

《Technical Report》

Description and Discussion of the Current State of the Knowledge about the Leidenfrost Phenomenon

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Leidenfrost 現象에 관한 最近 技術現況分析

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Abstract

The purpose of this report is to describe and discuss the current state of the knowledge about the Leidenfrost phenomenon which is a heavily studied subject in the field of boiling heat transfer. The strong interest is due to reactor safety considerations since it is desirable to obtain a better understanding of the physical mechanisms involved in the rewetting of high temperature surface after a loss of coolant accident.

Brief survey of the theoretical and experimental results from available open literatures indicates that considerable discrepancy exists in the prediction of the Leidenfrost temperature at the elevated pressures and more investigations are needed in this area.

요 약

본 보고서의 목적은 비등열전달 분야에서 많이 연구되고 있는 Leidenfrost현상에 관한 최근 기술 현황을 검토, 기술하는데 있다. 냉각재 상실사고후 고온표면의 냉각현상에 관계되는 물리적 구조를 이해하는 것은 원자로 안전성 측면에서 중요하므로 이 분야에 많은 관심을 갖게 된다. 조사된 참고 문헌의 이론적 및 실험적 결과를 토대로 높은 압력에서 Leidenfrost온도 해석에 상당한 차이가 있으므로 이 분야에 계속적인 연구가 필요하다는 것을 알았다.

1. Introduction

When a liquid droplet falls upon a hot surface, a film of vapor is promptly formed between the droplet and the hot surface. Heat is transferred

to the droplet by conduction through the vapor film which blankets the solid surface and by radiation from the hot surface. As a result, the film boiling heat transfer is considerably less than the heat transfer by direct contact, as for instance with nucleate boiling. Therefore, this

film boiling region should be avoided, if possible, in practical applications.

J.G. Leidenfrost, a German doctor, in 1756, observed the behavior of small drops of water on a glowing, well polished iron spoon. He found that the droplet is spherical on the hot spoon and that the total vaporization time of the droplet is relatively long. When the spoon is only slightly hotter than the boiling point of the water, the droplet spreads out on the surface and evaporates very quickly. This is generally accounted the first scientific study of boiling¹⁾ and in honor of him, the film boiling of small liquid masses, currently including larger masses is called the Leidenfrost phenomenon. During the past few years, a large number of experimental and theoretical studies have been devoted to the investigation of the Leidenfrost phenomenon which occurs in the transition from a dry heating surface to a partially wetted heating surface. The problems of Leidenfrost phenomenon are of particular importance for the analysis of the reflooding phase of the loss of coolant accident in PWR.

Several other applications of the Leidenfrost phenomenon are the use of water spray to cool steel billets, film cooling of a rocket nozzle, cooldown of cryogenic liquid storage tanks and transport lines, fuel vaporization in a diesel engine and the design of quick response steam generators by spraying liquid on a hot surface.

The earlier surveys of the Leidenfrost phenomenon have been done by Bell²⁾, Hsu³⁾, and recently by Liebert⁴⁾.

This report describes the current state of the knowledge about the Leidenfrost phenomenon and emphasizes the evaluation method of the Leidenfrost temperature and discusses various effects on the Leidenfrost temperature.

2. Theoretical consideration

2.1 Heat and mass transfer model

Several attempts have been made at quantitative analysis of the momentum, heat, and mass transfer mechanisms during the Leidenfrost phenomenon.

Gottfried et al.⁵⁾ used the spheroidal droplet model to investigate the behavior and the evaporation rate of small droplets on a hot flat surface. Baumeister and Simon⁶⁾ and Wachters et al.⁹⁾ assumed that the droplet is flat bottomed for its entire life. It was postulated that several physical processes occur over the droplet surface. Most of these analyses assumed that the vapor is generated on the lower surface of the droplet by heat conduction through the vapor film and that the vapor film and that the vapor is in laminar flow under the droplet due to a radial pressure gradient in the vapor film. The pressure gradient is computed from the Navier-Stokes equation with simplified assumptions.

The model proposed by Gottfried et al.⁵⁾ is described in Fig. 1. By a mass balance

$$\rho_l \frac{dV}{dt} = -(W_1 + W_2) \quad (1)$$

and by a heat balance

$$Q_c + Q_{R1} + Q_{R2} = W_1[\lambda + c_p(T_v - T_s)] + W_2\lambda \quad (2)$$

where Q_c is the heat conducted to the droplet, Q_{R1} and Q_{R2} are the net heat radiated to the

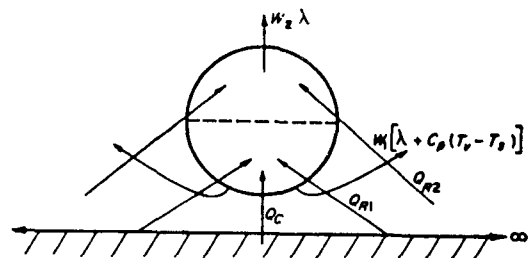


Fig. 1. Heat and Mass Transfer Paths for Droplet Model.

lower and upper surfaces respectively. W_1 and W_2 are the rate of evaporation on the lower and upper surfaces respectively. Some typical results are shown in Fig. 2. The agreement between theory and experiment is quite good considering simplified assumptions.

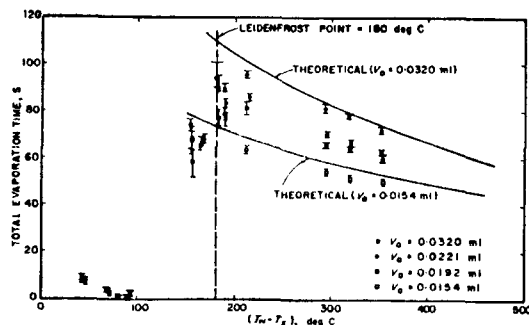


Fig. 2. Total Evaporation Time vs. ΔT for Water Droplets.

2.2 Geometric Configuration of the Liquid Masses

Various geometrical configurations of the liquid masses during the Leidenfrost phenomenon were proposed by Baumeister et al.⁷⁾ as shown in Fig. 3. If an average drop thickness l is defined by

$$l = \frac{V}{\pi r_{\max}^2} \quad (3)$$

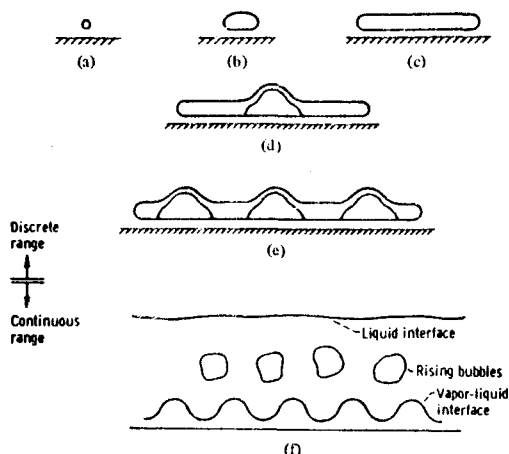


Fig. 3. Film Boiling States of Liquid Masses.

