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ON THE TRANSPLOSION PHENOMENON AND THE LEIDENFROST TEMPERATURE FOR THE MOLTEN COPPER–WATER THERMAL INTERACTION

WIKTOR ŻYSZKOWSKI*
Institute of Nuclear Research, Swierk near Warsaw, Poland

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Abstract—Inverse Leidenfrost phenomenon for molten metal (copper)–water system is considered. Transplosion occurred in series of 120 tests with molten copper in the temperature range between 160 and 750°C for water of 20°C and atmospheric pressure.

Analytical correlations for the Leidenfrost temperature based on the hydrodynamical- or thermodynamical approach are compared. The thermodynamical correlation describes better results for smooth surfaces and "stable courses" of the molten copper cooling. The hydrodynamical correlation seems to give the upper limit of the Leidenfrost temperature, if some effects disturb the cooling process.

The influence of such factors as nature and roughness of the surface material, metastable state of liquid, wettability of the hot surface, and cold liquid subcooling is discussed.

NOMENCLATURE

A,	atomic weight;
a,	dimensionless "direct contact"-parameter, equation (6);
b,	dimensionless pressure parameter, equation (13);
c_p,	heat capacity;
g, g_c,	gravity constant, and gravitational conversion constant, respectively;
h, h^*, h_m,	latent heat of vapourization: normal, modified, and molecular, respectively;
J,	rate of nucleation, equation (12);
Ja^*,	"quasi-Jakob" number, equation (7);
K,	contact model term;
k,	Boltzmann constant;
l,	vapour dome spacing parameter, equation (4);
m_N,	mass of liquid molecule;
N,	frequency of results;
p,	pressure;
s,	parameter, equation (12);
T,	temperature;
$\bar{T}$,	mean square value of temperature T;
t_b,	characteristic time, equation (17);
Z_1,	number of molecules per unit volume of liquid.

Greek symbols

$\bar{\alpha}$,	time-average heat-transfer coefficient;
β,	$= 1/\lambda\rho c_p$—material parameter;
ϕ,	$= T_{Sa}/T_{SN}$;
λ,	thermal conductivity;
μ,	viscosity;
ω,	parameter, equation (13);
ρ,	density;
Σ,	parameter, equation (10);
σ,	surface tension or standard deviation;
Θ,	dimensionless parameter, equation (5);
θ,	contact angle, equation (15).

Subscripts

CL,	cold liquid;
cr,	critical;
HM,	hot material;
iso,	isothermal;
L,	Leidenfrost;
l,	liquid;
max,	maximum;
min,	minimum;
MS,	metastable;
P,	transition;
real,	real value;
Sa,	saturation;
SN,	spontaneous nucleation;
v,	vapour;
I, II, III, IV,	regions in Figs. 2 and 3.

1. INTRODUCTION

A STUDY of the thermal interaction of the "molten metal/cold liquid" system is of interest for investigations into nuclear reactor safety [39]. Thermal explosion in the reactor core is considered for some hypothetical conditions requiring that the phenomenon be understood. Among the thermal aspects which may be important for the thermal explosion is the nature of the Leidenfrost phenomenon for the molten metal/cold liquid system.

Investigation of thermal interaction by means of the small metal drop experimental technique showed two main types of heat transfer for molten copper–water thermal interaction: "normal course", and thermal explosion [42]. The first type, the normal course of

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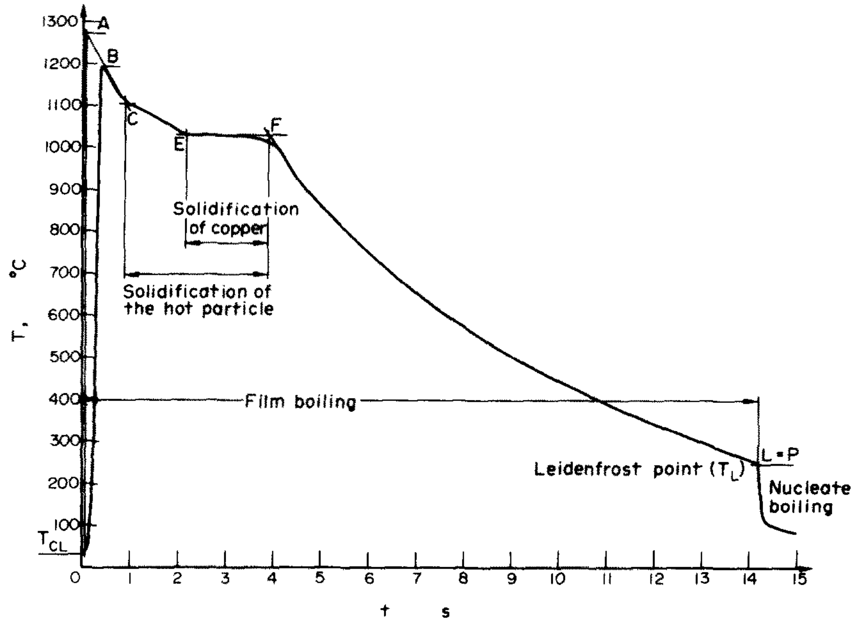

FIG. 1. Typical cooling history of the molten copper particle in water. (Mass of copper = 0.567 g. Copper was molten in air atmosphere.)

heat transfer, mainly relates to the cases where the hot material solidifies in a more or less regular form and no fragmentation is observed. On the other hand, thermal explosion is characterized by strong fragmentation of copper, rapid expulsion of substances from the thermal interaction zone and a high heat-transfer rate.

