INVESTIGATION OF THE TRANSITION FROM FORCED TO NATURAL CONVECTION IN THE RESEARCH REACTOR MUNICH II

S. SKREBA¹⁾, J. ADAMEK, H. UNGER

Abstract

The new research reactor Munich II (FRM-II), which is under construction at the Technical University Munich, Germany, makes use of a newly developed compact reactor core consisting of a single fuel element, which is assembled of two concentric pipes. Between the fuel element’s inner and outer pipe 113 involutely bent fuel plates are placed rotationally symmetric, forming 113 cooling channels of a constant width of 2.2 mm.

After a shut down of the reactor, battery supported cooling pumps are started by the reactor safety system in order to remove the decay heat by a downwards directed forced flow. Three hours after they have been started, the cooling pumps are shut down and so-called „natural convection flaps“ are opened by their own weight. Through a flow path, which is provided by the opening of the natural convection flaps, the decay heat is given off to the water in the reactor pool after the direction of the flow has changed and an upwards directed natural convection flow has developed.

At the Department for Nuclear and New Energy Systems of the Ruhr-University Bochum, Germany, a test facility has been built in order to confirm the concept of the decay heat removal in the FRM-II, to acquire data of single and two phase natural convection flows and to detect the dry out in a narrow channel. The thermohydraulics of the FRM-II are simulated by an electrically heated test section, which represents one cooling channel of the fuel element.

At first experiments have been performed, which simulated the transition from forced to natural convection in the core of the FRM-II, both at normal operation and at a complete loss of the decay heat removal pumps. In case of normal operation, the transition from forced to natural convection takes place single phased. If a complete loss of the active decay heat removal system occurs, the decay heat removal is ensured by a quasi-steady two phase flow.

In a second test series minimum heat flux densities leading to pressure pulsations up to limitting amplitudes of 0.1 bar, 0.2 bar and 0.3 bar at the transition from forced to natural convection have been determined.

Further tests have been performed to determine minimum heat flux densities leading to boiling processes in the cooling channel and critical heat flux densities causing dry outs of the cooling channel at downwards directed forced flow. During the tests, flow reversals have been observed because of the buoyancy forces in the coolant causing a mixed convection flow.

The last test series, which has been finished in March 1999, has been performed in order to determine critical heat flux densities during the transition from forced to natural convection and to measure the occuring pressure amplitudes.

All results prove the possibilty to remove the decay heat of the FRM-II by natural convection, even in case of a complete loss of the active decay heat removal system. Above this, large safety margins in the FRM-II concerning pressure pulsations, beginnig of boiling and dry out could be verified.

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1 CONCEPT OF THE FRM-II

At the Technical University of Munich (TUM) an efficient high flux neutron source, the research reactor Munich II (FRM-II), is under construction. A sectional view of the reactor building is shown in Figure 1. The areas of the reactor's main applications are basic research in physics as well as material technique and medicine.

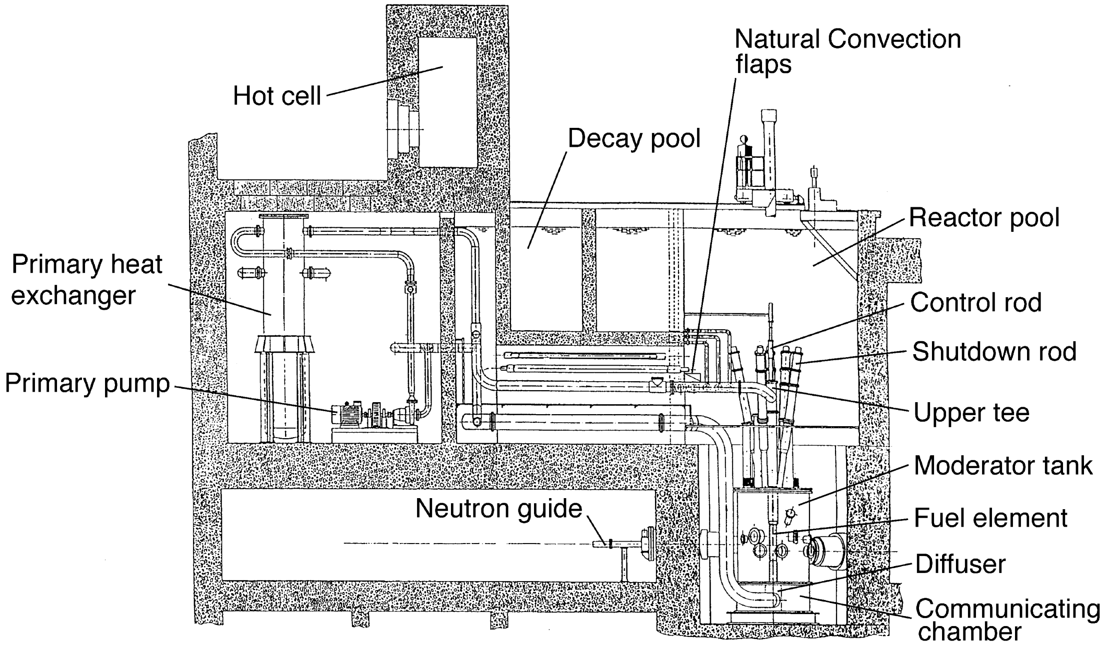

Fig. 1: Sectional view of the FRM-II reactor building

During normal operation of the reactor, the thermal power of 20 MW is removed by a flow rate of 300 l/s of light water, which is pumped through the horizontal part of the primary circuit into the upper tee. There the water changes the direction and flows downwards through the central channel tube and the cooling channels of the fuel element, see Figure 2. Inside the cooling channels a flow velocity of 17.4 m/s is reached during this operation mode of the reactor. After the water has left the fuel element it flows through a diffusor into a collecting chamber and is led back to the primary heat exchangers.