[a; small drop, b; large drop, c; extended drop, d; extended drop (single breakthrough), e; extended drop (multibubble breakthrough), f; film pool boiling]

a dimensionless average drop thickness l^* by

$$l^* = \frac{l}{V^{1/3}} \quad (4)$$

and a dimensionless drop volume V^* by

$$V^* = \frac{V}{(\sigma/\rho_l g)^{3/2}} \quad (5)$$

Baumeister et al.⁷⁾ have developed a curve, as shown in Fig. 4, of V^* (l^*) by three segments, i.e. extended drop, large drop, and small drop domains in Fig. 3. In this way, the mathematics is greatly simplified to obtain a closed form solution. From these quantities the evaporation time of a discrete liquid drop can be determined by an integration of the interface energy balance as shown in Fig. 5.

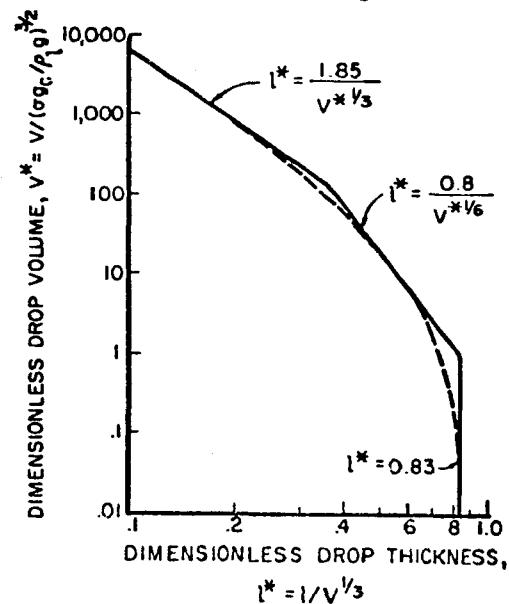


Fig. 4. Universal Average Drop Thickness Curve.

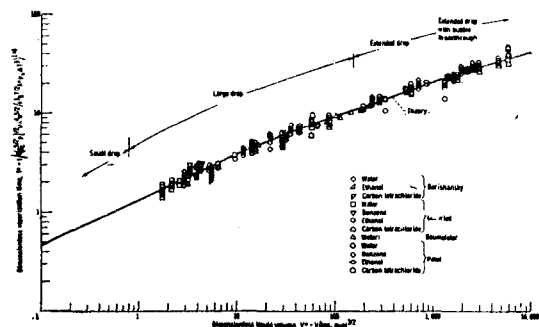


Fig. 5. Universal Total Vaporization Time Curve for Leidenfrost Drops.

In the analysis by Baumeister and Simon^{6,8)} the bottom surface of the drop was assumed to be flat with a stagnation flow of vapor. Although the flat surface was the most approximate model of the Leidenfrost drop among the models proposed, Wachters et al.⁹⁾ found better agreement with experimental data when the analytical model was based upon a flat-bottom assumption.

2.3 Surface Quenching Theory

Bankoff and Mehra¹⁰⁾ proposed the quenching theory based upon the fact that all of the heat flow may be attributed to periodic quenching of the hot surface. For the short times ($\ll 1$ second) it may be sufficient to assume that the heat conduction is one-dimensional and that convective terms are negligible. By using the classical solution¹¹⁾ to the one-dimensional transient conduction to a large slab of metal, they arrived at the relationship

$$q = 2kT_w \left(\frac{t_c}{\pi\alpha} \right)^{1/2} = \frac{T_w kd}{2\alpha} \quad (6)$$

where q is the total heat transferred to the liquid per contact, d is the thermal boundary layer thickness defined by

$$d = 4 \left(\frac{\alpha t_c}{\pi} \right)^{1/2} \quad (7)$$

By using Berenson's data¹²⁾ they found that flow per contact, q is very nearly a constant quantity and is independent of the surface temperature and weakly dependent on the surface roughness.

2.4 Evaluation Model of the Leidenfrost Temperature

The minimum heater surface temperature required to just sustain the stable film boiling process is defined as the Leidenfrost temperature. It was believed that the Leidenfrost temperature corresponds to the minimum point *B* on the boiling curve in Fig. 6. Several attempts have been made to predict either the minimum heat flux q_{\min} or Leidenfrost temperature difference ΔT_{\min} , assuming that the heating surface temperature is held uniform and constant at

ΔT_{\min} .

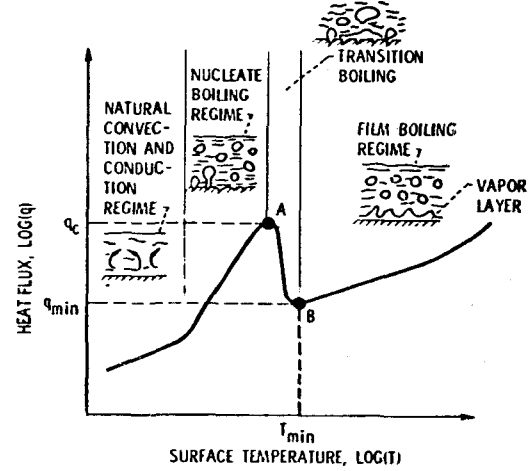


Fig. 6. Conventional Pool Boiling Curve.

Zuber¹³⁾ proposed a minimum heat flux equation based on Taylor's hydrodynamic instability criterion defined as

$$q_{\min} = \frac{\pi}{24} h_{fg} \rho_v \left[\frac{\sigma g (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4} \quad (8)$$

Zuber's maximum and minimum heat fluxes can be related by the ratio

$$\frac{q_{\max}}{q_{\min}} = \left(\frac{\rho_l + \rho_v}{\rho_v} \right)^{1/2} \quad (9)$$

To determine the Leidenfrost temperature based on a hydrodynamic model of the film boiling process, Berenson¹⁴⁾ used equations for both q_{\min} and h_{\min} , heat transfer coefficient. Berenson assumed that, near the Leidenfrost point (ΔT_{\min}), the bubble spacing is determined by the most dangerous wave length

$$\lambda_D = 2\pi \left[\frac{3\sigma}{g(\rho_l - \rho_v)} \right]^{1/2}$$

With the simplified assumptions and his own experimental observations, Berenson formulated the following expression for the film boiling heat transfer coefficient of the minimum point;

$$h_{\min} = 0.425 \left[\frac{k_v^3 g \rho_v (\rho_l - \rho_v) h_{fg}}{\mu_v \Delta T \sqrt{\sigma / g (\rho_l - \rho_v)}} \right]^{1/4} \quad (10)$$

Following the approach used by Zuber, Berenson formulated an expression for the heat flux at the minimum point with the coefficient

being 0.09 instead of $\frac{\pi}{24}$ in Eg. (8).

