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TRANSIENT CRITICAL HEAT FLUX IN LOSS-OF-FLOW-ACCIDENTS (L.O.F.A.)

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Abstract—Loss of flow transients with reference to L.O.F. accidents in nuclear reactor cores have been systematically studied employing freon 12 as coolant. Two pressures (with reference to BWR and PWR characteristic liquid to vapour densities ratios), three periods of the coast-down flow transients during the simulated pump trips, and different specific mass flow rates have been investigated. The uniformly heated channel ($L = 200$ cm, $D = 0.75$ cm), instrumented with wall thermocouples and inlet to outlet differential pressure enabled recording of the following transients, inlet specific mass flowrate, inlet pressure, inlet to outlet Δp, inlet fluid temperature, outlet wall temperature, outlet bulk temperature.

Through the wall temperature being close to the outlet it is possible to detect the onset of DNB and hence the time to DNB from the beginning of the flow transient. All the experimental runs (105) have been systematically compared with the G.E. (PEPE) code with the introduction of a CNEN DNB freon correlation. The results enable a series of conclusions which are extensively shown in the paper.

INTRODUCTION

Flow transients, both decay and flow stoppage, i.e. sudden loss of flow, have been studied in a broad spectrum of thermo–hydraulic situations. With special regard to the determination of the most important parameter for the safety of light–water nuclear power reactors (LWRs), i.e. the time-to-DNB, a basic understanding of the field equations during the transient as well as of the applicability of stationary correlations for two-phase flow models (i.e. bubble relative velocity ratio, etc.) and forthe DNB conditions seems quite desirable.

The present research has been undertaken to provide experimental data on the transient parameters as a consolidated basis for further improvements of the theoretical models. This data has been obtained from a Freon test loop.

A first approach, in this sense, is attempted herewith, employing one of the simplest proposed models.

From Tong *et al.* (1965) and from an overview of existing literature (Kastner & Mayinger 1970; Hein & Kastner 1972; Moxon & Edwards 1967; Lahey *et al.* 1971*a*,*b*; Lahey 1972) it may be deduced that:

- the time at which DNB first occurs cannot be predicted from inlet parameters only;
- this time can be predicted accurately through parameters calculated by means of computer codes in which two kinds of steady-state correlations have been introduced: that based on local values of heat flux, quality and flowrate, and that based on the local values of quality flowrate and boiling length, with almost equivalent results;
- some difficulties arise when DNB occurs at high quality and/or low flowrate, since only special correlations are suitable in these ranges.

BASIC EQUATIONS AND MAIN, SIMPLIFYING HYPOTHESES

The conservation equations for continuity, momentum and energy, neglecting in the last the gravitational potential and kinetic terms, may be written as

$$\frac{\partial \rho}{\partial t} + \frac{\partial G}{\partial z} = 0 \qquad \text{(continuity)} \qquad [1]$$

$$\frac{\partial G}{\partial t} + \frac{\partial [G^2/\rho]}{\partial z} = \frac{\partial p}{\partial z} - \rho g - \frac{f \cdot |G| \cdot G}{2D_h\rho} \qquad \text{(momentum)} \qquad [2]$$

$$\frac{\partial [\rho U]}{\partial t} + \frac{\partial [GH]}{\partial z} = q''', \qquad \text{(energy)} \qquad [3]$$

where ρ is the density, G the specific mass flow rate, p the pressure, f friction factor, D_h the hydraulic diameter, u the internal energy, H the enthalpy, q''' the power density, t the time and z the axial coordinate.

Obviously the equations are applied to a very simplified geometrical model of the heating channel, in which fluxes in the longitudinal dimension (z) are more important than those in the transversal dimensions.

The equations must be integrated through the knowledge of a function of state,

$$\rho = \rho(T; p; X),$$

of an empirical correlation for the friction factor f,

$$f = f(G; \rho; H; q''),$$

and of the general flow pattern along the channel.

For transient behaviour, with special reference to the loss of flow accident (L.O.F.A.), the following boundary conditions are assumed to be known:

initial conditions (at the onset of the transient) throughout the channel:	$G(z, o)$
	$H(z, o)$
	$p(z, o)$
● the inlet conditions during the transient:	$G(o, t)$
	$H(o, t)$
	$p(o, t)$
● the heat flux at the channel walls:	$q''(z, t)$.

Solution of the system provides the following, unknown magnitudes:

$$G(z, t); \quad H(z, t); \quad X(z, t)$$

Many simplifying hypotheses have to be made to permit solution of the system. Among them:

(a) sonic effects are negligible,

(b) the subcooled boiling regime may be neglected,

(c) homogeneous flow: the relative velocity ratio between the phases is constant and equal to 1,

(d) density variations are negligible: internal energy and enthalpy variations are coincident,

(e) channel pressure drops are negligible with respect to absolute pressure, i.e. along the channel the pressure is assumed constant and equal to the inlet value,

(f) thermodynamic equilibrium between the phases is assumed,

(g) as a simplifying boundary condition, heat flux to the fluid is assumed constant.

For simplifying purposes, hypothesis (e) allows the reduction to two of the number of equations, as the momentum equation becomes a linear combination of the remaining two.

A great simplification is attained if all the above hypotheses are assumed, as is done in the PEPE computer code from General Electric (Cumo *et al.* 1973). Following this approach with the further assumption that the inlet decay flow is well approximated by an exponential decay, an analytical solution of the governing equations is possible.

