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INTRODUCTORY LABORATORY STUDIES OF BOILING-WATER REACTOR STABILITY

by

M. BOGAARDT J. P. SIMON THOMAS C. L. SPIGT
(Technische Hogeschool te Eindhoven)

1963

Work performed under the Euratom contract No. 032-60-11 RDN
(EURAEC Report No. 270)

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PROCEEDINGS OF THE SYMPOSIUM ON TWO-PHASE FLUID FLOW
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Slip ratios and two-phase pressure drop values are reported and compared with data obtained by other investigators.

In a number of natural circulation calculations the effect of variations in subcooling and slip ratio is shown. The importance of accounting for the axial power distribution is also indicated.

Finally, attention has been given to the onset of instabilities in the natural circulation loop.

An outline is given of the subsequent experimental programme.

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THE INSTITUTION OF MECHANICAL ENGINEERS

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Paper 8

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By C. L. Spigt*, J. P. Simon Thomas*, and M. Bogaardt*

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INTRODUCTION

WHEN THE construction of the Halden boiling-water reactor was started in 1957, it proved to be necessary to perform a number of experiments in connection with the hydraulic characteristics of this reactor. In the Delft laboratory for Physics Technology a 30-atm test loop was constructed in which an electrically heated dummy fuel element could be studied. The main aim of the experiment was to determine whether a fuel channel of the Halden design was suited for the design power output. In other words, the only purpose was a performance test of the fuel channel. When the desired results had been obtained the experiment was closed down and the apparatus was transferred to the laboratory for heat technology and nuclear engineering of the Technical University at Eindhoven, where it was rebuilt so as to serve a more fundamental investigation into the static and dynamic behaviour of boiling-water reactors. The first results obtained in this programme, which is carried out under contract with the Euratom/U.S.A. Joint Research and Development Board, are reported in this paper.

It is well known that the behaviour of boiling-water reactors can at present not be predicted from fundamental data that follow immediately from the design. In fact, it has been necessary to perform zero energy experiments of the complete reactor, in order to be able to predict correctly the static and the dynamic behaviour of the boiling-water reactor under operating conditions. From the zero energy experiments the zero power transfer function is obtained which allows definite conclusions to be drawn regarding fuel power operation. It stands to reason that it is the designer's dream to have the means available one day to predict reactor behaviour from the results of simple laboratory experiments, together with a reactor model study. It is therefore important to try to understand the hydraulic behaviour of the system or to be able to derive from the laboratory experiments such characterizations of the hydraulics that satisfactory input data are obtained to feed into the reactor model. In the programme undertaken at the Eindhoven laboratory both courses are followed: efforts are made to obtain a fundamental understanding of the channel hydraulics under both static and dynamic conditions, but at the same time it is endeavoured to arrive at a hydraulic characterization of the channel that may satisfy the need of the design engineer.

In the present investigation, an attempt is made to separate the process variables, such as void fraction, power, fluid velocity, pressure and subcooling so as to be able to assess the influence of each variable. One of the means of arriving at the separation of the variables is the application of forced circulation. However, in the part of the programme that is reported here, only natural convection has

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* *Technological University of Eindhoven, Laboratory for Heat Transfer and Reactor Engineering.*

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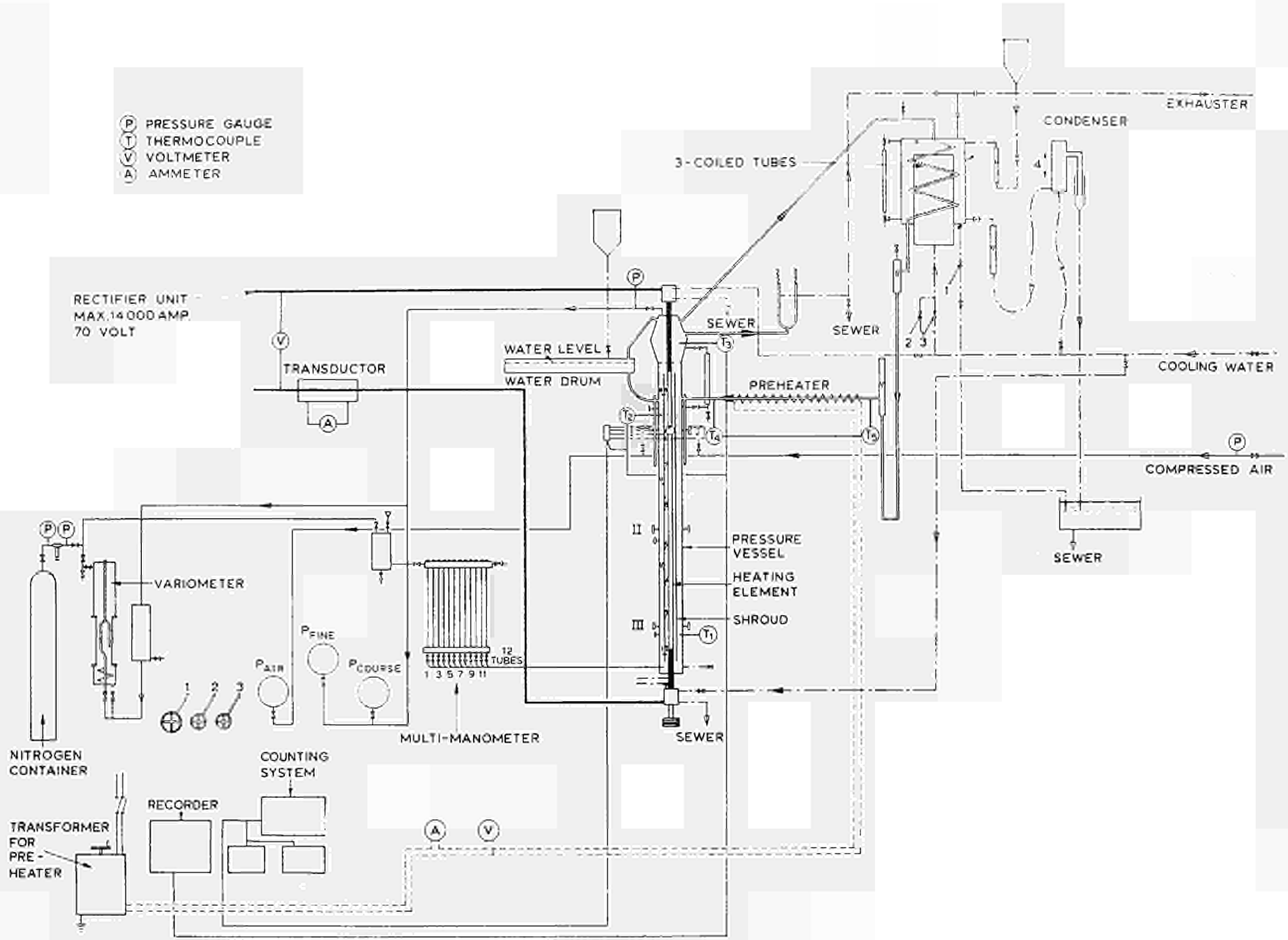