Since both h_{\min} and q_{\min} are available, a prediction for the Leidenfrost temperature can be obtained as

$$\Delta T_{\min} = \frac{q_{\min}}{h_{\min}} = 0.127 \frac{\rho_v h_{fg}}{k_v} \left[\frac{g(\rho_l - \rho_v)}{\rho_l + \rho_v} \right]^{2/3} \left[\frac{\sigma}{g(\rho_l - \rho_v)} \right]^{1/2} \left[\frac{\mu_v}{g(\rho_l - \rho_v)} \right]^{1/3} \quad (11)$$

This physical model proposed by Berenson is shown in Fig. 7. Henry¹⁵⁾ argued that this correlation does not work for liquid metals, water or Freon, cryogenic fluids, but works only for n-pentane and carbon tetrachloride.

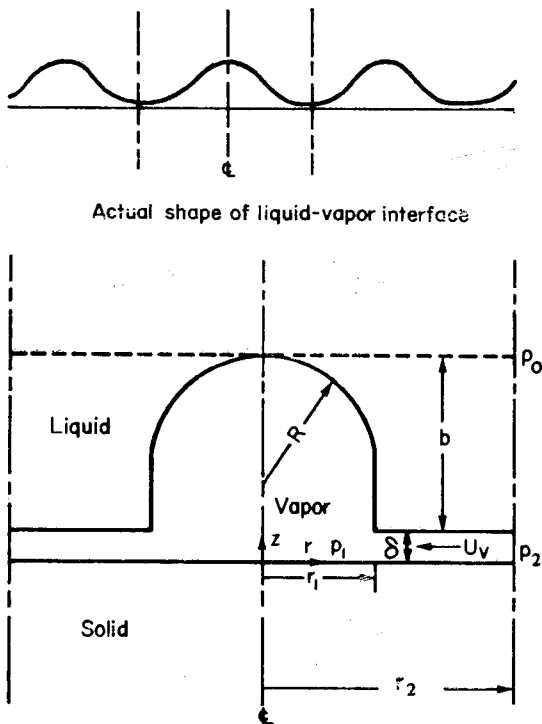


Fig. 7. Physical Model of Film Boiling from a Horizontal Surface.

Spiegler et al.¹⁶⁾ suggested that the Leidenfrost temperature is dependent on a thermodynamic properties of the liquid alone, independent of the substratum. They proposed to identify the Leidenfrost temperature with maximum metas-

table superheat temperature in the van der Waals equation defined as

$$P_r = \frac{8T_r}{3(V_r - 1/3)} - \frac{3}{V_r^2} \quad (12)$$

where $P_r = P/P_c$, $V_r = V/V_c$, $T_r = T/T_c$, with the condition that at the limiting superheat

$$\left(\frac{\partial P_r}{\partial V_r} \right)_{T_r} = 0$$

The limiting superheat thus obtained was equated to the Leidenfrost temperature, so that

$$\frac{T_o}{T_c} = \frac{27}{32} \quad (13)$$

The significant modelling error involved here is that contact between liquid and a hot surface does not ensure the quenching of the hot surface. A superheated layer of liquid may simply evaporate, following upon initial contact, and thereafter maintain an insulating vapor film with the wall. It is also noted that the Leidenfrost temperature discussed above is only determined by the properties of liquid. It is well known that the boiling curve and subsequently the Leidenfrost temperature are influenced by surface conditions.

Gunnerson and Cronenberg¹⁷⁾ proposed an expression for the Leidenfrost temperature for the liquid metal by applying a method parallel to that of Spiegler et al.¹⁶⁾.

$$T_s < T_o \leq$$

$$\frac{T_{\max}[(k\sqrt{\alpha})_w + (k\sqrt{\alpha})_l] - T_{MP}(k\sqrt{\alpha})_l}{(k\sqrt{\alpha})_w} \quad (14)$$

where T_{MP} is the lowest possible liquid temperature and T_{\max} , the maximum allowable liquid superheat temperature.

Yao and Henry¹⁸⁾ compared their experimental results for water on stainless steel plates with the prediction of the Leidenfrost temperature by the Taylor instability models of Berenson¹⁴⁾ and Henry¹⁵⁾ and the limiting superheat models of Spiegler et al.¹⁶⁾ and Baumeister and Simon⁴⁾ in Fig. 8. They concluded that none of these analytical formulations provide reasonable pred-

ictions at elevated pressures.

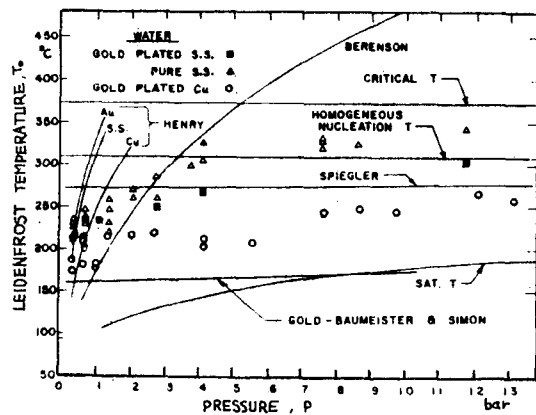


Fig. 8. Analytical Predictions of the Leidenfrost Temperature.

3. Determination of Leidenfrost Temperature

3.1 Measurement

As defined before, the Leidenfrost temperature is that temperature of the boiling surface at which the heat transfer coefficient in the film-boiling regime is a minimum. At that temperature the instantaneous vaporization rate and also the total vaporization time for a given initial liquid mass will be a maximum.

The Leidenfrost temperature can be evaluated by measuring the vaporization time of a liquid drop on a hot surface. The vaporization time data are plotted against the initial surface temperature and, then, the abscissa of point B as in Fig. 9 is the Leidenfrost temperature.

Fig. 10, taken from Patel and Bell result¹⁹⁾, is a typical plot of such data against the difference between the plate temperature and saturation temperature of the liquid. This method, however, may lead to some difficulties at a high pressure condition and possible errors due to the fact that the temperature at the Leidenfrost point in the moment of wetting may differ from the mean temperature of the plate.

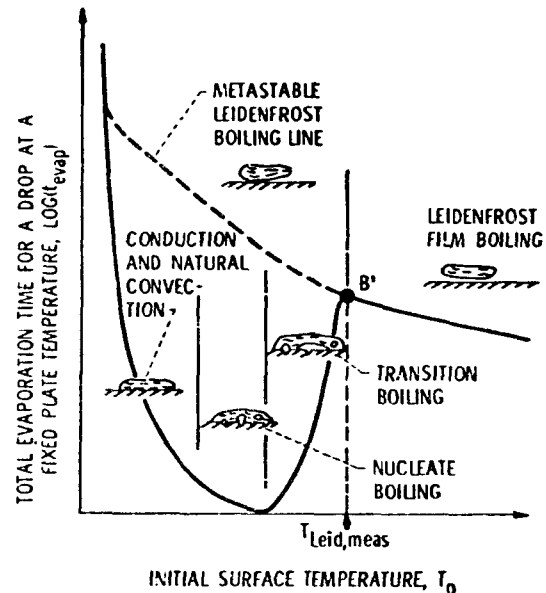


Fig. 9. Evaporation Time Curve of Liquid Drops in Contact with a Hot Surface for Drops of Equal Volume and Equal Initial Temperature.