Introducing the enthalpy:

$$H = U + \frac{p}{\rho}, \qquad [4]$$

[3] becomes:

$$\frac{\partial[\rho H - p]}{\partial t} + \frac{\partial GH}{\partial z} = q''', \qquad [5]$$

and then:

$$\frac{\partial[\rho H]}{\partial t}+\frac{\partial[GH]}{\partial z}-\frac{\partial p}{\partial t}=q'''. \quad [6]$$

Now, using hypothesis (e), supposing $q'''=q''P/A$ and with $G=\rho V$, one gets:

$$H\left[\frac{\partial\rho}{\partial t}+V\frac{\partial\rho}{\partial z}\right]+\rho\left[\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial z}\right]+\rho H\frac{\partial V}{\partial z}=\frac{q''P}{A}, \quad [7]$$

where ρ is the heated perimeter, A the flow area and V the velocity.

Substituting $G=\rho V$ in [1]

$$\frac{\partial\rho}{\partial t}+V\frac{\partial\rho}{\partial z}+\rho\frac{\partial V}{\partial z}=0, \quad [8]$$

and [8] in [7],

$$\rho\frac{DH}{Dt}=\frac{q''P}{A}. \quad [9]$$

Assuming

$$H=H_L+XH_{LG}; \qquad \rho=\frac{1}{v_L+Xv_{LG}}, \quad [10]$$

where X is the quality (for hypothesis (e) $H_V Hr$ *and* H_{LG} are constant), the energy equation becomes:

$$\frac{DX}{Dt}-\Omega X=\Omega\frac{v_L}{v_{LG}}, \quad [11]$$

with $\Omega=(q''P/A)\cdot(v_{LG}/H_{LG})$, which is the form previously derived in Lahey (1972).

Introducing [10] in the continuity equations,

$$\frac{\partial V}{\partial t}=-\frac{1}{\rho}\frac{D\rho}{Dt}=\rho\frac{D(1/\rho)}{Dt}=\rho\cdot v_{LG}\cdot\frac{DX}{Dt}. \quad [12]$$

The system [11] and [12] may now be solved exactly with the further assumption of the exponential decay of the inlet specific mass flowrate:

$$G(t)=G_0\cdot e^{-\alpha t}.$$

The resultant exact solution has been coded for rapid numerical evaluation (Lahey 1972). This code, PEPE, has been used for the determination of the time to DNB by the following DNB correlation whose structure, firstly derived at CISE, has been modified at CNEN (Bertoni *et al.* 1976), introducing a pressure-dependent term based on Freon 12 coolant, i.e. the fluid used in the present transient tests:

$$W_{BO}=\frac{a-X_{in}}{\left(1+\frac{b}{L}\right)}\cdot H_{LG}\cdot\Gamma\left[1-\frac{1/4-\pi}{(9/4-\pi)^2}\right] \quad [13]$$

C.G.S. System.

$$a=\frac{1-\pi}{\left(\frac{G}{100}\right)^{1/3}}; \qquad b=0.6\left[\frac{1}{\pi}-1\right]^{0.4}\cdot G\cdot D^{1/4}. \quad [14]$$

TEST APPARATUS AND EXPERIMENTAL RUNS

Since the research was concerned with the basic behaviour of the transient phenomena rather than on the measure of times to DNB, a Freon loop, extensively described in Hein & Mayinger (1972), has been employed, figure 1.

The fluid, Freon 12, enters at subcooled conditions and flows upward through a uniformly heated (Joule effect) test section of stainless steel, whose heated length is 2 m. The inner diameter is 7.8 mm and the wall thickness 1 mm.

Two wall thermocouples, at the outlet section, indicate the onset of DNB. Their hot junction, inserted within the wall thickness, enables wall delay time constants of 1 s, thus allowing a suitable determination of the time to DNB. Instrumentation is completed by two thermocouples immersed in the fluid at the inlet and outlet sections to measure bulk temperatures, by turbine flowmeters, a pressure transducer at the inlet of the heating channel, a Δp transducer across the channel itself and by the indicators of the electric parameters (voltage and direct current to the test section).

All the measured parameters are recorded continuously by a Multirecorder-Watanabe System.

The experimental runs have been all performed at constant and uniform axial heat flux in the test section and at constant inlet pressure. Decay curves of the inlet flowrate are well approximated by exponential functions. The flow decay has been implemented by means of an hydraulic-integrator loop, with a membrane damper in conjunction with pressurized air at different pressures (higher pressures correspond to greater time-constants of the flow decay).

Three decay time-constants have been selected, corresponding to the following values of $t_{0.5}$, the half-flow decay time: $t_{0.5} \simeq 0.7$ s (fast transients), $t_{0.5} \simeq 1.5$ s (intermediate transients) and $t_{0.5} \simeq 3.2$ s (slow transients).

Two pressures have been fixed, i.e. $p_{in} \simeq 11$ bar and $p_{in} \simeq 18$ bar (with reference to the scalar reduction with Freon 12, of the ρ_l/ρ_g ratios typical of boiling and pressurized water reactors, BWR and PWR's) and for each pressure, two initial specific mass flowrates ($G_0 \simeq 760$ kg/m^2 s and $G_0 \simeq 900$ kg/m^2 s) and four wall heat fluxes ($q'' = 2.9 \times 10^4$ W/m^2; 4.4×10^4 W/m^2; 6×10^4 W/m^2 and 7.5×10^4 W/m^2).

The full set of the experimental parameters are reported in table 1. Some runs have been repeated to examine the reproducibility of both the apparatus and the phenomenon.

