An analysis of the steady state and stability characteristics of a natural circulation boiling channel

AN ANALYSIS OF THE STEADY STATE AND STABILITY CHARACTERISTICS OF A NATURAL CIRCULATION BOILING CHANNEL.

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Abstract.

The paper deals with studies in the field of stability in a vertical boiling channel in which heat is generated by an electrically heated element and transferred to water circulating by natural convection under pressures up to 30 atm. Experimental and theoretical studies regard the static performance as well as the dynamic characteristics of the boiling channel. The aim of the static programme is to yield correlations for slip and pressure drop in two-phase flow, whereas the dynamic programme has led to the establishment of conditions under which instabilities start and to the prediction of the stability characteristics of the steady state by hand of transfer functions. The mathematical model by Jahnberg is used for comparison with experimental results.

Zusammenfassung.

Stabilitaetsfeldstudien in einem senkrechten Siedekanal, in welchem Waerme durch einem elektrischen Heizkoerper erzeugt wird und zum Wasser durch natuerlicher Konvektion unter einem Drucke von weniger als 30 Atm. uebertragen wird, werden behandelt. Das statische und dynamische Verhalten des Siedekanals wurde theoretisch und experimentell untersucht. Der Zweck des statischen Programmes war das Finden der Verhaeltnisse zwischen Gleiten und Druckfall in einem Zweiphasenstrom. Der Zweck des dynamischen Programmes war die Umstaende festzustellen unter welchen Unstabilitaeten beginnen und Voraussage der Stabilitaetseigenschaften des stationaeren Zustandes mit Hilfe von Uebertragungsfunktionen. Jahnberg's mathematisches Modell wird mit den Versuchsergebnissen verglichen.

Реферат

В работе излагаются исследования устойчивости в вертикальном кипящим канале, в которым создается тепло электрически нагретом элементе и переносят ее к воды, циркулирующей при естественной конвекции под давлениях не более 30 атм. Статические и динамические характеристики кипящего канала были изучены экспериментально и теорически. В статическом программе исследовали корреляции для скольжения и понижения давления в двух-фазном потоке, и в динамическом установили условия в которых неустойчивости начинаются и предсказание характеристиков устойчивости стационарного состояния с помощью функциях переноса. Употребляется математический модель Жанберга для сравнения со экспериментальным даннам.

ABSTRACT.

The paper deals with studies in the field of stability in a vertical boiling channel in which heat is generated by an electrically heated element and transferred to water circulating by natural convection under pressures up to 30 atm. Experimental and theoretical studies regard the static performance as well as the dynamic characteristics of the boiling channel. The aim of the static programme is to yield correlations for slip and pressure drop in two phase flow, whereas the dynamic programme has led to the establishment of conditions under which instabilities start and to the prediction of the stability characteristics of the steady state by hand of transfer functions. The mathematical model by Jahnberg is used for comparison with experimental results.

INTRODUCTION.

In the Laboratory for Heat Transfer and Reactor Engineering of the Technological University of Eindhoven systematic studies are being carried out on the heat transfer and stability characteristics of water-cooled nuclear reactors. Research is carried out by means of simple atmospheric loops allowing rather fundamental studies and the development of instrumentation as well as of high pressure loops for studies under pressures up to 150 atm.

The present report deals with studies in the field of stability in a vertical boiling channel in which heat is generated by an electrically heated element and transferred to circulating water under pressures up to 30 atm. This research is carried out under contract with the European Atomic Energy Community (EURATOM).

Both experimental and theoretical studies are under way regarding the static performance of a boiling channel as well as the dynamic behaviour of such a channel. The experiments are compared with results, obtained from known mathematical models and from models newly developed in the laboratory. In the present report only Jahnberg's (1) model is used for comparison. The aim of the static programme is to yield correlations for slip and pressure drop in two phase flow whereas the dynamic programme has led to the establishment of conditions under which instabilities start and the prediction of the stability characteristics of the steady state by hand of transfer functions. As a by-product of the research a comparison was made of various methods of processing data from the dynamic programme, that is, analogous versus digital processing. It should be mentioned that in the analysis the conventional concept of slip in two phase flow has been used. A more fundamental approach is at present being made by the Laboratory (2,3,4) in which both the radial velocity and phase concentration profiles are taken into account.

EXPERIMENTAL SET-UP.

A simplified flow scheme of the natural circulation pressurized boiling water loop is given in Fig. 1. The test section consists of an electrically heated element placed in a shroud. In the experiments reported in this paper, the steam-water mixture flows upwards by natural convection through this annular passage, the riser. The downcomer is the annular passage between the shroud and the stainless steel wall of the 40 atmosphere pressure vessel. The steam produced in the test section is separated from the water flow at the top of the riser and flows to the condenser, the condensate being returned to the downcomer through a preheater. The water flows to the inlet of the riser, passing a subcooler circuit which permits control of the subcooling at the inlet of the riser.

The heating element is a single rod of stainless steel with an outer diameter of 33.8 mm and a heated length of 2400 mm. It is heated by direct current and has a uniform heat flux distribution. The stainless steel shroud has an inner diameter of 50 mm and a length of 2628 mm. An other shroud has also been used with an inner diameter of 60 mm and the same length. The lower end of the shroud is 40 mm lower than the lower end of the heating element.

The d.c. power dissipated in the heating element can be varied continuously between 10 and 1000 kW. The pressure can be selected at any value between 14 and 450 p.s.i.a. and is controlled automatically. The subcooling can be adjusted between 0 and 50 degC, dependent on the pressure.

MEASURING TECHNIQUES, DATA PROCESSING AND ANALYSIS.

In the experiments the following quantities were measured or recorded as a function of power, pressure and subcooling (see Fig. 2).

Natural Circulation Rate.

The natural circulation rate was measured using the pressure drop across the inlet and the differential pressure from a pitot-tube. The differential pressures were calibrated in cold tests. The values from the two methods differed by less than ± 2 per cent. The pressure drop across the inlet and the differential pressure from the pitot-tube were also recorded. Inductive differential pressure gauges were used for the dynamic measurements.

Void Fraction.

The void fraction measurements were made using a radioactive method in which a Thulium γ - source was centrally placed inside the heating element, while four scintillation counters were grouped around the riser (5). The signals from the four counters were mixed and the sum was measured. A special feature of the γ-ray absorption technique as applied in this loop was that the amplification of the photomultipliers was kept constant automatically at an adjusted value by means of a spectrum stabilizer. For this purpose a small Cesium-137 source was placed in front of the crystal of each photomultiplier. In this way changes in amplification caused by temperature effects, magnetic fields and fatigue of the photomultipliers could be corrected. Also, impedance gauges were applied along the height of the riser in order to follow the fluctuations in void fraction and to measure the axial void distribution along the channel. In this system the heating element was used as one electrode while in the shroud four plates were embedded around the element at a certain height to act as the second electrode. In the steady state conditions the values of the void obtained from the impedance method have been compared with those from the radioactive method. In most cases the difference was not larger than 3 per cent void.

Static Pressure.
The static pressure along the riser and downcomer was measured on a multimanometer together with that from the pitot-tube. The absolute pressure was recorded using a capacitance gauge, developed in this laboratory.

Temperatures.
The temperatures were measured using calibrated chromel-alumel thermocouples. For recording purposes fast responding thermocouples were applied.

Burn-Out Detector.
A burn-out detector was used as a safety device. The signal from this detector, which gives an indication about the temperature fluctuation present in the rod, was recorded.

All the measured quantities in steady states have been corrected for instrumental and calibration errors. For obtaining the two phase friction pressure drop the measured distribution of the static pressure along the height of the channel had to be corrected for the pressure drop resulting from acceleration and buoyancy. For this a digital computer programme was written. In the same programme the slip factor was calculated from the measured values of void fraction, fluid temperature and channel power. Signals were recorded using a fast photographic recording system. For a detailed analysis the signals from the inductive differential pressure gauges connected to the pitot-tube and the pressure tappings across the inlet of the riser were recorded on a magnetic tape. In some programmes the analogue signals were converted to digital data and stored on a paper tape. This paper tape was then used to feed the experimental data into a digital computer. A digital computer programme was written (6) to compute the correlation functions, power density curves and transfer functions. In other programmes the correlation functions and power spectra were calculated by means of a special purpose analogue computer, ISAC (Instrument for Statistical Analog Computations).