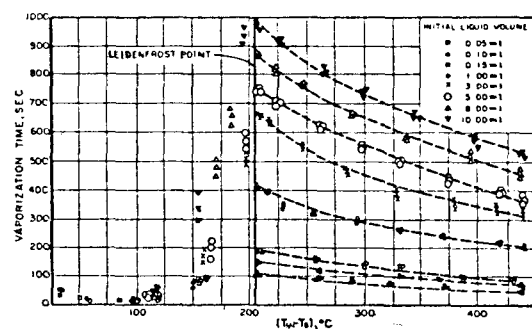


Fig. 10. Total Vaporization Time vs. ΔT : Water.

It is also possible to determine the Leidenfrost temperature from the boiling curve. However, there is some uncertainty in the selection of a minimum heat flux point and a small error in the minimum heat flux leads to a large uncertainty in Leidenfrost temperature.

When the Leidenfrost temperature is evaluated with temperature-time curves obtained by reflow experiments with heater rods, it is usually defined as the wall temperature just downstream of the quench front which is unaffected by

axial conduction. The temperature at the intersection of the linearly extrapolated pre-quenching cooling curve and the line of the steepest temperature-time gradient is defined as the quench temperature. This temperature so defined can not be the Leidenfrost temperature due to the axial conduction which is based on thermodynamic^{8),16)} and hydrodynamic theory¹⁴⁾. In flow boiling a universally accepted definition of the Leidenfrost temperature (often referred to also as sputtering, quenching, calefaction or minimum film boiling temperature but these terms are not exactly synonymous) does not exist.

More successful method proposed by Hein²⁰⁾ is a non-stationary method, i.e. by cooling down the surface of a probe until wetting occurs. With this probe, as shown in Fig. 11, it is possible to measure the temperature at that point of the surface at the moment of wetting,

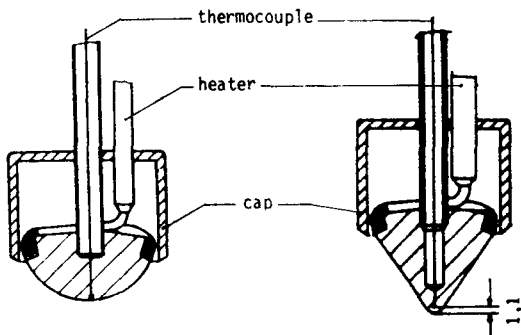


Fig. 11. Probes for the Determination of the Leidenfrost Temperature.

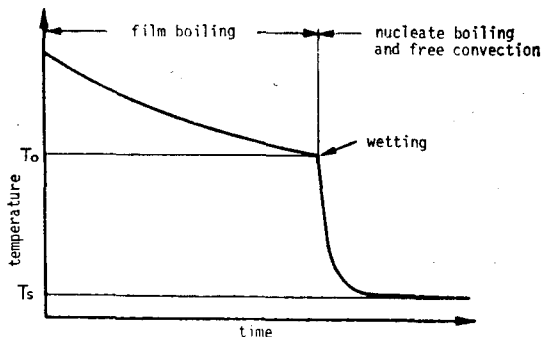


Fig. 12. Temperature-time Curve for the Cooling Down of a Probe.

while, in other cases, an incorrect value of the Leidenfrost temperature may be measured due to heat conduction caused by an advancing wetting front. By this method it is possible to measure the Leidenfrost temperature in the high pressure condition and to obtain more clear intersection due to the low heat capacity of the tip of the probe, as shown in Fig. 12.

Determination of the Leidenfrost temperature is not easy matter because of the presence of uncontrollable perturbations in the heat transfer mechanism at the Leidenfrost point.

3.2. Interpretation of temperature data

In most of the experiments in which the Leidenfrost temperatures were determined, the temperatures readings were taken from thermocouples embedded in the test section. When the local transient variation of the temperature takes place due to transient liquid/solid contact, thermocouples may not yield the real surface temperature. To correct this source of error, two semiempirical equations are recommended. Henry¹⁵⁾ used Berenson's T_{min} as the idealized isothermal transition point. In Henry's correlation, the temperature correction is correlated to the ratio of thermal properties of liquid and solid and to the enthalpy ratio.

$$\frac{T'_{min} - (T'_{min})_{iso}}{(T_{min}) - T_l} = 0.42 \left(\sqrt{\frac{(k\rho c)_l}{(k\rho c)_w}} \cdot \frac{h_{fg}}{c_w(\Delta T_{min})_{iso}} \right)^{0.6} \quad (15)$$

where $(T'_{min})_{iso} = (\Delta T_{min})_{iso} + T_s$

Henry concluded that his correlation is more general and more accurate than either Berenson's prediction or that of Spiegler et al.¹⁶⁾ since both Berenson and Spiegler models assumed an isothermal surface. However, at the elevated pressure, the Henry's predictions are far greater than the measured values shown in Fig. 8.

Baumeister and Simon⁸⁾ considered the liquid surface energy to relate the measured Leidenfrost temperature with the value predicted by Spiegler

et al.¹⁶⁾. The equation is

$$T_{0, \text{meas}} = \frac{\frac{27}{32} T_c \left\{ 1 - \exp \left(-0.52 \left(\frac{10^4 (\rho/A_t)^{4/5}}{\sigma_{lv}} \right)^{1/3} \right) \right\} - T_l}{\exp(0.00175\beta) \operatorname{erfc}(0.042\beta)} - T_l \quad (16)$$

Parameters used in the correlation are

$$\beta = \frac{1}{(k\rho c)_w}$$

$$\text{and surface parameter} = \frac{(\rho/A_t)^{4/3}}{\sigma_{lv}}$$

where ρ is solid density, A_t atomic weight, σ_{lv} the liquid-vapor interfacial energy and all the properties are in CGS units. Baumeister equation is not so easy to use as Henry's equation. However, the important feature of Eq. (16) is the inclusion of surface parameters to account for wetting energy.