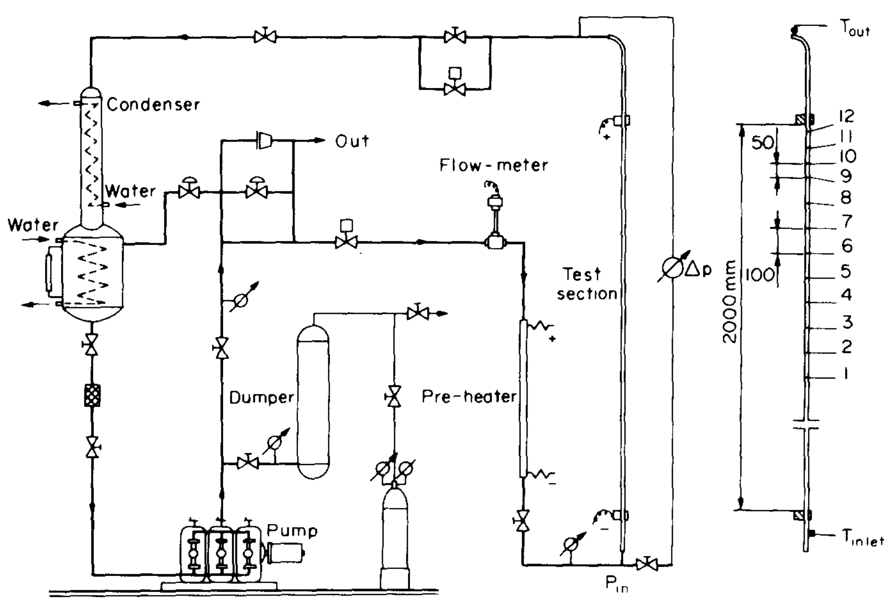

Figure 1. Sketch of the test section (right) and the Freon loop (left).

The following measures are continuously recorded through all the tests: $G(t)$, $T_{in}(t)$, $p_{in}(t)$, $\Delta p(t)$, $T_{w\,out}(t)$, $T_b\,out(t)$.

The onset of DNB is revealed by the first appearence of a positive slope in the $T_{w\,out}(t)$ curve, i.e. the first indication of a temperature rise of the wall of the test section at the outlet. From the graphs it is possible to determine the DNB time and, hence, the corresponding values of all the parameters.

The diagrams of figure 2 are an example of the recorded and computed magnitudes at different pressures, decay time constants and surface heat fluxes. It is possible to note the onset