The analysis of the noise present on the recorded signals in terms of auto correlation and power density curves has been used in studying the observed phenomena, particularly the stability of the steady state, the occurrence of a slug-type flow (7) and the maximum in the heat transfer rates.

The auto correlation is defined as:

$$\varphi(\tau) = \lim_{T\to\infty} \frac{1}{T}\int_0^{\infty} f(t)\, f(t+\tau)\, dt$$

where T is the sampling time of the signal considered; f(t) the signal written as a function of time; f(t+τ) the same signal, but a time τ shifted with respect to f(t). The square root of $\varphi(0)$ gives the root mean square noise. The Fourier transform of the auto correlation function gives the energy spectrum, power spectrum or noise frequency spectrum.

$$\Phi(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \varphi(\tau) \exp(-j\omega\tau)\, d\tau$$

where ω is the radian frequency.

For the direct determination of transfer functions, the apparatus used is the Boonshaft Transfer Function Analyzer which allows point to point measurements, to be made directly by performing a Fourier analysis of the signals at those two points.

In Fig. 3. the principal operation is shown. The input signals of sinusoidal character are transmitted to the fast response power control unit of the loop and a number of point to point transfer functions can be obtained, e.g. between loop power and void fraction, power and inlet flow etc. The unit has been extended recently with equipment for direct analysis of transient response. For the low frequency range as applied in these experiments there was no need for making corrections for the response characteristics of the sensors.

STEADY STATE MEASUREMENTS.
The steady state measurements have been performed for both geometries, that is shroud diameters of 50 and 60 mm, in a large range of the independent variables, that is of power, pressure and subcooling.

In Fig. 4. the exit void is given as a function of power for the two geometries at pressures of 28 and 222 p.s.i.a. respectively. It will be noticed that at the same power the exit void fraction in the case of the 60 mm shroud is lower, which is due to the higher mass flow and possibly also to a different radial void distribution.

In Fig. 5. the inlet flow rates are plotted against the input power for the two geometries and for pressures 22 and 222 p.s.i. respectively. The figure shows that the peak of the curves shifts towards higher powers and towards higher mass flow rates when the shroud diameter is increased.

In Fig. 6. the void fraction is plotted as a function of axial position. In fact that at lower power these curves are convex is due to the existance of subcooled boiling. The position where bulk boiling starts obtained from a heat balance, is indicated.
The pressure drop along the axis of the channel was divided into a term allowing for the hydrostatic head, one for the acceleration loss and a third term to take the two phase friction

losses into account. The total pressure drops and the individual terms are shown in Fig. 7. for 200°C, 0° subcooling and 80 and 150 kW.

The measurements reported here were only a small part of all the measurements taken in the laboratory and their analysis is reported in the next section.

ANALYSIS OF STEADY STATE MEASUREMENTS.

The results of the stationary measurements have been analyzed by means of a digital computer programme in order to obtain slip factors and two phase friction factors.

In this analysis the acceleration losses were computed on the basis of a heterogeneous model, which leads to minimum values of these acceleration losses and thus to maximum values of the two phase friction losses that were obtained by subtraction of the hydrostatic head and acceleration terms from the measured total pressure loss. Furthermore, the effect of subcooling was taken into account by using Bowring's criterion (8).

Plotting of the slip factors as a function of void fraction, quality or inlet mass flow does not lead to any coherent correlation. In fact, the calculated results show a large scattering and no reasonable correlation curve can be established. It therefore was endeavoured to make use of Zuber's approach (9), who takes into account both the non uniform flow profile and the concentration distribution, and introduces a relative velocity of the two phases (drift velocity). In Zuber's study, therefore, the overall slip concept was abandoned. In the present study Zuber's parameters, that is

$\frac{W_g}{\alpha} = \overline{V}_g$ and $W_l + W_g$ are plotted for 4 temperatures in Fig. 8. and additionally, for a given temperature at five different subcoolings in Fig. 9. The result is quite remarkable: straight lines are obtained with a slope very near to unity. This could indicate the existance of quite flat profiles of the void and velocity distributions.

The extrapolated intersection of the straight lines with the vertical axis yields the drift velocity, which turns out to be larger than that calculated by means of the correlations suggested by Zuber for slug flow and for bubbly churn turbulent flow. The same remarkable results have been obtained by Allis Chalmers in their study (10) of forced circulation.

The non-linear part in the curves of Fig. 8. and 9. at low power are due to the effect of subcooling and of non established flow profiles.

The two phase friction losses in Fig. 10. plotted, are compared with the predicted values by Martinelli-Nelson.

DYNAMIC MEASUREMENTS.

The Onset and Characterization of Instabilities.

The experiments were carried out by establishing an operating pressure in the loop and gradually increasing the power input. Inlet subcooling to the test section was controlled at various discrete values. The inlet flow, void fractions and pressure losses were recorded. In Fig. 11. a picture is shown of the Δp inlet signal under a number of pressures and operating conditions. It is seen that the amplitude of the signal is a function of input power for a given pressure condition. The onset of instabilities was determined by plotting the root mean square values of the oscillations in inlet pressure drop as a function of power and the results are shown in Fig. 12. for the experiments with shrouds of 50 and 60 mm diameter. It can be seen that the effect of an increased diameter of the shroud is to improve the stability of the loop and to increase the burn-out power. It should be noted, however, that at the same loop power at the same pressure the mass flow in the case of the 60 mm shroud is approximately three times as high as in the case of the 50 mm shroud.

In Fig. 13. a picture is shown of the effect of the inlet subcooling on the amplitude of the inlet pressure loss. It can be seen that increasing subcooling initially decreases the loop stability whereas at higher inlet subcooling the loop stability is improved again. The results of the measurements are compared with some theoretical predictions in section 6.3.

As it was possible to record the local void fraction as a function of axial position the local void oscillations could also be analyzed as a function of subcooling (Fig. 14).
It is seen that the largest oscillations occur at the lowest positions. When a certain degree of inlet subcooling was allowed, the position of maximum oscillations was shifted upwards as a result of an upward shift of the point of incipient boiling.

Direct Transfer Function Measurements.

Transfer function analysis was carried out by analogue computations using the Transfer Function Analyzer, mentioned in section 3. Furthermore, the recorded signals from the loop were digitalized and used for analysis by means of a digital computer.
From the figures the following can be concluded. As far as the influence of power level on the stability is concerned, increasing the power level makes the steady state less stable. Furtheron, it is shown in Fig. 15a. and 15b. that the resonance peak present increases in magnitude with power level while also the peak shifts to a higher frequency. In (12) it was concluded that this resonance peak, which is characteristic for a natural circulation system, is caused by the intercoupling effect of steam void and mass flow rate. This resonance peak is not present in a forced circulation system with the same conditions of inlet temperature, mass flow and power. The Fig. 15a. illustrates the development of this resonance peak as the power input is raised from 80 kW to 145 kW. In the absence of power modulation it was shown in Fig. 12. that at about 140 kW the operating power level, the flow rate and void fraction are subject to large random fluc-

tuations. When the power level is increased to 155 kW spontaneous flow oscillations occur. The frequency of these oscillations is 1.04 cycles/sec. It can be concluded then that the resonance peak at 145 kW has been transformed into spontaneous oscillations as a result of the flow-void feedback as present in natural circulation boiling systems. Fig. 15b. is similar to Fig. 15a. but is based on measurements using the 60 mm shroud. The peaks and frequencies are comparable with those of Fig. 15a. however the powerrange covered by the measurements is 204 kW whereas it was 65 kW for the 50 mm shroud. The power of 315 kW was 40 kW lower than the power at which the signals had lost their noise character.

From Fig. 16. it can be concluded that increasing the pressure increases the stability of the steady state. The same has been found in the experiments for the determination of the onset of the spontaneous flow oscillations.

