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FLOW REDISTRIBUTION IN RESEARCH REACTORS

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FLOW REDISTRIBUTION IN RESEARCH REACTORS

Abstract:

The critical heat flux limiting the power of low pressure water cooled reactors is generally a consequence of the flow rate redistribution.

The mechanism of this phenomenon is developed and a description is given of the out-of-pile tests in which its characteristic values are measured. The principle results are presented and the influence of principle parameters is shown.

The power of water cooled and moderated reactors is limited from the thermal standpoint by critical phenomena related to boiling. In general, an attempt is made to increase this power to a maximum while at the same time preserving reasonable margins of safety compatible with the operating conditions that are imposed. In order to narrow these margins, a better understanding is reqired of the thresholds at which critical heating appears. It generally apparent as a sudden increase of the cladding temperature leading to the destruction of the fuel element by melting.

Most of the time, critical heating that limits the power of reactors water-cooled at low pressure appears as a consequence of the phenomenon of flow redistribution that can take place in the reactor.

-- either during a temporary power increase,

-- or during a flow rate drop following a shutdown of the pumps on the primary cooling circuit, for example,

-- or during accidental depressurization of the same circuit.

Therefore, in the context of safety studies, out-of-pile loops for various current research reactors -- MELUSINE, PEGASE, SILOE, OSIRIS -- were studied and, most recently, in the preliminary project for the high flux reactor (HFR), the influence of the various parameters on the conditions of appearance of flow rate redistribution.

After a description of the process giving rise to this phenomenon and the test facilities used to measure the characteristic parameters, the principle results obtained will be described.

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I. THE FLOW REDISTRIBUTION PHENOMENON

Power is not distributed uniformly in the reactor core and certain channels must evacuate more heat than others. Flow rate redistribution is essentially related to hydraulic and thermal phenomena in these channels (hot channels) in which the water can begin to boil much sooner than it does in parallel channels (cold channels).

The reactor operating conditions are defined by the power, pressure, water entry temperature and pressure loss ΔP_{core} common to the ends of all of the channels. The operating point of each channel is then fixed on a chart of pressure loss vs. flow rate by the intersection of its internal characteristic ΔP_i and the line ΔP_{core} = constant.

Under imposed flux, water entry temperature and pressure conditions, this internal characteristic has the appearance shown in figure 1. It is commonly designated by the name of "S curve". The flow, first in simple phase with high M values, becomes by gradual decrease of the flow rate and, after the appearance of the boiling regime, a double phase flow, characterized by an increase of the pressure loss, which explains why the characteristic passes through a minimum.

Figure 2 shows the evolution of the internal characteristics at various flux rates $\varphi = 0$, φ_i and φ_R. The operating flow rates take the values M_0, M_i and M_R.

Operating points A_0 and A_i are stable points. On the other hand, A_R defined by the tangency of characteristics ΔP_i and ΔP_{core} is an unstable operating point. A small increase of the flux or a slight decrease of the flow rate causes a sudden displacement of A_R towards A'. The flow rate decreases suddenly from the value M_R but cannot reach the value M', which is very small, without intervention of critical heating of the channel walls. This sudden drop of flow rate in the hot channel related to intensification of the boiling characterized the phenomenon of flow redistribution, defined in this case by:

--a redistribution flux: φ_R

--a critical flow rate redistribution: M_R.

The pressure loss at the minimum of the S curve, ΔP_R is then equal to the imposed pressure loss ΔP_{core}.

