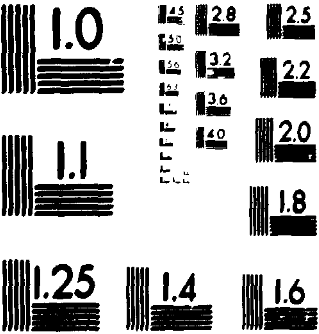
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COMITATO NAZIONALE PER LA RICERCA E PER LO SVILUPPO
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FLOW TRANSIENTS EXPERIMENTS WITH REFRIGERANT-12

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SUMMARY

Flow transients have been investigated in a wide range of thermal-hydraulics situations with Refrigerant-12.
Six pressures (including the reference to PWR and BWR characteristic liquid to vapour densities ratios), several periods of the flowrate transients coastdown during the simulated flow decays, and different specific mass flowrate have been studied employing a circular duct test section (D_i = 7,5 mm). Two heated lengths of the test section have been considered (L = 2300 and 1180 mm).
Experimental data have shown the complete inadequacy of steady-state critical heat flux correlations in predicting the onset of boiling crisis during fast flow transients (half-flow decay time, $t_h < 5.0 - 6.0$ s).
The flow transient does not show dependence, in terms of DNB conditions, upon the length of the test section: the ratio between transient and steady-state critical mass flowrate is not dependent on the tested geometry.
The time interval from the start of the flowrate transient to the onset of DNB (time to crisis), has been experimentally determined for all the runs.
Data analysis for a better theoretical prediction of the phenomenon has been accomplished, and a design correlation for DNB conditions and time to crisis prediction has been proposed.

1. INTRODUCTION

Onset of burnout under transient conditions has become an important area of study as far as nuclear reactor safety is concerned. In the case of the extremely unlikely event of a loss-coolant-accident (LOCA) due to a leakage in the primary system of the reactor, severe transients in system pressure, mass flow and heat flux would all occurr so to cause a complicated thermodynamic behaviour of the reactor coolant.

Before trying to go into detail with the combined mechanism of the burnout behaviour during a LOCA it seems necessary to understand first the several aspects related to these phenomena in simpler situations like mass flow, power and pressure transients occurring separately /1,6/.

The aim of the present paper is to investigate, as a first step of a research devoted to the analysis of complex and simultaneous transients, the mass flow transients behaviour, other parameters (power and pressure) being kept constant.

The influence of thermal power, pressure, transient quickness, inlet mass flowrate and geometry on transient behaviour is investigated.

Besides an attempt for the comprehension of the phenomenon, it seems also useful to define the bounds of validity of the steady-state critical heat flux correlations, widely available in scientific literature /7,13/, in predicting a transient situation.

2. EXPERIMENTAL APPARATUS

The experimental loop, schematically represented in fig. 1, consists mainly of a piston pump, a pre-heater, an electic heater, a condenser and a Refrigerant-12 tank. The employ of Refrigerant-12 as a coolant, being the present research focused essentially on the basic behaviour of the transient phenomena, enables to simulate water at much higher pressures and to get a more relevant number of experimental data, in comparison with water. Concerning the scaling laws, those proposed by S. Ahmad have been selected /14/ for a closer adherence to our data.

The maximum operating pressure of the loop is 3.5 MPa, whilst the maximum specific flowrate is 1800 $Kg/s\ m^2$; the available electric power is 5 KW for the electric heater and 10 KW for the test section.

The test section is a stainless steel, circular duct uniformly heated (Joule effect) over a length of 2300 or 1180 mm, with an inner diameter of 7.5 mm and a wall thickness of 0.9 mm. The test section instrumentation consists of 0.5 mm, K-type thermocouples distributed according to the scheme of fig. 1 for the wall (twelve) and the fluid (six) temperature measurements. The thermocouples located at the outlet section (the hot junctions are well inserted inside the wall thickness) indicates the onset of burnout. The Refrigerant-12 flow is upwards with subcooled inlet conditions (before the start of the transient). Data acquisition is accomplished by a Solarton "data logger", Orion D type, coupled with an eight channels graphic Multirecorder Watanabe System.

3. EXPERIMENTAL RUNS

3.1 Steady-state reference conditions analysis

In order to establish the boundary conditions for the transients analysis, an experimental set of steady-state critical heat flux tests has been carried out. In fig. 2 the forty-nine performed runs are plotted. Concerning the 2300 mm heated length, the pressure ranges between 1.25 MPa (corresponding to 8.0 MPa for water), and 2.75 MPa (corresponding to 16.2 MPa), whilst the mass flowrate ranges between 400 Kg/s m^2 and 1600 Kg/s m^2. The inlet subcooling is kept constant and equal to 23 °C.
Referring to the 1180 mm heated length, the tests have been carried out at a pressure of 2.0 MPa only.
As far as the prediction of experimental data is concerned, not many correlations are available in literature of Refrigerant-12, whilst the Ahmad criterion for the employ of water critical heat flux correlations is not immediate. A correlation proposed by M. Silvestri for Refrigerant-12 /7/ and modified by Cumo, Ferrari and Urbani /15/ has been tested and adopted with a further improvement concerning the pressure influence. The Sivestri correlation is the following:

$$q''_{DNB} = \frac{1}{S}\left(\frac{a-Xin}{1+b/L}\right)\Gamma\,\Delta h_v\; f(\pi) \qquad (1)$$

being

$$a = (1-\pi)/(G/100)^{.33}$$

$$b = 0.6\,(1/\pi - 1)^{.4}\,G\,D^{1.4}$$

$$f(\pi) = 1 - (.33-\pi)/(2.1-\pi)^2$$

$\pi = P/P_{cr}$ (reduced pressure)

$G\ |g/s\ cm^2|$ $D\ |cm|$

The comparison between experimental data and Silvestri modified predictions, plotted in fig. 3, shows a good agreement for all the runs: 96% of experimental data lie well within a ± 10% band from correlation (1).

3.2 Test matrix and flow transients characterization

The influence of five parameters has been tested in the mass flowrate transient experiments: the inlet pressure, P, the wall heat flux, q", the initial specific mass flowrate, G_o, the half-flow decay times, t_h, and the test section heated length, L.
The transient test matrix is the following:

P	|MPa|	1.2; 1.5; 2.0; 2.75
q"	$\|W/m^2\|$	ranging between 32000 and 85000
G_o	$\|Kg/s\ m^2\|$	1000; 1250; 1470
t_h	|s|	0.4; 1.0; 2.0; 3.0; 4.0; 5.0; 7.0; 10.0
L	|m|	2.3; 1.18

Concerning the "short" test section, the runs have been performed for all the values of t_h and q", but only for $G_o = 1470\ Kg/s\ m^2$ and and P = 2.0 MPa.
A 470 data set has been carried out, together with an additional number of repeated tests to check the behaviour reproducibility of both the apparatus and the phenomenon. According to the mentioned scaling laws, PWRs and BWRs reference pressures (16.5 and 7.0 MPa) are simulated by 2.75 MPa and 1.2 MPa respectively. The flow transients have been all performed at constant (and uniform) heat flux in the test section and constant inlet pressure and temperature.
The mass flowrate decay has been obtained by means of a hydraulic-integrator loop, made up with a regulating valve and a membrane dumper fed with pressurized air at different pressures (higher pressures correspond to greater flow decay time-costants). Decay curves of the inlet mass flowrate are well approximated by the following characteristic function:

$$\frac{G(t)}{G_o} = \frac{\gamma}{1 + \beta \exp(\alpha t)} \qquad (2)$$

The curve (2) is reported in fig. 4 for different half-flow decay times, t_h, together with the corresponding α and β values ($\gamma = 1 + \beta$) for each transient. In fig. 5 a typical experimental flow decay is compared with the function (2).