In Fig. 17. the effect of subcooling is shown on the transfer function from power to local void fraction. Also in these curves a resonance peak can be observed. But the magnitude of the peak is smaller than in the transfer function from power to mass flow, as can be seen by comparing the curves for 113 kW channel power and 0° subcooling. The remarkable effect of subcooling on the onset of hydraulic oscillations as shown in Fig. 13. can also be observed in Fig. 17. The magnitude of the resonance peak at 0° subcooling is higher than the one at 10°C, but lower than the one for 30°C. The effects shown in Fig. 17. tell that also in a stable steady state condition low subcooling has a destabilizing but high subcooling a stabilizing effect. The effect of subcooling on the resonance frequency is qualitatively the same as observed with the hydraulic oscillations. Increasing the subcooling shifts the resonance peak to lower frequencies.

The resonance frequency is for all physical quantities the same as can be observed with respect to the void in Fig. 18. where the transfer function is shown from power to local void fraction for three positions along the height of the channel. It can be concluded that for all frequencies up to about 1.5 cycles/sec the magnitude of the power induced oscillations in local void fractions are greater stream upwards. It is noted that these experiments have been carried out for zero subcooling. With subcooling a different effect may be expected. Reference is made to Fig. 14. where the same effect in local void fraction is shown.

<u>Theoretical Model of Jahnberg.</u>

For a more detailed analysis some theoretical computations have been made using a mathematical description of the process made by Jahnberg (1).

In this analysis a one dimensional flow was assumed and a constant pressure in the condenser. This means that there are only two independent variables, the axial coordinate x and the time t. The dependent variables represent mean values over the cross section of the boiling channel. In the original analysis the following assumptions have been made.

1. The conservation law of energy has been formulated neglecting the kinetic and potential energy. Furtheron, no diffusion of energy in axial direction and no energy worked on the fluid by friction forces have been assumed. Also the thermal capacity of the fuel was neglected, so that no energy equation for the fuel was used.
2. The pressure drop along the channel is small compared with the mean system pressure. As regards the conservation of energy this permits the use of space and time independent values for the specific density for both phases of the fluid and implies no change in boiling temperature along the channel. Regarding the conservation law of momentum this assumption is not correct. In parts Jahnberg disregards the possible occurrence of density waves. Also the specific heat of water and the heat of evaporation have been chosen as space and time independent values.
3. The temperature of the coolant entering the heated channel is constant, eliminating the use of the energy equation in the downcomer. This assumption is only valid if the passage time through the downcomer is large compared to the time constant associated with the instabilities.
4. The effect of subcooled boiling is neglected except for a small correction which is applied to the frictional pressure drop in the non-boiling region.
5. The internal energy has been put equal to the enthalpy.
6. The contribution of the acceleration of the fluid in the non-boiling region of the channel to the pressure drop has been omitted.

The assumptions mentioned above imply that the descriptions of the transient behaviour made by Jahnberg will only be correct at medium pressures.

In Jahnberg's procedure the conservation laws for mass, energy and momentum have been formulated. Additionally, experimental correlations have been used for the slip factor S which determines the relation between the void fraction and the steam quality x and the multiplier R for computing the two phase flow pressure gradient. Both were based on the work reported by Martinelli and Nelson. The following expressions have been used.

For the slip factor:

$$S = (1+C_3\ x^{\frac{3}{4}}),(0,795 + 0,410\ \frac{\rho f}{W_o})$$

where C_3 is a pressure dependent parameter. During the transient calculation the velocity dependence of the slip ratio is neglected.

For the friction multiplier:

$$R = 1 + a\ x^b$$

$$\text{where}\quad a = \frac{3.9.10^8 - 19.6\ p}{6.75.10^5 + p}$$

$$b = 1.025 - 1,74.10^{-8}\ p \text{ with p in } N/m^2.$$

The boundary conditions have been obtained by integrating the pressure drop over the heated channel. Two cases were considered (a) the pressure difference over the heated channel including inlet and outlet losses is prescribed (this is a reasonable approximation for a coolant channel in a reactor with many channels), (b) a complete natural circulation loop including riser and downcomer is being considered and the total pressure drop over the heated channel and over the downcomer is equal to zero.

The assumption of incompressible flow by Jahnberg is characteristic for his approach and in fact the assumption of a constant vapour density reduces the two phase mixture to an "incompressible" fluid, i.e. a fluid in which the density is not influenced by the pressure. This leads to a singularity at t=0 in the mathematical formulation, in case a pure step function in power as input is chosen.
The physical explanation of the sigularity is as follows. Along the length of the boiler the flow velocity will increase as a consequence of the vapour volume produced by boiling. The rate of increase of this flow velocity is directly coupled to the rate of vapour production, which is in turn proportional to the heat load. In case now a sudden increase in heat load occurs at t=0, the velocity distribution will have to change discontinuously at t=0 causing the velocity distribution to be two-valued at t=0. In a real fluid such a discontinuity would not be present as the increased vapour formation would be accompanied by a rate of increase in the local pressures and a corresponding increase in the local vapour density. This increased pressure gradient would result after some time in a change in the velocity distribution. This adjustment process is of an acoustical nature as it is accompanied by acoustical waves traveling along the boiler. As soon as the fluid is assumed to be incompressible such a process takes place at zero time. This results, however, in a singularity at t=0 which leads to serious computational difficulties.

Starting from the Jahnberg equations corrected for the effect mentioned under 6 and using a continuous heat load variation with time a digital computer programme has been written (11) with a large flexibility with respect to the choice of the expressions for the slip factor, the two phase friction multiplier and the heat distribution function over the channel length.
In studying the possible solution techniques of the set of equations it was found that this system possesses characteristics which make the computation procedure in the physical z-t plane much more straight forward than the finite difference technique as described in the original publication of Jahnberg. The solution of the system was programmed therefore using the method of characteristics which is a more or less "natural" method for the numerical solution of the system of partial differential equations in the z-t plane. The advantages are that the equations become simple and that the correct ratio between the integration steps in z and t direction is automatically obtained. The only equation which cannot be brought in a characteristic form is the external iteration condition which determines the inlet velocity V_o. This parameter has to be solved therefore for each step by an iterative procedure.

In the present application of the model the constant C_3 was determined from static measurements in the boiling loop under consideration. This means in fact that for each pressure condition a slip correlation was established, fitting the experimental static data.
The computation is started by calculating the steady state condition for a given pressure, subcooling and power. The results being known, the dynamic response following a 2 percent step input in power is computed over a period of 4 seconds. The eigen frequency of the system, being larger than 0,5 Hz that time is sufficient to judge the stability of the system. The variation with time of the most important quantities is then plotted.

By making a fair choice of two powers in the stability region and by considering the amplitude-maxima of the sinusoidally varying quantities it is possible to approximate very closely the third power which represents the indifferent condition of the system, that is the onset of instabilities (Fig. 19.). The computation is repeated for this power and continued if the estimation of the indifferent power had not been sufficiently accurate.

In the next table the values of the indifferent powers for different subcoolings are given. It shows a discrepancy between measured and computed values of the powers at which instabilities start, but it predicts correctly the effect of subcooling.

saturationtemperature 200°C

subcooling in °C	starting point instabilities in kW	indifferent power in kW
1,03	170	78
8,5	150	56
16,0	160	73
43,0	220	176

The outlet mass flow and inlet velocity as a function of time at an almost indifferent power are given in Fig. 20. It indicates the sharp increase of the mass flow at time t=0 caused by the mathematical singularity as mentioned before.

The void fractions along the channel axis as a function of time at an indifferent condition are given in Fig. 21. The distances between the positions at which the void fractions are shown are equal to those in the boiling loop. In correspondence with measured signals of void fraction c.f. Fig. 14. the calculated curves indicate a decreasing amplitude and increasing phaseshift with increasing height. The maximum amplitude is present at the position of the boiling boundary.
From the computations performed of which only a small part is presented in the figures, the conclusion can be drawn that the model qualitatively gives a good description of the behaviour of a boiling water channel but quantitatively it gives in all cases far too low values for the onset of instabilities.