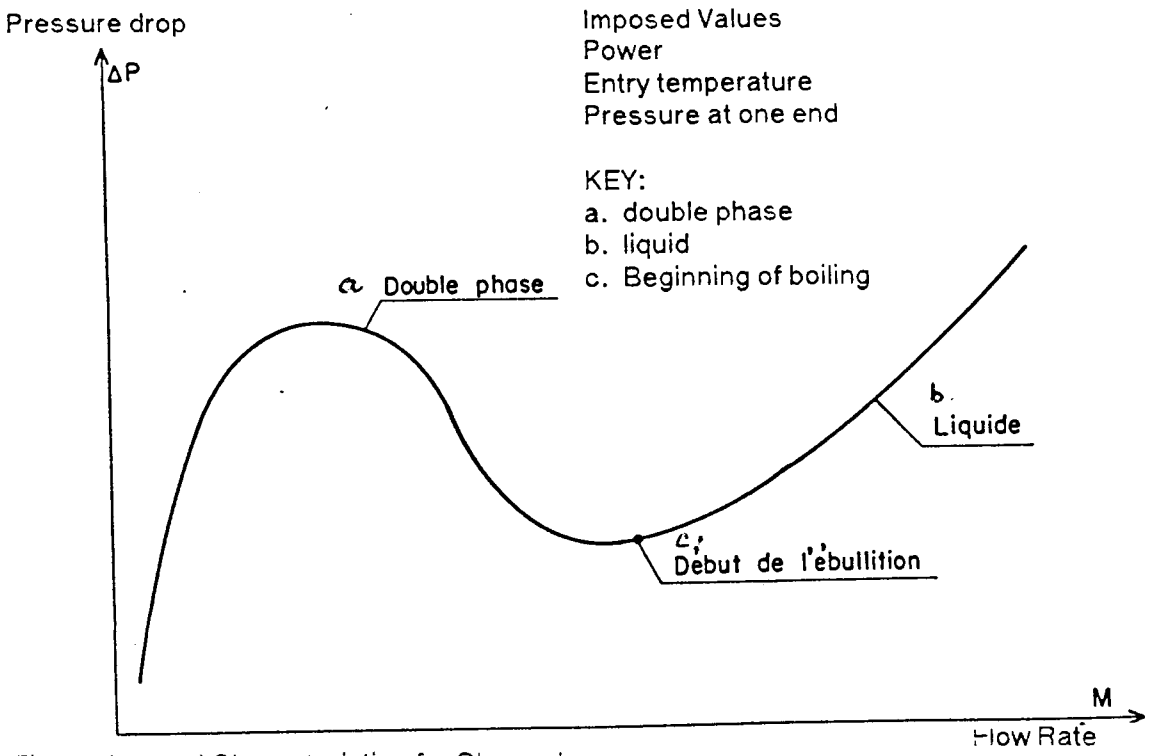

Fig. 1: Internal Characteristic of a Channel

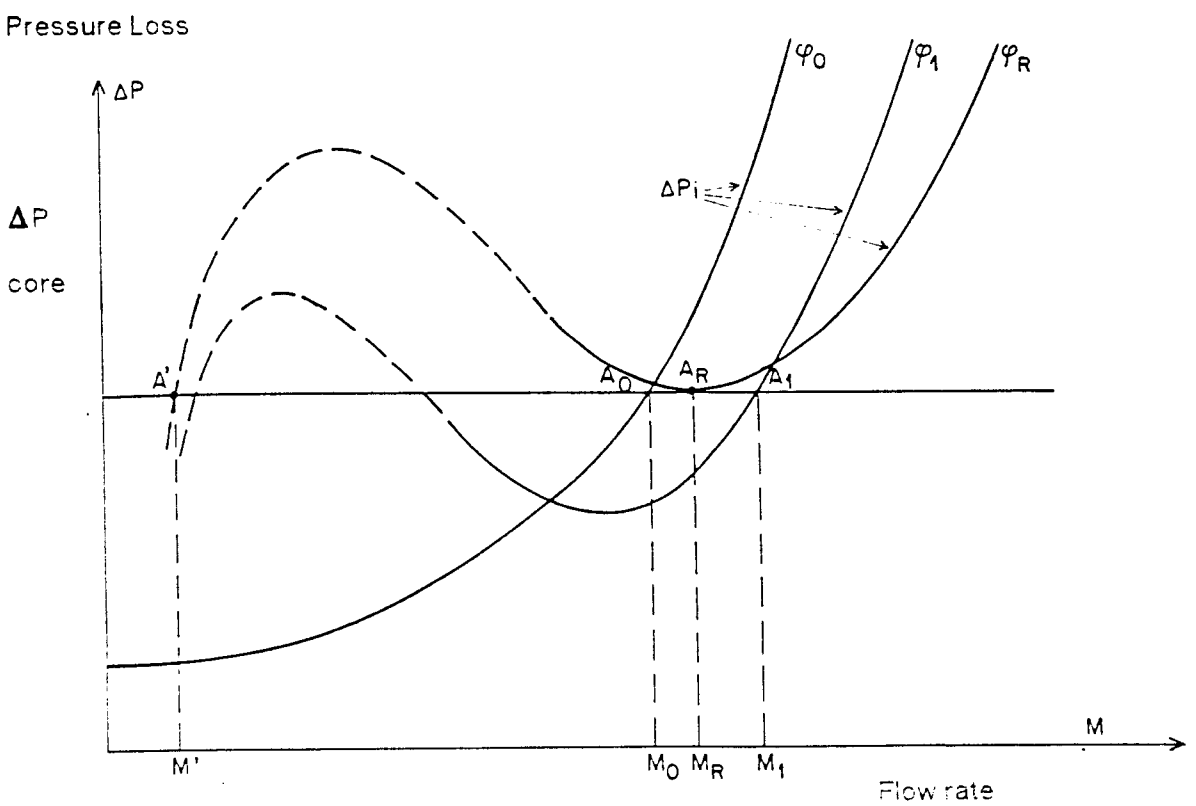

Fig. 2: Mechanisms of flow rate redistribution (by pressure increase)

Actually, the pressure loss along the channel is composed of three terms:

-- an entry peculiarity followed by a non-heating length in simple liquid phase:

-- pressure loss along the heating part;

-- an exit peculiarity preceded by a double phase non-heating length.

Calculating the first term is easy with classical fluid mechanics formulas, but the two other terms are more difficult to reach. In fact, research performed on pressure losses in the area of low pressure areas is fairly fragmentary and covers only a narrow range of the parameters not always related to what is needed [1], [2], [3], [4].

This is why an experimental program has been done in order to reach a better understanding of the phenomenon and of the ways to calculated it.

II. EXPERIMENTAL METHODS AND APPARATUS

Two methods can be used to achieve the conditions of flow rate redistribution experimentally.

-- Either by imposing a loss of head at the ends of the channel using a well-dimensioned by-pass and, for example, by very slowly increasing the flux until the phenomenon is triggered, with the temperature and input (or output) pressure kept constant. In this way φ_R and initial flow rate M_0 or the redistribution flow rate M_R are measured.

This method makes it possible to find the flow rate redistribution point and gives the overall result for a given channel. This is what is used on our "SUPER BOB" loop (Fig. 3).

-- Or by slowly lowering the flow rate so as to trace the internal characteristic of the channel for an imposed flux, input temperature and input or output pressure. Taking the coordinates of the minimum of the curve supplies to pair of values M_R and ΔP_R.

This second method, which is more flexible and has a more general application, allows a systematic study of the loss of head in double phase. In order to apply it, loops must be used that have a high head height so as to have, using a valve placed in series, an external characteristic with a large negative slope in order to eliminate any phenomenon of instability and redistribution in the range of the parameters being studied. It is used on our "BOB", "OSIRIS" and "CASIRMIR" loops (Fig. 4).

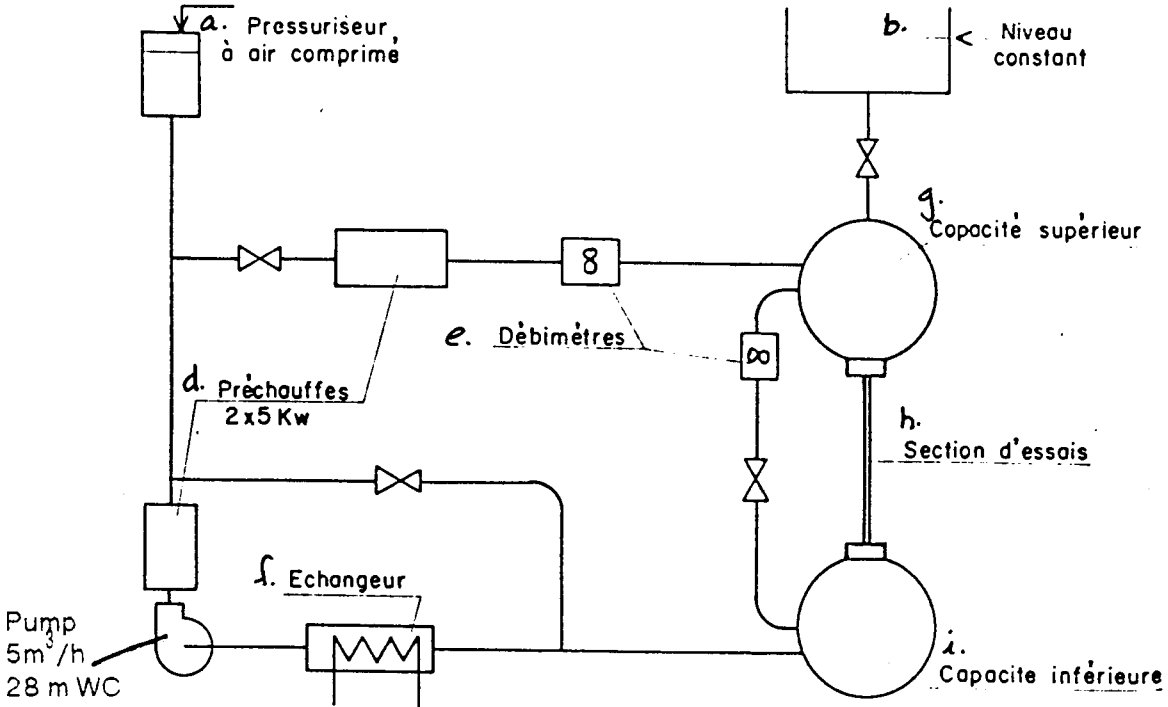

Fig. 3 -- SUPER BOB Test Loop

Key:
- A. Compressed air pressurizer
- B. Constant level
- c. Pump
- d. Preheated
- e. Flow meters
- f. Exchanger
- g. Upper container
- h. Test section
- i. Lower container