The normal course for molten copper–water thermal interaction begins with film boiling and via transition, and nucleate boiling results in pure convection and in the equilibrium state. The single processes of the normal course are satisfactorily described in literature, but some questions arise when thermal interaction of molten substances is considered. An important problem is the mechanism of transplosion [32] (Leidenfrost phenomenon), i.e. the mechanism of transition from film into nucleate boiling (with more or less short transition boiling), and the value of the Leidenfrost temperature.

In this paper some aspects of the transplosion phenomenon are discussed for the molten copper–water system. Transplosion occurred at the surface of small copper particles and, therefore, it can be called the inverse Leidenfrost phenomenon [20] in comparison to the classical Leidenfrost experiments with water drops on a hot plate.

2. EXPERIMENTAL RESULTS AND OBSERVATIONS

Below a certain copper temperature, the vapour generated at film boiling is not great enough to supply the amount required by growth and bubble departure rates, and transition from film into nucleate boiling (transplosion) occurs. It has a violent "implosive" character. Small scale metal drop experiments were performed to study this phenomenon. The experimental technique was described in [42]. In series of tests, the heating time of molten copper particles was varied. The heating process was conducted by means of a levitation coil in air or inert gas atmosphere (Ar or N_2). Then, the molten copper particle dropped into a small vessel filled with water, and molten copper–water thermal interaction began. The characteristic cooling history is shown in Fig. 1. Here, the Leidenfrost point is considered to mean the point L of the abrupt change in the slope of the temperature curve. This is the end of the film boiling regime. For some temperature measurements, the change of this slope is more gradual, and two characteristic temperatures, T_L and T_P, can be distinguished. Temperature T_P means beginning of the nucleate boiling regime.

The measurements carried out in this study indicate that transplosion can take place in the molten copper–water system in any point (Leidenfrost point) of a wide temperature range during the film boiling regime. Figures 2 and 3 show the bar charts of measurements, of the Leidenfrost temperature (T_L), and the transition temperature (T_P), respectively, for Cu/H_2O tests and also mean square values $\bar{T}_L$, $\bar{T}_P$ and standard deviations σ from the experimental results. The measurements were made with standard chromel–alumel thermocouples of the ground-type of 0.5 mm O.D. encased in a steel sheet lined with MgO insulating material. The thermocouple was located in the molten copper drop of about 0.5 g weight. The copper drop interacted thermally with about 20 ml of water the initial temperature of which was 18–22°C. The temperatures were transient and recorded by means of a high speed (500 Hz) digitizing system [42]. The thermometric lag of the thermocouples was 6–14 ms. The correction of the temperature measurements by the first derivative term [40], which is to take into account for the thermometric lag, shows the difference of about ±2.5°C existing between the measured and the corrected temperature values.

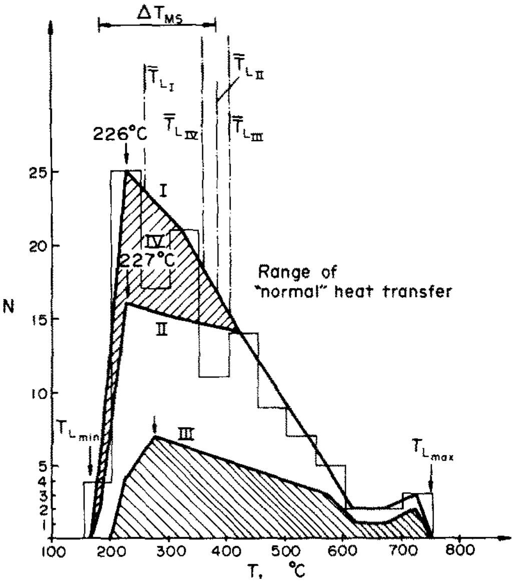

FIG. 2. Bar chart of the Leidenfrost temperature, T_L, measured in the copper–water tests. Curve I—summary of all results (in air and in inert gas atmosphere); $\bar{T}_{L,I} = 360°C$ ($N = 120$, $\sigma = 134°C$). Curve II—measurements in air; $\bar{T}_{L,II} = 385°C$ ($N = 96$, $\sigma = 134°C$). Curve III—results for irregular surface of the particle; $\bar{T}_{L,III} = 406°C$ ($N = 34$, $\sigma = 147°C$). Field IV—measurements in inert gas atmosphere; $\bar{T}_{L,IV} = 262°C$ ($N = 24$, $\sigma = 72°C$).