Fig. 8.1. Flow sheet of the pressurized boiling loop

Symp Two-Phase Flow

been studied and the input power has been kept constant during each experiment. In order to derive various transfer functions from the hydraulic system, it is necessary to vary the power input according to a chosen programme and it is with this requirement in mind that the power supply installed allows for controlled variations of the input to the experiment. Apart from periodic oscillations, this arrangement allows for reactor transients to be simulated.

In the experiments reported here, the pressure was kept constant during the experiment, whereas the power input was changed. Such quantities as fluid velocities, slip ratios and two-phase friction factors have been obtained. It has also been possible to determine for each set of pressure and temperature conditions the onset of flow instability and to obtain some indications regarding the boiling noise in the system.

Notation

- $\Delta\phi_v$ Heat losses of the equipment.
- ϵ' Void fraction at the measuring place.
- ϵ_b Average void fraction over boiling length.
- ϵ_{ex} Void fraction at the end of the heating element.
- ϕ_w Power generated in the heating element, kW.
- P Pressure, Newton/m^2.
- R Local two-phase fraction factor.
- $\bar{R}$ Average two-phase fraction factor over boiling length.
- S Slip ratio, ratio of the velocity of the gas phase to the liquid phase.
- T Temperature, °C.
- T_{sat} Saturation temperature.
- V Circulation rate, m/sec, as measured above the inlet of the riser.
- X' Steam quality at the measuring place of the void fraction.

DESCRIPTION OF THE SET-UPS

A flow scheme of the natural circulation pressurized boiling loop is given in Fig. 8.1, and a photograph in Fig. 8.2.

The test section consists of an electrical heating element, which replaces the fuel rod, centrally placed in a shroud. The steam–water mixture flows by natural convection through this annular passage. The downcomer is the annular passage between the shroud and the steel wall of the 30-atm pressure vessel. The steam produced in the test section is separated from the water flow at the top of this riser, flows to the condenser, and the condensate is then returned to the downcomer through a preheater.

The pressure vessel is made of stainless steel 316 and has a design pressure of 40 atm. The cylindrical part has an inside diameter of 150 mm and is 3000 mm long. The vessel is provided with the necessary connections for measuring equipment. The water level is kept within certain limits by means of a water drum parallel to the test section. A 3-in. diameter steam line leads to the condenser. The steam is condensed inside three coiled tubes and evaporates cooling water to the atmosphere. Condenser control is achieved by manual control of the coolant water flow which

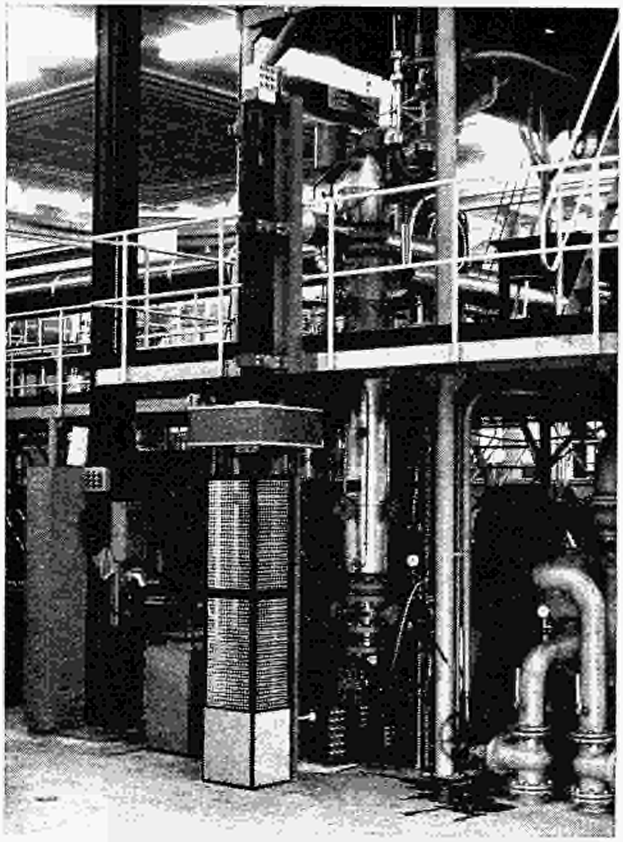


Fig. 8.2. The pressurized boiling loop

is sprinkled on the condenser tubes (points 1, 2 and 3 in Fig. 8.1). There is also a possibility of a level control (point 4 in Fig. 8.1).