3.3 Transient experimental results

A typical representation of the recorded graphs is drawn in fig. 6, for the "long" test section (L = 2300 mm): a characteristic fast transient is shown together with an intermediate and a slow one. The recorded magnitudes are the inlet mass flowrate, G_{in}, the inlet pressure, P_{in}, and the outlet wall temperature, T_w. The onset of departure from nucleate boiling is detected by the first indication of the temperature increase of the outlet test section wall. At the crisis instant the reference mass flowrate (i.e. the inlet value) is recorded as well.

Concerning the outlet mass flowrate, G_{out}, and the outlet steam quality, X_{out}, calculated trends are plotted in fig. 6; such calculations are briefly summarized in appendix.

Before presenting experimental data, it is necessary to introduce a parameter which will be widely employed in data analysis: we define "time transit parameter" the expression

$$t_t = \rho_{lo} L/G_o \qquad (3)$$

being G_o and ρ_{lo} evaluated at the steady-state, inlet conditions just before the transient.

It can be regarded as the time required by the inlet liquid to get out the test section setting the heat flux equal to zero (adiabatic conditions).

Considering now the ratio between the half-flow decay time, t_h, and the time transit parameter, t_t

$$\tau = t_h/t_t \qquad (4)$$

the experimental data analysis should be less dependent on experimental loop characteristics; the parameter τ will be employed also to characterize the transient quickness.

The experimental data are finally reported in fig. 7 (L = 2300 mm heated length), where the ratio between transient critical mass flowrate, $(G_{DNB})_{tr}$, and the steady-state one, $(G_{DNB})_{ss}$, is plotted versus the transient time parameter, τ, for different pressures, heat fluxes and inlet mass flowrates.

In fig. 8 a comparison between the long test section data and the short ones is drawn, for G_o = 1470 Kg/s m^2 and P = 2.0 MPa.
The experimental time interval between the beginning of the transient and the onset of departure from nucleate boiling (time to crisis), $(t_{DNB})_{exp}$, have been compared in fig. 9 with those computed, $(t_{DNB})_{calc}$, considering the crisis occurring when the inlet mass flowrate becomes equal to the steady-state corrisponding one.

4. DATA ANALYSIS

From the analysis of the data shown in figs. 7,8 and 9 some conclusions and comments may be derived. First of all it clearly appears the complete inadequacy of steady-state critical heat flux correlations in predicting the fast transient situations. Nevertheless it is possible to define the validity limit of the steady-state approach. It seems to be individuated by a value of the transient time parameter, τ , approximately equal to 8, considering the whole range of the investigated parameters. For τ greater than 8 (slow transients) the steady-state approach gives a good agreement in the transient analysis, within, of course, the accuracy of the employed correlations; for τ less than 8 the inadequacy of the steady-state increases with a decrease in τ. Anyway, although such inadequacy is conservative, the low degree of approximation is obviously unacceptable even for screening calculations.
As far as the influence of the investigated parameters on experimental data is concerned, the following experimental evidences stand out:

- the system pressure, p, is only slightly affecting the transient critical mass flow, $(G_{DNB})_{tr}$, versus and towards the higher pressures;
- the inlet mass flowrate influence on the $(G_{DNB})_{tr}$ trend seems to be quite negligible;
- the heat flux. i.e. the margin Δq to the static curve, seems to influence the transient behaviour only for τ less than two, whilst beyond this limit no appreciable influence can be observed;
- the flow transient is not affected by the test section heated length: DNB occurs for the same value of the ratio $(G_{DNB})_{tr}/(G_{DNB})_{ss}$, being $(G_{DNB})_{ss}$ depending on the channel length;
- finally, the main parameter affecting the transient behaviour is the transient parameter, τ , as it is well evidenced in the graphs of fig. 7.

5. AN EXPERIMENTAL DESIGN CORRELATION

Bearing in mind the above mentioned limitations in the steady-state approach and the experimental evidences underlined, an attempt to propose, limitedly to the ranges of the explored parameters, the formulation of a simple transient critical heat flux design correlation enabling to calculate the time to critical heat flux, has been made.

Starting from the steady-state critical mass flowrate (by means of a reliable correlation, e.g. the proposed correlation (1) in our case) the transient critical value can be expressed in terms of initial conditions by:

$$\frac{(G_{DNB})_{tr}}{(G_{DNB})_{ss}} = 1 - \exp\left(-.87(\pi)^{-.57}(\tau)^{.54}(q''/q''_{DNB,ss})^{2.8/\tau}\right) \qquad (5)$$

In correlation (5), $q''_{DNB,ss}$ is the critical heat flux corresponding, in a steady-state situation, to the inlet mass flowrate before the onset of the transient. It can be computed employing the same correlation previously applied for the critical mass flow calculation.

Correlation (5), coupled with the inlet mass flowrate decay law (eq.(2)), gives a two-unknowns two equations system, which enables the prediction of the time to DNB, with the inlet mass flowrate at the time in which DNB occurs.

The comparison between experimental and computed data for the time to DNB is shown in figs. 10, 11, 12 and 13 in which the different investigated parameters have been separately stressed. The agreement is good, being 86% of experimental data within a ± 20% band from correlation (5) line.

6. CONCLUDING REMARKS

An experimental data set of about 470 mass flowrate transients has been performed in a Refrigerant-12 loop with the main aim to characterize the transient behaviour from a basic viewpoint.

Concerning system pressure, half-flow decay time, margin to the crisis (i.e. inlet mass flowrate and heat flux) with reference to the steady-state situation, and test section geometry, an analysis of their influence on the transients has been accomplished.

The validity bounds of the steady-state approach in predicting the transient critical heat flux conditions have been established, and a design correlation that starting from the steady-state situation and flow transient characteristics enables to predict the critical mass flowrate and the time to crisis in mass flow transient has been proposed.