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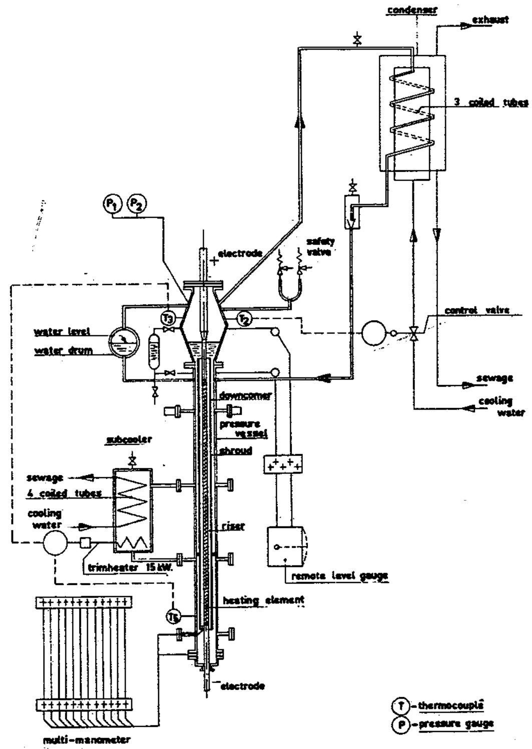
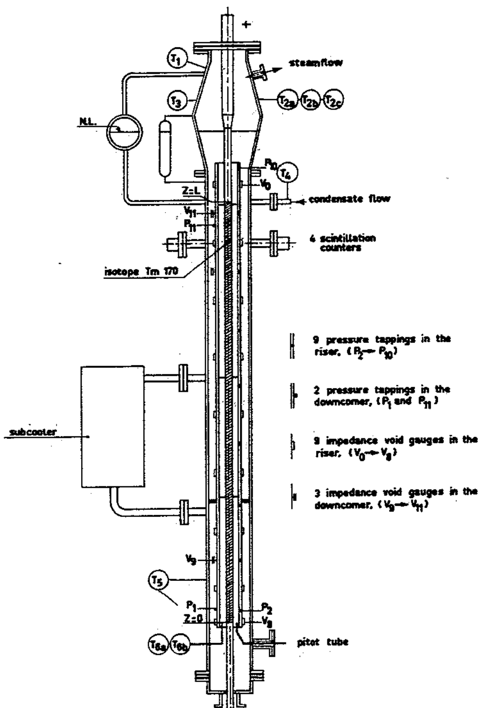
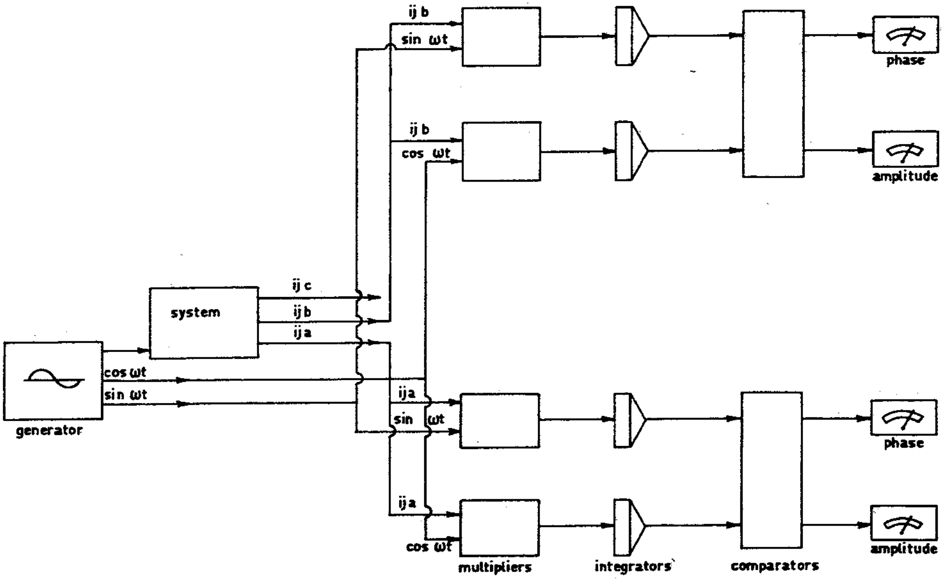


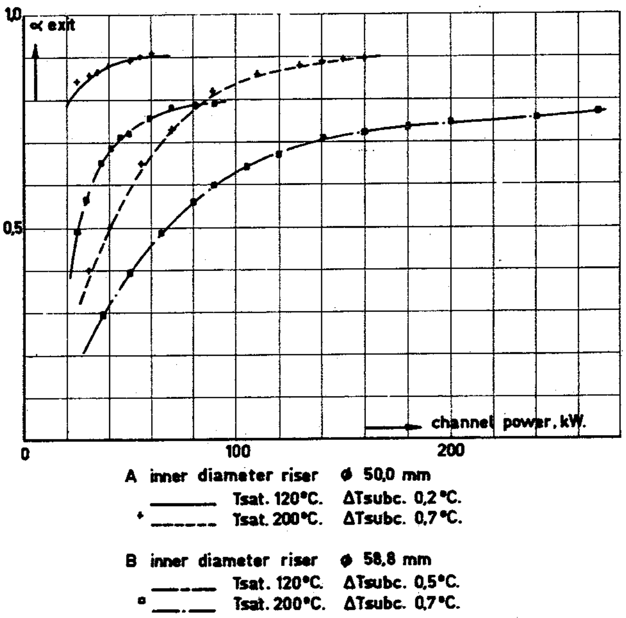
1. Flowsheet of the pressurized boiling water loop.



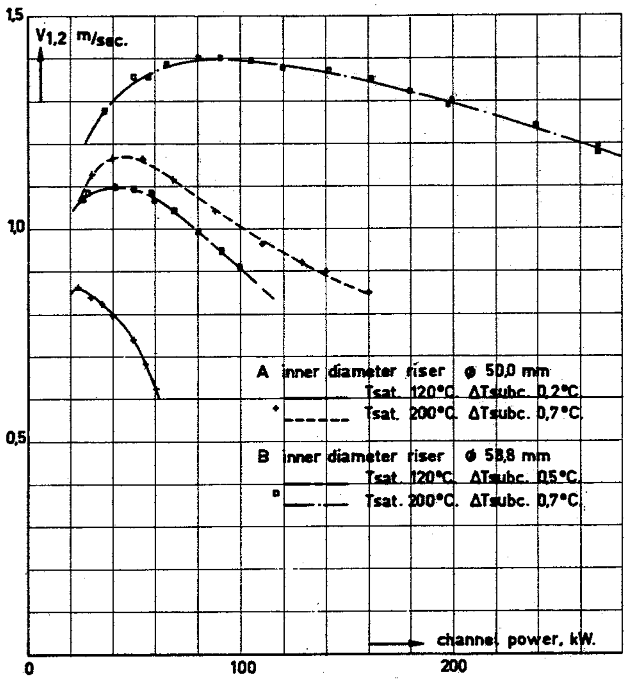
2. Sketch of the test section with instrumentation.



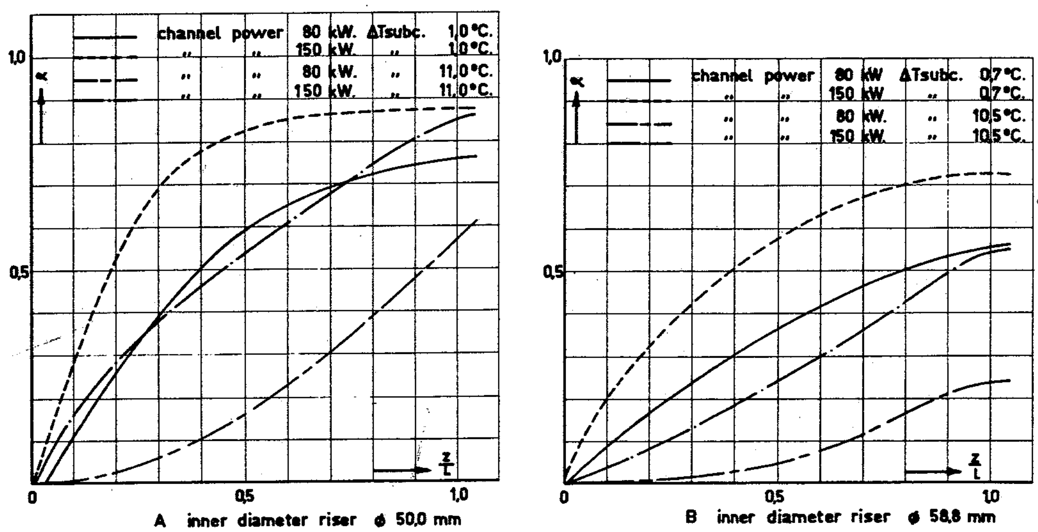
3.
Block diagram point to point measurement with transfer function analyzer.