The reactor can be shut down on the one hand by moving the absorber part of the control rod vertically into the inner tube of the fuel element and on the other hand by moving at least 4 of the 5 shut down rods into the moderator tank surrounding the fuel element.

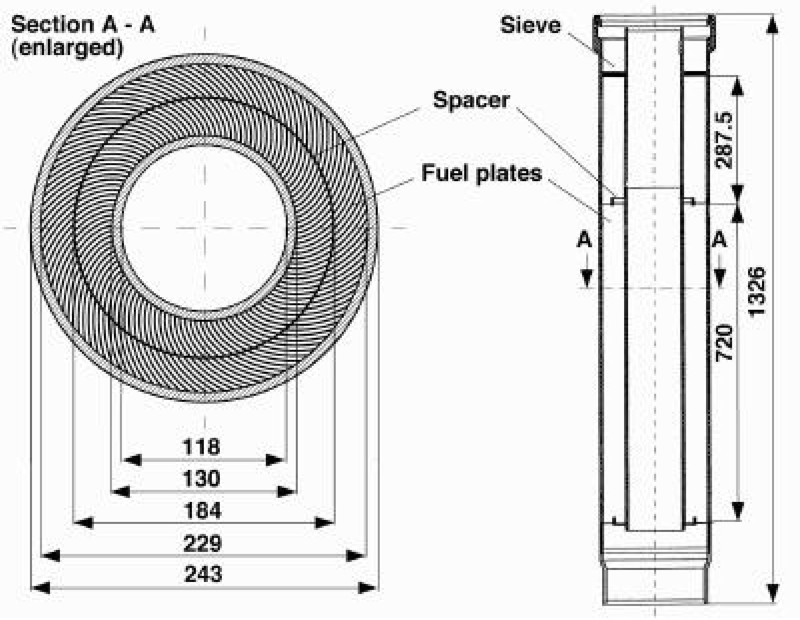

Fig. 2: Cross and longitudinal section of the FRM-II-fuel element

After a shut down of the reactor, battery supported cooling pumps are started by the reactor safety system in order to remove the decay heat. These cooling pumps provide a volumetric cooling water flow rate of 60 l/s, which leads to a reduction of the downwards directed flow velocity in the cooling channels to 3.2 m/s. Three hours after the start of the cooling pumps, the heat flux in the fuel element has decreased to 0.85% of the heat flux during the normal operation of the reactor, which is low enough to allow a shut down of the decay heat removal pumps. During the coast down of the cooling pumps the pressure in the reactor's primary circuit decreases and so-called „natural convection flaps“, which are located in the horizontal part of the primary circuit, are opened by their own weight. The opening of these natural convection flaps provides a connection between the central channel tube, in which the fuel element is located, and the reactor pool. Through this flow path the decay heat is given off to the water in the reactor pool after the direction of the flow has changed and an upwards directed natural convection flow has developed.

In order to provide a maximum neutron flux density of $8 \cdot 10^{14}$ neutrons/($cm^2 \cdot s$) at a thermal power of 20 MW, a new compact core fuel element, shown in Figure 2, was designed. The fuel element consists of two concentric pipes, between which 113 involutely bent fuel plates are placed in a rotationally symmetric way. Between the plates 113 cooling channels of a constant width of 2.2 mm are formed. The fuel plates consist of three layers: two outer claddings, which are 0.38 mm thick each and an inner U_3Si_2/Al-meat, which is 0.60 mm thick. In order to provide a high thermal neutron flux at a comparatively low thermal power, highly enriched uranium (93% U-235) is used in the FRM-II. The neutrons are moderated by heavy water located in the moderator tank surrounding the central channel tube, in which the fuel element is placed.