APPENDIX

The outlet mass flowrate and steam quality have been computed applying the conservation equations:

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

$$\frac{\partial G}{\partial t} + \frac{\partial (G^2/\rho)}{\partial z} = \frac{\partial p}{\partial z} - \rho g - \frac{fG^2}{2D\rho} \qquad \text{(momentum)}$$

$$\frac{\partial (\rho E)}{\partial t} + \frac{\partial (Gh)}{\partial z} = \frac{Q}{V} \qquad \text{(energy)}$$

being E the specific internal energy.
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 one. The equations must be integrated with the knowledge of a state function:

$$\rho = \rho(T,P,X)$$

of an empirical correlation for the friction factor f,

$$f = f(G,\rho,h,q'')$$

and of the general flow patterns 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;
- the inlet conditions during the transient;
- the heat flux at the channel walls.

Other simplifying hypotheses have to be made to allow the solution of the system. Among them:
(a) sonic effects 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 negligible: internal energy and enthalpy variations coincident;
(e) channel pressure drops 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;
(g) heat flux to the fluid constant.

For simplifying purposes, hypothesis (e) allows the reduction to two the number of equations, as the momentum equation becomes a linear combination of the remaining two.
Solution of the system provides the following, unknown magnitudes:

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

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NOMENCLATURE

a	parameter defined in eq. (1)
b	parameter defined in eq. (1)
D	diameter
E	internal energy
f	friction factor
g	gravity acceleration
G	specific mass flowrate
L	length
P	pressure
q"	heat flux
Q	heat
t	time
V	volume
z	coordinate
X	steam quality
Δh_v	latent heat of vaporization

Greek letters

α	parameter defined in eq. (2)
β	parameter defined in eq. (2)
γ	parameter defined in eq. (2)
π	reduced pressure
τ	transient time parameter
Γ	mass flowrate

SUBSCRIPTS

calc	calculated
cr	critical point
DNB	departure from nucleate boiling
exp	experimental
h	half-flow
in	inlet
o	referred to the inlet situation before the transient
out	outlet
ss	steady-state
t	transit
tr	transient

REFERENCES

1. LAHEY R.T., The Analysis of Transient Critical Heat Flux, GEAP 13249, (1972)
2. HEIN D, MAYINGER F., Burnout Power in Transient Conditions, Paper presented at the Seminar on Two-Phase Flow Thermoydraulics, Rome (1972)
3. SHIRALKER B.S., et al. Transient Critical Heat Flux-Experimental Results, GE Co. Report GEAP-13295 (1972)
4. LEUNG J.C.M., Transient CHF and Blowdown Heat Transfer Studies, ANL/RAS/LWR-80-2, ANL, April (1980).
5. MOXON D, EDWARDS P.A., Dryout During Flow and Power Transients, AEEW R(1967)
6. CUMO M., FABRIZI F., PALAZZI G., Transient Critical Heat Flux in Loss of Flow Accident, CNEN RT/ING(77)14, (1977).
7. BERTOLETTI S., GASPARI G.P., LOMBARDI C., PETERLONGO G., SILVESTRI M., Heat Transfer Crisis with Steam-Water Mixtures, Energia Nucleare, Vol. 12 No. 13 (1965).
8. HEWITT G.F., KEARSY H.A., COLLIER J.G., Correlation of Critical Heat Flux for the Vertical Flow of Water in Uniformly Heated Channels, AERE-5590 (1970).
9. BECKER K.M., An Analytical and Experimental Study of Burnout Conditions in Vertical Round Ducts, AE-178 (1965.
10. BECKER K.M., BAGER J., DJURSING D., Burnout Correlations in Simple Geometries: Most Recent Assessments, KTH-NEL-18 (1972).
11. THOMPSON B., MACBETH R.V., Boiling Water Heat Transfer Burnout in uniformly Heated Round Tubes: a Compilation of World Data with Accurate Correlations, AEEW-R-356 (1964).
12. TONG L.S., Boiling Crisis and Critical Heat Flux, AEC Critical Review Series (1972).
13. HETSRONI G., Handbook of Multiphase Flow, McGraw Hill (1982).
14. AHMAD S.Y., Fluid to Fluid Modelling of Critical Heat Flux: A Compensated Distortion Model, Int. J. Heat Mass Transfer, 16, 641-661 (1973).
15. CUMO M., FERRARI G. URBANI G., Prediction of Burnout Power with Freon up to the Critical Pressure, La Termotecnica, n. 5, (1973).

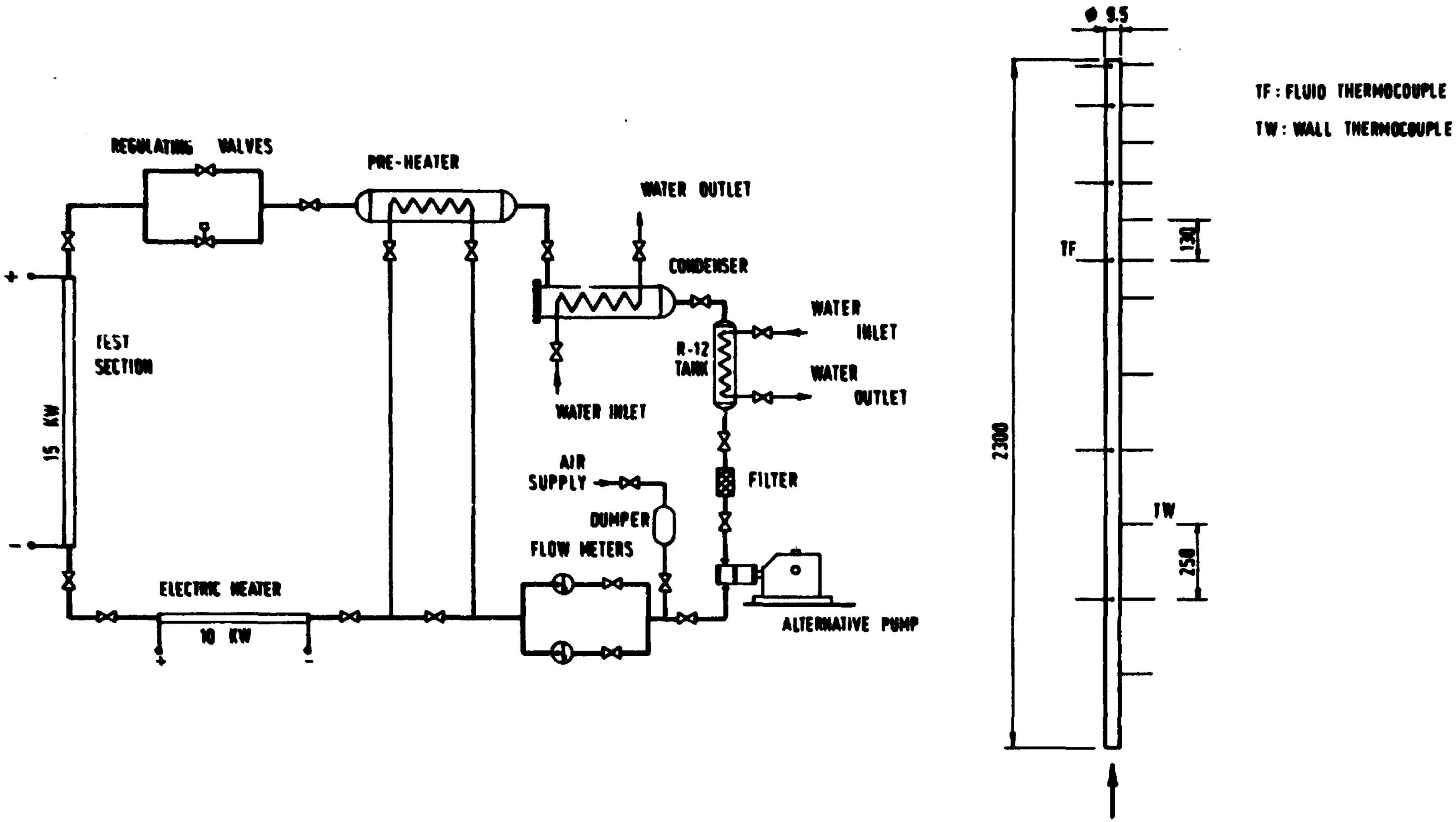

Fig. 1 - The experimental apparatus and the test section.