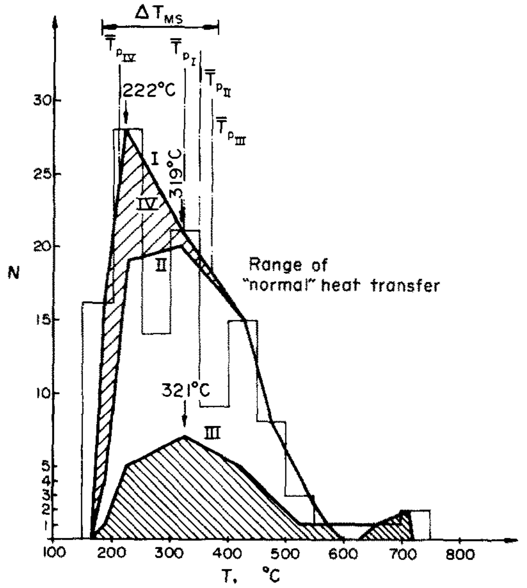

FIG. 3. Bar chart of the transition temperature, T_P, measured in the copper–water tests. Curve I—summary of all results (in air and in inert gas atmosphere); $\bar{T}_{P,I} = 322°C$ ($N = 119$, $\sigma = 121°C$). Curve II—measurements in air; $\bar{T}_{P,II} = 349°C$ ($N = 96$, $\sigma = 118°C$). Curve III—results for irregular surface of the particle; $\bar{T}_{P,III} = 372°C$ ($N = 34$, $\sigma = 142°C$). Field IV—measurements in inert gas atmosphere; $\bar{T}_{P,IV} = 208°C$ ($N = 23$, $\sigma = 42°C$).

The lowest value measured of the Leidenfrost temperature was $T_{L\min} = 165°C$, and the highest $T_{L\max} = 750°C$. The frequency distribution curve of the temperature measurements as a function of the copper temperature has its maximum at 226°C for the Leidenfrost temperature (Fig. 2), and at 222°C for the transition temperature (Fig. 3).

Curve I in Figs. 2 and 3 represents a generalized frequency distribution curve of all 120 results in these experiments as a function of the measured values of the Leidenfrost and transition temperatures. Part of these measurements were made in air atmosphere (curve II in Figs. 2 and 3), i.e. the copper particles were melted in air before thermal interaction, and part were made in an inert gas atmosphere [42]. The results of the measurements performed in inert gas atmosphere therefore correspond to field IV between the curves I and II in Figs. 2 and 3.

The solidification process took place during the cooling history of the molten copper particle. This process sometimes resulted in an irregular broken surface of the copper particle or caused some sort of fins to be formed (solidified "jets" from the molten metal into the surrounding water [41, 42]). Curve III in Figs. 2 and 3 shows the Leidenfrost- and transition temperature measurements for the irregular surface of the particles. The field between curves I and III illustrates the results for smooth surface particles.

The transplosion phenomenon seems to have a random character for the molten copper–water system. Before transplosion occurs by "normal" heat transfer, some destabilization of the vapour film was observed. Then the vapour film was broken within an interval well below 0.3 ms. A "cloud" of small air (or inert gas) bubbles dispersed from the particle surface.* Acoustic effects and strong disturbances of the surrounding water were observed during transplosion. The thermocouples in water, 5 mm from the hot copper particles, recorded some temperature peaks at this moment. Similar observations are described in [8, 32, 33].

The foregoing description of the transplosion phenomenon is somewhat in contradiction with the stability analysis given recently in [21]. The stability analysis of the Leidenfrost drop behaviour shows that oscillations of the drop liquid surface occur less readily when the temperature difference decreases between the hot and the cold surfaces.

3. ANALYTICAL CORRELATIONS FOR THE LEIDENFROST TEMPERATURE

Calculations of the Leidenfrost temperature can be based on the hydrodynamical model and combined with the saturation temperature of the liquid (e.g. [4, 7, 23]), or in a different approach, the Leidenfrost temperature can be considered as a thermodynamic property of the liquid in the superheated metastable state and combined with its critical temperature. The simplest of such approaches is based on the Van der Waals equation of state [31]. The formulae derived from these models should be completed by terms taking into account thermal properties of the hot material. The Leidenfrost temperature measured on a real surface ($T_{L,\mathrm{real}}$) is higher than the temperature measured on an

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*Air (or inert gas) originated from the chimney existing when the particle dropped into the cold liquid [42].

isothermal surface ($T_{L,\mathrm{iso}}$), assuming both surfaces have the same finish and wetting characteristics. The parameter characterizing the hot material is $\beta_{HM} = 1/(\lambda \rho c_p)_{HM}$ [2, 3], and it can be written that:

$$T_{L,\mathrm{iso}} = \lim_{\beta_{HM} \to 0} T_{L,\mathrm{real}} \tag{1}$$

where λ, ρ, c_p are the thermal conductivity, the density, and heat capacity, respectively, of the hot material (HM).

This means that the Leidenfrost temperature is considered as the temperature of transplosion and is measured (or calculated) in the hot material. Then, the short duration time of the transplosion phenomenon and a "sudden" change of the heat transfer conditions should be regarded in calculations.