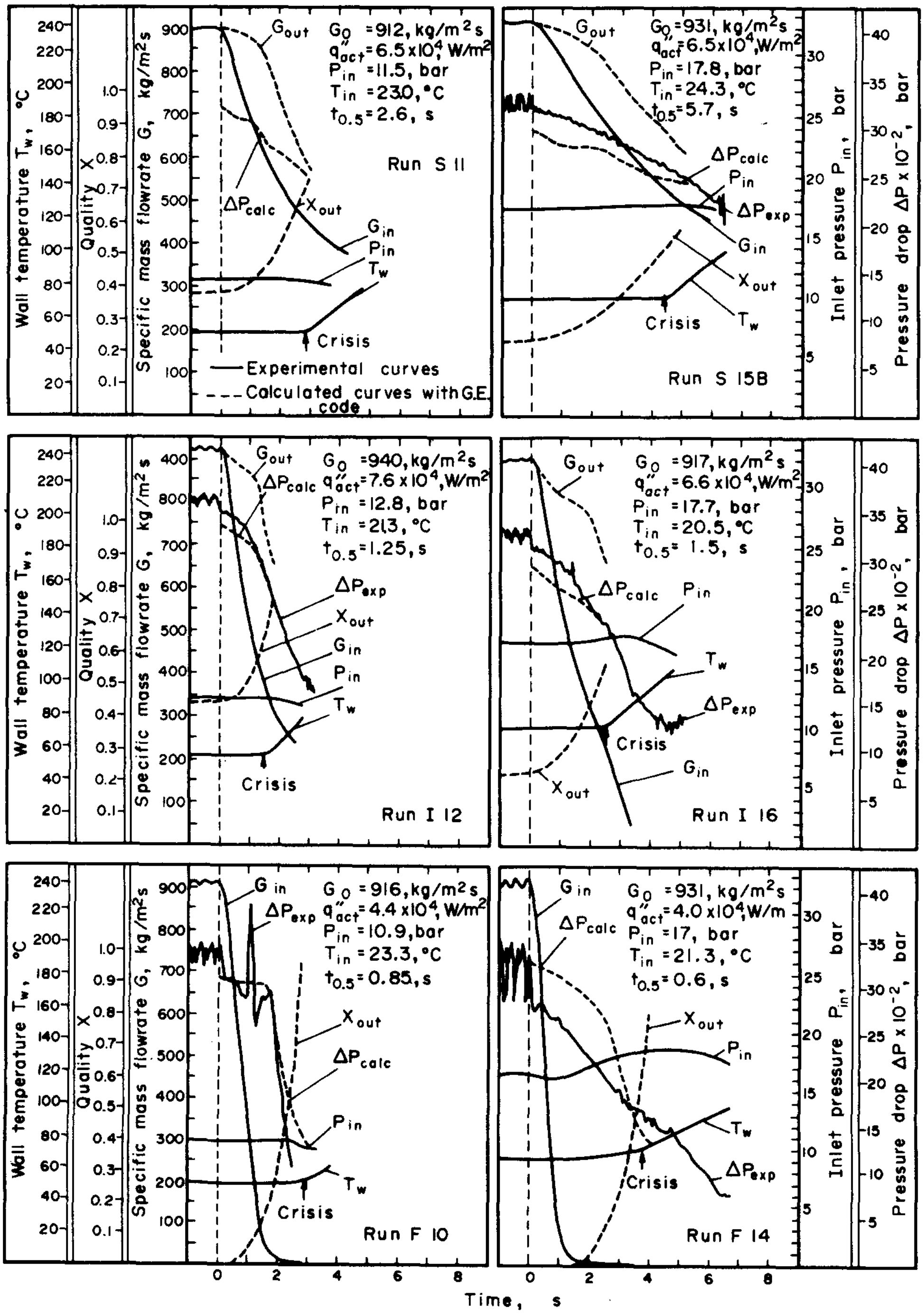

Figure 2. Examples of the measured and computed trends of the described parameters in the transient tests: the DNB occurs at the first rise of the T_w values, evidenced by the change in slope of the curves.

Table 1.

Run No.	P_{in} bar	T_{in} °C	G_0 kg/m² s	q'' ×10⁴ W/m²	$t_{0.5}$ s	t_{crisis} s	G_{in} kg/m² s	Run No.	P_{in} bar	T_{in} °C	G_0 kg/m²s	q'' ×10⁴ W/m²	$t_{0.5}$ s	t_{crisis} s	G_{in} kg/m² s
S1	10.8	20.00	762	2.9	7.20	no crisis	–	I6	17.5	20.30	771	4.4	1.60	4.60	4
S2	11.4	19.00	764	4.4	7.00	11.50	295	I6b	17.5	20.30	769	4.4	1.60	5.00	2
S2b	11.4	19.50	770	4.4	6.80	11.60	295	I7	17.5	20.30	760	6.5	1.60	2.00	330
S3	11.5	19.00	770	6.5	6.00	4.10	471	I7b	17.4	19.80	764	6.5	1.60	2.10	313
S3b	11.4	19.00	764	6.5	6.00	3.90	492	I8	17.5	19.5	769	7.3	1.70	1.15	485
S4	12.4	19.00	779	7.4	5.60	1.35	665	I8b	17.5	19.5	767	7.3	1.65	1.00	524
S4b	12.3	18.70	770	7.4	5.50	1.23	655	I9	10.7	20.3	912	2.9	1.55	6.45	10
S5	17.6	19.30	770	3.1	4.80	11.90	38	I10	11.4	20.5	923	4.4	1.40	no crisis	–
S6	17.6	19.00	779	4.0	3.70	8.10	76	I10b	11.4	20.5	919	4.4	1.45	4.55	86
S6b	18.0	19.50	772	4.0	3.60	8.13	70	I11	12.9	21.0	921	6.5	1.35	2.25	293
S7	17.4	18.30	773	5.9	3.20	3.70	348	I11b	11.7	20.8	921	6.5	1.30	2.25	293
S7b	17.5	18.80	762	5.8	3.50	3.80	365	I12	12.7	21.3	940	7.6	1.25	1.50	400
S8	17.1	19.00	770	6.6	4.00	2.75	465	I12b	12.7	21.3	940	7.6	1.30	1.45	431
S8b	17.2	19.50	764	6.6	4.00	2.45	484	I13	17.6	20.3	912	3.1	2.00	8.65	0
S9	10.7	27.00	893	2.9	3.40	no crisis	–	I14	17.4	20.8	925	4.0	1.50	6.10	0
S9b	10.6	27.00	879	2.9	3.40	no crisis	–	I15	17.4	21.0	923	5.8	1.45	3.25	38
S10	10.4	24.00	904	4.4	3.10	no crisis	–	I15b	17.4	20.8	931	5.8	1.50	3.25	48
S10b	10.3	23.80	904	4.4	3.40	7.10	300	I16	17.4	20.5	917	6.6	1.50	2.40	274
S11	11.5	23.00	912	6.5	2.60	2.80	462	I16b	17.6	20.8	921	6.6	1.50	2.40	274
S11b	11.6	23.00	940	6.5	2.90	2.90	456	F1	11.5	19.0	760	2.9	0.70	5.60	0
S12	12.4	22.50	902	7.5	2.60	1.60	596	F2	10.8	19.8	771	4.4	0.80	3.00	2
S12b	12.4	22.30	914	7.5	2.60	1.50	608	F2b	10.7	20.0	769	4.4	0.75	3.00	2