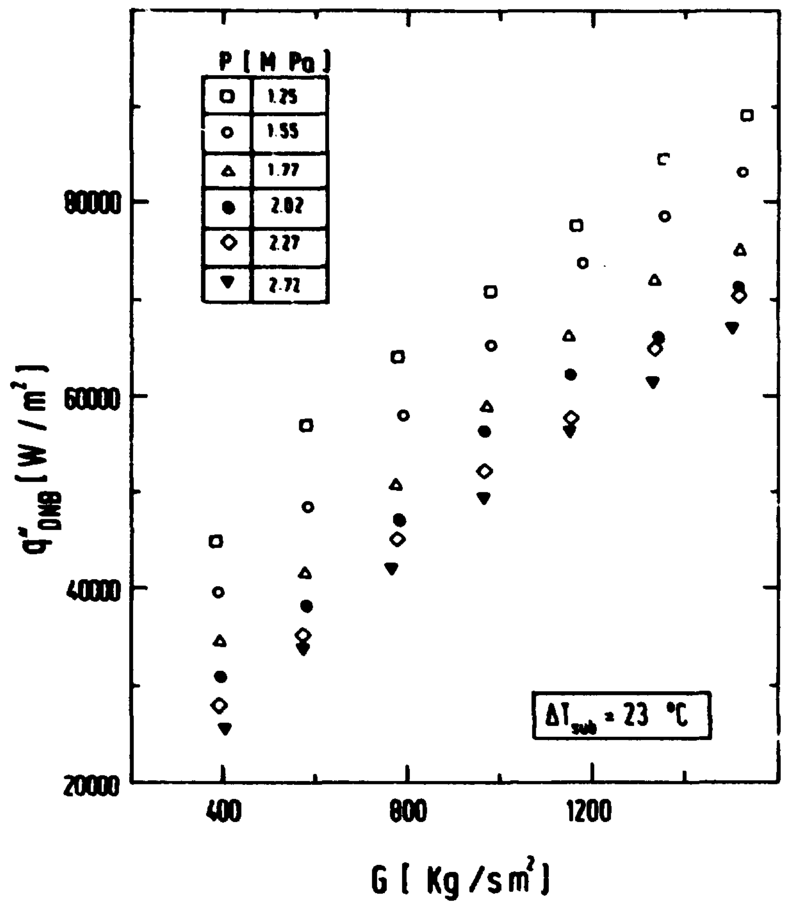

Fig. 2 - Steady-state critical heat flux versus inlet mass flowrate.

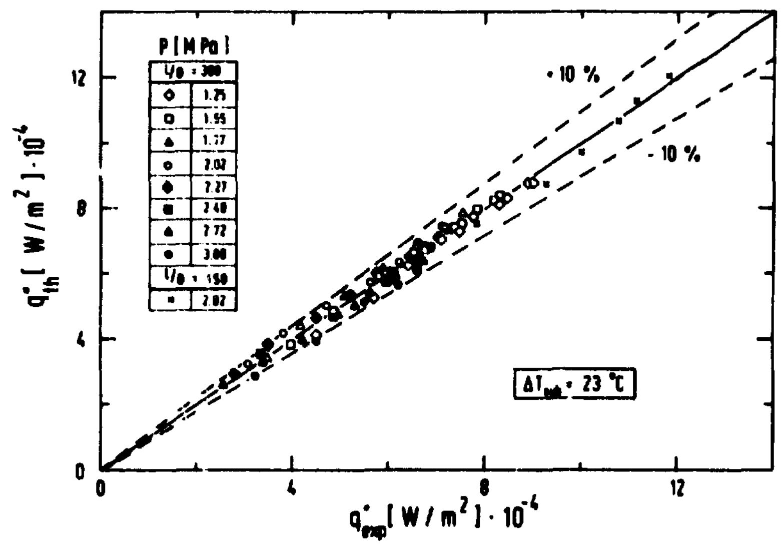

Fig. 3 - Comparison between steady-state experimental critical heat flux data and computed ones by means of correlation (1).

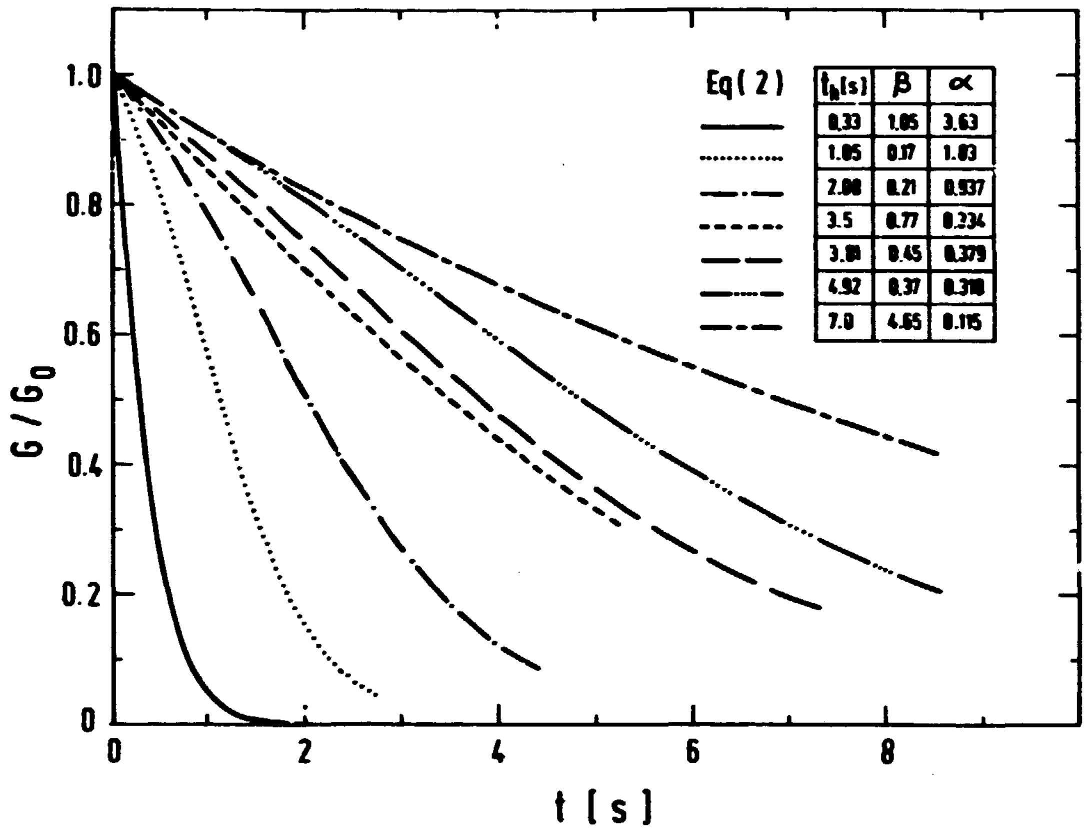

Fig. 4 - The typical mass flow transients.