3.1. *Hydrodynamic correlation for the Leidenfrost temperature*

The hydrodynamic Leidenfrost temperature correlation can be derived by combining the expression for the minimum film boiling temperature for pool boiling on a horizontal isothermal surface [5] with the "direct contact" model. Such occasional contact is assumed to exist between the hot and cold substances during transplosion. The isothermal surface expression is based on the assumption that the vapour removal from the surface in film boiling is governed by the Taylor instability [5, 29]. Arguments in favour of the "direct contact" are that in the vicinity of the Leidenfrost point, as the vapour bubble departs from the hot surface, the liquid rushes toward this surface and instantaneously contacts and wets it locally [6]. This short contact causes transient cooling of the hot surface. The amount of cold liquid remaining at the hot material surface is determined by the wetting characteristics of both substances.

From the foregoing considerations follows that the correlation for the Leidenfrost temperature can be written in the following form:

$$T_{L,\mathrm{real}} = (1+\Theta)(T_{Sa} + \Delta T_{\mathrm{min,iso}}) + \Theta T_{CL} \tag{2}$$

where $\Delta T_{\mathrm{min,iso}} \overset{\mathrm{def.}}{=} T_{L,\mathrm{iso}} - T_{Sa}$, the minimum temperature difference above the saturation temperature (T_{Sa}) in film boiling from an isothermal horizontal surface, is calculated from the following formula [5]:

$$\Delta T_{\mathrm{min,iso}} = 0.127 \frac{\rho_v h}{\lambda_v} \left(\frac{\boldsymbol{g}(\rho_l - \rho_v)}{\rho_l + \rho_v} \right)^{2/3} l \left(\frac{\mu_v}{\boldsymbol{g}(\rho_l - \rho_v)} \right)^{1/3} \tag{3}$$

where: h = latent heat of vapourization; ρ_v, ρ_l = specific weight of vapour and liquid, respectively; $\boldsymbol{g}$ = gravity constant; μ_v = vapour viscosity; λ_v = heat-conduction coefficient of the vapour; and l = vapour dome spacing parameter equal to:

$$l = (\sigma_{lv} g_c / (\rho_l - \rho_v) \boldsymbol{g})^{1/2} \tag{4}$$

where: σ_{lv} = surface tension of vapour–liquid surface, and $\boldsymbol{g}_c$ = gravitational conversion constant.

Θ characterizes the temperature drop at the instantaneous direct contact and is calculated by the following formula [23]:

$$\Theta = 0.42(1/a\,Ja^*)^{0.6} \tag{5}$$

where:

$$a = \sqrt{(\beta_{CL}/\beta_{HM})} \tag{6}$$

characterizes the transient heat conduction between the cold liquid (CL) and the hot material (HM), $\beta_{CL} = 1/(\lambda \rho c_p)_{CL}$; and:

$$Ja^* = c_{p,HM} \Delta T_{\mathrm{min,iso}} / h^* \tag{7}$$

"quasi-Jakob number" which characterizes the vapourization process. However, it should be pointed out that the Ja^*-number describes both the hot material and the cold liquid. The heat capacity $c_{p,HM}$ is related to the hot material, while $h^* = h + 0.5 c_{p,CL}(T_{Sa} - T_{CL})$, the modified latent heat of vapourization, and $\Delta T_{\mathrm{min,iso}}$ are related to cold liquid parameters.

3.2. *Thermodynamic correlation for the Leidenfrost temperature*

The thermodynamic correlation for the Leidenfrost temperature can be derived by assuming the maximum possible superheat temperature of the liquid at the transplosion and by combining with an appropriate contact model between the hot and cold substances and the resulting temperature drop in the hot material. Then, the following correlation can be written:

$$T_{L,\mathrm{real}} = (T_{SN} - T_{CL})K + T_{CL} \tag{8}$$

where: T_{SN} means the maximum superheat temperature (or the spontaneous nucleation temperature) of the liquid, and K is a contact model term.

In a simple case, the spontaneous nucleation temperature can be calculated from the minima of the Van der Waals equation. For pressures well below the critical pressure, this temperature can be expressed in the following form [3]:

$$T_{SN} = 27 T_{cr}(1 - \Sigma)/32 \tag{9}$$

where T_{cr} is the critical temperature of the liquid (in °K) and Σ characterizes the role of the surface tension forces at the contact of hot surface with the liquid. For the contact of a pure metal with a liquid, it can be calculated as follows [3]:

$$\Sigma = \exp\left(-0.52(0.1(\rho_{HM}/A_{HM})^{4/3}/\sigma_{lv})^{1/3}\right) \tag{10}$$

where σ_{lv} is the liquid–vapour surface tension evaluated for the metastable state conditions [N/m], and A_{HM}, ρ_{HM} are the atomic weight [kg/mol] and density [kg/m^3] respectively, of the hot material.