3.3. Empirical Correlation

The knowledge of the Leidenfrost temperature is required to predict the progress of quench front during reflood stage after a loss of coolant accident in PWR. Up to now many correlations for the Leidenfrost temperature are available on the reflood study. Most of correlations are obtained as function of water subcooling. Performing bottom flooding experiments with subcooled water on stainless steel and inconel tubes at atmospheric pressure, Kim and Lee²¹⁾ obtained an empirical correlation using the dimensional analysis as

$$T_0 = 19.51 \times (T_w - T_s) \times \left(\frac{T_s - T_l}{T_w - T_s} \right)^{0.107} \times \left(\frac{c_p \cdot G \cdot \rho}{k} \right)^{-0.162} \times \left[\frac{k\rho^2(T_w - T_s)}{\delta \cdot G^3} \right]^{-0.0989} \times \left(\frac{z}{\delta} \right)^{-0.163} + T_s \quad (17)$$

where the temperatures are expressed in °K. They concluded that the correlated values fall within $\pm 10\%$.

Siegel and Carbajo²²⁾ proposed a correlation based on experimental data from the Semiscale and PWR-FLECHT tests.

$$T_{\min} = (10 + \ln q') (8.49 + 2.8 \ln p) U^{0.029}$$

$$\times (0.00309 T_{\text{PEAK}} + 0.452) \quad (18)$$

with the following conditions and units

Pressure (p) = 1.38 to 4.14 bar

Peak temperature (T_{PEAK}) = 350 to 1,200°C

Subcooling = 0°C (Saturation)

Water velocity (U) = 0.003 to 0.033 m/s
(possible up to 0.1 m/s)

linear heat generation rate (q') = 0.5 to 40 kW/m

Kalinin et al.²³⁾ found the following empirical relation

$$\frac{T_0 - T_s}{T_c - T_l} = 1.65 \left\{ 0.1 + 1.5 \left[\frac{(k\rho c)_l}{(k\rho c)_w} \right]^{0.25} + 0.6 \left[\frac{(k\rho c)_l}{(k\rho c)_w} \right] \right\} \quad (19)$$

with range described in Ref. 23).

This correlation fits his experimental results within $\pm 35\%$. It is significant to note that he did not find any effect of liquid velocity.

4. Effect of Parameters on the Leidenfrost Temperature

All theoretical predictions for the quenching process by the various models require the knowledge of the Leidenfrost temperature. Any errors in the prediction of the Leidenfrost temperature lead to a significant uncertainty in the theoretical predictions. Thus it is of interest to discuss the parameters which affect the Leidenfrost temperature. There are a number of experimental factors that may be accounted for the large variations in the measured values of the Leidenfrost temperature reported in Table 1.

4.1. Surface material and condition

With regard to the properties of the surface material it is expected that the thermal diffusivity of the material is one of the important factors influencing the Leidenfrost temperature as the result of transient liquid-solid contact. Emmerson²⁴⁾ investigated the influence of the thermal diffusivity by three surfaces of material

〈Table 1〉 Summary of Reported Leidenfrost Temperature under Atmospheric Pressure.

Ref. No	Fluid	Experimental Type	Surface Material	Surface Condition	T_s (°C)	T_o (°C)	$T_o - T_s$ (K)	Remarks
5	Water	Droplet 0.0154/0.032ml	Stainless Steel	—	100	280	180	No effect of mass volume
24	"	Droplet 0.0293ml	"	Roughness 0.31 μ m	100	282	182	
6	"	Droplet 0.032/6ml	"	Roughness 3~4rms μ in	100	305/325	205/225	No effect of subcooling
25	"	Droplet 3.29mm dia	"	Smooth	100	290	190	
24	"	Droplet 0.0293ml	Monel	Roughness 0.28 μ m	100	315	215	
24	"	"	Brass	Roughness 0.3 μ m	100	284	184	
6	"	Droplet 6ml	"	Roughness 3~4rms μ in	100	200	100	Fresh polish surface
6	"	Droplet 0.032/6ml	"	"	100	230/235	130/135	Normal surface
25	"	Droplet 3.29mm dia	"	Smooth	100	178	78	
6, 8	"	Droplet 0.032/6ml	Aluminium	Roughness 3~4rms μ in	100	155/200	55/100	
6, 8	"	"	"	"	100	230/235	130/135	
6, 8	"	Droplet 6ml	"	Roughness 25rms μ in	100	265	165	
27	"	Droplet 0.011ml	Gold plated copper	Lapped	100	283	183	
27	"	"	"	Sand blasted	100	305	205	
27	"	Droplet 0.035ml	"	"	100	245	145	
6	"	Droplet 6ml	Gold	Fresh polish very smooth	100	184	84	
25	"	Droplet 3.29mm dia	Carbon steel	Smooth	100	195	95	
25	"	Pool/Plate	Aluminium	No. O emery finish	100	258	158	
16	"	Pool/Rod	Copper	—	100	283	183	Cu-rod, 25mm ϕ
16	"	"	"	—	100	255	155	Cu-rod, 50mm ϕ
33	"	Pool/Wire	Platinum	—	100	150	50	Boiling Curve by q_{min} not clear pt 0.13mm ϕ
20	"	Pool/Sphere	Copper	—	100	456	356	Boiling Curve by q_{min} $T_l=95^\circ\text{C}$
20	"	"	"	—	100	578	478	Boiling Curve by q_{min} $T_l=53.3^\circ\text{C}$
20	"	"	"	—	100	655	555	Boiling Curve by q_{min} $T_l=26.6^\circ\text{C}$
34	"	Spray/Plate	Nickal	—	100	257	157	
32	Freon 11	Pool/Plate	Aluminium	No. O emery finish	23.8	112.7	88.9	
35	"	Pool/Rod	Stainless Steel	"	23.8	102	78.2	
35	"	Pool/tube	Nickel	"	23.8	121	97.2	
35	"	"	Chrome plated Copper	"	23.8	127	103.2	
36	Freon 13	Pool/plate	Aluminium	—	47.6	126	78.4	

Ref. No	Fluid	Experimental Type	Surface Material	Surface Condition	T_i (°C)	T_o (°C)	$T_o - T_i$ (K)	Remarks
6.8	Ethanol	Droplet 0.0125ml	Stainless Steel	Roughness 3~4rms μ in	78.5	190	111.5	
22	"	Droplet 0.006/0.014ml	"	—	78.5	178.5	100	
6.8	"	Droplet 0.0125ml	Aluminium	Fresh polish 3~4rms μ in	78.5	157	78.5	
6.8	Ethanol	Droplet 0.0125/6ml	Aluminium	Roughness 3~4rms μ in	78.5	155/157	76.5/78.5	
5	Carbontetrachloride	Droplet 0.00913ml	Stainless Steel	—	78	235	157	
36	"	Pool/Plate	Aluminium	—	78	159	81	
12	"	"	Copper	—	78	156	78	
5	Benzene	Droplet 0.0162/0.00748ml	Stainless Steel	—	80.1	185.1	105	
12	Pentane	Pool/Plate	Copper	—	35.7	96.7	61	
12	"	Pool/Plate	Inconel	—	35.7	101.7	66	
12	"	"	Nickel	—	35.7	96.7	61	
37	Liquid N ₂	Pool/Tube	Copper	500 emery Polish	-195.8	-178/-174.6	17.1/21.1	Cleansed with acetone
38	"	"	"	—	-195.8	-147.8	48	Cleansed with HCl, dry with acetone
39	"	Pool/Plate	"	—	-195.8	-175.8	20	

such as stainless steel, brass and monel and reported that the Leidenfrost temperature is independent of the thermal diffusivity and is probably dependent on the wettability of the hot surface which the forming and breaking of liquid contact at the heating surface is controlled by wettability. Patel and Bell¹⁹⁾ and Michiyoshi and Makino⁴⁰⁾, however, found that a higher thermal diffusivity of the surface material yields a lower Leidenfrost point.