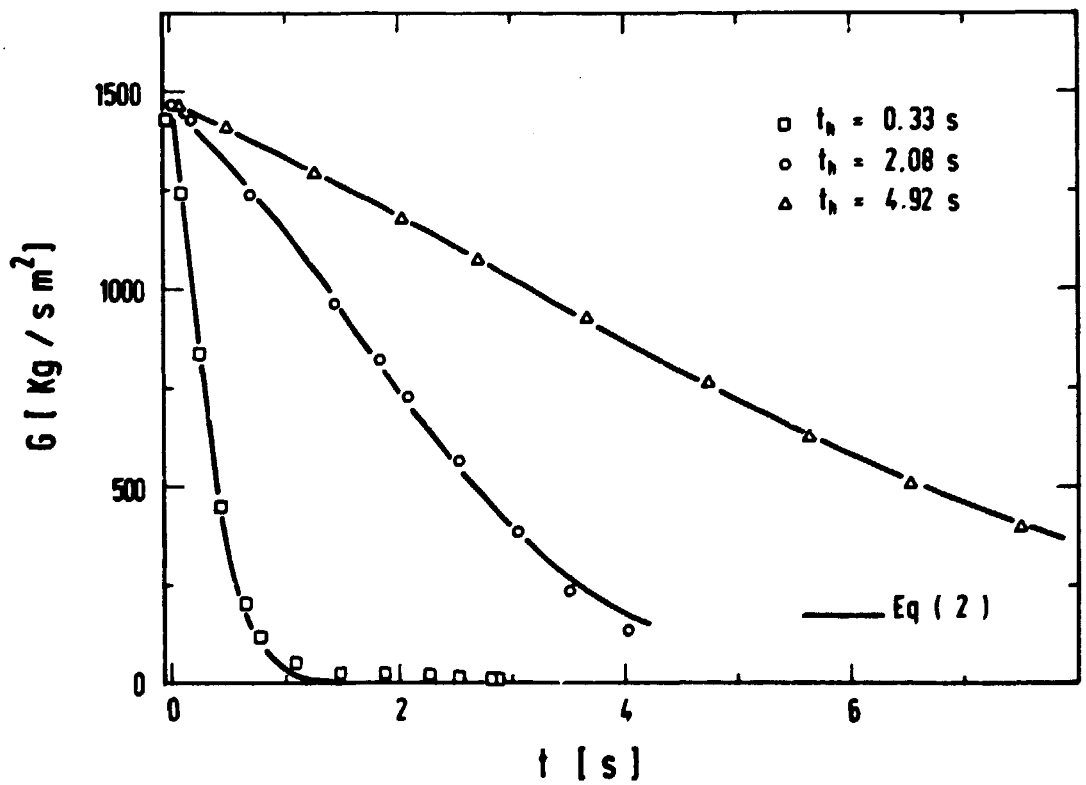

Fig. 5 - Comparison between the experimental mass flow transients and their mathematical prediction.

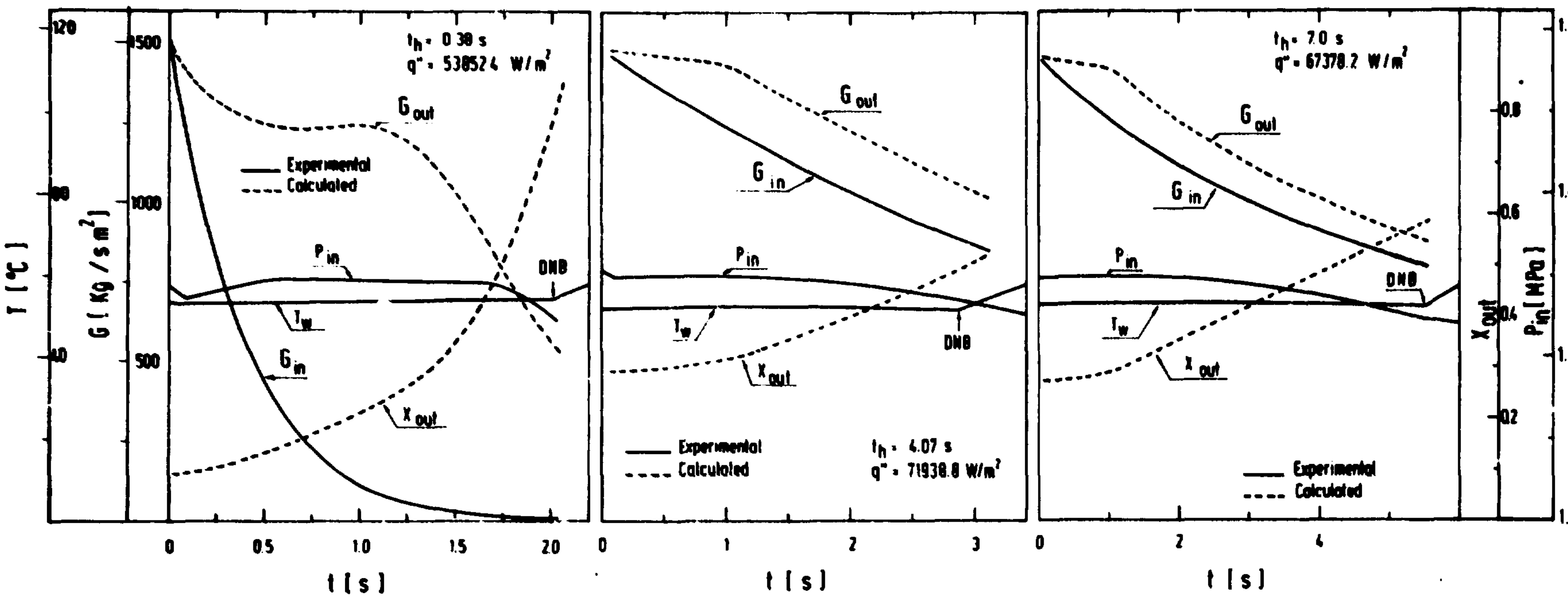

Fig. 6 - Typical representation of experimental and calculated magnitudes during the transients.