The material used for the heating elements is stainless steel hot soldered to top and bottom electrodes. The electrodes are water-cooled. An asbestos graphite packing with spring pressure at the bottom electrode allows for expansion of the element. The weight of the bottom electrode keeps the element under tension. A check of the proper behaviour of the gland is obtained by measuring the displacement of the bottom electrode with respect to the pressure vessel. At the present two types of heating element are being used. Both are 2400 mm long. One has an outer diameter of 32 mm with a constant thickness along the length. The other has a stepwise variation of the wall thickness approximating a 'cosine' distribution of the heat generation. The two heating elements are stiffened on the inside by means of a bar of porcelain.

Also, several types of shroud made of glass or aluminium are available. The aluminium ones are models of the shrouds of the fuel charge of the Halden reactor.

The elements are heated with direct current from two rectifiers, one for continuous power control and the other one for stepwise power control, which are fed by two transformers. The controlled rectifier can continuously supply 870 kW at 62 volts, 14 000 amps. The unit can be controlled by varying the transductor excitation over the range from 62 volts down to a value of 15 volts. The voltage of the adjustable rectifier can be set with an on–off switch at 10, 13, 16, 19 and 21 volts with a maximum current of 14 400 amps. The two rectifiers can be used independently or in series. A very interesting feature of the power supply is the possibility of fast control, for example, controlled variations by a factor of 3 within 1 sec.

The heat generation and the power of the preheater are measured electrically by means of precision instruments with mirror-reading.

Temperatures are measured at five places in the circuit by means of chromel–alumnel thermocouples (points T1 to T5 in Fig. 8.1).

Other connections for thermocouples are available.

The circulation velocity is measured using small Pitot tubes installed in the lower end of the coolant channel or by measuring the pressure drop across the lower section of the shroud. A 12-tube-multimanometer is available for measuring these and other pressures. The signal from the Pitot tubes has been calibrated in terms of the mean water velocity in the riser.

Separate sensing elements have been installed for obtaining fast signals from differential pressures. Pressure drops can be measured down to 2 mm water head and with an overall time constant of 30 msec.

The void fraction can be measured in three positions along the length of the shroud (positions I, II and III in Fig. 8.1), using the γ-ray absorption technique. A thulium source can be positioned inside the heating element. In four places around the shroud (for each height position) the γ-absorption is at present measured using Geiger–Müller counters. Since this technique is rather well known, it will not be further discussed here, see (**1**) and (**2**)*. Only position I is in use. The counters are air-cooled.

At present, the counter tubes are being replaced by scintillators and photomultipliers so as to obtain a much larger signal from the same thulium source, and therefore to decrease the counting time to about 0·01 sec per measurement. The new arrangement also permits a better discrimination between direct and scattered γ-rays to be made, so that the void measurement becomes more sensitive.

In order to obtain reliable results in steady states, the relative change of pressure with respect to the time is measured by a differentiating manometer (variometer). The instrument permits the detection of relative changes of 10^{-5} sec^{-1}.

Further the pressure in the vapour space and the flow in the condensate line are measured.

EXPERIMENTS

The experiments reported here have been carried out with the heating element with a stepwise variation of the wall thickness along the axis, approximating a 'cosine' distribution of the heat flux. An aluminium shroud was used with inlet and outlet holes in the wall (Fig. 8.3). This assembly is a replica of a unit cell of the first core loading of the Halden boiling-water reactor in Norway.

The natural circulation rate, the void fraction near the outlet holes and several temperatures were measured as a function of the total heat production and the pressure in the

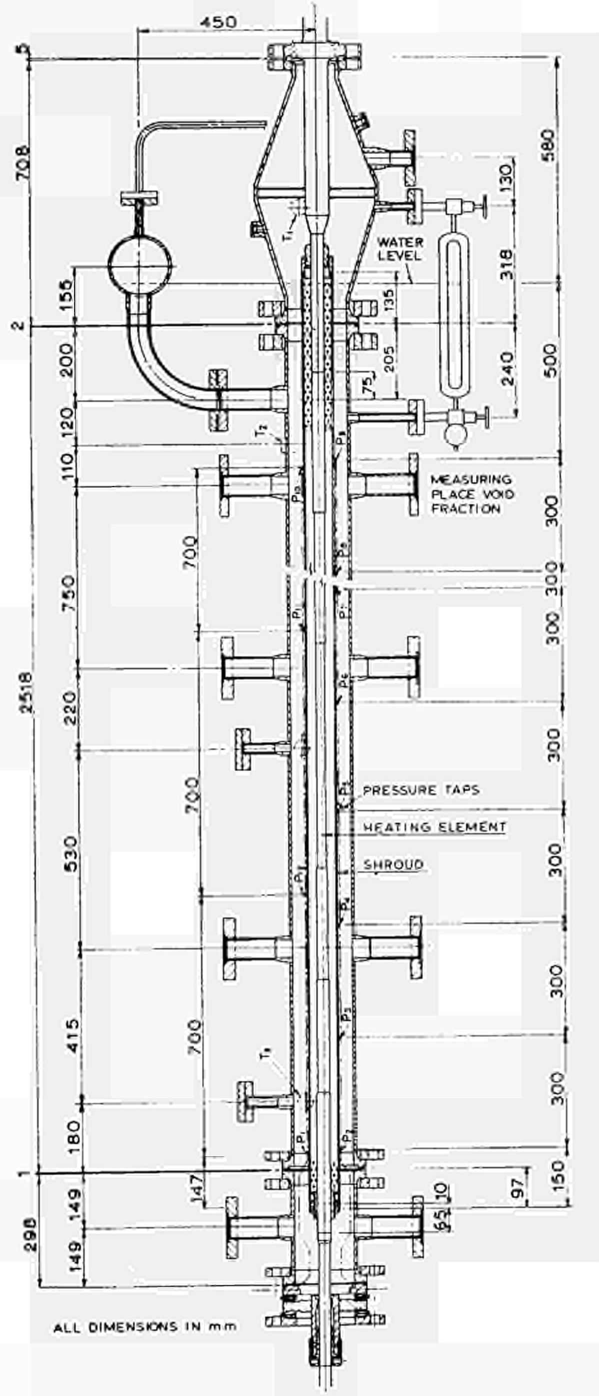


Fig. 8.3. Assembly of a model of a unit cell of the first core loading of the Halden reactor