The spontaneous nucleation temperature can also be calculated more precisely from the metastable state theory considering the probability of the critical vapour nucleus formation in the superheated liquid [30, 35]. The following implicit relation can be obtained:

$$T_{SN} = T_{Sa}/\{1 + s + \sqrt{[s(2+s)]}\} \tag{11}$$

where:

$$s(T_{Sa}, \omega) = -8\pi f \sigma_{lv}^3 \left(\frac{\rho_l - \rho_v}{\rho_v \rho_l} \right)^2 / 3kh^2 T_{Sa} \ln(J/Z_1 \omega) \tag{12}$$

$$\omega(T_{Sa}, T_{SN}) = (6\sigma_{lv}/(3-b)\pi m_N)^{1/2} \exp(-h_m \phi/k\, T_{Sa}) \simeq 5 \times 10^9\ \mathrm{s}^{-1} \quad (13)$$

$$f = f(v) = (1+\cos v)^2(2-\cos v)/4 \quad (14)$$

$$\cos v = (\sigma_{HM,v} - \sigma_{HM,l})/\sigma_{lv} \quad (15)$$

J is the rate of nucleation, i.e. the number of the nuclei of critical size per unit volume and unit time, which continue to grow to the macroscopic size. This rate is usually assumed to be equal to $1\ \mathrm{n/cm^3\,s}$ [35]; $\phi = T_{Sa}/T_{SN}$; $Z_1 = Z_1(T) = \rho_l/m_N$ is the number of molecules per unit volume of liquid; m_N is the mass of one molecule of the liquid; $b = 1 - p_l/p_{MS}$; p_l, p_{MS} is the pressure of the surrounding liquid and of the liquid at the metastable state, respectively; $h_m = h_m(T) = hm_N$ is the molecular latent heat of vapourization, k is the Boltzmann constant, $\sigma_{HM,v}$, $\sigma_{HM,l}$ is the surface tension between the hot material–vapour and –liquid, respectively.

Calculation of the spontaneous nucleation temperature according to equation (11) increases the result round about 5% in comparison to equation (9) for pressures well below the critical pressure.

The contact model term depends on the geometry and on the assumed cooling model, and e.g. for the "direct contact" of semi-infinite bodies, it has the following form:

$$K = (1+a)/a \quad (16)$$

or for the transient convective cooling of the flat hot material surface [3]:

$$K = 1/\exp(\bar{\alpha}^2 t_b \beta_{HM})\,\mathrm{erfc}[\bar{\alpha}\sqrt{(t_b \beta_{HM})}] \quad (17)$$

where $\bar{\alpha}$ is the time-average heat-transfer coefficient at the transplosion, and t_b is the characteristic time, e.g. the very short time in which the initial transient occurred. The estimated value for small water drops on a hot plate is [3]: $\bar{\alpha}^2 t_b \sim 11\,000\ \mathrm{kJ^2/m^4\,h\,(degC)^2}$.

In Table 1, the results of the numerical calculations according to correlations (2) and (8) are presented for various hot materials and water. For the correlation (8), the formulae (9), (10) and (17) are used.

In Table 2, the experimental results from the literature are specified for the Leidenfrost temperature measurements by means of the "Leidenfrost drop technique" on the hot plate.

A comparison of experimental and calculated results exhibits large discrepancies of the data.

4. DISCUSSION OF THE RESULTS

The temperature registered in these experiments in the hot material particle at the moment of transplosion has a random character and takes a value within the wide temperature range and can also sometimes considerably exceed the critical temperature of the surrounding cold liquid. The experimental results for the Leidenfrost temperature taken from the literature suggest similar conclusions. Analytical correlations allow to calculate some determined values of the Leidenfrost temperature but do not take into account all factors which may influence the molten metal–cold liquid system.

4.1. *Role of the surface material and roughness*

It can be expected that the conditions existing at the surface of the hot material particle decide upon the measured Leidenfrost temperature as well as upon the transplosion itself. For these measurements in which the thermocouple was almost in the centre of the copper particle [42], and the temperature drop in the particle itself was relatively small, the large discrepancies between the values of the Leidenfrost temperature registered in series of tests can be explained by the factors which influence the heat transfer at the hot material surface. One of them which seems to play an important role in these tests is the roughness of the surface, and the second factor is the existence of the oxide contents at the surface of the hot particle. The roughness depends on the processes during solidification of the copper particle. Examination of the particle surface after thermal interaction shows in some cases irregularities or sortes of fins (solidified "jets" [42]). The processes which led to such irregularities are briefly discussed in [42]. The oxide contents in the hot material depends in these experiments on the conditions in which the copper particle was molten. The percentage of the hot particle mass which contains copper oxide can reach about 30% depending on the gas atmosphere and the duration of heating. For the inert gas atmosphere, the oxide content is negligible [42].