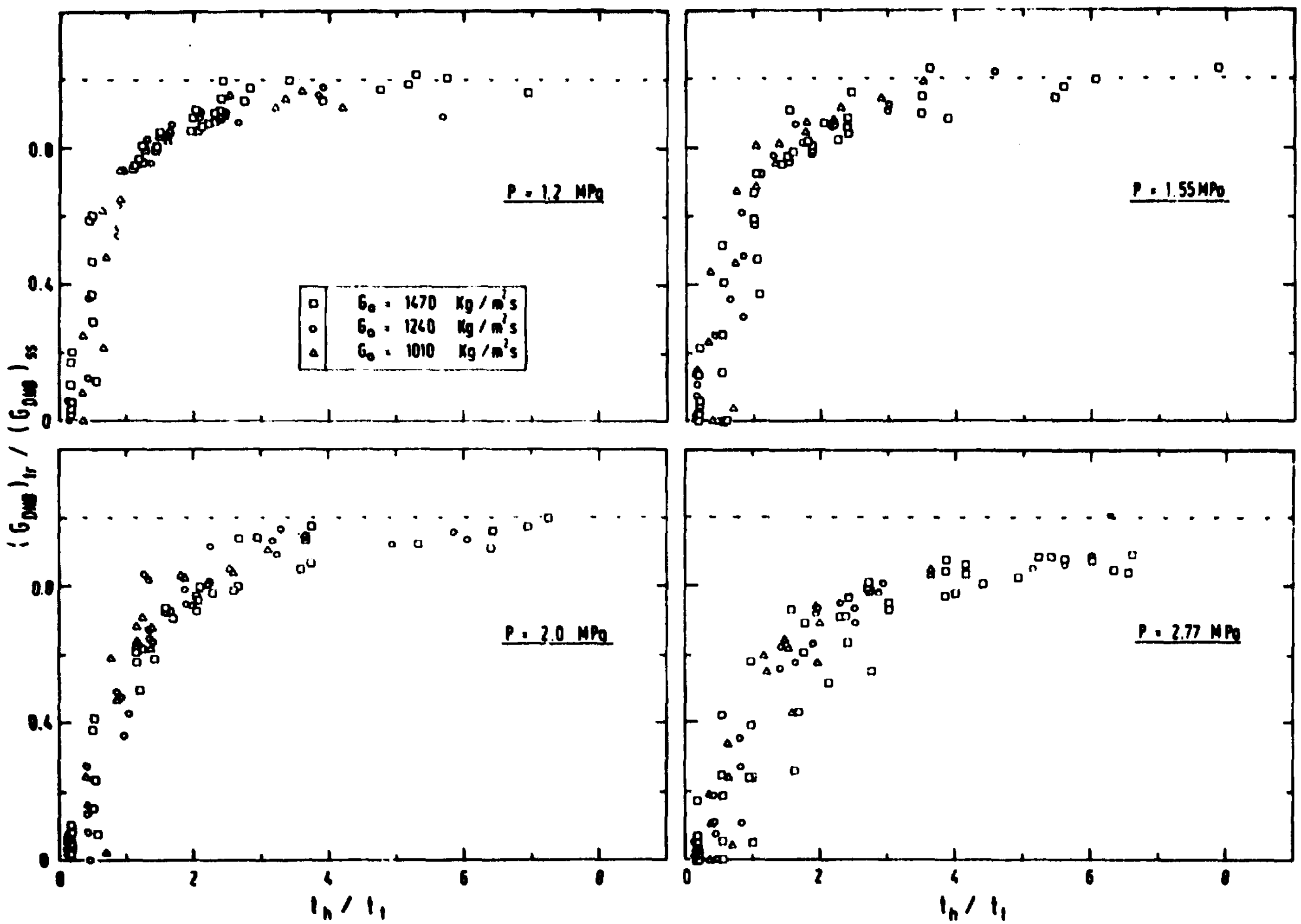

Fig. 7 - Experimental transient to steady-state critical mass flow ratios versus transient time parameter, t = t_h/t_t, for different inlet mass flowrates and system pressures.

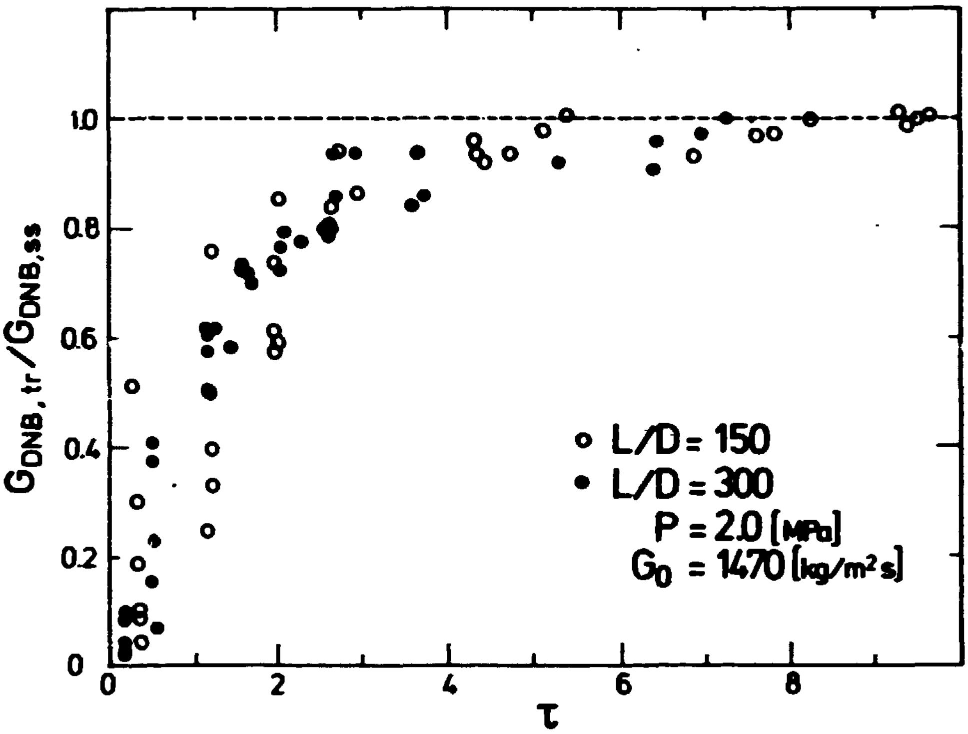

Fig. 8 - Experimental transient to steady-state critical mass flow ratios versus transient time parameter, $t = t_h/t_t$: a comparison of the two heated lengths data.

