t) + \int_0^t \psi(r, t - \tau) \frac{d\theta_{\text{int}}(\tau)}{d\tau} d\tau. \quad (4)$$

Substituting from equations (2) and (3), solving, and non-dimensionalizing, we obtain

$$\frac{\theta(\rho, Fo)}{\Theta} = e^{-Fo/Fo_0} + \frac{2}{\rho} \sum_{n=1}^{\infty} \frac{(-1)^n e^{-Fo/Fo_0} - \lambda_n Fo e^{-\lambda_n^2 Fo}}{\lambda_n (1 - \lambda_n Fo)} \sin(\lambda_n \rho) \quad (5)$$

where reduced mass $\rho = r/R$ and $Fo_0 = \alpha t_0/R^2$ is the Fourier modulus at $t = t_0$. Averaging over space, we have

$$\frac{\bar{\theta}(Fo)}{\Theta} = e^{-Fo/Fo_0} + \sum_{n=1}^{\infty} \frac{\lambda_n Fo_0 e^{-\lambda_n Fo} - e^{-Fo/Fo_0}}{\lambda_n [1 - \lambda_n Fo_0]} \quad (6)$$

The instantaneous surface heat flux to the droplet is then

$$q''(t) = \frac{1}{4\pi R^2} \frac{dQ(t)}{dt} \quad (7)$$

where $Q(t)$ is the cumulative energy absorbed by a single droplet given by

$$Q(t) = \frac{4\pi R^3 \rho_F c_F}{3} \bar{\theta}(t) \quad (8)$$

The heat transfer coefficient is then

$$h(t) = \frac{q''(t)}{\theta_{\text{int}}(t) - \theta(t)} \quad (9)$$

and the transient Nusselt number is

$$Nu(t) = \frac{h(t)D}{k}$$

A combination of the equations (7), (8), (9), and (10) gives

$$Nu(Fo) = \frac{\frac{1}{Fo_0} e^{-Fo/Fo_0} - \sum_{n=1}^{\infty} \frac{e^{-Fo/Fo_0} - (\lambda_n Fo_0)^2 e^{-\lambda_n^2 Fo}}{\lambda_n Fo_0 (1 - \lambda_n Fo_0)}}{9 \sum_{n=1}^{\infty} \frac{\lambda_n Fo_0 e^{-\lambda_n Fo} - e^{-Fo/Fo_0}}{\lambda_n (1 - \lambda_n Fo_0)}} \quad (11)$$

At this point it is useful to examine the result of the pure conduction model in order to see qualitatively some of the salient feature of the problem. Based on the assumptions stated earlier we estimate that vapor first encounters the spray when it has become saturated vapor at 1500 K. For a laser driver the vapor must be reduced to 955 K (T_{sat} at 10 Pa) and we choose a spray temperature of 843 K. Further we choose an allowed condensation time, τ , which is smaller than our design repetition period. From these choices the parameter in equation (3) are found to be $\Theta = 657$ K and $t_0 = 0.0225$ s for $t = 40$ ms and $t_0 = 0.0450$ s for $t = 80$ ms.

In Figure 1 we show radial temperature profile in a 10 μ m diameter Flibo drop as predicted by equation (5) for $t = 40$ and for some selected times. First it is evident that the thermal penetration thickness is small (less than a millimeter for the time scale of the problem). Next we note that this surface layer is very rapidly heated initially, however after only about 19 ms the temperature gradient (heat flux) at the surface is reduced to zero. Therefore the heat flux is reversed, i. e., the drop begins to evaporate. Once the point of zero surface heat flux is reached a drop becomes a liability (a vapor source). Apparently further condensation must depend upon the introduction of new cold surface by the continuous spray. This means that control of the residence time is desirable.

Figure 2 shows the average drop temperature predicted by equation (6) for drop

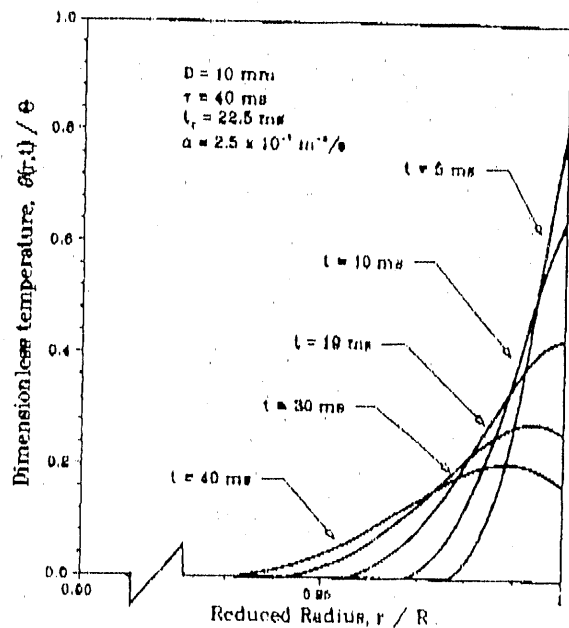


Figure 1. Temperature profile from pure conduction model, Equation 5, for Flibe.