S13b	18.5	23.50	931	2.9	9.00	20.80	60	F3	11.8	19.5	769	6.5	0.70	1.70	14
S14	18.3	24.00	893	4.4	5.35	10.20	171	F3b	11.4	19.8	760	6.5	0.75	1.70	19
S14b	18.8	23.80	917	4.4	5.35	9.60	213	F4	12.3	19.8	770	7.4	0.80	1.20	213
S15	17.8	24.50	922	6.5	5.50	4.00	560	F4b	12.3	19.8	771	7.4	0.70	0.90	277
S15b	17.8	24.30	931	6.5	5.70	4.50	542	F5	8.7	22.3	794	2.9	0.65	7.10	0
S16	18.8	24.80	935	7.6	5.65	2.50	688	F6	17.5	19.5	779	4.4	0.50	3.30	0
S16b	18.4	23.50	946	7.6	5.20	2.75	660	F6b	17.6	19.5	779	4.4	0.60	3.35	0
S17	17.0	21.50	906	3.1	3.60	10.80	115	F7	17.4	19.8	769	6.5	0.65	1.45	15
S17b	18.0	23.75	928	2.9	8.50	22.60	115	F7b	17.4	19.8	769	6.5	0.60	1.45	17
S18	16.0	23.75	900	4.0	2.70	7.50	138	F8	16.7	19.8	771	7.2	0.60	0.90	114
S18b	17.0	23.50	881	4.0	6.60	12.40	231	F8b	17.6	20.0	769	7.2	0.60	0.60	133
S18c	17.3	22.25	913	4.0	2.60	7.40	120	F9	10.8	22.8	921	2.9	0.80	5.15	0
S18d	17.3	24.00	881	4.0	2.20	7.00	97	F9b	10.7	22.8	912	2.9	0.80	5.35	0
S19	17.4	23.50	906	5.8	2.60	3.70	317	F10	11.0	23.0	921	4.4	0.80	2.80	0
S19b	17.5	23.50	926	5.8	6.80	6.10	490	F10b	10.9	23.3	916	4.4	0.85	3.40	0
S19c	17.3	23.00	912	5.8	2.30	4.00	253	F11	11.5	23.3	916	6.5	0.80	1.90	11
S20	17.4	23.25	926	6.6	2.70	2.75	436	F11b	11.6	24.3	921	6.5	0.75	1.90	23
S20b	17.5	24.00	926	6.6	6.30	4.50	563	F12	12.0	23.5	940	7.6	0.60	1.15	95
S20c	17.4	23.00	932	6.6	2.10	2.50	413	F12b	12.0	23.5	940	7.6	0.80	1.25	125
S21	11.0	20.00	911	4.4	7.50	no crisis	—	F13	17.0	19.3	931	3.1	0.55	6.70	0
S22	12.7	20.25	911	6.5	5.80	4.60	529	F14	17.0	21.3	931	4.0	0.60	3.75	0
S23	13.3	20.00	911	7.6	5.80	1.60	745	F14b	17.2	22.3	931	4.0	0.60	4.25	0
I1	11.0	19.3	764	2.9	2.10	6.60	95	F15	17.3	20.5	925	5.8	0.65	2.25	4
I1b	11.0	19.3	760	2.9	1.90	6.45	95	F15b	17.4	20.8	925	5.8	0.65	2.10	6
I2	11.4	19.5	760	4.4	1.85	4.45	162	F16	17.3	21.3	940	6.6	0.50	1.50	13
I2b	11.2	19.8	760	4.4	1.80	4.40	139	F16b	17.2	21.0	940	6.6	0.60	1.60	11
I3	11.7	20.3	760	6.5	1.55	1.90	317	F17	10.8	19.0	892	2.9	0.70	4.50	0
I3b	11.7	20.0	760	6.5	1.55	1.90	329	F18	10.8	19.0	892	4.4	0.70	2.75	7
I4	12.3	20.5	764	7.2	1.55	1.30	441	F19	11.9	19.0	896	6.5	0.70	1.40	15
I4b	12.0	20.3	760	7.2	1.60	1.30	418	F20	12.6	19.3	913	7.6	0.60	1.00	37
I5	17.7	20.5	773	2.9	2.00	9.10	0								

of crisis at the change in slope of T_w curves, the rather good prediction of the homogeneous model of the overall Δp (this model obviously greatly simplifies calculations), and the graphical determination of the critical value of the outlet quality, as well as the increase in the outlet specific mass flux, G_{out}, with respect to the corresponding, inlet value, G_{in}.

Obviously, G_{out} and X_{out} values are computed from the experimental inputs by means of the above mentioned code utilizing with all the simplifying hypotheses.

The influence of the decay time constant, expressed through the half-decay time $t_{0.5}$, is well evidenced in graphs of the type of figure 3. The more rapid the flow decay, the greater the difference between static crisis G values (along the continuous curve, which has been determined through quasi-static tests on the same experimental apparatus) and the actual values of G_{inlet} at the onset of crisis.

From similar graphs it is possible to deduce that the difference between the two values of G_{inlet}, the 'static' and the 'transient', depends both on $t_{0.5}$ and on the initial, representative position in the $q'' - G_{inlet}$ diagram.

In turn, for a given thermal–hydraulic situation, i.e. for a given DNB curve in the $q'' - G_{inlet}$ plot, DNB depends on either the ΔG margin to the static curve or the $\Delta q''$ margin to the DNB value of heat flux corresponding to the initial flowrate G_0.

So, both the 'static displacements' to DNB (computed along either of the axis), or the ratios of the critical to initial values, may be introduced as describing parameters.

An intrinsic limitation of such a representation also appears in the diagrams of figure 3 when, in correspondence with fast decays (small $t_{0.5}$ times), the inlet flowrate at DNB is practically zero, thus inhibiting further screening of the decay effects. Another form to represent experimental data may be adopted, grouping them at the same heat flux values. The plot may adopt time-to-DNB vs a parameter in which both the inlet flowrate (G_0) and the transient value of the inlet flowrate at DNB (G^*_{inlet}) are introduced. 'Slow' test data ($t_{0.5} \simeq 3.2$ s) are grouped close to the ordinate axis (figure 4), while 'fast' test data are grouped close to the abscissae, approaching an equilateral hyperbolic trend as $G^*_{inlet} \to 0$ with lower times to DNB at higher q''.

TIME TO DNB

The critical parameter of this investigation, i.e. the time interval from the onset of the transient in flowrate to the onset of DNB has been experimentally determined for all the runs.