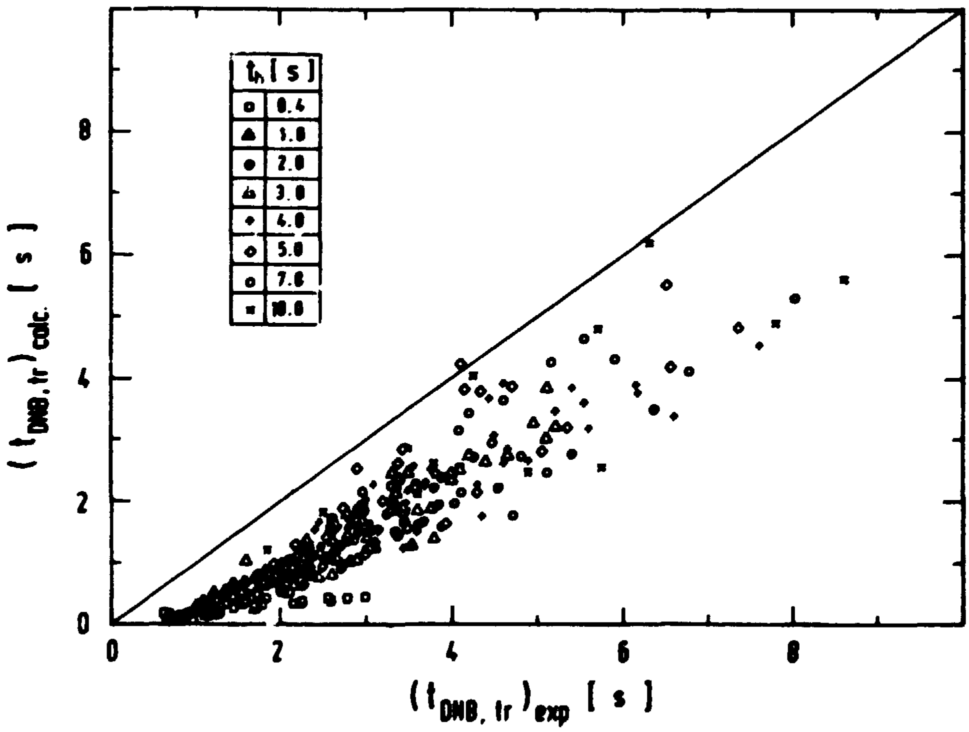

Fig. 9 - Prediction of transient time to crisis according to the steady-state approach.

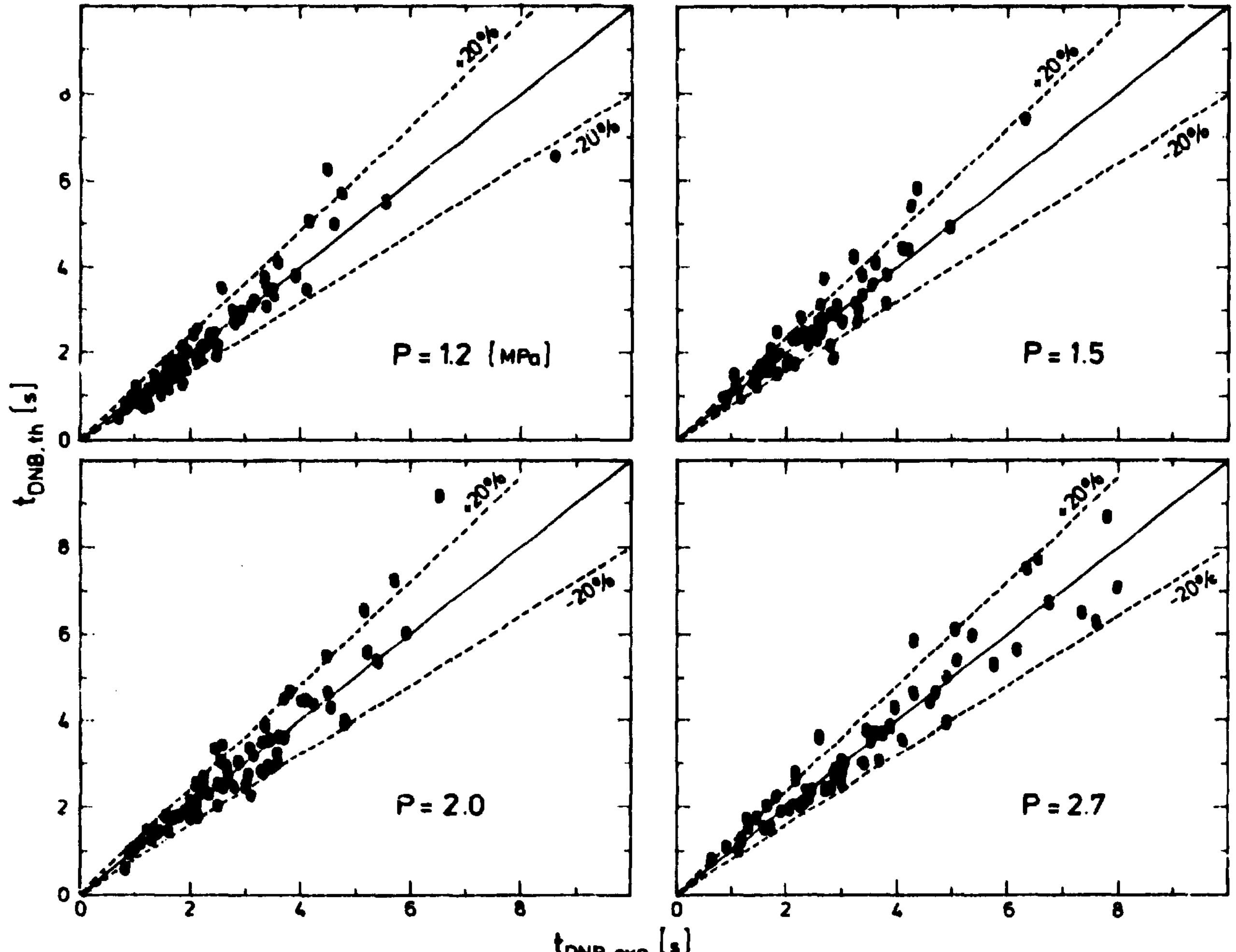

Fig. 10 – Prediction of transient time to DNB by means of the design correlation (5), with the pressure as a parameter.