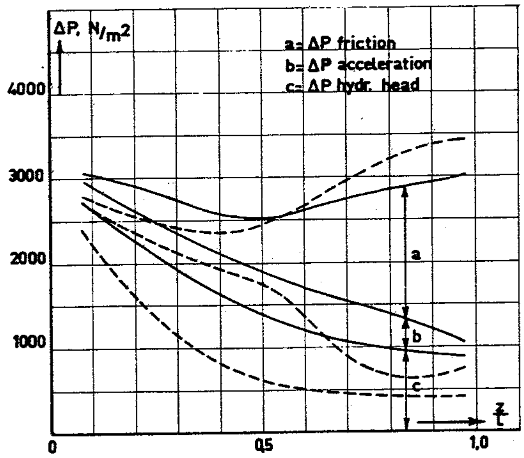
4. The exit void fraction as a function of channel power and pressure for two geometries.



5. The flow rate as a function of the channel power and pressure for two geometries.

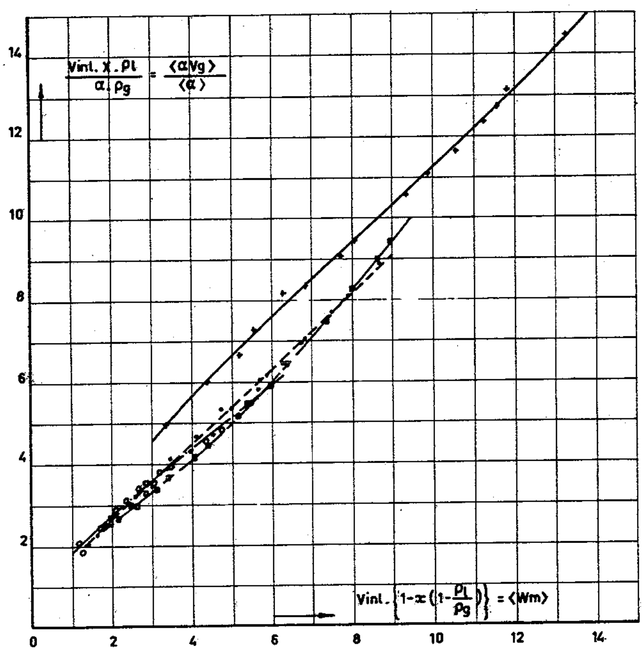


6. Void distribution along the channel as a function of subcooling for two geometries.



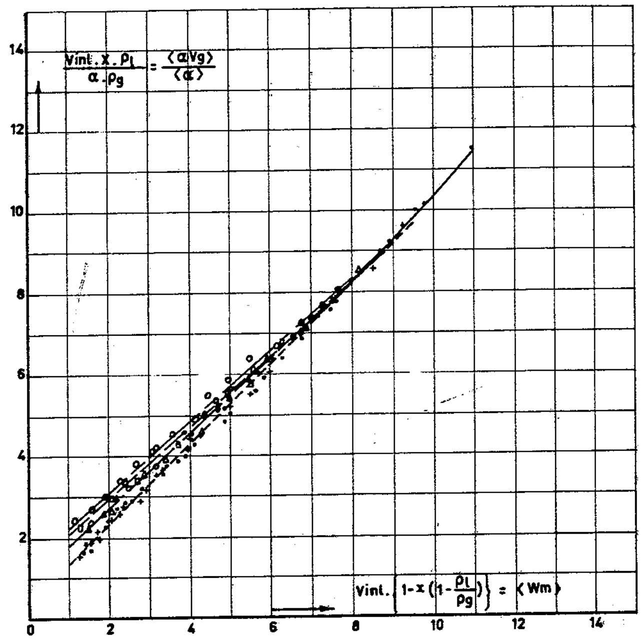
——— Tsat. 200°C. channel power 89,5 kW. ΔTsubc. 1,03 °C.
------ Tsat. 200°C. channel power 130,7 kW. ΔTsubc. 1,03 °C.

7. Pressure drops along the channel.



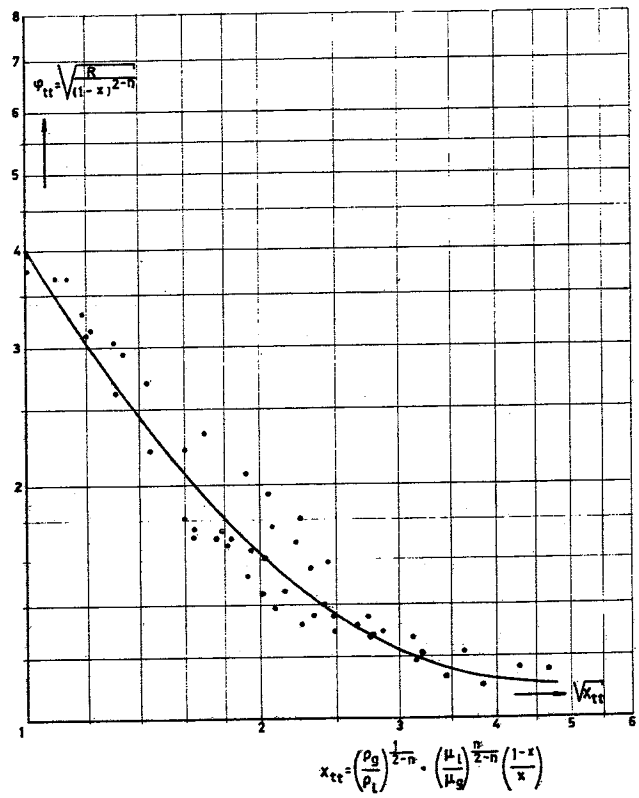
• ——— Tsaturation 120 °C. ΔTsubcooling 0,20 °C.
• ------ Tsaturation 200 °C. ΔTsubcooling 0,70 °C.
o —·—·— Tsaturation 220 °C. ΔTsubcooling 0,90 °C.
□ —— —— Tsaturation 234 °C. ΔTsubcooling 0,80 °C.