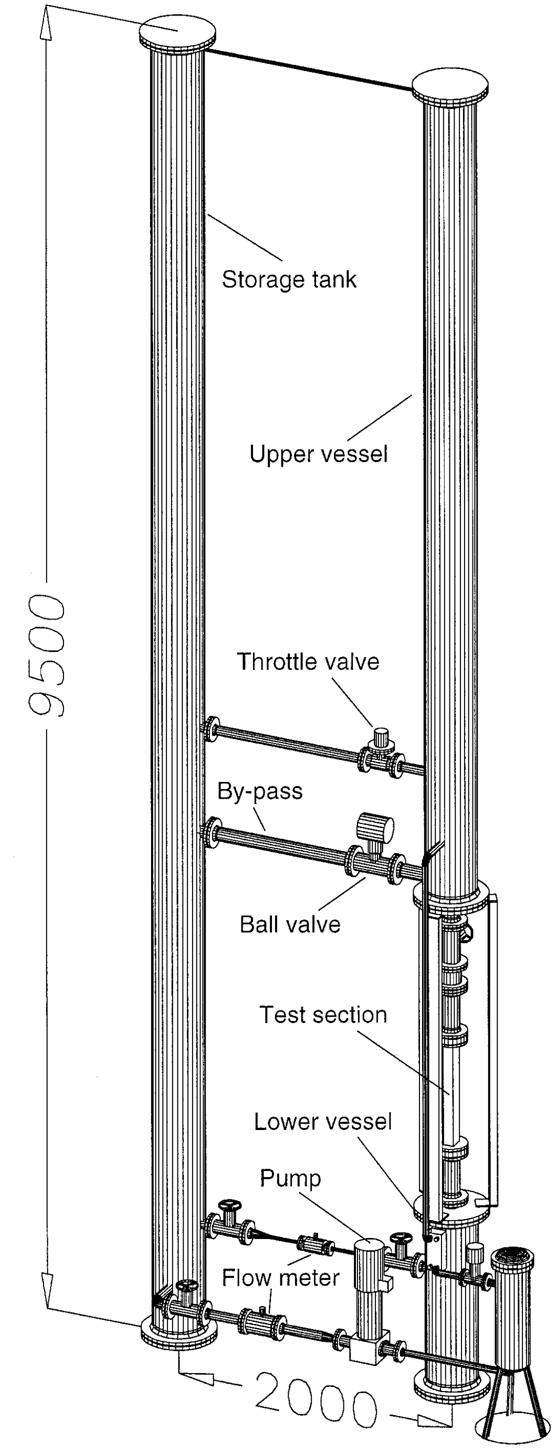

Fig. 3: Facility to investigate the decay heat removal in the FRM-II

2 TEST FACILITY

In order to investigate the physical processes during the transition from forced to natural convection in the fuel element of the FRM-II and to prove the concept of the decay heat removal, a test facility, which can be seen in Figure 3, was built at the Department for Nuclear and New Energy Systems of the Ruhr-University of Bochum. The test facility simulates the thermohydraulics of the reactor during the decay heat removal. It provides a pool water temperature of about 40°C and an absolute pressure of about 2 bar at the lower end of the core. The core itself is represented by a test section, which is located between two vessels, representing the amounts of water above and below the original fuel element. The third vessel, which is called „storage tank“, represents the reactor pool itself. By means of a pump and several valves, two different flow circuits are realized in the test facility simulating the downwards directed forced convection flow as well as the upwards directed natural convection flow, which develops in the FRM-II-core after the coast down of the cooling pumps.

In order to simulate the downwards directed forced flow in the reactor core, the ball valve, which is located in the by-pass between the upper vessel and the storage tank, is closed. A flow rate between 0.6 l/s and 2.9 l/s is pumped from the storage tank through a vertical pipe into the upper vessel. There the flow is divided: one part flows through the horizontal pipe, in which the throttle valve is located, back into the storage tank, the other part flows downwards through the test section into the lower vessel and back into the storage tank. A difference between the water levels in the storage tank and in the upper vessel exists representing the driving pressure difference at the test section. This pressure difference is adjusted by means of the throttle valve, so flow velocities between 0.3 m/s and 3.2 m/s (normal operation of the decay heat removal pumps) are reached in the test section.

The processes during the opening of the natural convection flaps in the FRM-II are simulated by means of the ball valve located in the by-pass between the upper vessel and the storage tank. If the by-pass, which shows a comparatively large diameter of 80 mm, is opened, the pressure difference between the upper vessel and the storage tank decreases immediately and the downwards directed flow in the test section breaks down. Because the walls of the test section are heated electrically, an upwards directed natural convection flow develops.

3 TEST SECTION

In order to simulate the specific thermohydraulic circumstances in the fuel element of the FRM-II, a test section was developed, which represents one cooling channel of the fuel element. The test section forms a cooling channel with a sectional area of 2.2 mm x 35 mm and a length of 720 mm, which is the length of an original cooling channel. Figure 4 shows a cross section of the test section, which is planar in contrast to the involutely bent cooling channels in the FRM-II-fuel element. The smallest radius of curvature of the FRM-II-cooling channels is about 30 times larger than the width of the cooling channel, therefore the curvature does not influence the fluid flow inside the channel, so that a planar test section can be used.

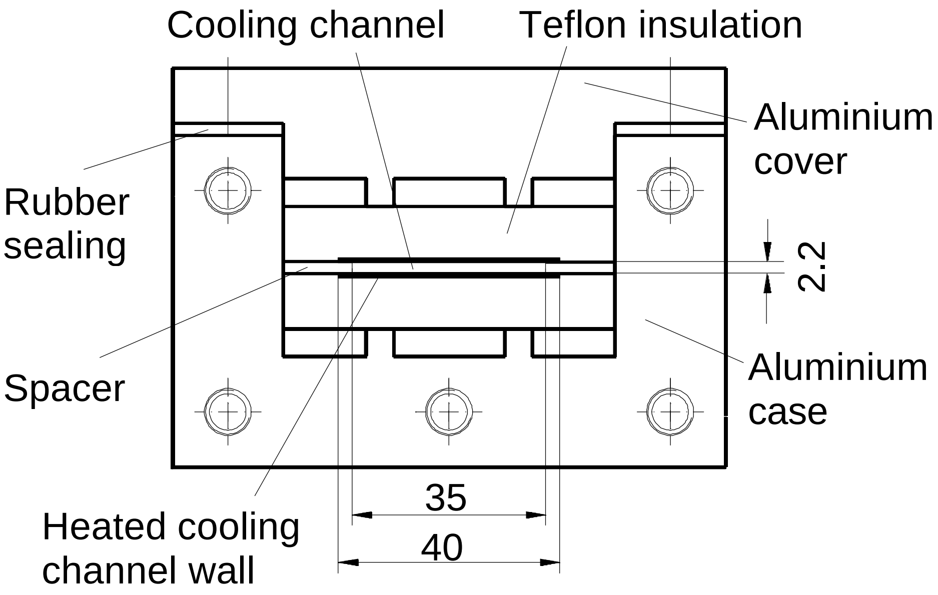

Fig. 4: Cross section of the test section

In order to reach heat flux densities up to 40 W/cm^2, the walls of the test section, which consist of stainless steel, are heated electrically by means of a controllable transformer, which provides a direct current of up to 800 A. In order to reduce the current needed to reach these high heat flux densities, the sectional area of the test section is about half the sectional area of an original cooling channel, which is 2.2 mm x 69.4 mm. The hydraulic diameters of the test section and the original cooling channel differ by just 3%.