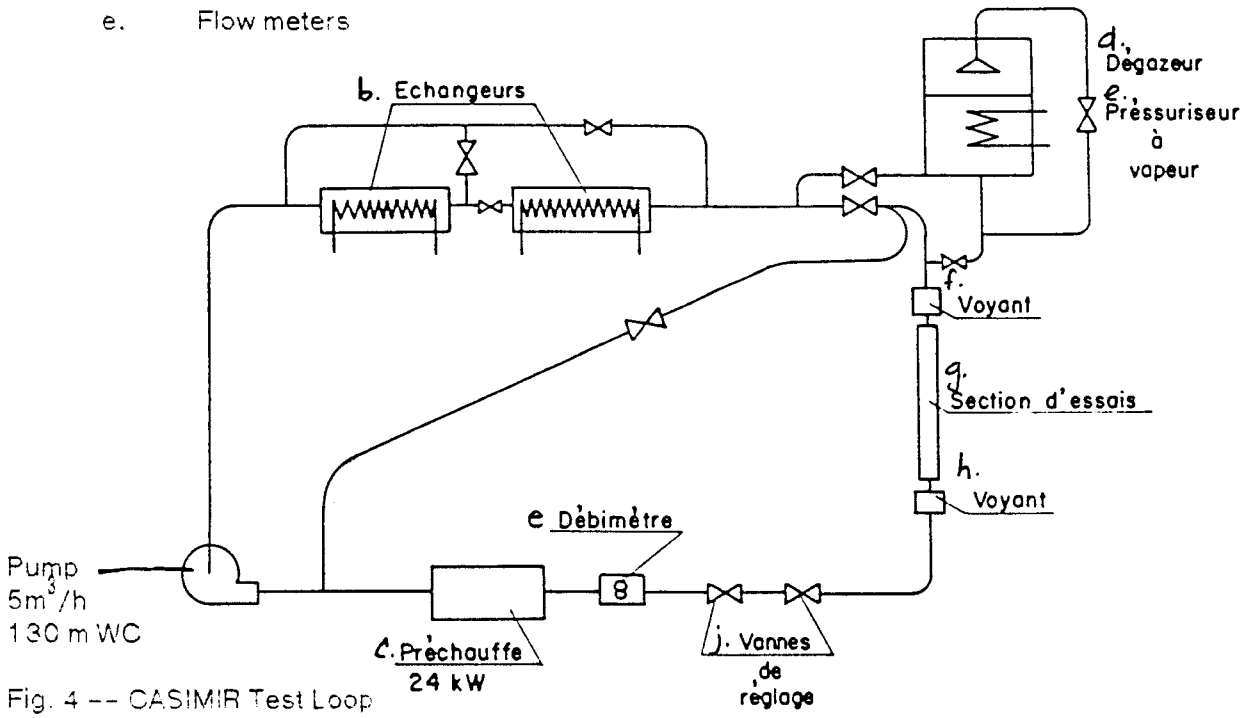

Fig. 4 -- CASIMIR Test Loop

Key:
- a. Pump
- b. Exchangers
- c. Preheated
- d. Degaser
- e. Vapor pressurizer
- f. Light
- g. Test Section
- h. Light
- i. Flow meter
- j. Adjustment valves

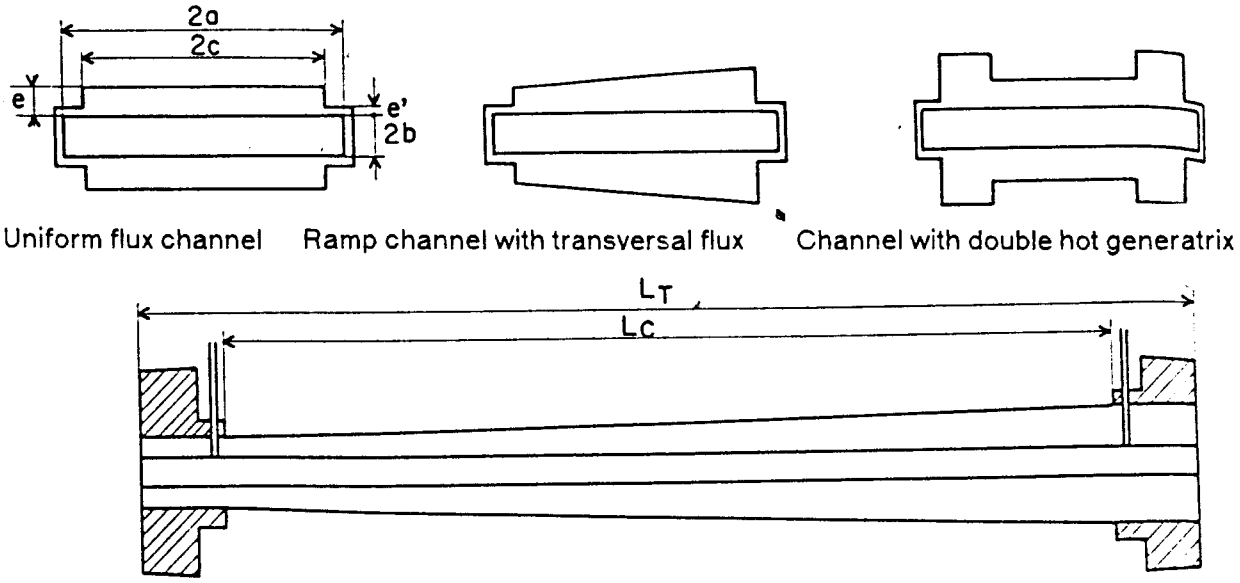

Fig. 5 – Channel geometry

This latter facility has served in particular to study the influence of the dissolved gas content of the water on the pressure loss at the flow rate redistribution point, as well as the influence of the shape of the flux.

The specifics of the two facility types, SUPER BOB and CASIMIR, should be detailed.

The SUPER BOB loop has a vessel with a constant level that makes it possible to maintain a constant pressure of 1.70 kg/cm^2 absolute in the large volume that tops the channel. On the other hand, another device makes it possible to impose any pressure between 1.5 and 5 kg/cm^2 absolute in this volume in order to set a constant reference pressure at the output (or input) of the channel. The fluid used is permuted water whose dissolved gas content is close to saturation under the pressure and temperature conditions that exist at the channel entry. Finally, the direction of flow in the test section is descending.

The CASIMIR loop has the peculiarity of being able to use a degassed water thanks to the presence of a vapor pressurizer that also operations as a degasser. It allows tests up to 11 kg/cm^2

absolute.

Water flow in the test channel is ascending.

We can also work with a water with a known gas content that changes very little during a test by using a membrane pressurizer (not shown on the figure). In this latter case, we are limited to 5 kg/cm^2.

The channels used have one section with rectangular geometry. They simulate two fuel element half-plates, with nuclear heating being replaced by electric heating. They are stainless steel and the thickness of the heating walls is:

-- either constant: which produces a uniform distribution of the flux longitudinally and transversely;

-- or variable along one of the two directions, in order to allow study of the influence of the flux shape on the flow rate redistribution conditions.

Figure 5 shows a transversal cross-section of the various test channels used. They have the following values as common dimensions:

Hydraulic width:	$2a = 38$ mm
Hydraulic length of plate:	$2c = 35$ mm
Heating thickness of edges:	$c' = 0.5$ mm
Heating length:	$L_c = 600$ mm generally
Total length:	$L_T = 675$ mm