The first question which must be answered is what is the error in a straight-forward approach in which both a static DNB correlation and the $G_{in}(t)$ values are used, i.e. computing the DNB heat flux by means of the known inlet value of the flowrate. Such an answer gives an initial estimate of the solution, providing also a comparison term. Figure 5 shows the poor agreement of such a conservative approach, obviously unacceptable even for scoping calculations.

The PEPE code, equipped with the Freon 12 physical properties and the Freon 12 static DNB correlation, [13], allows, for the considered transient, the computation of the outlet values $G_{out}(t)$ and $X_{out}(t)$, as well as the continuous comparison, at different time intervals, of the X_{out} value with the DNB value of X computed by means of [13], and hence, the time to DNB.

Comparison of computed and experimental values of times to DNB results in figure 6, where 'fast' ($t_{0.5} \simeq 0.7$ s), 'intermediate' ($t_{0.5} \simeq 1.5$ s) and 'slow' ($t_{0.5} \simeq 3.2$ s) decay results are gathered and, without systematic deviation, are grouped in a band of ±20%.

Thus the highly simplified code PEPE, allows one to achieve satisfactory results.

A further step for the sake of simplification would be the straight forward formulation of a transient DNB correlation which alone, is able to provide times to DNB. Such a correlation would require a very great amount of experimental data with different fluids, geometries and types of transients. Indeed, the amount of empirical information in it would be prodigious.

In our particular case, limited to the ranges of the explored parameters an attempt may be

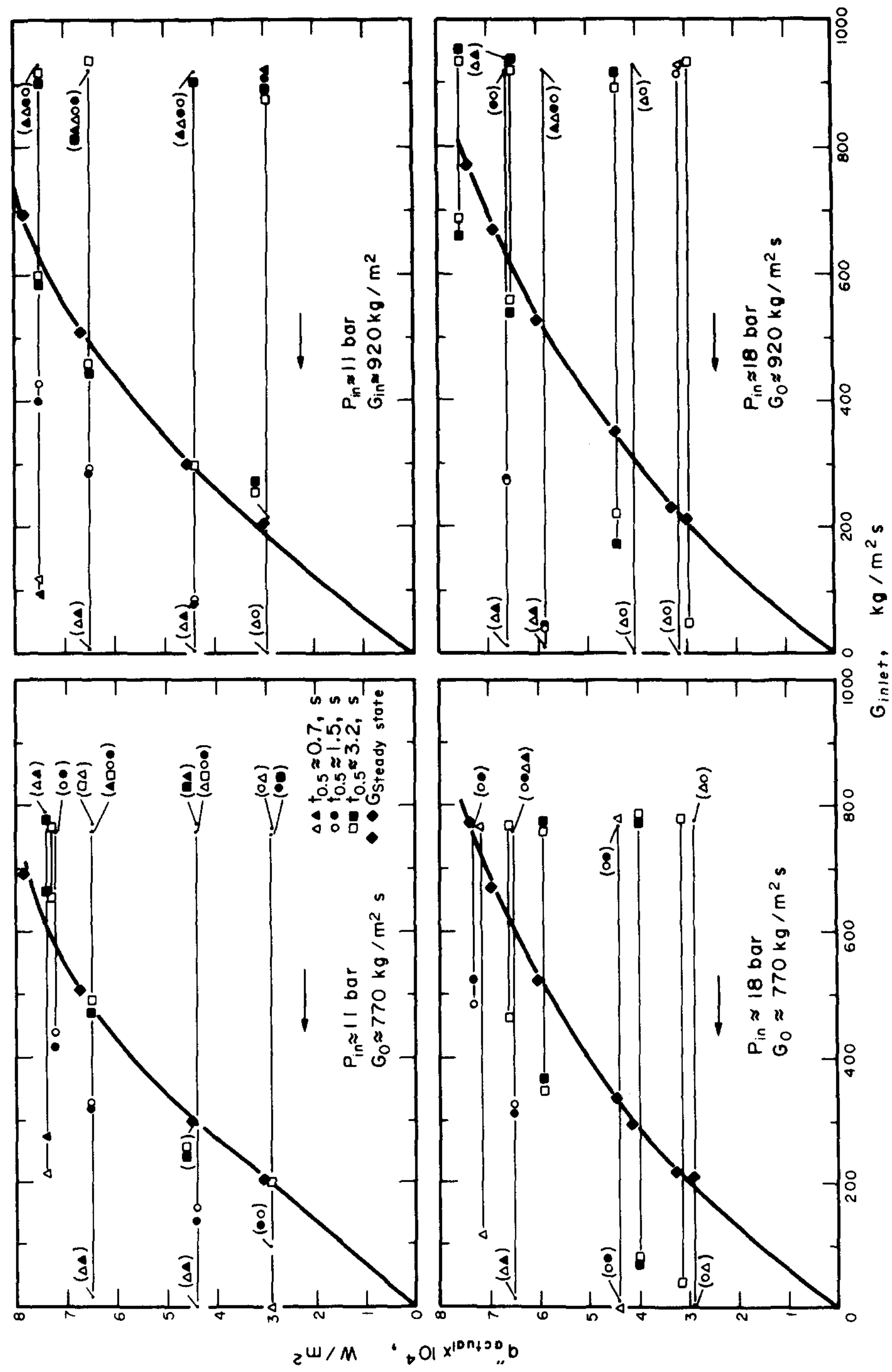

Figure 3. Plot of the transient DNBs: the quicker the flow decay, the greater the disequilibrium between the static (continuous curve) and the actual DNB values (Hein-Mayinger plot).