8. Void fraction data plotted according to Zuber and Findlay.

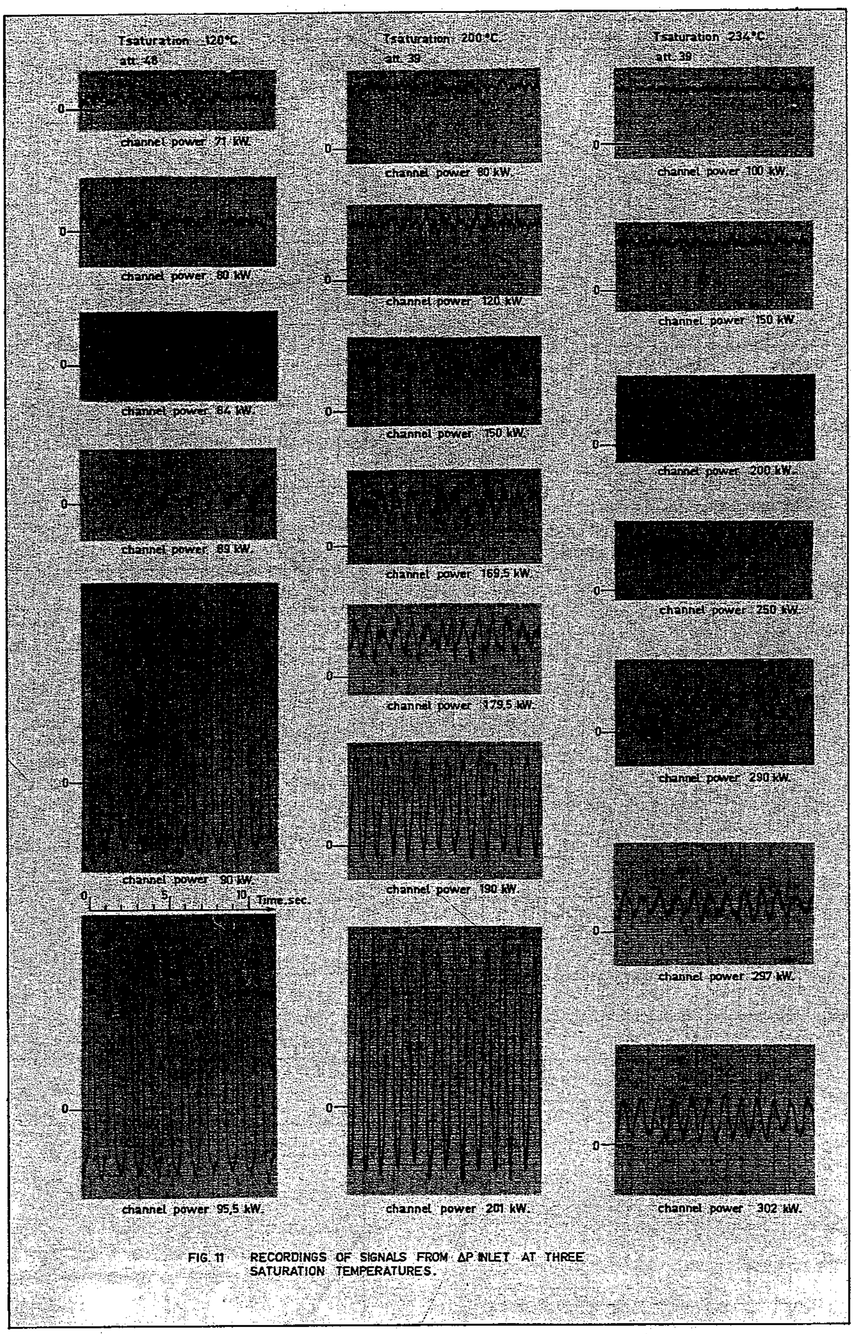


• ——— Tsaturation 200 °C. ΔTsubcooling 1,03 °C.
+ ------ Tsaturation 200 °C. ΔTsubcooling 6,25 °C.
Δ —·—·— Tsaturation 200 °C. ΔTsubcooling 8,50 °C.
o —— —— Tsaturation 200 °C. ΔTsubcooling 10,95 °C.
□ ——— Tsaturation 200 °C. ΔT subcooling 18,00 °C.

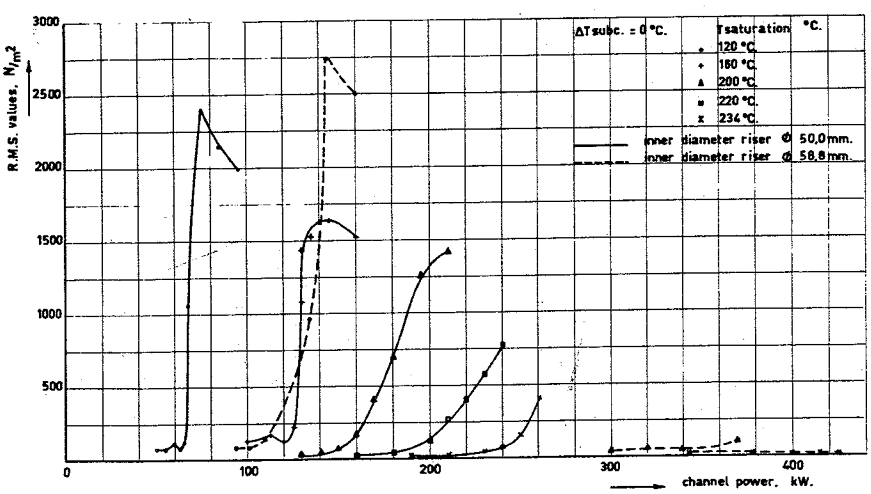
9. Void fraction data plotted according to Zuber and Findlay.



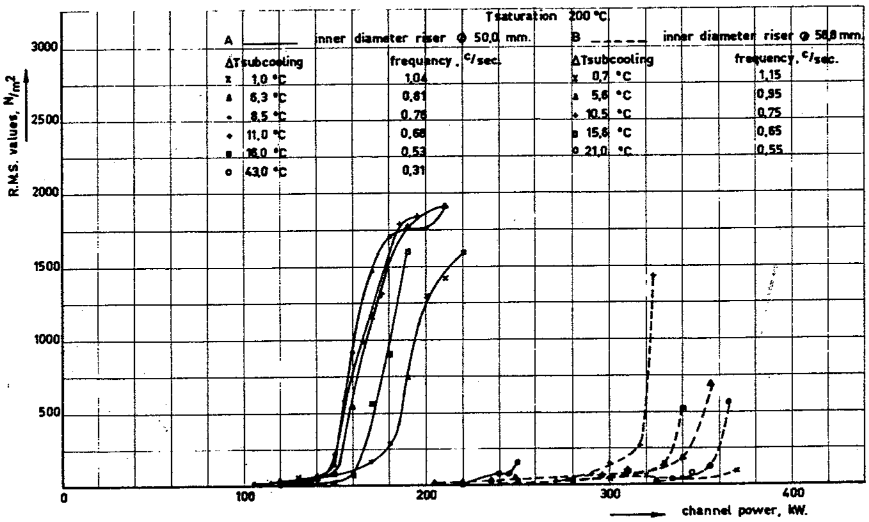
10. Two phase friction multiplier plotted as ϕ_{tt} versus $\sqrt{X_{tt}}$ according to Martinelli-Nelson.