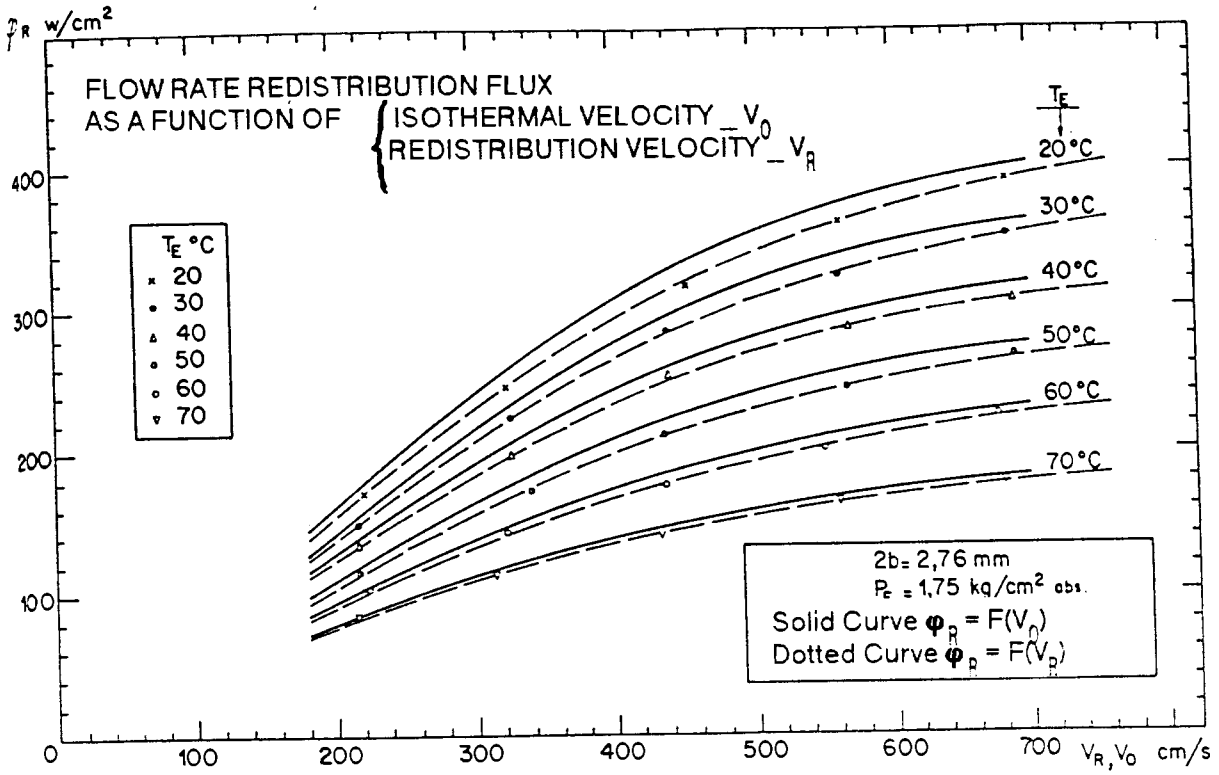
φR w/cm²
FLOW RATE REDISTRIBUTION FLUX
AS A FUNCTION OF
ISOTHERMAL VELOCITY _ V0
REDISTRIBUTION VELOCITY _ VR
TE
20°C
30°C
40°C
50°C
60°C
70°C
TE °C
20
30
40
50
60
70
2b= 2,76 mm
PE = 1,75 kg/cm² abs.
Solid Curve φR = F(V0)
Dotted Curve φR = F(VR)
0
100
200
300
400
500
600
700
VR, V0 cm/s

FIG. 6.

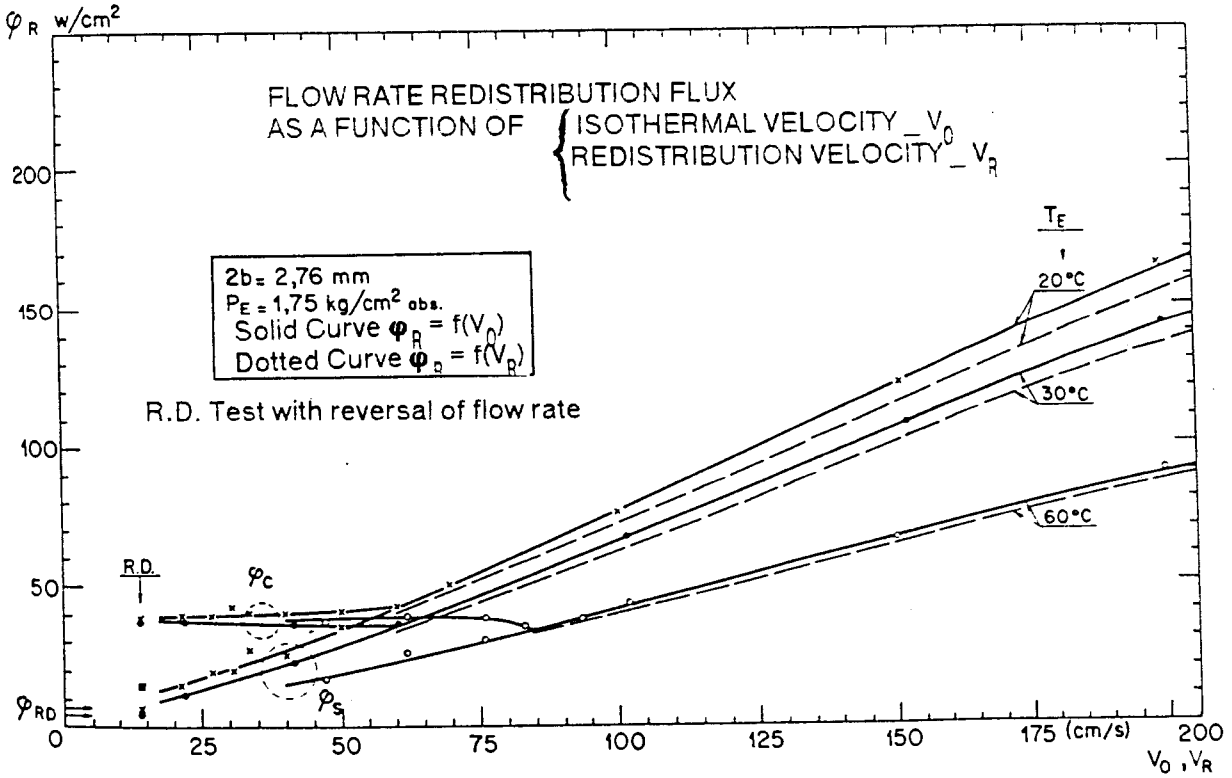
φR w/cm²
FLOW RATE REDISTRIBUTION FLUX
AS A FUNCTION OF
ISOTHERMAL VELOCITY _ V0
REDISTRIBUTION VELOCITY _ VR
TE
20°C
30°C
60°C
2b= 2,76 mm
PE = 1,75 kg/cm² abs.
Solid Curve φR = f(V0)
Dotted Curve φR = f(VR)
R.D. Test with reversal of flow rate
R.D.
φC
φS
φRD
0
25
50
75
100
125
150
175 (cm/s)
200
V0 , VR

FIG. 7.

III. TEST RESULTS

For fluxes up to 700 W/cm^2 and various water thicknesses (2b) between 1.8 mm and 3.6 mm, the influence of the following parameters on flow rate redistribution has been studied:

-- input water temperature between 20 and 70^0 C;

-- the pressure imposed either at the input or the output of the channel, varying from 1.5 to 11 kg/cm^2;

-- the longitudinal and transversal distribution of the flux;

-- the dissolved gas content of the cooling water;

-- finally, the influence of vapor recondensation that takes place at the exit of the heating length of the channel.

It needs to be pointed out that the flow rate redistribution conditions have been reached in a *permanent regime*, that is, during a sufficiently slow variation of one of the operating parameters.

A) Influence of the Input Temperature and Hydraulic Diameter

Tests were performed on the "SUPER BOB" circuit imposing:

-- the pressure of 1.75 kg/cm^2 at the channel entry, with descending flow;

-- loss of head at its ends so as to obtain velocities varying from several cm/s to 700 cm/s.

Results are presented for a channel with a given water thickness in the form of a network of curves showing the evolution of the flow rate redistribution flux φ_R as a function of the initial velocity V_0, or of the velocity at the time of redistribution V_R. Parametering is done at the input temperature T_E.

Figures 6 and 7 showing this evolution are related to a channel with an average gap of 2.76 mm.

It can be noted that, generally, at a given velocity and input pressure, the flow rate redistribution flux is inversely related to the water temperature at the channel entry.

As for the effect of the hydraulic diameter on the redistribution flux, examination of the network of curves obtained for various gaps makes it possible to see the following trend: the increase of flux

with the gap is inversely proportional to the entry temperature and directly proportional to the flow rate (Fig. 8).

B) **Behavior at Low Flow Rates**

It is interesting to note the peculiarity that these curves present at low velocities. Figure 7 shows that there is a limiting velocity, specifically related to the value of T_E below which two distinct phenomena are detected experimentally.