During the test runs, the temperatures of the channel walls are registered at 14 different places by means of Fe-CuNi-thermocouples, which are each covered by a stainless steel tube with an outer diameter of 1 mm. The thermocouples themselves are insulated against their stainless steel coatings by a mineral insulation, which impedes an influence on the measuring signal by the heating current. Because of the small outer diameter, the thermocouples have a response time of approximately 0.1 s and are therefore qualified to register even very fast temperature changes of the cooling channel walls. Above that the water temperatures at the upper and the lower end of the cooling channel are detected by two Fe-CuNi-thermocouples. The amplitudes of the pressure pulsations in the cooling channel caused by boiling processes are measured by three pressure transducers, which are able to record pressure frequencies up to about 100 kHz. The membranes of the pressure transducers are situated in the plane of one cooling channel wall in order to detect the pressure pulsations without any delay.

The pressure difference at the test section is measured with a capacitive pressure transducer, which is able to record pressure differences in a range of 400 mbar. The velocity and the direction of the flow inside the test section are registered by means of an inductive flow meter, which is placed in the horizontal pipe between the lower vessel and the storage tank. The heat flux density is determined by measuring the current and the voltage at the test section, so the electric power can be refered to the surface of the stainless steel walls.

During the test runs all measured data are recorded in intervalls of 250 ms while the signals of the pressure transducers in the cooling channel are recorded with sample rates between 500 Hz and 6 kHz. The data recording and storage as well as some controlling tasks, i.e. switching off the pump or the heating current at a certain temperature of the cooling channel wall, are managed by a personal computer by means of appropriate software.

4 RESULTS

4.1 Verification of the Concept for the Decay Heat Removal in the Fuel-Element of the FRM-II

At first experiments were performed, which simulated the transition from forced to natural convection in the core of the FRM-II, both at normal operation of the cooling system and at a complete loss of this security device [1 - 4]. The transition from forced to natural convection during the test runs was initiated 10 s after the data recording was started. In the first 10 seconds of each test run, a downwards directed forced flow with velocities between 0.57 m/s (loss of one decay heat removal pump and occurence of the maximum leakage at the most critical position in the cooling circuit of the FRM-II) and 3.2 m/s (normal operation of the cooling system) exists in the test section. In case of normal operation of the cooling system, the heat flux, which has to be removed by natural convection after the coast down of the pumps, is 2.6 W/cm^2. As shown in Figure 5, the flow in the test section remains single phased after the transition from forced to natural convection in case of normal operation of the cooling system. No boiling processes, especially no pressure pulsations, appear, because the wall temperatures do not exceed 96.5°C, which is 23.5 K below the boiling temperature at the given pressure in the test section. If a complete loss of the cooling system occurs, none of the three cooling pumps will start working after a shut down of the reactor. In this case the entire decay heat has to be removed by natural convection, causing a heat flux of 10.6 W/cm^2 in the channel walls during the development of the natural convection flow. The test results displayed in Figures 5 and 6 show an increase of the wall temperatures up to about 131°C, while in the middle of the test section maximum pressure pulsations with amplitudes of approximately 0.5 bar at frequencies between 15 Hz and 30 Hz are registered.

These results indicate the occurence of boiling processes in case of a complete loss of the active decay heat removal system and the development of a two phase natural convection flow inside the test section. However, after the transition to natural convection, a steady state is reached ensuring the removal of the decay heat even in case of a complete loss of the active decay heat removal system. By means of numerical calculations it could be shown, that the maximum pressure amplitude of 0.51 bar, which was observed at a complete loss of the active decay heat removal system, does not endanger the mechanical integrity of the fuel element.

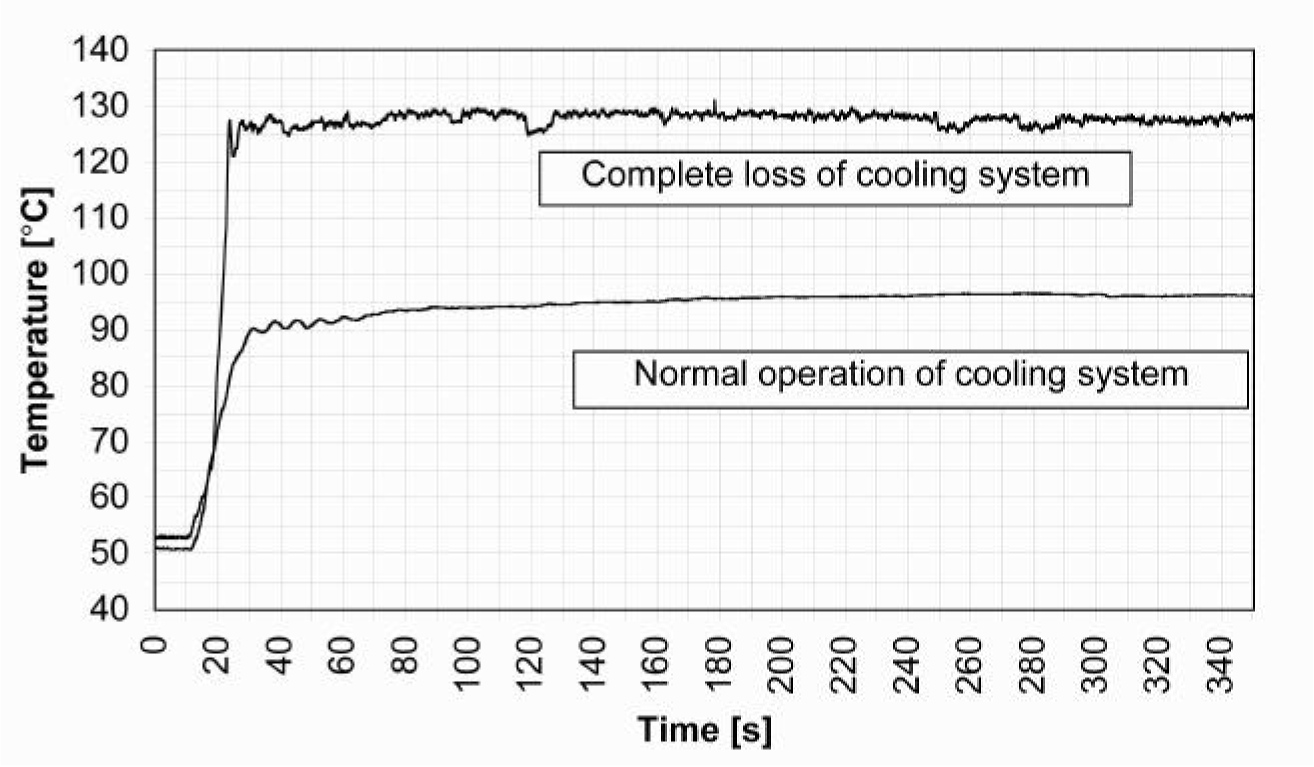

Fig. 5: Wall temperatures at the hottest spot of the test section during the transition from forced to natural convection