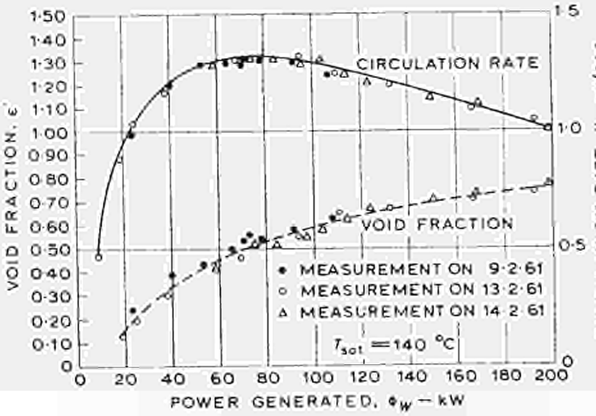
* *A numerical list of references is given in Appendix 8.1.*

steam head up to 30 atm. Additionally, static pressure readings were made along the length of the shroud, giving an idea of the pressure drop in the boiling and non-boiling sections of the riser as well as of the downcomer. The maximum power input obtained was 225 kW, which means a heat flux of 1400 kW/m². The power was limited to this value, in order to avoid burn-out. When inspecting the heating element after the experiments had been performed, it was found that some parts had acquired a blue colour, due to the high temperature.

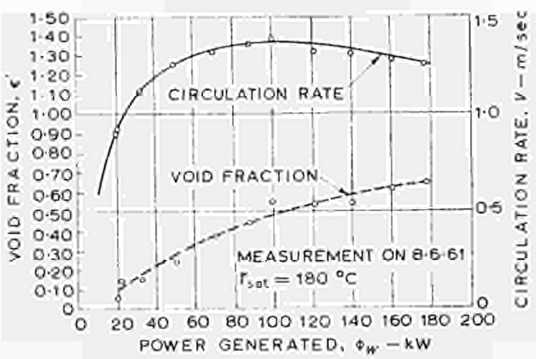
Results

In Fig. 8.4 the results are given of two series of measurements. The measured values of circulation rate and void fraction, repeated at various intervals, are plotted against power for two temperatures, 140°C and 180°C respectively. As can be seen from Fig. 8.4*a*, the reproducibility is fairly good.

In Figs. 8.5 and 8.6 the smoothed curves for seven different temperatures are given, while in Fig. 8.7 a cross-plot has been made in a temperature–power diagram. Lines of constant circulation rate and constant void fraction have been drawn in this diagram. The broken-line curve at the left side in the diagram, represents the heat losses of the equipment as a function of temperature.



a At 140°C.



b At 180°C.

Fig. 8.4. The measured void fraction and circulation rate as a function of power

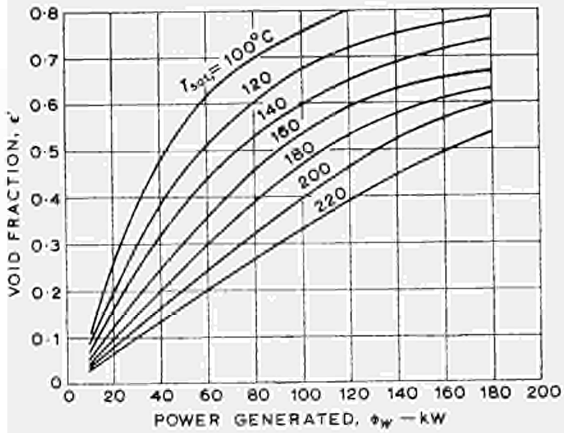


Fig. 8.5. The void fraction as a function of power for different temperatures

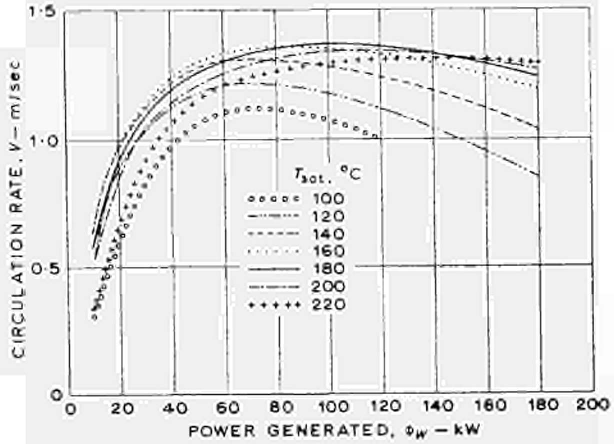


Fig. 8.6. The circulation rate as a function of power for different temperatures

As follows from Fig. 8.7, there is a maximum in the circulation rate–power curve taken at constant temperature. At low power, the driving head increases with power as a result of the increase in void fraction. At high power, the fraction losses of the two-phase flow become progressively more important, resulting in a decrease of the circulation rate with increasing power in the high-power range.