First, when the flux reaches a value φ_S by gradual increase, a flow rate instability that instantly gives rise to an expulsion regime of a stable periodic nature accompanied by a *local* and *temporary* burn-up of the wall at the hot point of the channel (the wall is periodically dried up, then rewet). The frequency of expulsions then increases with the flux until the latter reaches a critical value corresponding to the *total* and *definitive* burn-up of the wall leading to critical heating. The critical heat flux φ_c appears to be independent of the input temperature and velocity for any given gap.

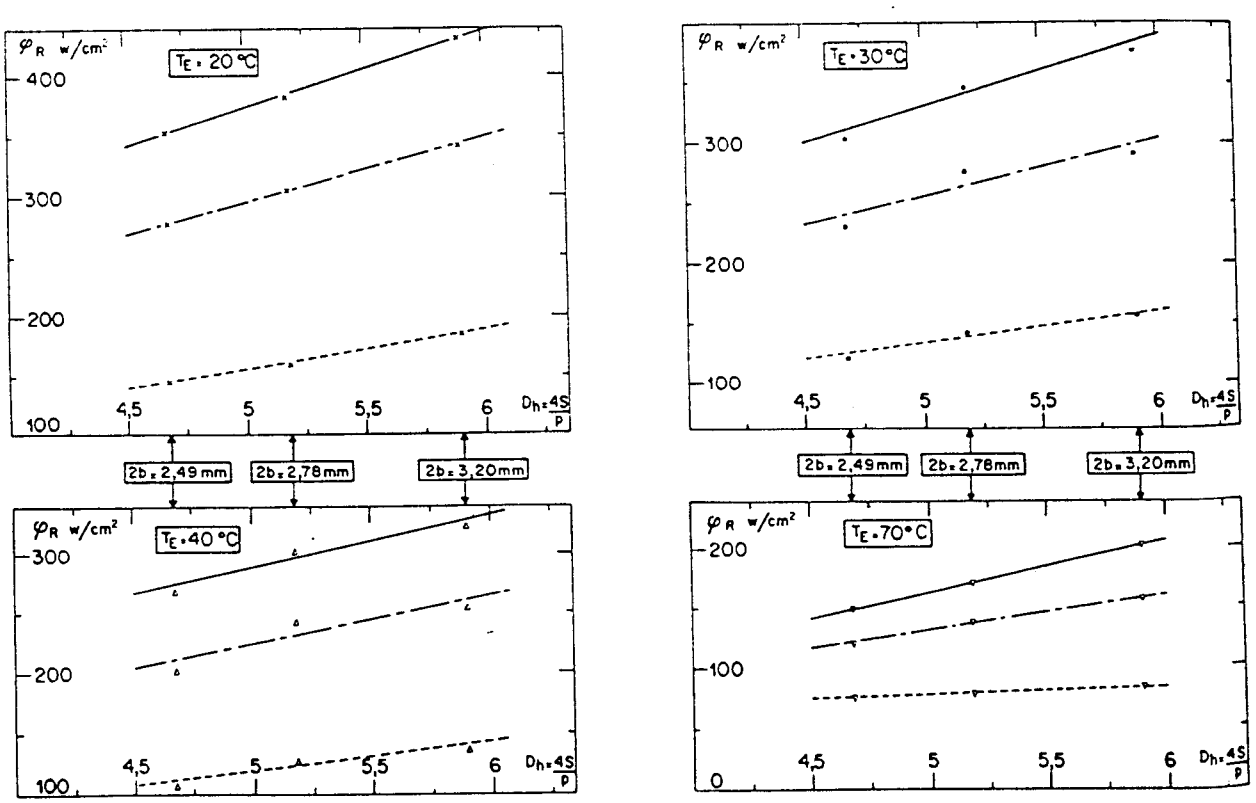

Fig. 8 – Flow Rate Redistribution Flux as a function of hydraulic diameter $\left\{ \begin{array}{l} V_r = 600\ cm/s \\ V_r = 400\ cm/s \\ V_r = 200\ cm/s \end{array} \right.$

Beyond the limiting velocity (60 to 80 cm/s along T_E for the channel with a 2.76 mm gap, definitive burn-up takes place starting with the first instability which, in this case, causes a sudden drop of flow rate in the channel. The flux at which the flow rate redistribution appears is then measured directly. The evolution of the latter as a function of velocity prolongs the one marking the instability threshold.

Finally, for tests at very low velocity (below 15 cm/s), flow rate reversal is obtained at fluxes φ_{RD} approximately three times lower than those at which the instabilities appear.

C) Influence of Pressure

Tests were performed on the OSIRIS circuit (paragraph 2) on a channel with a 2 mm gap. The pressure imposed at the channel exit varies in the range of 1.5 to 5 kg/cm^2 absolute.

The results presented on Figure 9 show the evolution of the pressure loss in the channel at the time of the flow rate redistribution as a function of the output pressure for three flux values (250, 350 and 450 W/cm^2) and an input temperature of 40^0 C.

At a given flux, a pressure increase causes a decreasingly large decrease of the pressure loss at redistribution. This should be compared to the evolution of the saturation temperature with the pressure.

To this end it has been shown from experimental results that there exists a certain degree of correlation between the temperature increase T_S,T_E and the difference T_{SATS}-T_E. For all of the points it has been found that the ratio

$$R_R = \frac{T_S - T_E}{T_{SATS} - T_E} = \frac{W/C_P M_R}{T_{SATS} - T_E}$$ varies between 0.64 and 0.92.

T_S = Water exit temperature

T_E = Water input temperature

T_{SATS} = saturation temperature calculated at exit pressure

C_p = Specific heat of the water

W = power released in the channel

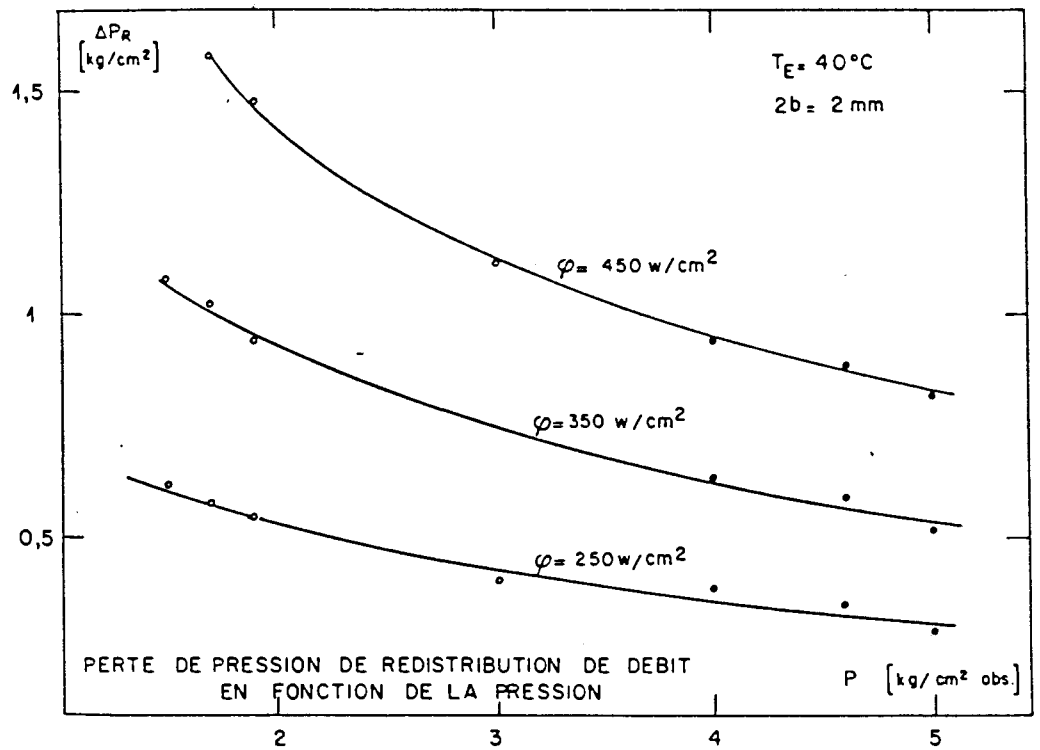

Figure 9 -- Flow Rate Redistribution Pressure loss as a function of Pressure

If tests at low velocity are ignored for which the flow direction can have an influence at low pressure with descending flow, there is a still a certain dispersion because of the non-negligible influence on input temperature, flux, output pressure and the ratio of length to hydraulic diameter (L/D) characterizing the geometry. The ratio varies between 0.73 and 0.90 and allows as a mean value R_R = 0.80 which is also the value found by other researchers [5] in a more limited range of parameters.