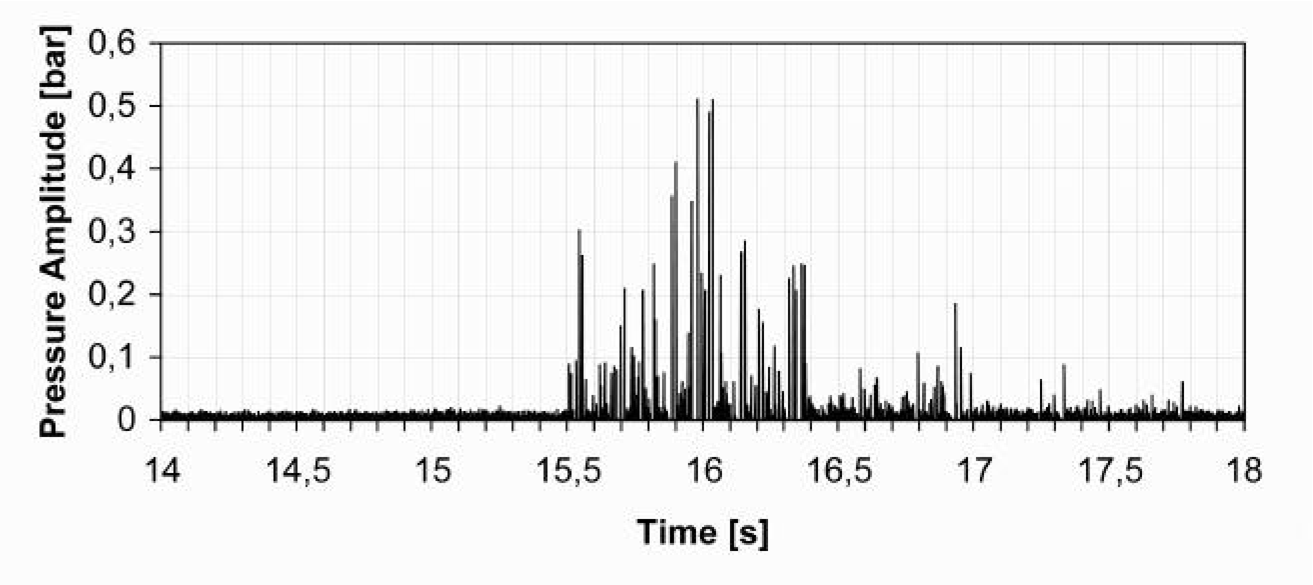

Fig. 6: Amplitudes of pressure pulsations after the transition from forced to natural convection at a complete loss of the active decay heat removal system

4.2 Heat Flux Densities leading to Given Limitting Pressure Amplitudes due to Boiling Processes at the Transition from Forced to Natural Convection

The aim of a second test series was to determine minimum heat flux densities, which lead to maximum pressure pulsations reaching limitting amplitudes of 0.1 bar, 0.2 bar and 0.3 bar after the transition from forced to natural convection [5, 6]. The velocities of the downwards directed forced flow, which were adjusted before the start of the data logging were between 0.57 m/s and 3.2 m/s. During the test series, no implicit functional dependence between the heat flux and the occuring maximum pressure pulsations could be found. In order to get a sufficient data base, pressure pulsations were recorded with sample rates between 500 Hz (period of data logging: 32 s) and 6 kHz (period of data logging: 2.67 s) during 255 tests. The demanded heat flux densities were determined by analysing the maximum pressure amplitudes from the time history of the pressure transducers. In Figure 7 the maximum pressure amplitudes are plotted as a function of the averaged heat flux density, which occured in the cooling channel during the recording of the pressure data. From this graph, the demanded heat flux densities, which are listed in Table 1, can be determined.