In Fig. 8.7 it can be seen that for constant power there is a maximum in the circulation rate too. At high temperature, the driving head decreases with temperature due to the decrease in void fraction with pressure, resulting in a decrease in circulation rate. In the low temperature and pressure range, the hydrostatic effects become important. The variation of the saturation temperature as a function of height causes a decrease in boiling length with decreasing temperature. The driving head and the circulation rate will therefore decrease with decreasing temperature at constant power.

It can be concluded from Fig. 8.7 that an absolute maximum for one combination of power and pressure would exist.

From the results given, some fundamental quantities, such as boiling lengths, steam qualities, slip ratios, two-phase friction factors and exit void fractions have been calculated. When making these calculations, the variation of the saturation temperature as a function of height, as well as the 'cosine' distribution of the heat flux generated in the element, and the subcooling caused by the heat losses were taken into account.

Slip ratios

The liquid- and vapour-phase velocities can be found by calculating the steam quality at the spot where the void fraction is measured. The ratio of these two velocities, usually called slip ratio, is given in Fig. 8.8 as a function of steam quality at the measuring place of the void fraction for various temperatures. It must be kept in mind that the circulation rates along these curves vary. The steam quality and circulation rate appear as interconnected variables. This is due to the fact that the subcooling is mainly caused by the heat losses and is therefore a direct function of temperature. Separation of the variables influencing the slip ratio was impossible in the present experiments. In Fig. 8.8 some experimental points are given which were deduced from graphs given by the Argonne National

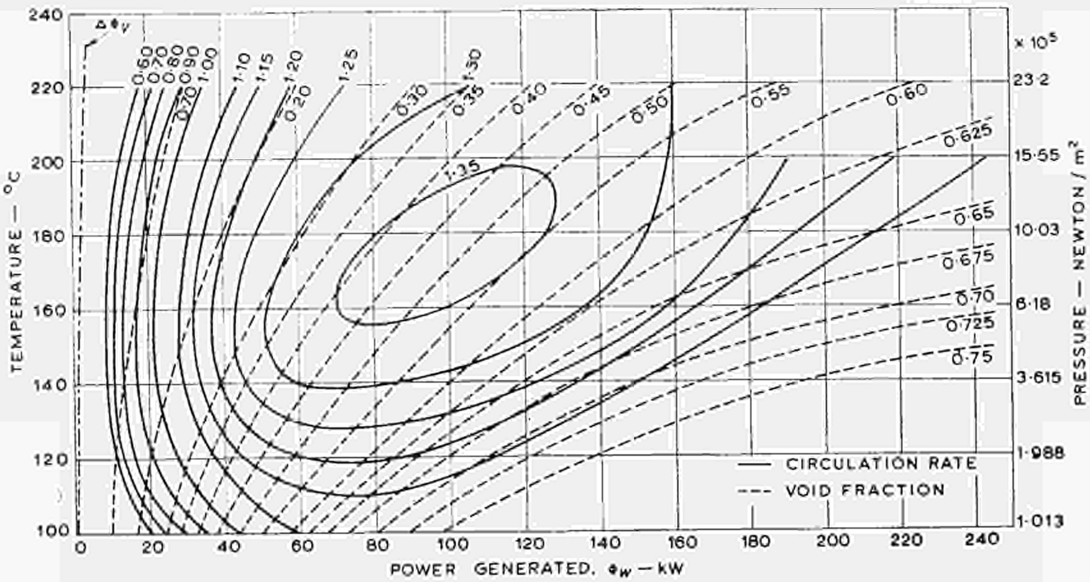


Fig. 8.7. Temperature–power diagram with lines of constant void fraction and circulation rate

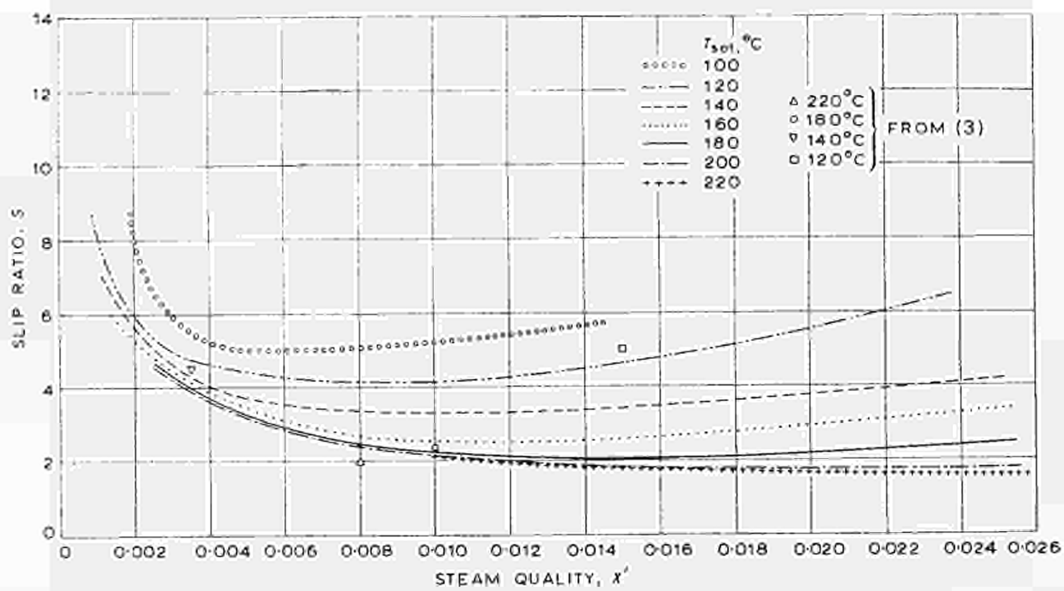


Fig. 8.8. The slip ratio as a function of steam quality for different temperatures