11. Recording of signals from Δp inlet at three saturation temperatures.



12. Values of the power spectra of the Δp inlet signal at different temperatures.



13. Values of the power spectra of the Δp inlet signal at different subcooling temperatures.

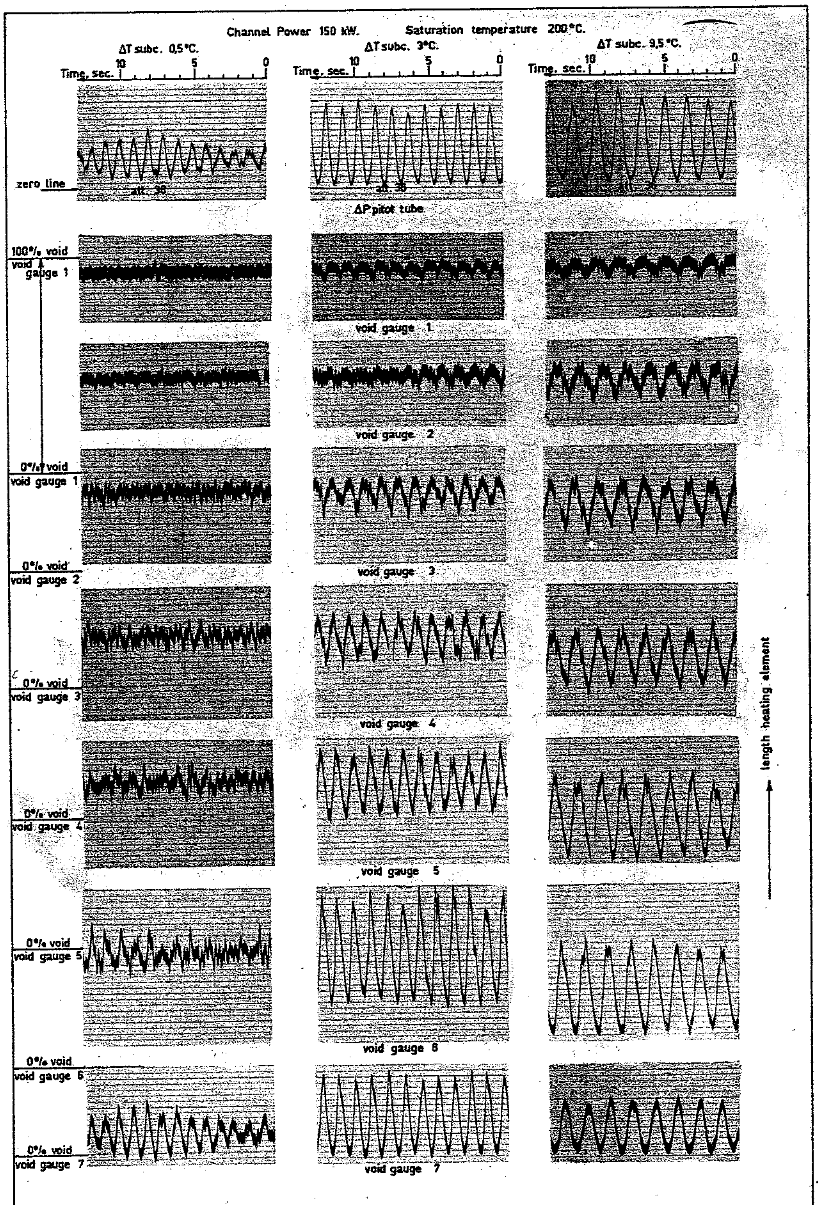
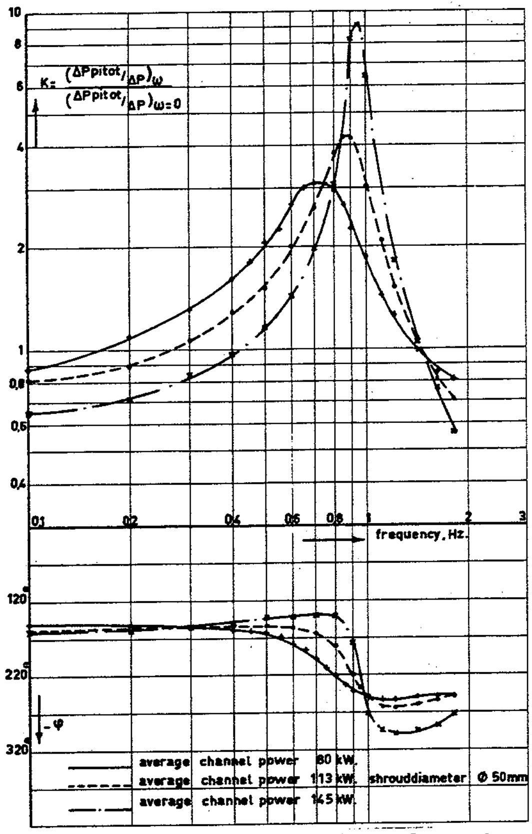
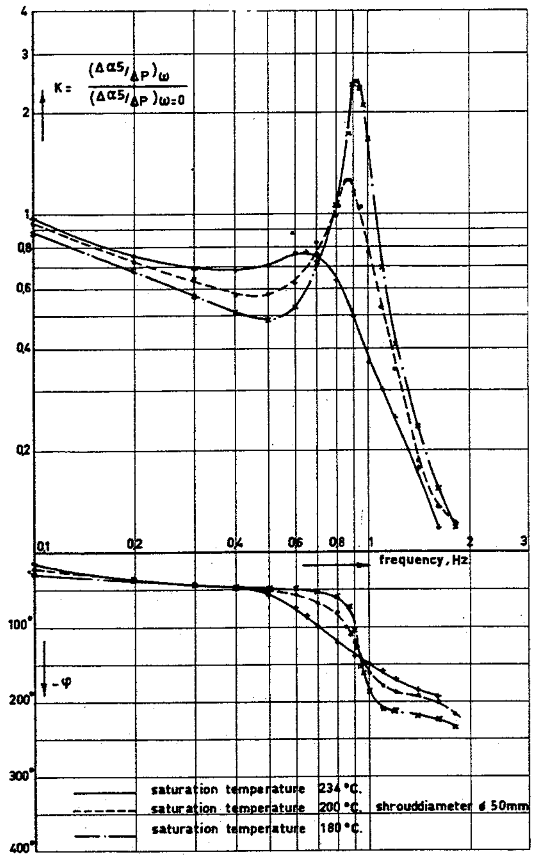


FIG. 14 SIGNALS FROM DIFFERENT QUANTITIES DURING HYDRAULIC INSTABILITIES WITH INCREASING SUBCOOLING.

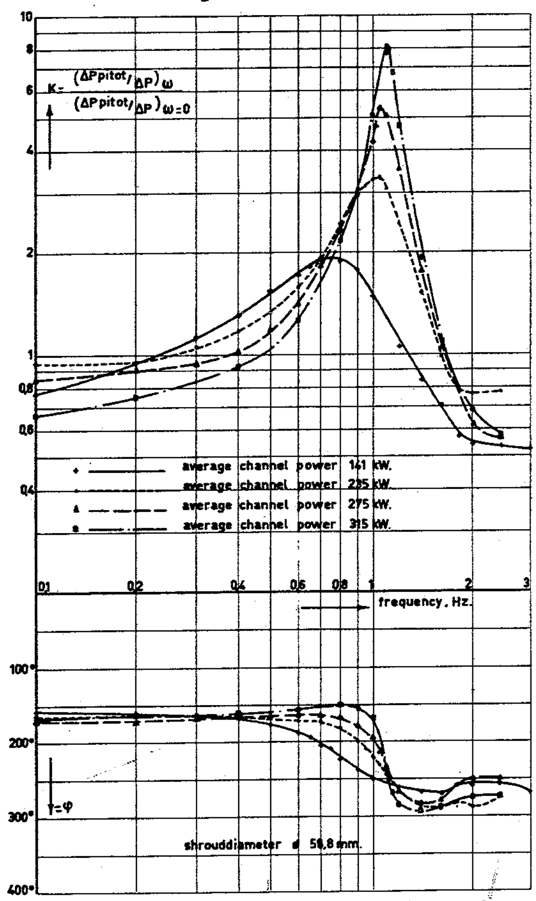
14.
Signals from different quantities during hydraulic instabilities with measuring subcooling.



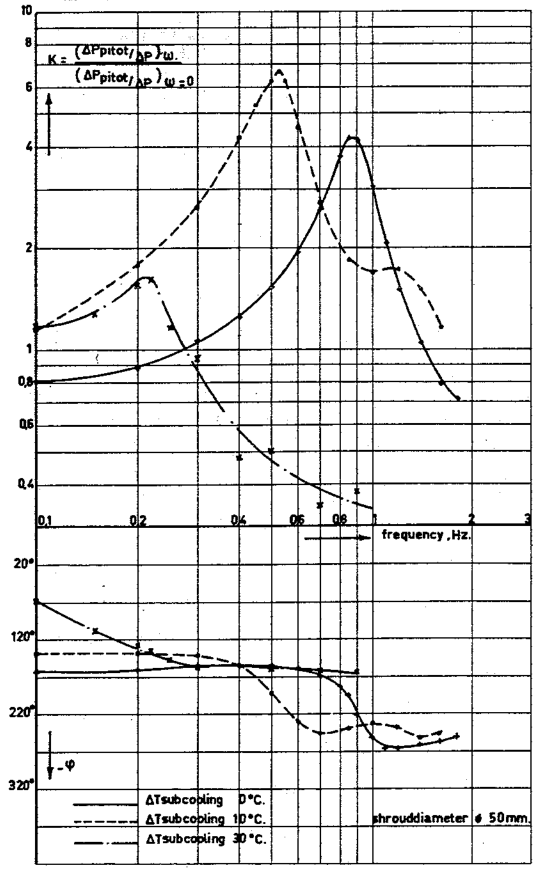
15a. Measured transfer functions from channel power to Δ p pitot tube at a saturation temperature of 200°C without subcooling at different powers.