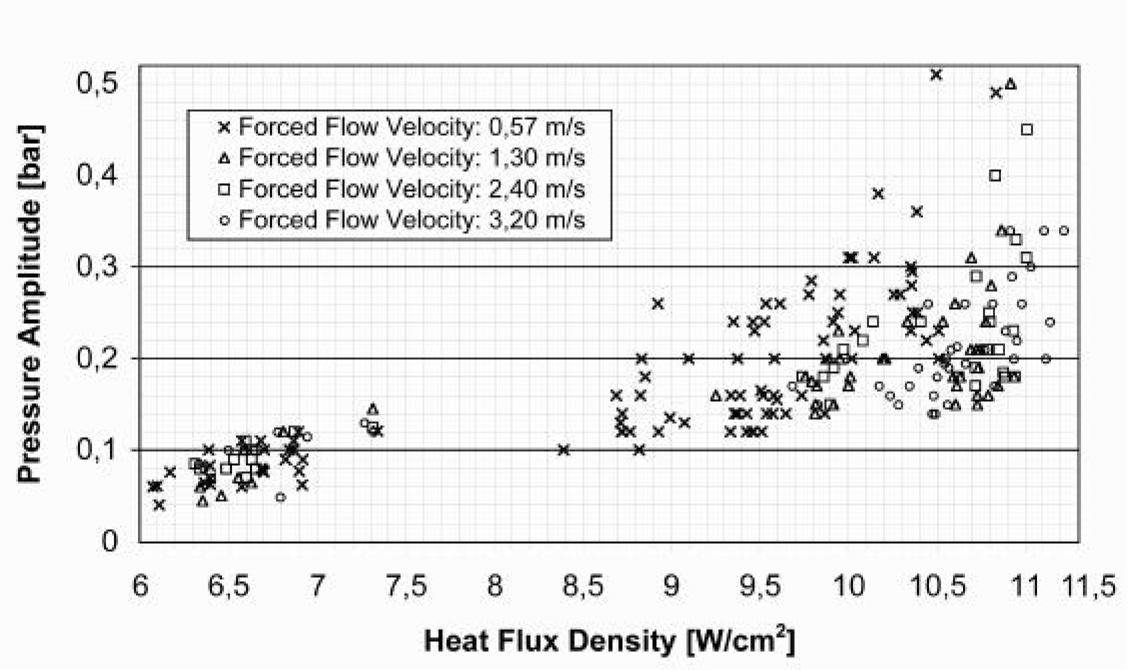

Fig. 7: Maximum pressure amplitudes recorded after the transition from forced to natural convection

Table 1: Minimum heat flux densities [W/cm^2] leading to given limitting pressure amplitudes

Limitting Amplitude [bar]	Forced Flow Velocity [m/s]			
	0.57	1.30	2.40	3.20
0.1	6.4	6.6	6.6	6.5
0.2	8.8	9.9	10.0	10.4
0.3	10.0	10.7	10.8	10.9

Table 1 does not show significant differences of the results in a velocity range between 1.3 m/s and 3.2 m/s. If a still smaller forced flow velocity of 0.57 m/s, representing the loss of one decay heat removal pump and the occurence of the maximum leakage at the most critical position in the cooling circuit of the FRM-II, is established in the test section before the transition from forced to natural convection, the limitting amplitudes are reached at lower heat flux densities. The reasons for that are the higher wall temperatures of the cooling channel at the beginning of the transition to natural convection, caused by the reduced cooling of the test section because of the slower forced flow in that case.

4.3 Minimum Heat Flux Densities Leading to Boiling Processes at Mixed Convection

Further tests were performed to determine minimum heat flux densities leading to boiling processes in the cooling channel and critical heat flux densities causing dry outs of the cooling channel at downwards directed starting velocities between 0.3 m/s and 0.9 m/s. During the tests, flow breakdowns were observed because of the buoyancy forces in the coolant causing a separation of the boundary layers from the cooling channel walls. Figure 8 shows the measured flow velocity inside the cooling channel at a downwards directed starting velocity of 0.3 m/s and a heat flux density of 4.51 W/cm^2. A downwards directed velocity is displayed negatively, upwards directed velocities are displayed positively. From the beginning of the data logging a slow decrease of the velocity inside the cooling channel is observed due to the heating of the walls, which produces buoyancy forces in the fluid. At about 70 s a rapid decrease of the velocity is noticed followed by an unstable flow condition, during which the heat transfer is less effective than at natural convection. Therefore the minimum heat flux density which leads to boiling processes at mixed convection is 4.51 W/cm^2 whereas it is 6 W/cm^2 for free natural convection.

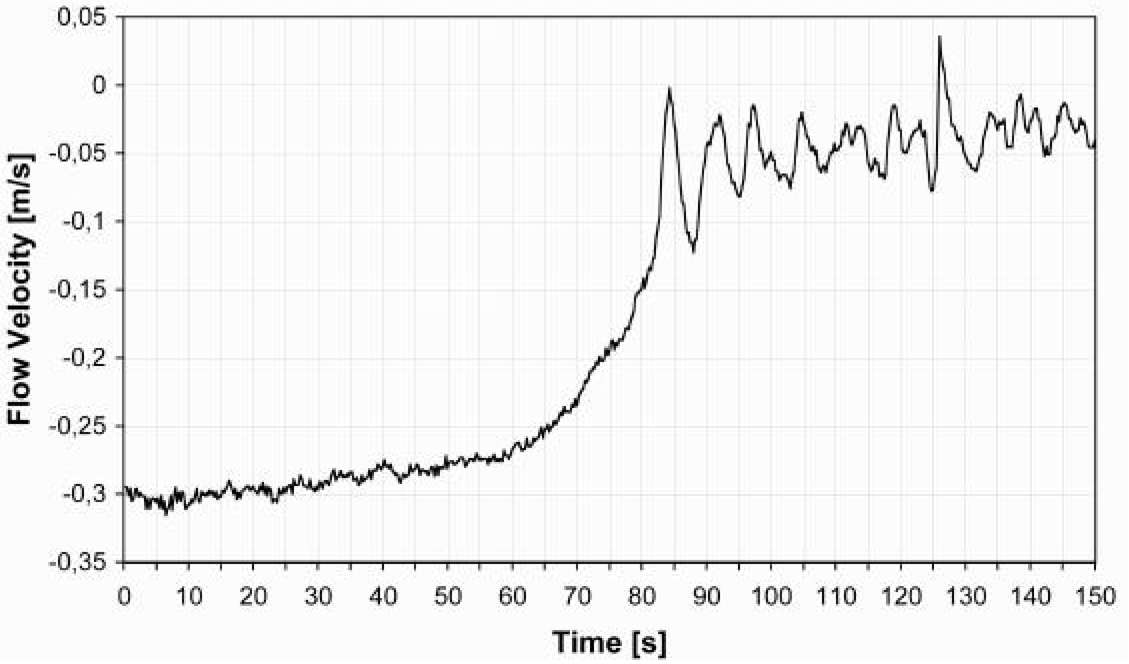

Fig. 8: Flow velocity in the cooling channel at a downwards directed starting velocity of 0.3 m/s and a heat flux density of 4.51 W/cm^2

Table 2 shows the minimum heat flux densities that lead to boiling processes because of flow breakdowns in the cooling channel at starting velocities between 0.3 m/s and 0.9 m/s. For heat flux densities above 18 W/cm^2

a test section with cooling channel walls of 1.0 mm thickness had to be used, because of the greater stiffness of these walls compared to the cooling channel walls previously used, which showed a thickness of 0.5 mm.