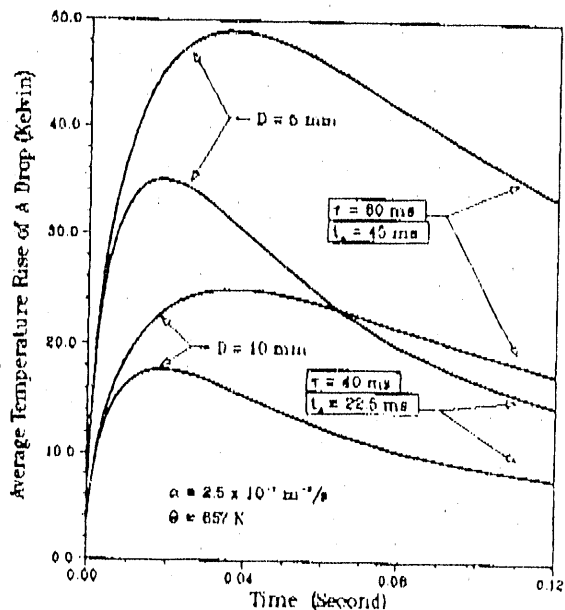


Figure 2. Average drop temperature predicted by pure conduction model with exponential forcing function for Flibe.

diameter of 5 mm and 10 mm and for τ of 40 and 80 ms. This figure indicates the presence of peaks consistent with the reversal of surface heat flux noted in the last paragraph. The time of the peak depends upon the condensation time τ (and therefore t_0) but it is not sensitive to change in drop size. The transient Nusselt number predicted by the pure conduction theory, equation(11), is plotted in Figure 3. The heat transfer coefficient becomes zero at the instant when the surface heat flux is zero. As seen from Figure 1 the surface temperature at this time is still higher than the average temperature of the drop.

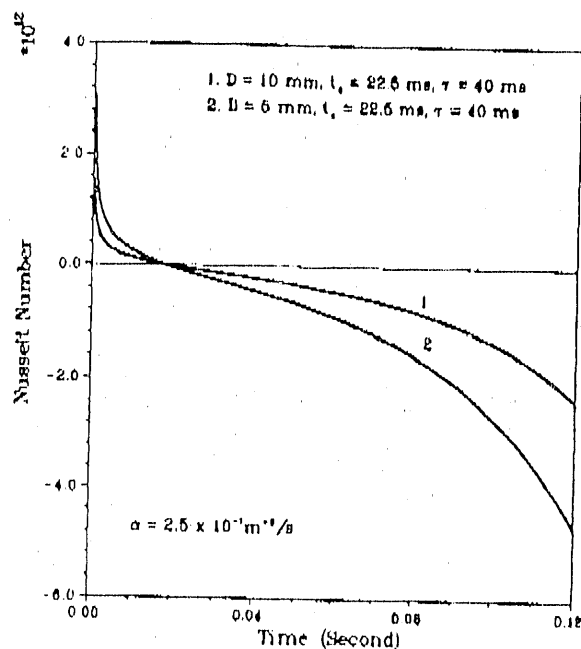


Figure 3. Nusselt number predicted by pure conduction model with exponential forcing function.

Therefore beyond this time the heat transfer coefficient is negative until the temperature difference is reversed.

As noted earlier, convection is known to enhance the heat transport within the drop. For an approximate treatment we assume that the enhancement is a constant factor, f , independent of time. (We shall call f the Hijikata factor). Then the enhanced heat transfer coefficient (denoted by the superscript $*$) is

$$h^*(t) = f h(t) \quad (12)$$

The temperature history of a single droplet subject to combined conduction and convection can then be found by establishing the overall heat

balance equation on the drop

$$m c_p \frac{d\bar{\theta}^*(t)}{dt} = h^*(t) A [\theta_{sat}(t) - \bar{\theta}^*(t)] \quad (13)$$

where $\bar{\theta}^*(t)$ is the temperature difference in the conduction-convection model, and m is the mass of the droplet. The initial condition is