The summary of the Leidenfrost temperature measurements presented in Figs. 2 and 3 demonstrates a shift of the measurement results as a function of the hot material surface characteristic and the oxide content in the metal particle as compared with all results. The mean square value $\bar{T}_{LIII} = 406°\mathrm{C}$ can be observed for the "irregular surface" against $\bar{T}_{LI} = 360°\mathrm{C}$ for the "smooth surface" of the particle, and the maximum frequency values: $T_{LIII,\max} = 274°\mathrm{C}$ and $T_{LI,\max} = 226°\mathrm{C}$, respectively. As the "smooth surface" is in this case considered to be the surface of the solidified copper particle without any irregularities visible to the eye, as e.g. slits, "jets", broken subsurfaces, etc.

The effect of the surface material is illustrated by the shift of results of measurements in air and in inert gas atmosphere, which is for the surface with the oxide contents (tests in air) $\bar{T}_{LII} = 385°\mathrm{C}$, and for the pure copper surface (tests in inert gas atmosphere and "smooth surface" of particles) $\bar{T}_{LIV} = 262°\mathrm{C}$. The latter value is in excellent agreement with the value given by equation (8) for copper (Table 1).

Analogous conclusions are possible for the transition temperature measurements.

Similar observations were made in [36] where the influence was studied of the surface nature upon the heat transfer from a hot wall to impinging mist droplets in the spheroidal state. Measurements for methyl alcohol on a hot copper surface, whose finish was smooth, oxidized and roughened, respectively, show an increase in the average heat flux at the hot surface during the impact, and higher threshold temperatures.

The highest value measured in these experiments for the Leidenfrost temperature is in good agreement with

Table 1. Analytical values of the Leidenfrost temperature

						T_{L}, real				
						Eq. (2)			Eq.(8), $T_{CL}=20^{o}C$	
Sub-stance	λ [15,34]	ρ [15]	c_p [15,34]	β	a	$T_{CL}=0^{o}C$	$T_{CL}=20^{o}C$	$T_{CL}=50^{o}C$	$\Sigma = 0$	$\Sigma \neq 0$
	W/m deg C	kg/m³	kJ/kg deg C	m⁴ h deg²C/kJ²	---	°C	°C	°C	°C	°C
Pb	33.5	10850	.131	$5.83 \cdot 10^{-6}$	4.353	1005	1081	1193	387	235
Sn	66.3	7270	.222	$2.60 \cdot 10^{-6}$	6.523	656	700	764	358	230
Au	310	19290	.138	$3.35 \cdot 10^{-7}$	18.175	525	556	602	321	233
Fe	54.7	7850	.490	$1.32 \cdot 10^{-6}$	9.145	426	449	481	341	283
Ag	418	10500	.234	$2.70 \cdot 10^{-7}$	20.24	418	439	471	320	240
Cu	356	8850	.431	$2.04 \cdot 10^{-7}$	23.24	336	350	369	317	262
Mg	157	1700	1.30	$7.97 \cdot 10^{-7}$	11.77	303	314	329	333	166
Al	267	2670	.992	$3.92 \cdot 10^{-7}$	16.79	297	307	322	323	240
PbO	.214	8500	.250	$6.05 \cdot 10^{-4}$	.4264	2410	2620	2930	1010	
SnO_2	25.0	7020	.343	$4.61 \cdot 10^{-6}$	4.897	616	656	714	377	
FeO	.558	5990	.753	$1.10 \cdot 10^{-4}$	1.001	879	944	1040	716	
CuO	3.35	6570	.586	$2.15 \cdot 10^{-5}$	2.265	681	727	794	473	
Cu_2O	4.51	6100	.628	$1.61 \cdot 10^{-5}$	2.622	621	662	721	448	
MgO	20.0	3500	.879	$4.51 \cdot 10^{-6}$	4.949	431	453	486	377	
Al_2O_3	15.0	3900	1.05	$4.54 \cdot 10^{-6}$	4.936	407	427	457	377	

$\beta_{H_2O} = 1.105 \cdot 10^{-4}$ m⁴ h deg² C/kJ² ; $\Delta T_{min,iso} = 89.8$ °C

Table 2. Leidenfrost temperature measurements for water in drop on hot plate experiments

No.	Surface	Water temp. °C	Leidenfrost temp. °C	Reference	Remarks
1	Pyrex glass	100	500	2	.032 ml drop
2	" "	26	> 700	2	"
3	Stainless Steel	26 and 100	285	2	"
4	" "	"	325	2	6 ml drop
5	Aluminium	26	230	2	.032 ml drop
6	"	26 and 100	235	2	6 ml drop
7	Aluminium O-gauge	100	265	2	"
8	Aluminium (fresh polish)	26	155	2	.032 ml drop
9	" "	100	> 200	2	6 ml drop
10	-	-	240	10	35 ml drop; study of wettability
11	Graphite	20	310	7	.0465 ml drop
12	"	85	255	7	"
13	Brass	19	222	7	"
14	"	89	194	7	"
15	Copper	20	250	7	"
16	"	85	237	7	"
17	Stainless Steel	25	285	18	.0265 - .0415 ml drop
18	" "	25	280(250-310)	19	.0154 - .03196 ml drop
19	" "	25	305	28	.05 - 10 ml drop
20	" "	25	320	16	.0058 - .032 ml drop
21	" "	~ 100	265	16	.1 - 8
22	" "	~ 100	161	16	1.5
23	Brass	15	185	25	Ø 12 mm drop /flat/
24	Copper	-	~ 120-400	26	In dependence on droplet diameter and thickness
25	Duraluminium	-	~ 120-240	26	"
26	Permalloy and SS	-	~ 120-400	26	"
27	Glased ceramic plates	-	~ 600	26	
28	Rough ceramic plates	-	~ 800	26	
29	Teflon	-	> melting point	26	
30	Copper		244	14	
31	-		257	11	

the results calculated for the copper oxide surface given by equation (2). However, it should be noted that the copper oxide content usually resulted in the irregularities of the particle surface.