D) Influence of Flux Shape

All of the experiments previously described were performed on channels with a uniform heat flux surface density. Now, that is not the case in a reactor. In addition to the overall cosine shape at the core level, the flux density undergoes considerable rises on the scale of each fuel element. Therefore, it is necessary to determine what influence the flux shape has on flow rate redistribution.

This influence has been revealed by studying the case of the longitudinally variable flux in the direction of flow of the water and the case of a flux varying transversely in a direction perpendicular

to the flow.

Non-uniform heat fluxes are easily achieved on test sections heated directly by Joule effect. It is sufficient for the metal heating walls to have a variable thickness.

1. Channels with a longitudinally non-uniform heat flux

A 51.7 cm long rectangular test channel with a 3.6 mm gap was constructed whose heating plates have a thickness e that varies linearly with length. This makes it possible to have a heat flux with a hyperbolic variation (proportional to l/e) that is still fairly close to linear variation (see figure 10). Thus, from one end to the other the flux goes from the value of φ to 1.37 φ.

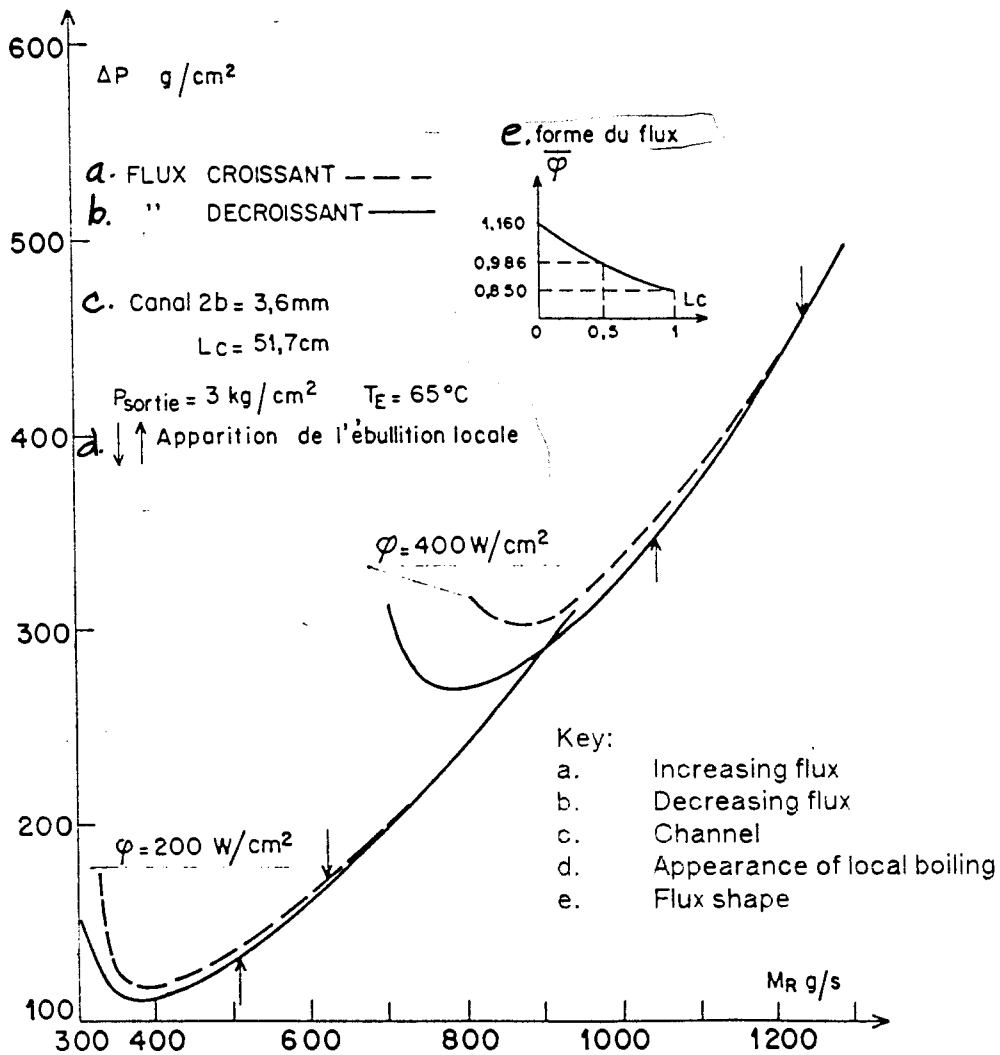

Figure 10 -- Influence of a longitudinal flux variation on pressure losses

Depending on the direction of flow of the water in the test channel, there is an increasing or a decreasing flux.

For these two configurations, the characteristic and pressure loss ΔP curves were drawn as a function of the flow rate M in the following parameter range:

$200\ W/cm^2 < \varphi_{av.} < 400\ W/cm_2$

$25^0 < T_E < 65^0\ C$

Outlet pressure $P_S = 3\ kg/cm^2$ absolute

Results related to two of these curves have been drawn on figure 10. Note that the direction of evolution of the flux along the flow has a slight influence on the pressure losses at the limits of the channel. This influence is due to the fact that, in the two configurations, the appearance of local boiling does not take place for the same flow rate and the lengths boiling are, therefore, very different.

The difference on pressure loss at the curve minimum governing the flow rate redistribution remained below 11% during these tests, with the increasing flux configuration producing higher pressure losses.

Calculations made from classical correlations of pressure loss at local boiling established for uniform fluxes and using local variables take into account the differences observed experimentally.

2. *Channels with transversely non-uniform heat flux*

Two configurations were studied:

a) A linear flux ramp

This profile was achieved on a 60 cm long channel with a 3.6 mm gap. From one side to the other the flux evolves from φ to 1.37 φ (fig. 11).

b) A flux profile that will be called "profile with double hot generatrix."

This profile was done on a 60 cm long channel with a 1.8 mm gap (fig. 12) with a ratio of 1.57 between the minimum flux and the hot generiatrix flux.

In both cases the test channels have their two identical heating plates.