$$\bar{\theta}^*(0) = 0.$$

The cumulative heat absorbed by the drop

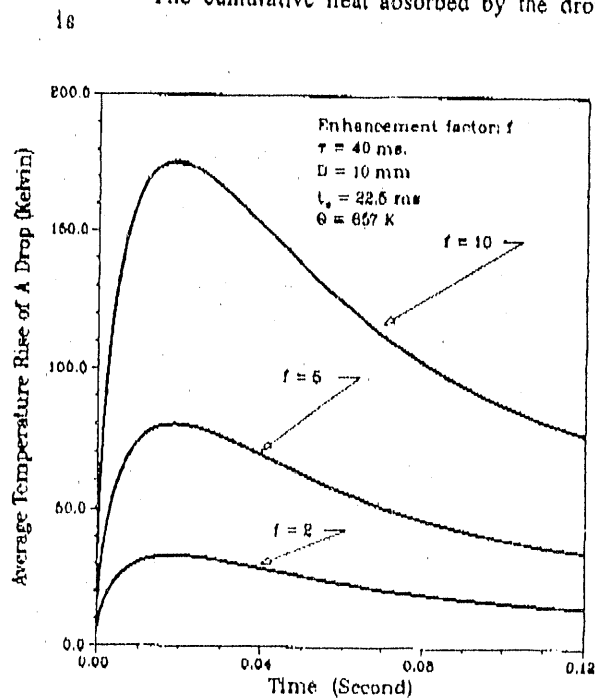


Figure 4. Average drop temperature predicted by the approximate calculation with convection for Flibe.

$$Q^*(t) = \frac{4\pi R^3 \rho c_p}{3} \bar{\theta}^*(t) \quad (15)$$

The solution to equation (13) has been plotted in Figure 4 for condensation time of 40 ms and for droplet diameter of 10 mm with different enhancement factors. In Figure 5 the

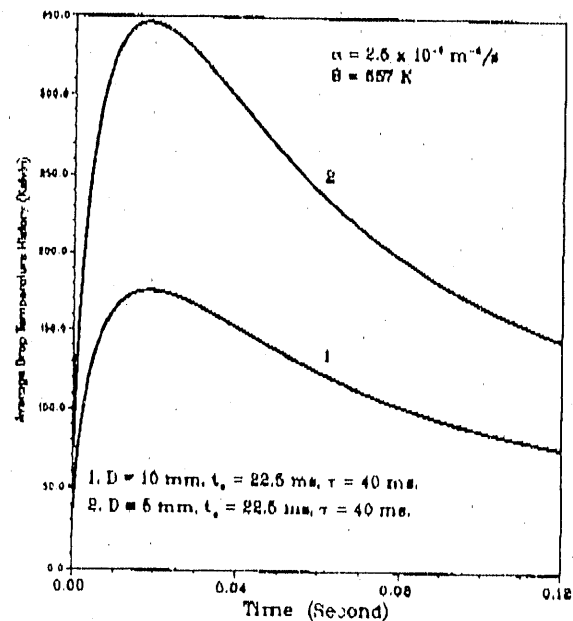


Figure 5. Average drop temperature predicted by convection model with $f = 10$ for Flibe.

predictions by equation (13) with an enhancement factor $f = 10$ are compared for drop diameters of 5 and 10 mm. The overall shapes of these curves are similar to those of the unenhanced heat transfer coefficient case, but convection greatly increases the drop temperatures. It is seen by comparing Figure 2 with Figure 5 that convection causes drop temperatures to be higher than in pure conduction closely by the enhancement factor throughout their histories. This result is to be expected. The fraction of the energy gained that is lost by recooling is not changed by convection, but the absolute energy finally removed is, of course, increased.

We have recently started collaboration with Hijikata to carry out numerical solution of the convection problems with the time dependent boundary condition. This work will be reported in a later paper. Some early results for Peclet number of 10^6 and a forcing function defined by $\Theta = 4,157$ K and $t_0 = 11.1$ ms have been compared with predictions of the present approximate method. This has given a preliminary indication that the approximate method using a constant factor f matches the exact numerical calculation within a few percent when the appropriate value is chosen for f (approximately $f = 2$ for the example). It also indicates that convective enhancement is not as great for HYLIFE conditions as may have been implied by Hijikata's original work¹.