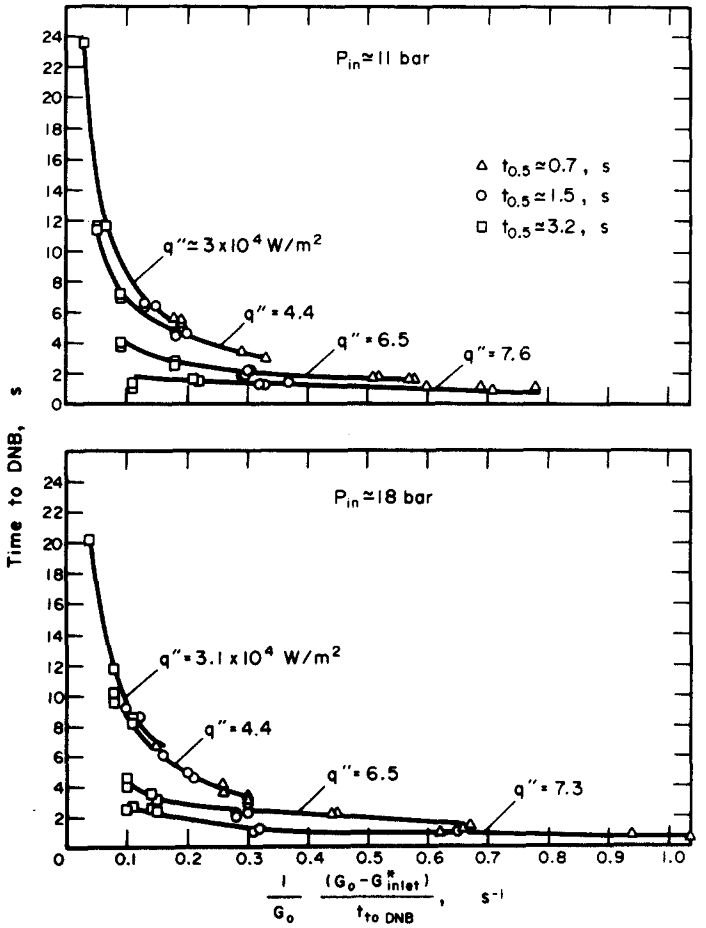

Figure 4. Representation of experimental data at different heat flux values.

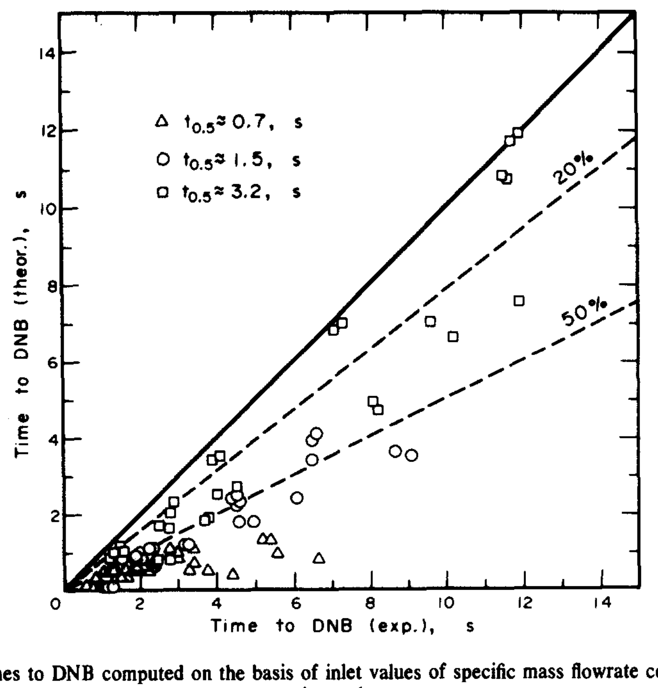

Figure 5. Times to DNB computed on the basis of inlet values of specific mass flowrate compared to the experimental ones.

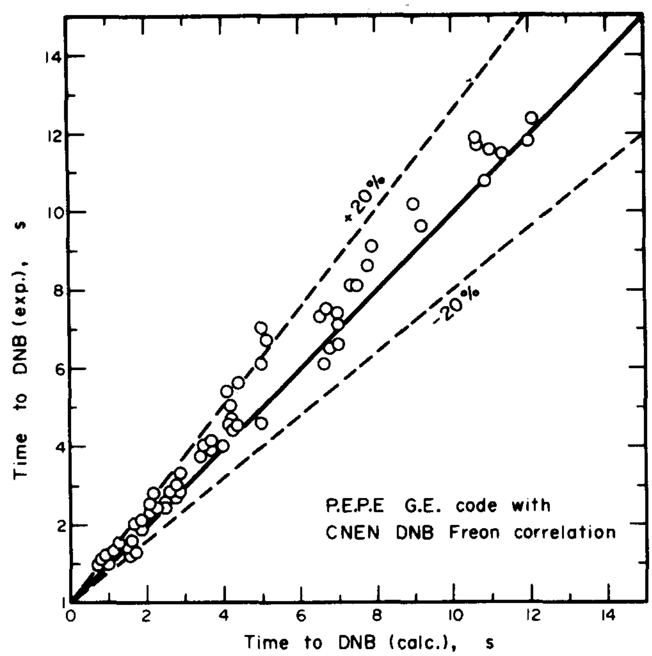

Figure 6. Comparison between computed and experimental times to DNB for all the tests. (PEPE code with CNEN correlation.)