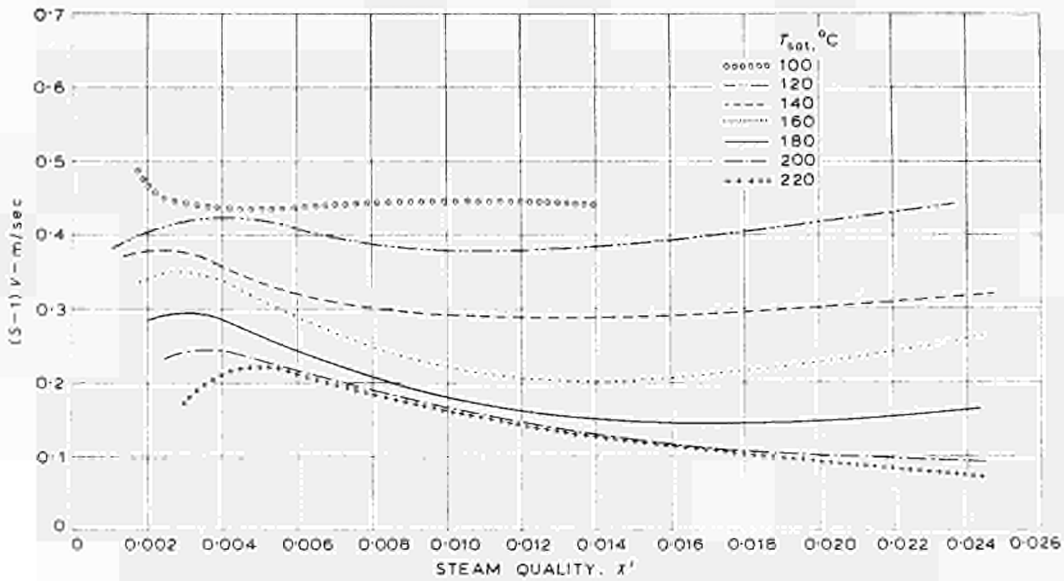


Fig. 8.9. $(S-1)V$ as a function of steam quality for different temperatures

Laboratory (A.N.L.) (**3**) showing a fairly good correspondence. It seems, however, that in these experiments the influence of the mass flow is somewhat stronger than indicated in (**3**). Comparisons with the results of other investigators are under way.

In Fig. 8.9 the quantity $(S-1)V$ has been plotted against steam quality. According to some investigators (**4**) (**5**), this quantity should only be dependent on pressure and would thus be represented by horizontal lines in Fig. 8.9. Inspection of the experimental data indicates that this statement holds fairly good for low temperatures, but that it remains valid only for higher steam qualities at higher temperatures.

Two-phase friction factors

The friction losses in two-phase flow are usually expressed as a two-phase friction factor R times the friction losses that would exist if all the fluid were liquid and the whole cross-section were occupied by the liquid. As the friction factor will vary along the height, according to the variation of void fraction, steam quality, etc., an average value $\bar{R}$, taken over the boiling part of the channel, will be considered.

The value of the two-phase friction losses can be calculated from the momentum equation for the riser. In this equation the driving head, the inlet and outlet losses, the acceleration losses and the friction losses in the non-boiling and in the boiling lengths will appear. The driving head has been determined by assuming that the slip ratio was constant along the height. This had to be done because the void fraction was measured at one position only. The inlet and outlet losses are known from the static pressure readings (Fig. 8.3). The acceleration losses and friction losses in the non-boiling length can be calculated from the measured values of the void fraction and circulation rate and the calculated value of the non-boiling length.

Actually, the value of $\bar{R}$ was not calculated for the whole boiling length, but up to the measuring position of the void fraction, due to the complexity of the outlet phenomena. The results are given in Fig. 8.10 as a function of the mean value of the void fraction. In this instance, it must again be borne in mind that steam quality and circulation rate are hidden variables.

The accuracy of the results is not too great. The accurate determination of the boiling length is important. In this series of experiments this determination is somewhat doubtful due to the fact that—especially at low powers—the condensate flow was somewhat subcooled. Although the condensate flow is very small in comparison with the circulating flow, the effect may have had some influence.

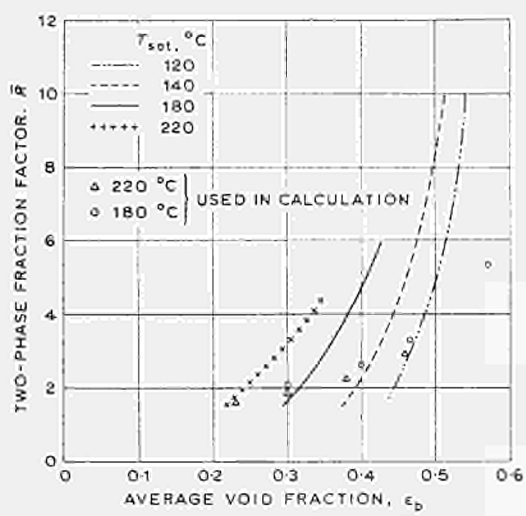


Fig. 8.10. The two-phase friction factor $\bar{R}$ as a function of average void fraction

Subcooled boiling can also be of influence; this effect has not been taken into account. Owing to these effects the values determined for R for mean void fractions of 0·20 and less were less than one and were therefore omitted in the figure.

In Fig. 8.10 the points representing the accepted values of R in the theoretical calculations (see next section) are also given. The conformity is rather poor.