NUMBER OF DROPLETS REQUIRED IN CONDENSATION PROCESS

Now we consider the residence time in the chamber and forcing function experienced by each drop. All drops that are in the chamber at the start of condensation see the same forcing function but they leave the chamber at different time depending on their initial position. A drop at the top of the chamber at $t = 0$ has a residence time, t_r , determined from

$$H = v t_r + 0.5 g t_r^2 \quad (16)$$

where H is the height of the chamber and v is the velocity of spray. If the gravitational effect is negligible

$$t_r = \frac{H}{v} \quad (17)$$

A drop near the bottom of the chamber at $t = 0$ has a shortened residence time. Drops that are sprayed during the condensation period see the forcing function, equation (3), but with a time delay. In order to account for all the different circumstances we assign the drops to groups by dividing the height of the chamber into m equal intervals so that each interval has the height

$$\xi = \frac{H}{m} \quad (18)$$

The behavior of all drops in a group is represented by a drop at the geometric center of the group. The group translation time is

$$t_g = \frac{\xi}{v} \quad (19)$$

The number of groups entering the cavity during the condensation time is

$$\eta = \frac{t}{t_g} \quad (20)$$

Therefore the total number of groups contributing to the condensation is

$$\Gamma = m + \eta \quad (21)$$

of which m are inside the cavity at $t = 0$ and η are outside. We number the groups from the bottom up as shown in Figure 6.

Since all drops in the first m groups start at the initial point on the forcing function, the energy absorbed by each drop in the group is given by the history of a drop, as in Figure 7, evaluated at the time that group exits the chamber, i. e.,

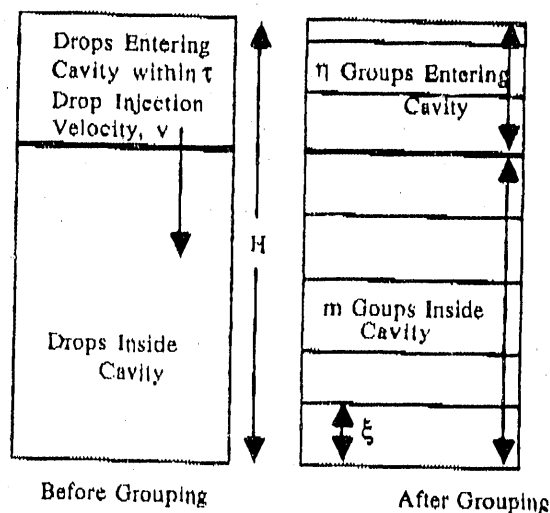


Figure 6. Schematic graph of grouping the droplets within a specific condensation period.

$$Q_n^* = Q_i^* \left(\frac{2n-1}{2} t_g \right) \quad (22)$$

where $n = 1, 2, \dots, m$ and Q_i^* is obtained from

equation (15) with $\bar{\theta}$ evaluated at $t = \frac{2n-1}{2} t_g$.

We see that, for example, group 1 exits the chamber

at $t = \frac{t_g}{2}$, group 2 exits at $t = \frac{3 t_g}{2}$, etc.

For groups $n > m$ it is necessary to resolve the entire problem for forcing functions unique to each group

$$\theta_{\text{sat}, n, m} = \theta \exp \left\{ - \frac{t + \frac{(n-m) t_g}{2}}{t_g} \right\} \quad (23)$$

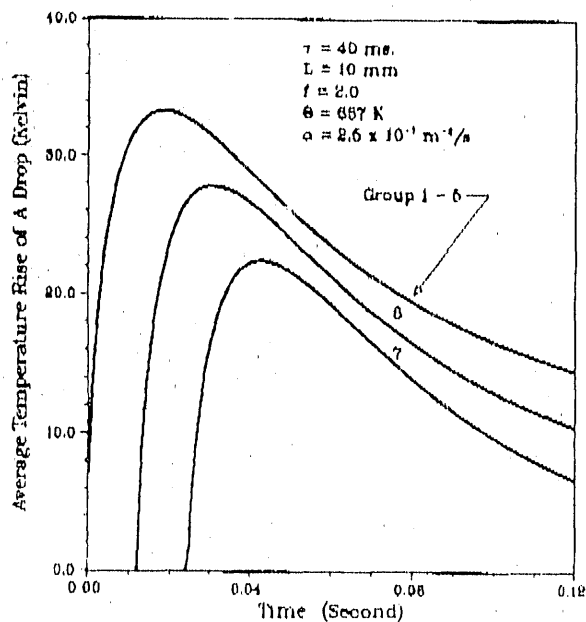


Figure 7. Average temperature history for different drop groups predicted by convection model with exponential forcing function.

where $n = m + 1, m + 2, \dots, m + [\eta]$ and $[\eta]$ is the largest whole number less than η . In general the last group may have a size less than ξ . It is given by

$$\xi_1 = \eta - [\eta] \quad (24)$$

and it sees the forcing function

$$\theta_{sat, m + [\eta] + 1} = \theta \exp \left\{ - \frac{t + \left(m + \left(\eta + \frac{\eta - [\eta]}{2} \right) t_g \right)}{t_0} \right\} \quad (25)$$