Most important surface effects are roughness, oxidation or crud deposits, contact angle and surface tension. Bradfield²⁵⁾ showed that the intermittent liquid-solid contact exists during Leidenfrost phenomenon and contact is dependent on the surface roughness and the nature of the heat flow is strongly influenced by surface characteristics. Iloeje²⁶⁾ found the following theoretical relationship and no conflicting tendencies in the fact that the value of ΔT_{min} increases as surface roughness increases.

$$\frac{\epsilon}{\Delta T_{min}^{1/3}} = \text{Constant} \quad (17)$$

Surface roughness effect was manifested by the necessity for Baumeister and Simon⁶⁾ to use the liquid surface energy parameter to correct the Leidenfrost temperature. They found that the Leidenfrost temperature of water on freshly polished surfaces to be about 152°C, which is nearly 75°C lower than that on the conventional contaminated surface. Thus a thin coat of fouling could make a 75°C difference in the Leidenfrost temperature. They believed that this surface fouling effect seems to be brought on by the reaction of water with the fresh surface or by deposits from dissolved salts which form a residue on the surface after some liquid vaporizes.

The surface condition of the hot surface should be considered separately to determine more properly the effect of metal roughness fouling and surface oxidation. Cumo et al.²⁷⁾ argued that the roughness itself should not

have a great influence on the Leidenfrost point since it apparently has no effect on burnout.

Fouling insulating layers, instead, inhibit heat transfer to the droplet during contact periods. Oxidation increases the wettability of the surface via reduction in the contact angle since decreasing the contact angle increases the wettability of the surfaces.

4.2 Drop size

Baumeister and Simon^{6,8)} confirmed, experimentally and analytically that the Leidenfrost temperatures on aluminum and brass was nearly independent of the initial drop volume while that on stainless steel was sensitive to the initial drop volume. Gottfried et al.⁷⁾ concluded that Leidenfrost temperature on the stainless steel is found to be essentially independent of drop size for the range up to 0.032ml.

4.3 Subcooling

Experimental results from drop evaporation tests in Ref. 6,8) confirmed that Leidenfrost temperature is independent of subcooling and except for the non-isothermal glass surface the subcooling effect is seen. It is likely that subcooling of drops depends upon the enthalpy of evaporation. It is clear that in the case of water at atmospheric pressure the enthalpy of evaporation accounts for the major fraction of the heat transmitted to the vapor film. Consequently, the water drop at atmospheric pressure can be expected to be relatively insensitive to subcooling. Bradfield²⁵⁾ suggested that subcooling has a strong effect on the Leidenfrost temperature for a solid sphere copper in a pool. This observation is consistent with the finding of Farahat and Armstrong²⁸⁾ for stainless steel spheres in water. It can be noted that the difference between pool and drop tests is due to the fact that small subcooled liquid drops quickly heat to the saturation temperature. Bradfield²⁵⁾ concluded that, for pool boiling, increasing subcooling results in a shift of the

transition curve toward higher wall superheats. According to his data, a correlation is expressed as

$$T_o = T_s + 177 + 6.5 \Delta T_{\text{sub}} \quad (20)$$

This correlation is similar to the form proposed by Hein and Liebert.²⁰⁾

$$T_o = T_s + 160 + 10 \Delta T_{\text{sub}} \quad (21)$$

The correlations presented above imply the strong effect of subcooling on the Leidenfrost temperature.

4.4 Pressure

It can be expected that the pressure influences the Leidenfrost temperature, just as the saturation temperature varies. A clear increase in rewetting rate with increasing pressure was observed in flooding experiments by many workers²⁹⁾. It has been well known that this effect is a result of increasing the Leidenfrost temperature with pressure.

Emmerson²⁴⁾ concluded by the experiments in the pressure range up to 5 bar that the Leidenfrost temperature increases with pressure since the latent heat of vaporization decreases with increase in pressure. In the case of the stainless steel, it increases markedly as the pressure increases as shown in Fig. 13. He also found that effects of pressure on the Leidenfrost temperature result from increasing the wettability rather than from varying the thermal diffusivity of the heating surface.

Recently Emmerson and Snock³⁰⁾ conducted an experimental study, dealing with effects of

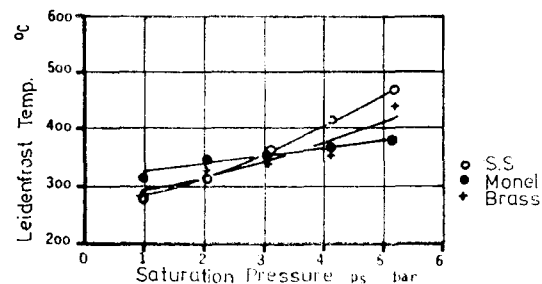


Fig. 13. Effect of Saturation Pressure on the Leidenfrost Temperature.

pressure ranging to the critical pressure on the Leidenfrost temperature of discrete drops of Freon and suggested a dimensionless correlation of the form:

$$\frac{T_s}{T_o} \text{ VS } \frac{P_o}{P_c} \quad (22)$$

as plotted in Fig. 14.

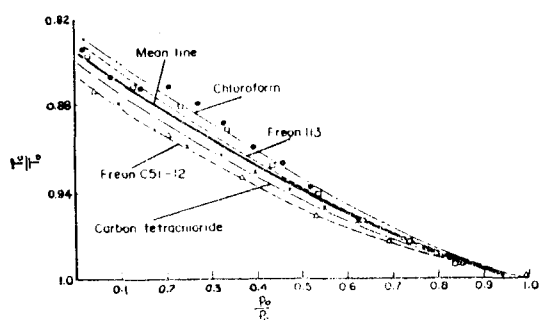


Fig. 14. Dimensionless Leidenfrost Correlation for Organic Liquids.

This correlation serves very well for each of the organic liquids except in the case of water.

Hein and Liebert²⁰ conducted the experiments to investigate the pressure effects in a range up to critical pressure for Freon 12 and suggested that when the pressure rises the value of the temperature difference between the Leidenfrost and the saturation temperature, $(T_o - T_s)$ decreases due to the contraction of fluid superheating rate.