4.2. *Role of the metastable state of liquid*

A liquid can exist in the liquid state until the metastable state limit is reached and spontaneous nucleation occurs upon heating of this liquid. A reciprocal limit upon cooling is assumed in the thermodynamical approach to the Leidenfrost phenomenon [equation (8)]. Some experimental results indicate, however, that the lowest limit of the Leidenfrost temperature is very close to the saturation temperature of the liquid [1]. Often, however, the temperature of about 160°C for water at atmospheric pressure is measured at the first contact between water and the hot surface [4, 7, 10, 16, 17, 19, 22, 25, 36, 37]. It is conceivable that all temperature values from the temperature range between the saturation line and the metastable state limit are admissible and depend on the external and internal disturbances in the system.

These measurements of the Leidenfrost temperature for copper/water thermal interactions demonstrate the importance of disturbances and external factors. The superheat limit of water at atmospheric pressure is $\Delta T_{MS} \simeq 202$°C above the saturation line. Sixty-five per cent of all Leidenfrost temperature measurements (Fig. 2) and 74% of all transition point measurements (Fig. 3) are in the ΔT_{MS}-temperature range counted from the lowest registered value. All measurements made in inert gas atmosphere are in this temperature range.

4.3. *Role of the hot surface wettability*

An important effect on the transplosion phenomenon may be exerted by the wetting characteristic of the hot material surface.

Collapsing of the Leidenfrost drops may be related to the temperature sensitivity of this effect [22]. The Langmuir theory of wetting [38] requires that the solid must acquire an absorbed molecular layer of liquid before wetting can proceed. This depends strongly on the temperature. The survey of the experimental material yields, however, very limited data, depending on such factors as the wetting angle, chemistry and state of the heating surface, dimensions, shape and orientation of the surface in the boiling process [12].

In [10], the influence of the heating wall temperature on wettability was studied experimentally for water droplets on a hot plate. By statistical determinations conducted on numerous pictures, the fraction of the wetted area of the heating wall with respect to the total area hit by the drop was found to be a function of the wall temperature. There is an abrupt decrease in this fraction in the temperature range from 150 to 250°C for water at atmospheric pressure. This results in a definitely lower heat-transfer rate above 250°C. Examination of the pictures did not allow to ascertain whether the drops directly touch (wet) the hot surfaces or whether they are rather insulated from it by a very thin vapour layer.

Dirty surfaces also increase the Leidenfrost temperature [9]. The wetting characteristic of the hot surface plays also an important role in nucleate boiling [27]. If the "liquid-hot material" contact is an important parameter in transition boiling, the contact angle must occur at transplosion. In [8], it has been established experimentally, that liquid–solid contact exists even in the "stable" film boiling regime. The contacts may be periodic (as in case of the bouncing droplets) or continuous, if sufficient roughness exists. The contact occurs more frequently if film boiling approaches transplosion. This observation is, however, in contradiction with the results of the stability analysis given in [21]. The stability analysis of film boiling on vertical surfaces shows that higher surface forces result in the stabilization of the vapour film [24].

The role of surface wettability is expressed in equation (12) by the factor f given by equation (14) which theoretically can take values from 0 to 1 dependent on the "surface tension forces–temperature" characteristic. Thus, the spontaneous nucleation temperature can be equal to the saturation temperature if $f = 0$.

The role of the surface wettability is also described by the factor Σ given by equation (10) [3]. Comparison of the numerical results for $\Sigma = 0$ ($\sigma_{HM,l} = 0$ ideal wettability) and for $\Sigma \neq 0$ according to equation (10) (Table 1) shows considerable reduction of the Leidenfrost temperature for the latter case.

4.4. *Role of cold liquid subcooling*

Some measurements of pool boiling [6, 8, 13] indicate that the Leidenfrost temperature $T_{L,\text{meas}}$ increases linearly with the subcooling. At higher subcooling rates, the vapour blanket is thinner and therefore the heat flux increases.

The Leidenfrost temperature measurements by means of the "liquid drop on the hot plate"-technique indicate that the Leidenfrost point is independent of subcooling [3, 9]. Small subcooled liquid drops heat quickly to the saturation temperature, while a subcooled pool continually draws heat away from the boiling interface.

In these experiments, a statistical character of the Leidenfrost temperature was found, but the limited number of data obtained in the tests performed at various water temperatures suggests only a similar range of the Leidenfrost temperature for water temperatures different from 20°C.