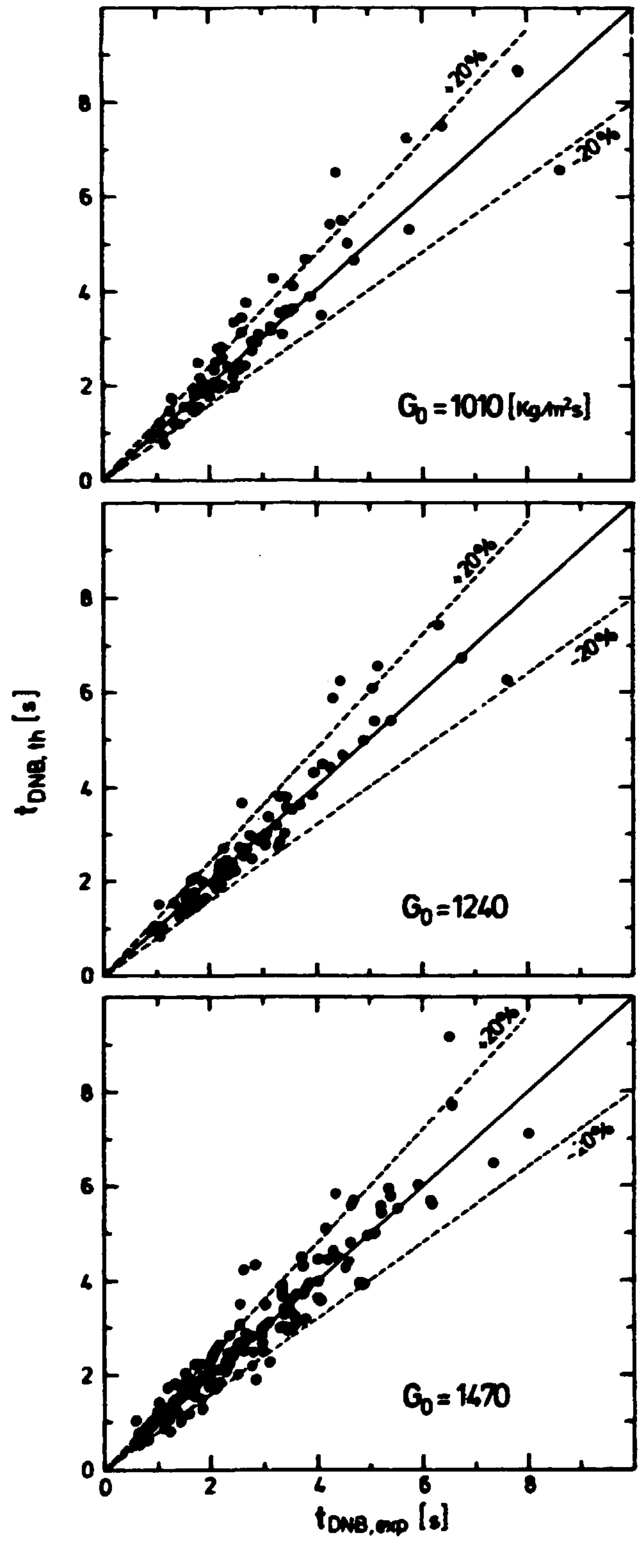

Fig. 11 - Prediction of transient time to DNB by mea.ıs of the design correlarion (5), with the initial specific mass flowrate as a parameter.

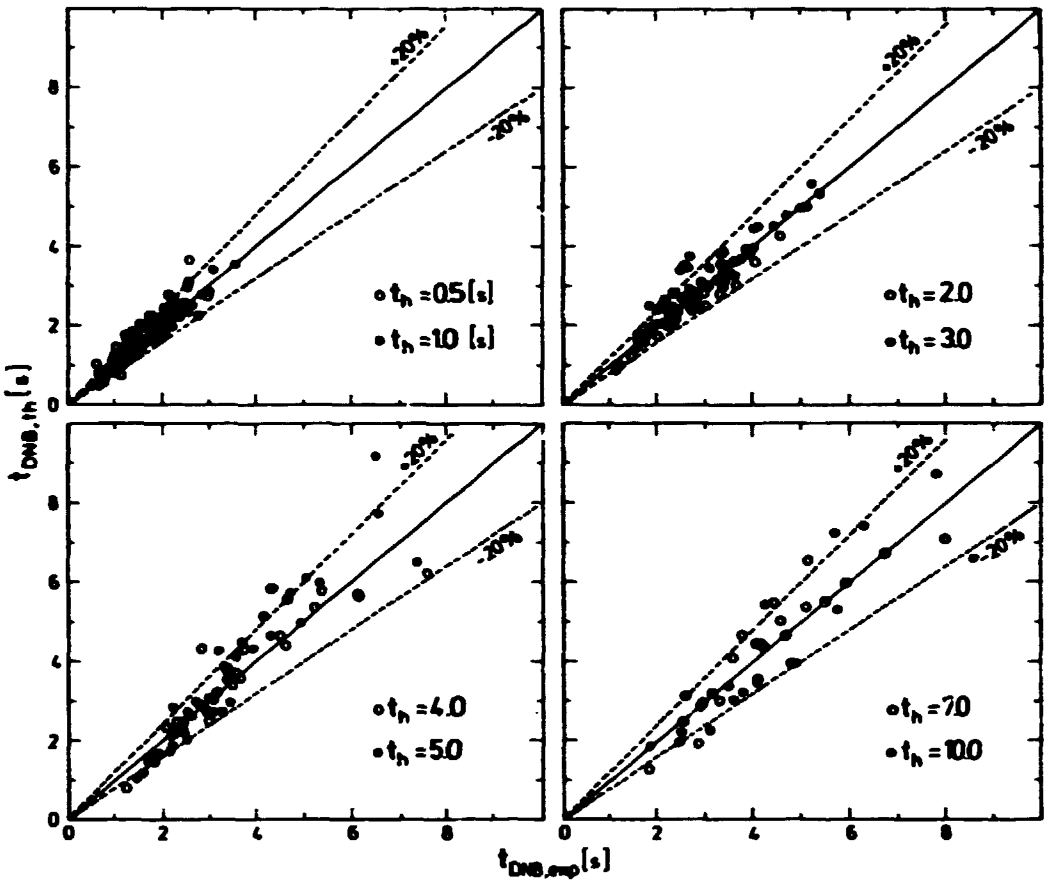

Fig. 12 - Prediction of transient time to DNB by means of the design correlation (5), with the halp-flow decay as a parameter.

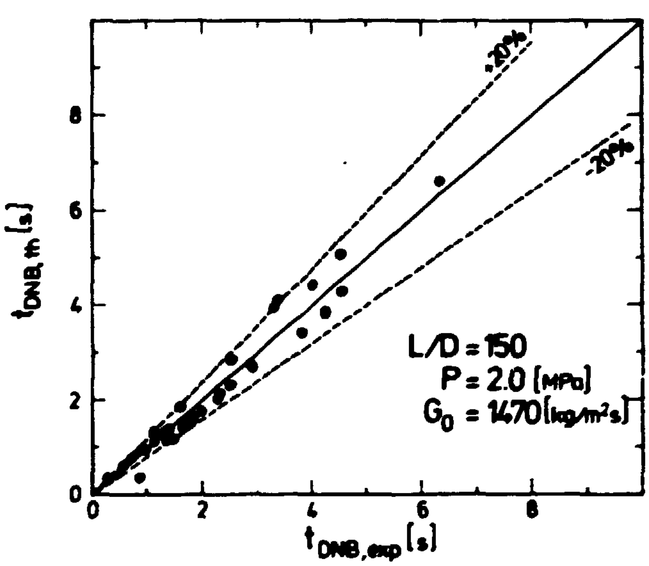

Fig. 13 - Prediction of transient time to DNB by means of the design correlation (5) for the "short" test section.

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