HYDRAULIC CALCULATIONS

An attempt was made to approximate the experimental results by means of some theoretical calculations. The calculations have been made in the usual manner (**6**) (**7**) on an I.B.M. computer, by assuming a value for the exit void fraction and calculating the flow rate and channel power. The slip ratio and degree of subcooling were put in as independent parameters. The values for the subcooling were chosen in accordance with the subcooling in the actual experiments as a result of the heat losses. The values of the slip ratio were determined from the corresponding A.N.L. graphs (**3**) for the values of the flow rates and steam qualities to be expected. The slip ratio was taken constant along the length.

For the calculation of the acceleration forces, the formula was taken from (**8**).

The friction losses were divided in three parts: the entrance losses and the friction losses in the non-boiling and boiling parts of the channel. The entrance losses were determined experimentally in several cold-tests in the experimental set-up. The calculation of the pressure losses in the non-boiling part is straightforward and will not be dealt with here. For the determination of the two-phase friction losses, the method indicated in (**7**) was accepted. In this method a correction is given for the velocity effect to the two-phase friction factor of the Martinelli–Nelson correlation (**8**). In order to use the corrected Martinelli–Nelson factor in the calculations they must be integrated over the boiling length. For a linear relation between steam quality and height this has already been done by R. W. Bowring for the Halden boiling-water reactor* and the values obtained by him were put into the calculations (Fig. 8.10).

The calculations have been made for two types of heat flux distribution: the stepwise distribution as used in the experiments and a uniform distribution. In the calculations no allowance was made for subcooled boiling or for a variation of the saturation temperature with height. Some results of the calculations for the case of a 'cosine' distribution of heat flux are given in Figs. 8.11 and 8.12. The plots show the effect of slip ratio for a fixed value of the subcooling on the relation between circulation rate, exit void fraction and power, as well as the influence of subcooling for a fixed value of the slip ratio. The effect of the slip ratio on the circulation rate and exit void fraction is particularly pronounced.

A comparison between the results obtained with a uniform and a stepwise distribution of the power along the height is made in Fig. 8.11; in the curve for a subcooling of 15 per cent and a slip factor of three ($S = 3$) the data represent the results obtained for a uniform heat flux.

For a comparison with the experimental results, the exit void fraction has been calculated from the experiment assuming the slip ratio to be constant. An interpolation was made in the calculated curves for the actual values of

* *Private communications, Halden project.*

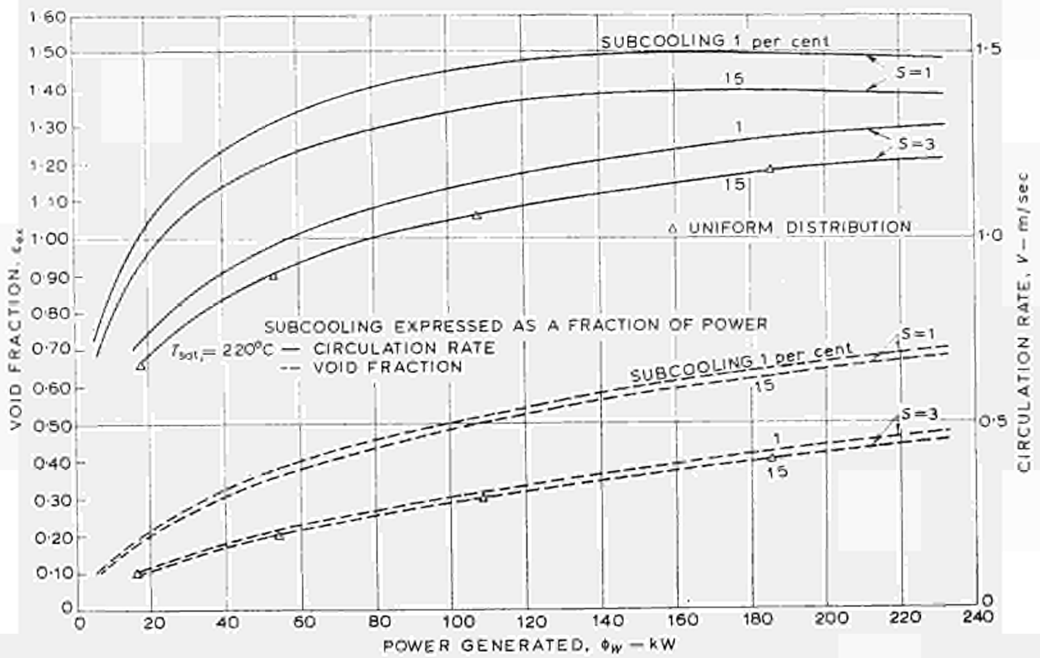


Fig. 8.11. The influence of subcooling, slip factor and flux distribution on calculated circulation rate and void fraction at 220°C

the subcooling obtained in the experiment and the correct variation of slip ratio according to the variation of steam quality and circulation rate in the experiments. The result is given in Fig. 8.13.