5. CONCLUSIONS

The following conclusions can be drawn with respect to the transplosion phenomenon and the Leidenfrost temperature for the molten copper–water systems:

1. Transplosion has a random character and occurs in series of tests with molten copper in the range of temperatures between 160 and 750°C for water of 20°C and at atmospheric pressure.
2. Processes occurring during solidification of copper have an influence on the Leidenfrost temperature. This is caused by the generation of

various forms of the solid copper surface. Sorts of fins as solidified "jets" were observed.

3. Contents of copper oxides have an influence on the solid character of the surface and therefore on the measured value of the Leidenfrost temperature.
4. Analytical correlations of the Leidenfrost temperature can be based on the hydrodynamical or thermodynamical approach.

   According to these experiments on the molten copper–water system, the thermodynamical correlation for the Leidenfrost temperature better describes the results for smooth surfaces and "stable courses" of cooling, but on the other hand, the hydrodynamic correlation seems to give the upper limit of the Leidenfrost temperature, if some effects disturb the cooling process.
5. Some problems as e.g. wetting characteristic of the real hot surface, character of the cold liquid–hot surface contact of transplosion, the triggering mechanism of transplosion are still unsettled and more experimental and theoretical work will be useful in this respect.

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PHENOMENE DE TRANSPLOSION ET TEMPERATURE "LEIDENFROST" POUR L'INTERACTION THERMIQUE DE CUIVRE FUSE AVEC L'EAU

Résumé—On étudie le phénomène "Leidenfrost" pour le système métal fusé (cuivre)–eau. Des transplosions avaient lieu pendant une série de 120 expériences portant sur le cuivre fusé dans la région de températures de 160 à 750°C avec l'eau à 20°C et à la pression atmosphérique.

On compare les corrélations analytiques valables pour la température "Leidenfrost" et obtenues par une approximation hydrodynamique ou thermodynamique. La corrélation thermodynamique décrit mieux les résultats valables pour les surfaces lisses et une "course stable" du refroidissement de cuivre fusé. La corrélation hydrodynamique semble fournir la limite supérieure de la température "Leidenfrost" pour le cas que quelques effets sont gênants au processus de refroidissement.

On discute l'influence exercée par des facteurs comme la nature et la rugosité du matériau de surface, l'état métastable du liquide, l'aptitude au mouillage de la surface chaude et le sous-refroidissement du liquide froid.

ÜBER DAS TRANSPLOSIONS-PHÄNOMEN UND DIE LEIDENFROST-TEMPERATUR BEI DER THERMISCHEN WECHSELWIRKUNG VON GESCHMOLZENEM KUPFER UND WASSER

Zusammenfassung—Es wird das inverse Leidenfrost-Phänomen für das System "geschmolzenes Metall (Kupfer)–Wasser" betrachtet. Transplosion trat in einer Serie von 120 Versuchen in einem Temperaturbereich von 160 bis 750°C auf, wobei flüssiges Kupfer mit Wasser von 20°C bei atmosphärischem Druck thermisch reagierte.

Analytische Beziehungen für die Berechnung der Leidenfrost-Temperatur, basierend auf hydrodynamischen oder thermodynamischen Ansätzen, werden gegeben. Die thermodynamische Beziehung beschreibt die Ergebnisse für glatte Oberfläche und "stabilen Verlauf" der Abkühlung des geschmolzenen Kupfers besser. Die hydrodynamische Beziehung scheint die obere Grenze der Leidenfrost-Temperatur zu ergeben, wenn irgendwelche Effekte den Abkühlungsprozess stören.

Einflüsse von Faktoren, wie Art und Rauhigkeit der Oberfläche des heißen Materials, metastabiler Zustand der Flüssigkeit, Benetzbarkeit der heißen Oberfläche und Unterkühlung der kalten Flüssigkeit werden diskutiert.

О ЯВЛЕНИИ ТРАНСПЛОЗИИ И ТЕМПЕРАТУРЕ ЛЕЙДЕНФРОСТА ПРИ ТЕПЛОВОМ ВЗАИМОДЕЙСТВИИ РАСПЛАВЛЕННОЙ МЕДИ С ВОДОЙ

Аннотация — Рассматривается обратное явление Лейденфроста в системе расплавленный металл (медь) — вода. В 120 опытах с расплавленной медью в диапазоне изменения температур от 160 до 750°C при температуре воды 20°C и атмосферном давлении имеет место трансплозия. Проводится сравнение аналитических корреляций для температуры Лейденфроста, полученных гидродинамическим или термодинамическим методами. Термодинамические корреляции лучше описывают результаты для гладких поверхностей и «стационарном» охлаждении расплавленной меди. Представляется, что гидродинамическая корредяция дает верхний предел температуры Лейденфроста, если некоторые эффекты возмущают процесс охлаждения.

Обсуждается влияние таких факторов, как природа материала поверхности и ее шероховатость, метастабильное состояние жидкости, смачиваемость горячей поверхности и переохлаждение холодной жидкости.