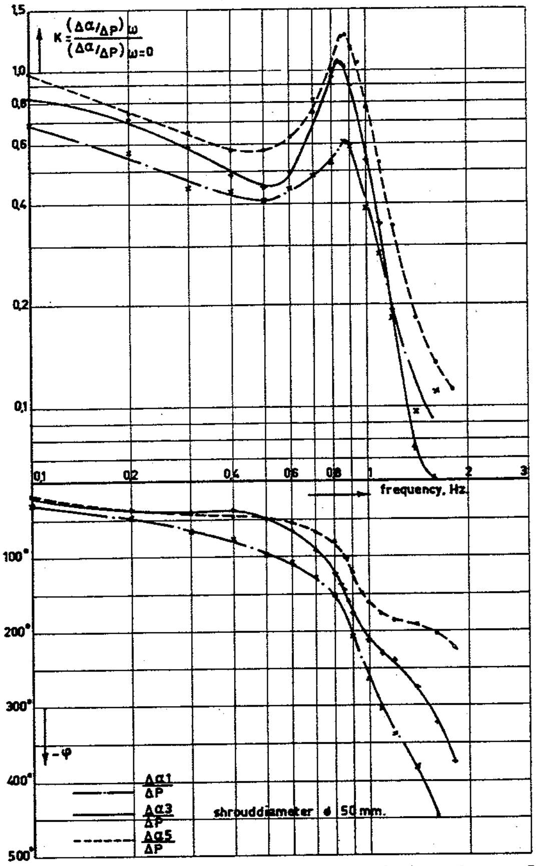
16. Measured transfer functions from channel power to void at an average channel power of 113 kW, without subcooling as a function of saturation temperature.



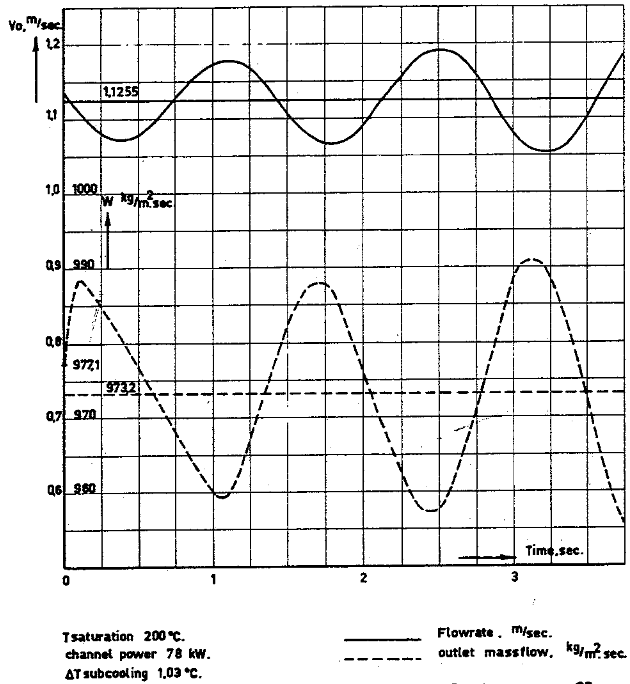
15b. Measured transfer functions from channel power to Δp pitot tube at a saturation temperature of 200°C without subcooling at different powers.



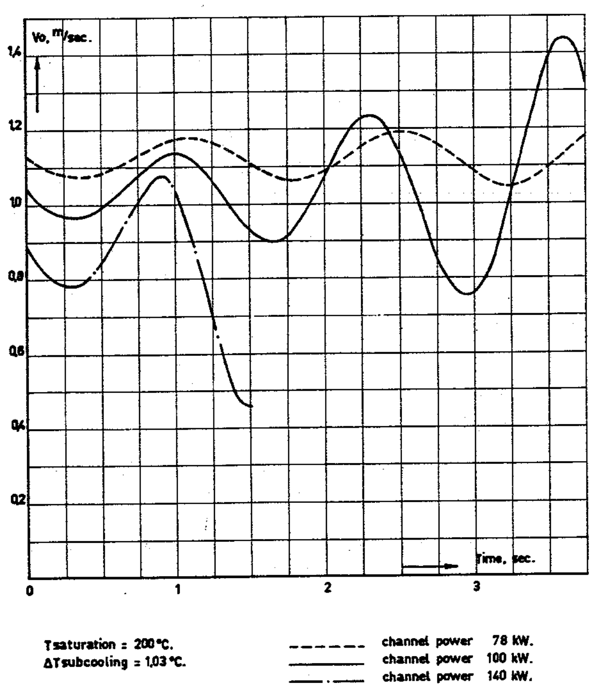
17. Measured transfer function from channel power to Δp pitot tube at a saturation temperature of 200°C and an average channel power of 113 kW as a function of subcooling.



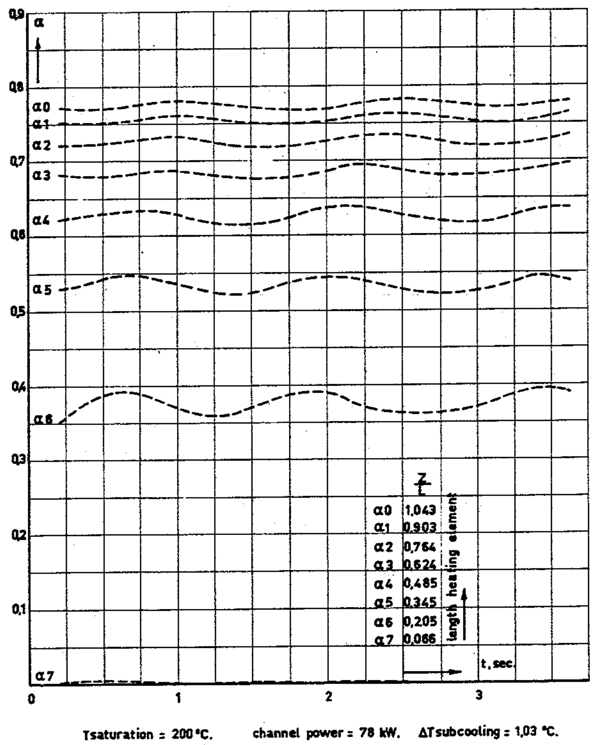
18. Measured transfer functions from channel power to void at a saturation temperature of 200°C, without subcooling and an average channel power of 113 kW.



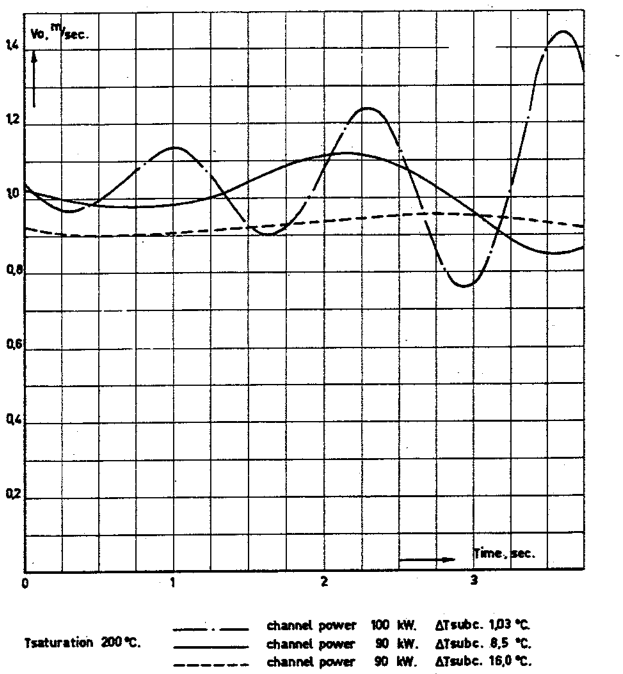
20. Calculated flow rate and outlet mass flow as a function of time.



19. Calculated flow rate as a function of time at different powers.



21. Void distribution along the channel as a function of time.



22. Calculated flow rate as a function of time for different subcoolings.