made, representing the value of the DNB heat flux in transient conditions as a function of the DNB value corresponding to the inlet value of specific mass flowrate in a stationary DNB correlation, (e.g. [13]) and of the main transient parameters (i.e.: G_0 and $t_{0.5}$). We are able to calculate the time to DNB. Expressing q'' in an additive form:

$$q''_{\text{actual}} = q''_{\text{DNB}}\,[G_{\text{in}}(t)] + C.F. \qquad [15]$$

where the correlation factor, $C.F.$, is given by

$$C.F. = \begin{cases} 0 & \text{if} \quad \dfrac{t_{0.5}\cdot q''_{\text{actual}}}{q''_{\text{DNB}}(G_0)}\left(\dfrac{p_{cr}}{p}\right)^{2.2} > 24\text{ s} \\ \{q''_{\text{DNB}}(G_0) - q''_{\text{DNB}}\,[G_{\text{in}}(t)]\}\,e^{-gt} & \text{with} \quad g = 0.82(t_{0.5})^{0.15}\sqrt{\left(\dfrac{p_{cr}}{p}\right)}. \end{cases}$$

An overall comparison of [15] with all the data is shown in figure 7, where a rather good agreement is reached.

CONCLUSIONS

Flow decay transients have been studied with the goal of assessing the simplifications in the PEPE code and their limits of applicability.

When the simplifying assumptions (a) to (g) are adopted, all the available test results are well predicted as shown in figure 6.

A further step would be a 'transient' DNB correlation from which to deduce the required time to DNB. by equating the transient to the actual value of surface heat flux.

Limited to our experimental set up and within the explored ranges of parameters the following correlation has been deduced:

$$q''_{\text{actual}} = q''_{\text{DNB}}\,(G_{\text{in}}(t)) + C.F.$$

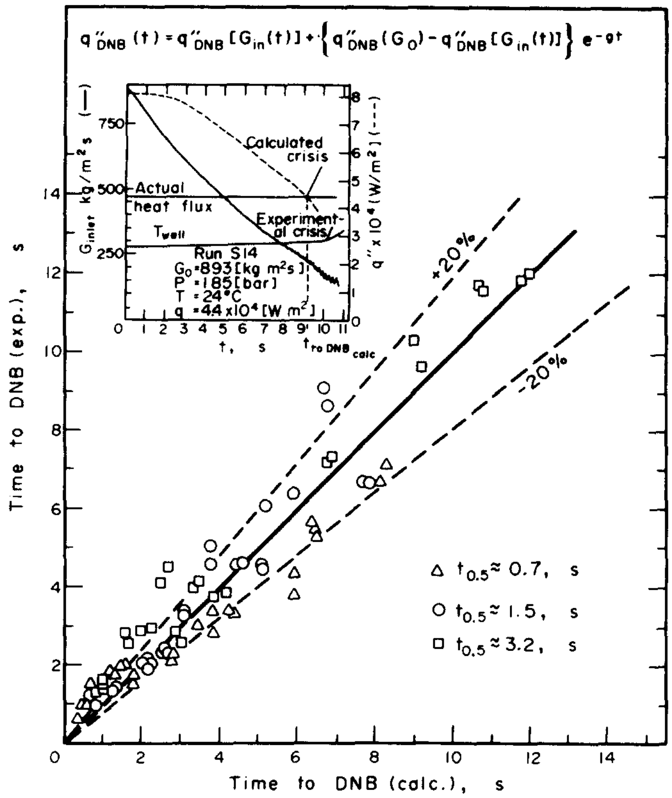

Figure 7. Comparison of the transient DNB correlation with experimental data.

where:

$$C.F. = \begin{cases} 0 & \text{if} \quad \dfrac{t_{0.5} \cdot q''_{\text{actual}}}{q''_{\text{DNB}}(G_0)} \left(\dfrac{p_{cr}}{p}\right)^{2.2} > 24\,\text{s} \\[2ex] \{q''_{\text{DNB}}(G_0) - q''_{\text{DNB}}[G_{\text{in}}(t)]\}\,e^{-gt} & \text{with} \quad g = 0.82\,(t_{0.5})^{0.15} \cdot \sqrt{\left(\dfrac{p_{cr}}{p}\right)}. \end{cases}$$

The comparison of this correlation with experiments is shown in figure 7.

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NOMENCLATURE

- A flow area, m^2
- D_h hydraulic diameter, m
- f friction factor
- g acceleration due to gravity m/s^2
- G specific mass flowrate, $kg/m^2\,s$
- H enthalpy, J/kg
- H_{fg} latent heat of vaporization, J/kg
- L length *m*
- p pressure, N/m^2
- Δp pressure drop, N/m^2
- P heated perimeter, m
- q'' surface heat flux, W/m^2
- q''' power density, W/m^3

t	time, s
T	temperature, °C
U	internal energy, J/kg
v	specific volume, m^3/kg
V	velocity, m/s
W	thermal power, W
X	quality
z	axial coordinate, m

Greek symbols

α	decay constant, s^{-1}
π	ratio between actual and critical pressure, p/pcr
ρ	density, kg/m^3
Γ	mass flow rate, kg/s

Subscripts

b	bulk
BO	burn out
cr	critical
DNB	departure from nucleate boiling
L	liquid
G	gas or vapour
in	inlet
w	wall
0	refers to initial point of the transitory
0.5	half-flow

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