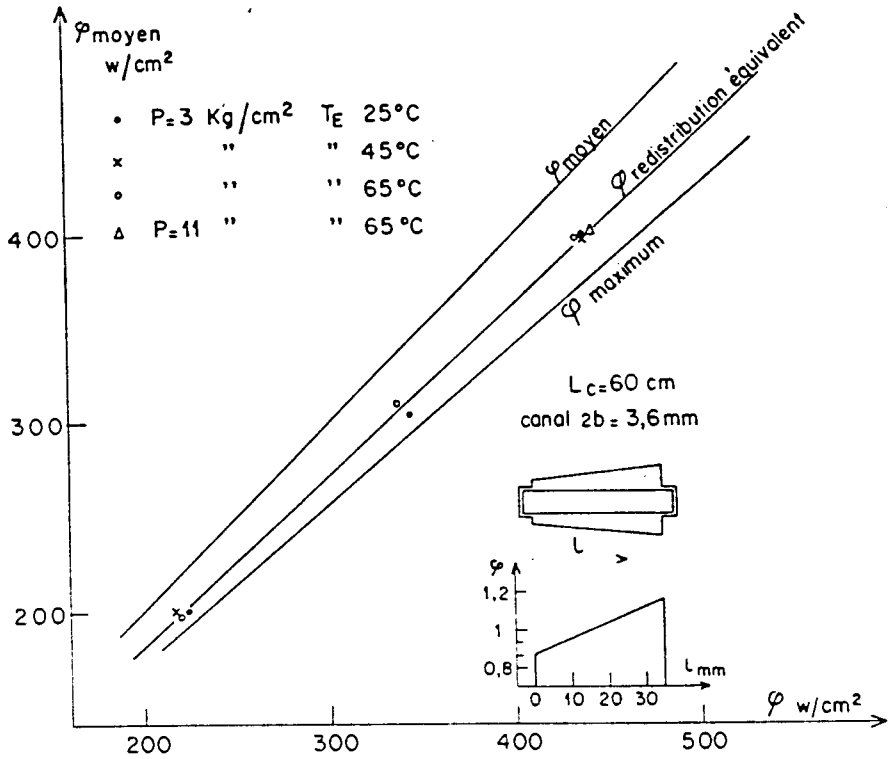

Fig. 11 – Flux redistribution of a channel with transveral flux ramp

Key:
a. Mean
b. Redistribution equivalent
c. Channel

The results concerning the S curves obtained on these channels have been compared to those obtained on channels with uniform flux with the same geometric characteristics releasing the same electrical power under the same flow conditions.

It was noted that the flow rate and the pressure losses at the redistribution point were higher than those in the channel with uniform flux. The average flux is, therefore, not representative of the redistribution phenomenon and, more seriously, it is not a conservative parameter.

By drawing the ΔP^R curves for the uniform flux channels as a function of the flux, one can find in a network [of curves] of this sort to which equivalent uniform flux the redistribution conditions of the non-uniform flux channel correspond.

This equivalent flux is shown on figures 11 and 12, located in relation to the average flux and the maximum flux. In the range of parameters studied, it is practically independent of the entry temperature and pressure conditions.

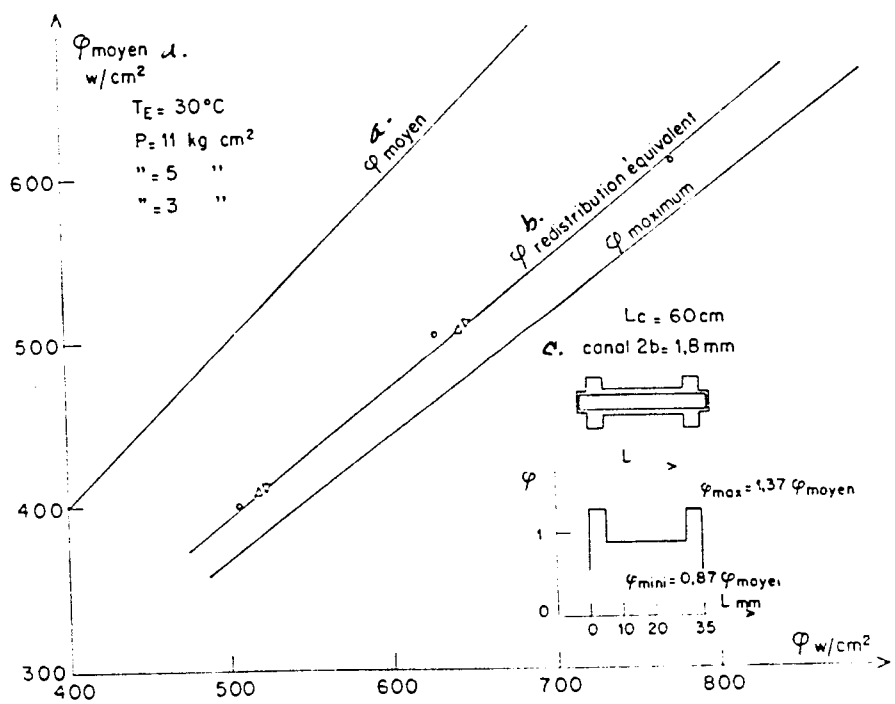

Figure 12 - Redistribution flux of a channel with "double hot generatrix"

Key: a. Mean
b. Redistribution equivalent
c. Channel

In both configurations, the following relationship exists: $\varphi_{equivalent} = 0.94\ \varphi_{maximum}$. This figure of 0.94 can obviously not be applied to all the flux shapes. However, it can be seen that a conservative and not too stringent approximation consists of considering a channel with a non-uniform flux as having a constant flux equal to the maximum flux.

In the case of a non-uniform longitudinal flux, the redistribution conditions can be found by calculation using codes involving equations applied in one dimension only. On the other hand, for the case of transversely non-uniform flux, codes with bidimensional equations that involve interactions between adjacent fluid streams must be used. The experimental points obtained on the channels with non-uniform flux could then be used to adjust these codes.

E) **Influence of Dissolved Gases**

In the majority of cases, for reasons of reproducibility and purity of the phenomena, the experimenters use degassed water in their test facilities.

Now, in certain nuclear reactors, especially in pool type reactors, the presence of a gas plenum and release of radiolysis gas means that the cooling water can contain a certain quantity of dissolved gas. It is known [6] that, in the case of cooling by gassed water there will be degassing prior to the appearance of local boiling. This degassing is reflected by the formation of non-condensable bubbles and it is interesting to know whether this presence of bubbles will have repercussions on the pressure losses and, consequently, on the flow rate redistribution.

Many experiments have been performed on rectangular channels with a 3.6 mm gap with gassed and degassed water. Gassing the water in the test loop is done by circulating the water in a tank with an air plenum. The dissolved air content is determined by measuring the dissolved oxygen content with a Beckman oxygen analyzer.

Various characteristic curves have been drawn in the following parameter ranges:

$200 < \varphi < 400\ W/cm^2$ $\quad$ $25^\circ C < T_E < 65^\circ C$

Exit pressure: $3\ kg/cm^2$ $\quad$ Oxygen content: $200\ \gamma/l < \delta < 24\ 000\ \gamma/l$