As shown in Fig. 15, the difference between the Leidenfrost temperature and the saturation temperature at any given pressure below about

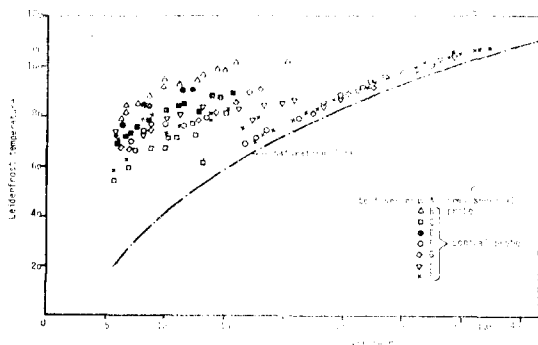


Fig. 15. Leidenfrost Temperature as a Function of Pressure for Freon 12.

17–20 bar remained nearly constant. Above that pressure, the difference rapidly decreased. This tendency is also observed in experiments³¹ for the case of water although the data above 40 bar is scattered in Fig. 16.

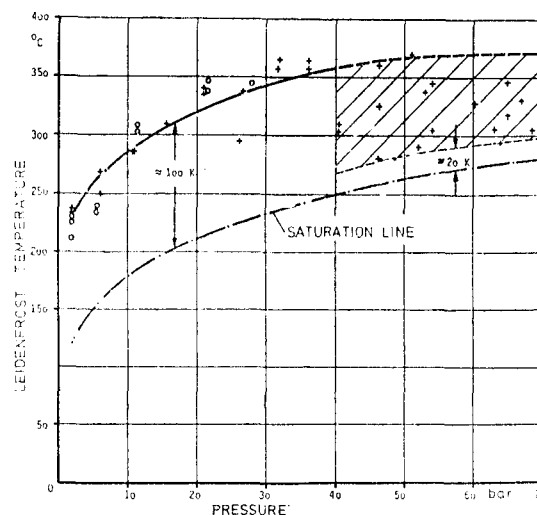


Fig. 16. Leidenfrost Temperature as a Function of Pressure for Water.

The sudden change to lower Leidenfrost temperature above a certain pressure range seems to be caused by the boiling fluid hydrodynamics. More work is required to determine under what conditions the sudden change occurs since this trend is not desirable in the reactor safety point of view. To find the reliability of measuring methods, Fig. 17 compared the Lei-

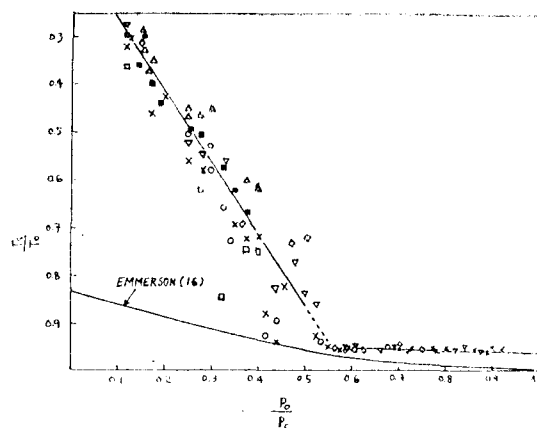


Fig. 17. Comparison of Leidenfrost Data at the Elevated Pressure to Freon 12 (Droplet Evaporation in Nitrogen Environment)

denfrost data of Hein and Liebert's result²⁰⁾ with Emmerson and Snock's results³⁰⁾ by using the mean data line and showed the significantly different behaviour of the Leidenfrost temperature at the elevated pressures.

The Leidenfrost data under high pressure conditions have been limited due to the difficulty in the experiments. Thus it is required to develop the advanced techniques to predict the Leidenfrost phenomenon in the elevated pressure conditions.

5. Conclusions

From this review work it is clear that experimental and analytical studies provide the consistent knowledge about the Leidenfrost phenomenon. In addition, the theoretical predictions with the flat bottom model agree with the general experimental trends of vaporization time. However, significant differences still occurs in predicting the Leidenfrost temperature.

Further work is needed to predict the Leidenfrost phenomenon at the elevated pressures and quenching with a high velocity impinging jet.

It is also interesting to investigate the surface effect of a heater rod or fuel rod with an oxidation layer used in reflood tests.

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Nomenclature

A_i atomic number
 c specific heat
 d thermal boundary layer thickness
 G mass flow rate
 h heat transfer coefficient

h_{fg} latent heat of evaporation
 k thermal conductivity
 l equivalent thickness of a flat drop
 p pressure
 P_c critical pressure
 Pr reduced pressure P/P_c
 Q_c total heat conducted through the vapor film
 Q_{R1} net radiation from plate to lower half of droplet
 Q_{R2} net radiation from plate to upper half of droplet
 q heat flux
 q' linear heat generation rate
 r_{max} maximum radius of drop
 T temperature
 T_c Critical temperature
 T_o Leidenfrost temperature
 Tr reduced temperature T/T_c
 T_s saturation temperature of liquid
 Tw wall temperature
 tc mean contact time of liquid and hot surface
 U water velocity
 V Volume
 V_o molar volume of the metal
 V_c critical volume
 V_r reduced volume V/V_c
 W_1 rate of evaporation over lower half of droplet
 W_2 rate of evaporation over upper half of droplet
 Z axial distance from the inlet
 α thermal diffusivity
 δ wall thickness
 λ heat of vaporization of saturated liquid
 λ_D most dangerous wave length
 μ viscosity
 ρ density
 σ surface tension
 ϵ surface roughness

Subscripts

iso isothermal
 l liquid
min minimum
 s saturation
sub subcooling
 v vapor
 w wall