Table 2: Minimum heat flux densities [W/cm^2] leading to boiling processes at mixed convection

Downwards Directed Starting Flow Velocity [m/s]	Cooling Channel Wall Thickness 0.5 mm	Cooling Channel Wall Thickness 1.0 mm
0.3	5.21	4.51
0.57	11.01	10.03
0.9	18.00	18.46

The values of the determined heat flux densities show a linear increase from about 5 W/cm^2 at a starting velocity of 0.3 m/s to about 18 W/cm^2 at a starting velocity of 0.9 m/s. In case of loss of one decay heat removal pump and the occurence of the maximum leakage at the most critical position in the cooling circuit of the FRM-II, a velocity of 0.57 m/s occurs in the cooling channels of the reactor core. Immediately after the coast down of the primary pumps a maximum axially averaged heat flux density of 10.6 W/cm^2 appears, which can lead to quasi-steady boiling processes with wall temperatures up to 130°C. These boiling processes do not endanger the decay heat removal in the FRM-II, because of the moderate wall temperatures. Above this they last only a short period, because of the decreasing heat flux density.

4.4 Critical Heat Flux Densities at Mixed Convection

In another test series critical heat flux densities, which lead to dry outs in the cooling channel, were determined for the same flow regime. The dry outs were indicated by very fast escalations of the wall temperatures, whereby the critical heat flux density was defined as the minimum heat flux density causing a wall temperature of at least 170°C. In order to protect the test section, the controlling computer switched off the power supply of the test section if 170°C were exceeded at one thermocouple at the cooling channel wall. Because of the high heat flux densities considered of above 20 W/cm^2, flow breakdowns occured shortly after the start of the data logging of every measurement during this test series. Figure 9 shows the time history of the wall temperature in the upper part of the test section and the heat flux density at an experiment with a starting velocity of 0.3 m/s and an averaged heat flux density of 26.52 W/cm^2.

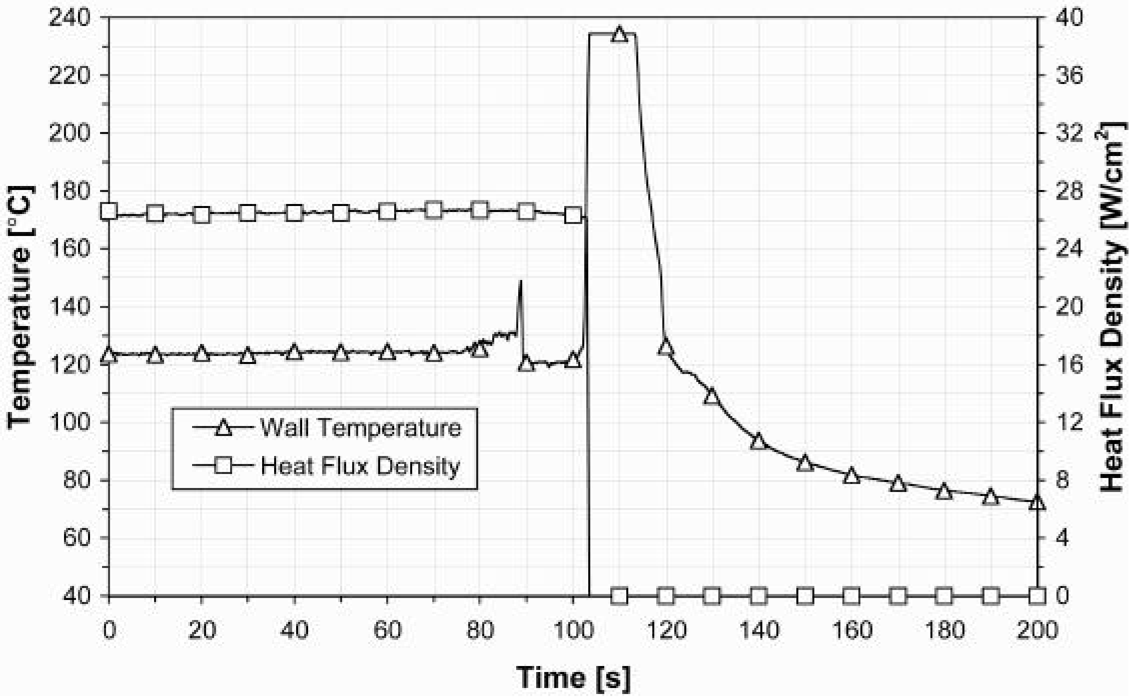

Fig. 9: Wall temperature in the upper part of the test section and heat flux density during the determination of critical heat flux densities at mixed convection

In the experiment displayed in Figure 9 wall temperatures of about 126°C, indicating quasi-steady boiling processes, occured immediately after the beginning of the data logging due to a breakdown of the downwards directed flow velocity. At about 90 s a first temperature escalation reaching a maximum value of 150°C is observed. About 13 s later the wall temperature increases rapidly and exceeds 234°C, which is the maximum value that can be measured with the present configuration of the measuring equipment, for 10 s. After this, the wall temperature decreases, because the power supply has been switched off by the controlling computer, when 170°C were reached and so the downwards directed fluid flow sets in again.

Normally, as shown in Figure 9, boiling processes were observed after the breakdown of the flow before dry out phenomena appeared. At one experiment within this test series a spontaneous dry out was observed without previous boiling processes. Table 3 shows the minimum heat flux densities, that lead to dry outs at mixed convection in the cooling channel at downwards directed starting velocities between 0.3 m/s and 0.9 m/s.