In the near future an attempt will be made to improve

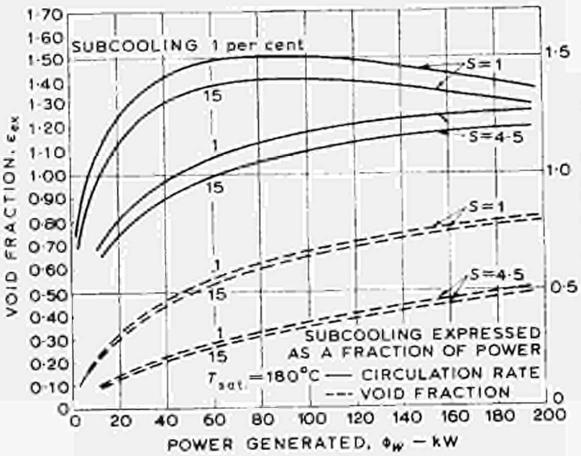
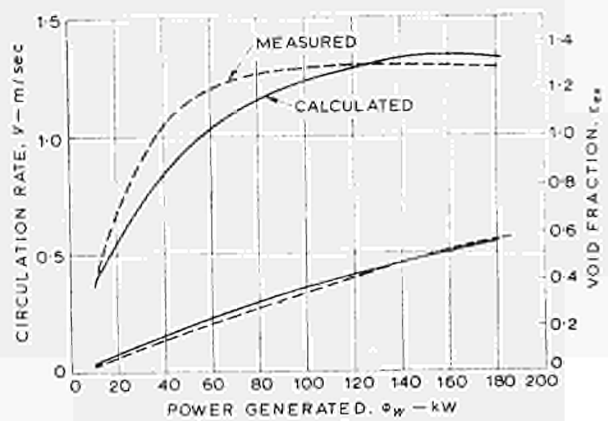
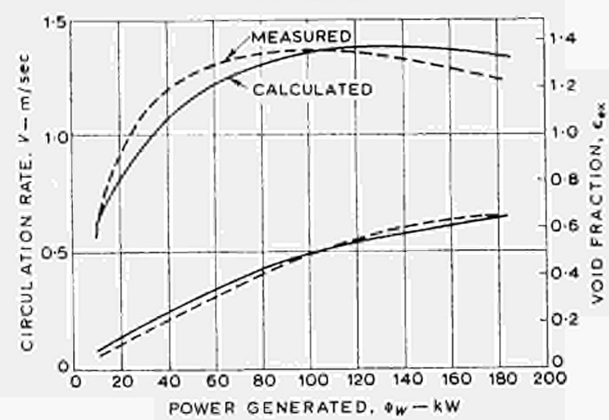


Fig. 8.12. The influence of subcooling and slip factor on calculated circulation rate and void fraction at 180°C



a At 180°C.



b At 220°C.

Fig. 8.13. Comparison between calculated and experimental results

the calculations by incorporating the influence of variation of saturation temperature with height and of subcooled boiling. Also the slip ratio will be varied along the height, while in determining the two-phase friction factor the correct variation of steam quality with height will be included. A further analysis of the influence of flux distribution will be made.

INSTABILITIES

During the experiments the fluctuations in absolute pressure, as a result of boiling noise and two-phase instabilities, could be detected by using a specially designed fast pressure gauge. The signal was made visible both on an oscilloscope and by means of a light galvanometer recorder. Some photographs of the oscilloscope screen are given in Fig. 8.14. Under normal operating conditions, pressure fluctuations exist with frequencies of about 10 Hz and with amplitudes of about 8 cm water head. At high power, large fluctuations of about 50 cm water head and a low frequency (less than 1 Hz) show as a superposition to the low-power boiling noise.

The large fluctuations in the absolute pressure appear by increasing the power at constant temperature or by decreasing the temperature at constant power in the higher power range. The onset of these large fluctuations seems to occur at a higher power than the one at which the maximum flow rate is obtained in the circulation-rate–power curve at constant temperature. The amplitude of the fluctuations increases by further increasing the power. The slope of the circulation-rate–power curve seems to be of influence on the onset of the instabilities as well as on the rate of increase of the amplitude with time.

Some tests carried out with glass shrouds with open ends, showed more severe instabilities than were found in the tests presented in this report which were performed with the Halden shroud. The onset as well as the character of the instabilities are strongly dependent on the geometry of the assembly, particularly in so far as this geometry influences the pressure losses in the natural circulating system.

Methods of analysing the type of signals found and the means of improving the detection methods are being studied. There is a fast differential pressure gauge under development for the detection of fluctuations in the circulation rate. As can be understood this will be a better parameter for the study of instabilities. Some problems arise from the higher harmonics on these signals induced by the electrical heating currents.

It is expected that in the next series of measurements the accuracy will be improved and that the results will be more reliable, so that they will be good enough for analysis by means of the I.B.M. computer available.

FUTURE PROGRAMME

The future programme can roughly be divided into two parts: one dealing with the heat transport in steady states,

a b c d

a Horizontal 1 cm = 0·5 sec. Vertical 1 cm = 10 cm water head. Power 115 kW, Halden shroud.
b Horizontal 1 cm = 0·5 sec. Vertical 1 cm = 10 cm water head. Power 150 kW, Halden shroud.
c Horizontal 1 cm = 1 sec. Vertical 1 cm = 10 cm water head. Power 190 kW, Halden shroud.
d Horizontal 1 cm = 1 sec. Vertical 1 cm = 10 cm water head. Power 60 kW glass shroud.

Fig. 8.14. Absolute pressure recordings at 140°C

whereas in the other the attention is especially directed to dynamic measurements.

For the steady-state programme an external stainless-steel circuit is being installed, providing a possible means of subcooling the mass flow before it is returned to the test section. By incorporating a pump this circuit will also be used for forced circulation measurements. With this equipment, it will be possible to separate the influencing parameters on the different fundamental quantities as steam quality and circulation rate.

Another important subject of the steady-state programme is the study of the onset, the origin and character of the instabilities. Special attention will be given to the changes in instabilities with geometry and internal hydraulic resistance of the assembly.

In the dynamic measurements the transfer functions will be determined from power, pressure and subcooling to the characteristic quantities such as void fraction and circulation rate. Attention will also be paid to the transient response of the variables to step and other input functions of the power, pressure and subcooling. In some of these experiments the neutronic characteristics of a reactor will be simulated by means of an analogon machine, which controls the power supply of the boiling-water loop.

Two atmospheric glass loops have been constructed to study atmospheric boiling in more detail, including such phenomena as bubble formation, slip, boiling noise, etc. These glass loops can be used either for water–steam or for water-air mixtures.

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APPENDIX 8.1

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