References

- 1) Leidenfrost, J.G., "On the Fixation of Water in Diverse Fire", *Int. J. Heat Mass Transfer*, Vol. 9, p. 1153-1166 (1966).
- 2) Bell, K.J. "The Leidenfrost Phenomenon: A Survey" *Chemical Engineering Progress Symposium Series*, 63(79), p. 73-82 (1967).
- 3) Hsu, Y.Y., "A Review on Film Boiling", *Int. Advances in Cryogenic Eng.*, Vol. 17, p. 361-381 (1972).
- 4) Liebert, H., "Untersuchungen zur Druckabhängigkeit der Leidenfrosttemperatur", Diplomarbeit, Techn. Univ. München (1976).
- 5) Gottfried, B.S., Lee, C.J. and Bell, K.J., "The Leidenfrost Phenomenon: Film Boiling of Liquid Droplets on a Flat Plate" *Int. J. Heat Mass Transfer*, Vol. 9, p. 1197-1187 (1966).
- 6) Baumeister, K.J. and Simon, F.F., "Role of the Surface in the Measurement of the Leidenfrost Temperature," *Augmentation of Convective Heat and Mass Transfer*, ASME, New York, p. 91-101 (1970).
- 7) Baumeister, K.J., Hamill, T.D. and Schoessow, G.J., "A Generalized Correlation of Vaporization Times of Drops in Film Boiling on a Flat Plate", *Proc. 3rd. Int. Heat Trans. Conf.* Vol. 4, p. 66-72 (1966).
- 8) Baumeister, K.J. and Simon, F.F., "Leidenfrost Temperature; Its Correlation for Liquid Metals, Cryogenics, Hydrocarbons and Water", *J. of Heat Transfer*, Trans. ASME, 5C (2) p. 166-173 (1973).
- 9) Wachters, L.H.J. et al., "The Heat Transfer from a Hot Horizontal Plate to Sessile Water Drops in the Spheroidal State", *Chem. Eng. Sci.*, Vol. 21, p. 923-936 (1966).
- 10) Bankoff, S.G. and Mehra, V.S., "A Quenching Theory for Transition Boiling", *I. & E.C. Fundamentals*, Vol. 1, No. 1 (1962).
- 11) Carslaw, H.S. and Jaeger, J.C., "Conduction of Heat in Solids", 2nd ed., p. 88, Oxford Univ. Press (1959).
- 12) Berenson, P.J., "Experiments on Pool-Boiling Heat Transfer", *Int. J. Heat Mass Transfer*, Vol. 5, p. 985-999 (1962).
- 13) Zuber, N., "Stability of Boiling Heat Transfer", *Trans. ASME*, 80, p. 711-720 (1958).
- 14) Berenson, P.J., "Film Boiling Heat Transfer from a Horizontal Surface", *J. of Heat Transfer*, *Trans. ASME*, 83, p. 351-358 (1961).
- 15) Henry, R.E., "A Correlation for the Minimum Film Boiling Temperature", *AIChE Symp. Ser.* 70, 138, p. 81-90 (1974).
- 16) Spiegler, P. et al., "On-Set of Stable Film Boiling and the Foam Limit", *Int. J. Heat Mass Transfer*, Vol. 6, p. 987-994 (1964).
- 17) Gunnerson, F.S. and Cronenberg, A.W., "On the Thermodynamic Superheat Limit for Liquid Metals and its Relation to the Leidenfrost Temperature", *J. Heat Transfer*, *Trans. ASME*, Vol. 100. (1978).
- 18) Yao, S.C. and Henry, R.E., "An Investigation of the Minimum Film Boiling Temperature on Horizontal Surface", *J. Heat Transfer*, *Trans. ASME*, Vol. 100 (1978).
- 19) Patel, B.M. and Bell, K.J., "The Leidenfrost Phenomenon for Extended Liquid Masses", *Chem. Eng. Prog. Symp.*, Vol. 62 (64), p. 62-71 (1966).
- 20) Hein, D. and Liebert, H., "The Influence of Pressure on the Leidenfrost Temperature for Freon 12", Paper presented at the European Two-Phase Flow Group Meeting, Erlangen (1976).
- 21) Kim, A.K. and Lee, Y., "A Correlation of Rewetting Temperature", *Lett. Heat and Mass Transfer*, Vol. 6, p. 117-123 (1979).
- 22) Siegel, A.D. and Carbajo, J.J., "A New Empirical Correlation for the Rewetting Temperature", *Trans. ANS*, p. 327-328 (1980).
- 23) Kalinin et al., "Investigation of the Crisis of the Crisis of Film Boiling in Channels", *Proc. of "Two-Phase Flow and Heat Transfer in Rod Bundles"*, Winter Annual Meeting of ASME, Los Angeles, Calif (1969).
- 24) Emmerson, G.S., "The Effect of Pressure and Surface Material on the Leidenfrost Point of Discrete Drops of Water", *Int. J. Heat Mass Transfer*, Vol. 18, p. 381-386 (1975).
- 25) Bradfield, W.S., "Liquid-Solid Contact in Stable Film Boiling", *I. & E.C. Fundamentals*, Vol. 5,

- No. 2 (1966).
- 26) Iloeje, O.C., "A Study of Wall Rewet and Heat Transfer in Dispersed Vertical Flow", MIT Ph. D. Thesis (1975).
 - 27) Cumo, M., Farello, G.E. and Ferrari, G., "Notes on Droplet Heat Transfer", Chem. Eng. Prog. Sym. Ser. 65(92), p. 175-187 (1969).
 - 28) Farahat, M.M. and Armstrong, D.R., "Transient heat transfer between hot metal spheres and subcooled water", *Atomkernenergie (ATKE)*, Vol. 29(1) (1977).
 - 29) Sawan, M.E. and Carbon, M.W., "A Review of Spray-Cooling and Bottom-Flooding Work for LWR Cores", Nuc. Eng. Des. 32, p. 191-207 (1975).
 - 30) Emmerson, G.S. and Snoek, C.W., "The Effect of Pressure on the Leidenfrost Point of Discrete Drops of Water and Freon on a Brass Surface", *Int. J. Heat Mass Transfer*, Vol. 21, p. 1081-1086 (1978).
 - 31) Liebert, H. and Schneider, E., "Bestimmung der Leidenfrost Temperatur bis zum Betriebsdruck von Dampferzeugern", Techn. Report KWU/R 513/4/77 (1977).
 - 32) Hosler, E.R. and Westwater, J.W., "Film Boiling on a Horizontal Plate", *ARS Journal*, Vol. 32 (9), p. 553-558 (1962).
 - 33) Peterson, W.C. and Zaalouk, M.G., "Boiling Curve Measurements from a Controlled Heat Transfer Process", *J. Heat Transfer*, Trans. ASME, 93c(4), p. 408-412 (1971).
 - 34) Cumo, M. and Pitimado, D., "On the Determination of the Leidenfrost Temperatures", *Thermotechnica*, Vol. 22, No. 8, p. 373-381 (1968).
 - 35) Stock, B.J., "Observations on Transition Boiling Heat Transfer Phenomena", ANL-6175 (1960).
 - 36) Kautzky, D.E. and Westwater, I.W., "Film Boiling of a Mixture on a Horizontal Plate", *Int. J. Heat Mass Transfer*, Vol. 10, p. 253-256 (1967).
 - 37) Bergles, A.E. and Thompson, W.G., "The Relationship of Quench Data to Steady-State Pool Boiling Data", *Int. J. Heat Mass Transfer*, Vol. 13, p. 55-68 (1970).
 - 38) Flynn, T.M., Draper, J.W. and Roos, J.J., "The Nucleate and Film Boiling Curve of Liquid Nitrogen at one Atmosphere", *Advances in Cryogenic Eng.*, Vol. 7, Plenum, New York (1962).
 - 39) Peyayopanakul, W. and Westwater, J.W., "Evaluation of the Unsteady-State Quenching Method for Determining Boiling Curves", *Int. J. Heat Mass Transfer*, Vol. 21, p. 1437-1445 (1978).
 - 40) Michiyoshi, I. and Makino, K., "Heat Transfer Characteristics of Evaporation of a Liquid Droplet on Heated Surfaces", *Int. J. Heat Mass Transfer*, Vol. 21, p. 605-613 (1978).