The total energy absorbed by all groups is then

$$Q_1 = N \left\{ \sum_{n=1}^{m + [\eta]} Q_n^* + (\eta - [\eta]) Q_{m + [\eta] + 1}^* \right\} \quad (26)$$

where $Q_{m + [\eta] + 1}^*$ is the energy absorbed by the last group N is the number of drops per group, and Q_1 is the total energy required to be absorbed in order to bring down the cavity pressure. Solving equation 26 for N , we are able to find the required spray rate of drops

$$\omega = \frac{N}{t_g} \quad (27)$$

and the spray mass flow rate

$$\dot{m}_s = \frac{1}{6} \pi D^3 \rho \frac{N}{t_g} \quad (28)$$

For an example calculation we choose

$$\begin{aligned} t &= 40 \text{ ms} \\ D &= 10 \text{ mm} \\ v &= 25 \text{ m/s} \\ H &= 3 \text{ m} \\ m &= 5 \\ \eta &= 1.66 \\ t_g &= 0.024 \text{ s} \\ t_r &= 0.12 \text{ s} \end{aligned}$$

For convective results we choose $f = 2$. Drop average temperatures for each group are shown in Figure 7. From these histories we calculate the average temperatures of each group as it exits the spray field. The results, together with the energy removed by each group are summarized in Table I. Further, for the conditions of the example, it is found that the required spray is

$$\begin{aligned} N &= 2.93 \times 10^5 \text{ drops / group,} \\ \omega &= 1.22 \times 10^7 \text{ drops / s,} \\ \dot{m}_s &= 1.31 \times 10^4 \text{ kg / s.} \end{aligned}$$

For comparison, a curtain of 400 10 cm diameter jets at 25 m/s requires a Flibe flow rate of 1.57×10^5 kg/s, so the spray is only 7.7% of the total Flibe flow rate. The spray to jet surface area ratio is 1.22 so the assumptions of the approximate method seem reasonable.

CONCLUSIONS

An approximate method has been developed to calculate transient condensation on spray. The method accounts for the role of convection within the drops and the time dependence of the vapor pressure. Due to the transient vapor pressure, drops are initially heat sinks for condensation but quickly begin to reevaporate. This feature of the problem makes very small drops undesirable in the ICF

Table I. Drop Exit Temperature and Energy Absorbed by Group

Groups	Average Exit Temperature K	Energy Absorbed % of Total
1	31.8	
2	30.2	
3	23.6	
4	19	
5	15.6	
6	15	
7	10	

application.

Preliminary comparison with exact numerical solutions of the convection problem show that the present model is very accurate (when f is known) and the computational effort is a small fraction of that required for direct numerical solution. Additional numerical solutions will be needed to characterize f in terms of the problem parameters. The approximate method should be an efficient tool for use in design optimization studies.

ACKNOWLEDGEMENTS

This work was sponsored by the Lawrence Livermore National Laboratory and the Department of Energy.

NOMENCLATURE

A - Surface area of drop
 c_p - Specific heat capacity
D - Drop diameter
Fo - Fourier number
 f - Enhancement factor
 $h(t)$ - Transient heat transfer coefficient
k - Thermal conductivity
m - Number of drop groups inside chamber
 \dot{m} - Mass flow rate
N - Number of drops per group
n - Whole number
Nu(t) - Transient Nusselt number
Q(t) - Cumulative energy absorbed by a single drop
 Q_t - Total energy absorbed by all groups
R - Drop radius
 t_g - Group translation time
 t_0 - Time constant

t_r - residence time

q'' - Instantaneous surface heat flux

v - Drop velocity

α - Thermal diffusivity

Γ - Total number of groups

21.9 $\Psi(r,t)$ - Solution of fundamental transient conduction problem

20.8 λ_n - Eigenvalues

16.3 θ - Temperature history

13.1 Θ - Step temperature rise

10.7 τ - Condensation time

10.3 ρ - Drop density

6.9 η - Number of drop entering cavity during condensation time

ξ - Height that each group occupies inside cavity

ω - Drop spray rate

References

1. K. Hijioka,

[2]. Clift, R.; Grace, J. R.; and Weber, M. E., " Bubble, Drops and Particles ", Academic Press, 1978.

[3]. Carslaw, and Jaeger, " Conduction of Heat in Solids " 2nd Ed. Oxford at the Clarendon Press, 1959.

- END -

DATE FILMED

11 / 1 / 90