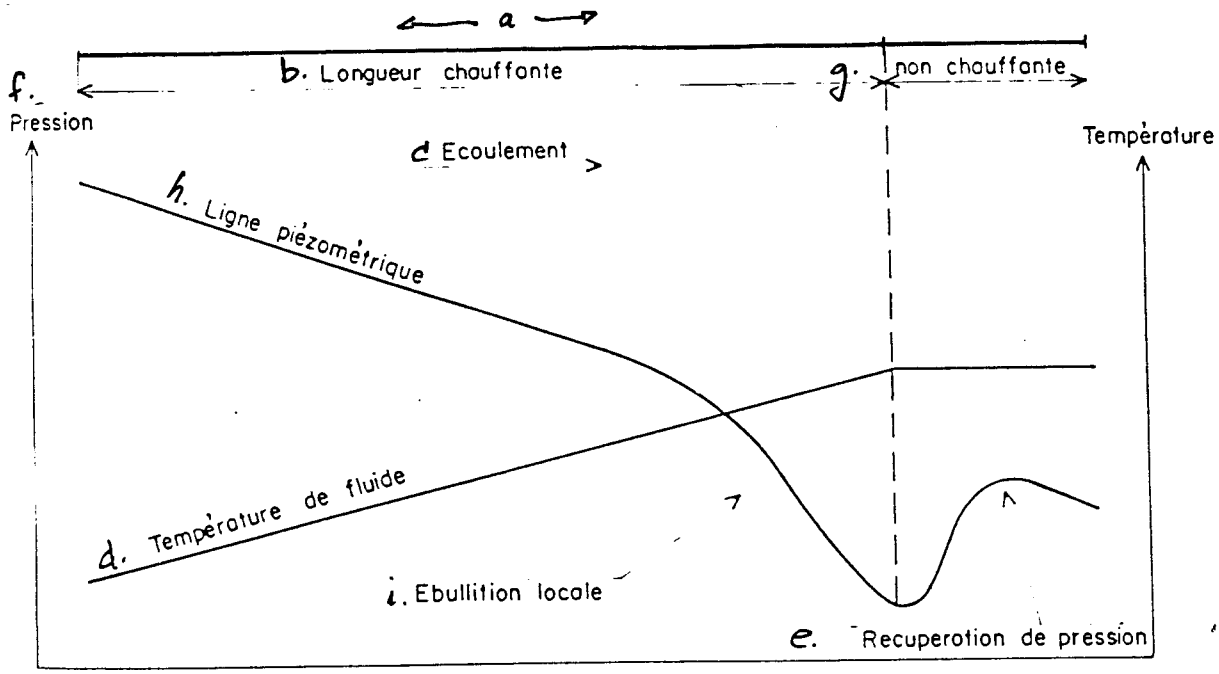

Fig. 13 – Revelation of pressure recovery

Key:				
	a.	Channel	f.	Pressure
	b.	Heating length	g.	Non-heating
	c.	Flow	h.	Piezometric line
	d.	Fluid temperature	i.	Local boiling
	e.	Pressure recovery		

What is important is not the absolute value of the oxygen content but its relative value compared to saturation, evaluated for example under the input conditions of the test section. Thus 24 000 γ/l corresponds to saturated water at 3 kg/cm^2 at 25° C.

During the tests it was noticed that degassing contributed to slightly increasing pressure losses slightly, but this increase still remained below 5% at a minimum of the S curve, that is, to the redistribution point.

F) Exit Peculiarity – Effect of a Non-heating Length

In reactor fuel elements, for reasons of construction, the radioactive portion containing the uranium generally ends several centimeters from the ends of the plates.

When the flow is in simple phase, it is possible to evaluate the influence of this non-heating length. However, when there is local boiling in the channel (near the minimum of the S curve), calculation is more difficult given the fact that there can be vapor condensation in this zone and that,

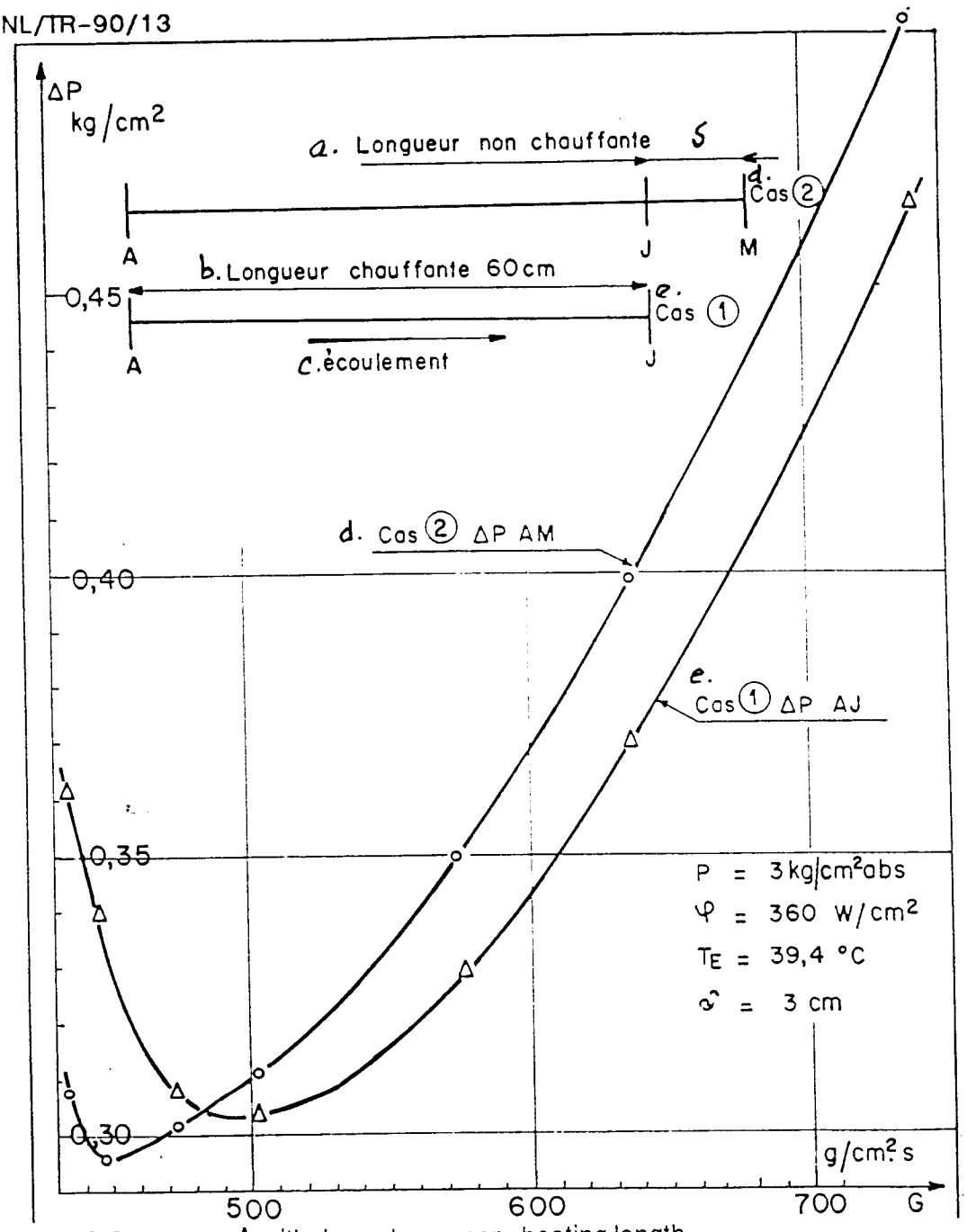

Fig. 14 – S Curves Δ with downstream non-heating length

O without downstream non-heating length

Key:

a.	Non-heating length	d.	Case 2
b.	Heating length 60 cm	e.	Case 1
c.	Flow		

under certain conditions, it is accompanied by a pressure recovery (see fig. 13).

Comparison of the characteristics (ΔP, M) of a channel with or without a non-heating length at the exit, shows that the influence of pressure recovery is slight on the coordinate of the minimum (difference of several %) and that the results of the S curves obtained with a channel without non-heating length are conservative (see figure 14).

This pressure recovery has been studied systematically: conditions of appearance, amplitude, recovery length. The information obtained on the conditions of appearance of the vapor in local boiling are used in the up-dating of the calculation codes for the pressure losses in local boiling at low pressure.

IV. CONCLUSION

The tests undertaken to determine the conditions of flow rate redistribution have made it possible to study the influence of many parameters on this phenomenon which thermally limits the power of low pressure water cooled reactors.

The results obtained have been used to set the safety margins with a good approximation for several research reactors. In addition, they have produced a lot of information on local boiling.

The experimental results are currently being used for up-dating a calculation code for pressure loss along the channel un boiling with a view to applying it to channels with any longitudinal distribution of heat flux.

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