Table 3: Minimum heat flux densities [W/cm^2] leading to dry out at mixed convection

Downwards Directed Starting Flow Velocity [m/s]	Dry Out after Boiling	Spontaneous Dry Out
0.3	26.32	Not Observed
0.57	24.10	21.49
0.9	23.85	Not Observed

As can be seen in Table 3, the critical heat flux density decreases with increasing starting velocity. This is explained by the increasing pressure difference, which is needed to reach higher starting velocities. After the breakdown of the flow, the pressure difference opposes the development of an upwards directed natural convection flow, so that a higher critical heat flux density is reached at lower starting velocities due to the better heat transfer in this case. The lowest critical heat flux density occuring during the tests is 21.49 W/cm^2, which is about twice as high as the maximum axially averaged heat flux density appearing immediately after the coast down of the primary pumps in the FRM-II.

4.5 Critical Heat Flux Densities and Maximum Pressure Amplitudes at the Transition from Forced to Natural Convection

Finally a test series, which has been finished in March 1999, was performed in order to determine critical heat flux densities during the transition from forced to natural convection and to measure the occuring pressure amplitudes. The critical heat flux densities were determined in the same way as at mixed convection, whereas the starting velocities of the downwards directed forced flow were in the range between 0.57 m/s and 3.2 m/s. The transition from forced to natural convection was initiated 10 s after the start of the data logging by opening the by-pass in the test facility. Table 4 shows the minimum heat flux densities that lead to dry outs after the transition from downwards directed forced flow to upwards directed natural convection.

Table 4: Minimum heat flux densities [W/cm^2] leading to dry out after the transition from forced to natural convection

Downwards Directed Starting Flow Velocity [m/s]	Critical Heat Flux Density after the Transition from Forced to Natural Convection [W/cm^2]
0.57	27.39
1.30	27.53
2.40	27.93
3.20	27.92

As shown in Table 4 the critical heat flux densities were found to be independent of the downwards directed starting velocity, because the earliest dry out appeared 54 s after the transition from forced to natural convection where the conditions in the test section are independent of the starting conditions at forced convection. Above this, in contrast to the experiments at mixed convection, no spontaneous dry out was observed during this test series. The lowest critical heat flux density of 27.39 W/cm^2 is about 28% higher than the value of mixed convection due to the undisturbed heat transfer at free natural convection.

Another aspect of this test series was the determination of the maximum pressure amplitudes appearing at the transtion to natural convection. As already mentioned in chapter 4.2, no functional dependence between heat flux density and maximum pressure amplitudes could be found. But it was evident in this test series, that the maximum pressure amplitudes at both ends of the test section are about three times higher than the amplitudes in the middle of the cooling channel. This is explained by the water flowing back into the cooling channel from both ends after being dashed out by the strong evaporation processes. The maximum pressure amplitude of the whole test series, which was recorded in the upper part of the cooling channel, is 1.81 bar.

5 SUMMARY AND CONCLUSION

In order to perform a test sequence concerning the concept of the decay heat removal in the new research reactor FRM-II, a test facility has been built at the Ruhr-University Bochum, Germany. The main attention of the experiments focusses on the thermohydraulic processes, which occur during the transition from forced to natural convection in the FRM-II-fuel element. The thermohydraulic conditions in one cooling channel of the FRM-II-fuel element were simulated by means of an electrically heated test section.

The results in general prove the concept of the decay heat removal of the FRM-II. At normal operation of the active decay heat removal system (heat flux density: 2.6 W/cm^2), neither boiling processes nor pressure pulsations occur after the transition from forced to natural convection. At a complete loss of the active decay heat removal system (heat flux density: 10.6 W/cm^2), a quasi-steady two-phase flow occurs with constant wall temperatures up to 130°C. The maximum pressure amplitudes during this mode of operation reached 0.51 bar and do not endanger the mechanical integrity of the fuel element.

The aim of a second test series was to determine minimum heat flux densities, which lead to maximum pressure pulsations reaching limitting amplitudes of 0.1 bar, 0.2 bar and 0.3 bar after the transition from forced to natural convection. Even the minimum heat flux density, which is needed to reach the smallest pressure amplitude considered, is by a factor of 2.5 higher than the maximum axially averaged heat flux density occuring during the transition from forced to natural convection at normal operation of the decay heat removal system in the FRM-II.

A further test series was performed concerning the beginning of boiling processes during mixed convection in the cooling channel at starting velocities of the downwards directed flow between 0.3 m/s and 0.9 m/s. During the experiments rapid changes of the flow velocity due to the separation of the boundary layers from the cooling channel walls were observed worsening the heat transfer and therefore leading to boiling processes. At a forced flow velocity of 0.57 m/s, representing the loss of one decay heat removal pump and the occurence of the maximum leakage at the most critical position in the cooling circuit of the FRM-II, the determined minimum heat flux density leading to boiling processes is in the range of the maximum axially averaged heat flux density immediately after a shut down of the reactor. Therefore quasi-steady boiling processes with constant wall temperatures up to 130°C may occur for a short period after the shut down of the reactor. These boiling processes do not endanger the decay heat removal in the FRM-II, because of the moderate wall temperatures.

Another important part of the investigations was the determination of critical heat flux densities, i.e. minimum heat flux densities, which lead to dry out effects in the narrow cooling channel, at different flow conditions. The critical heat flux densities were detected by a very fast increase of the wall temperature. The controlling computer switched off the power supply of the test section if 170°C were exceeded at one thermocouple at the cooling channel wall. These experiments were performed at mixed convection as well as at the transition from forced to natural convection. At mixed convection a range of the downwards directed starting velocities between 0.3 m/s and 0.9 m/s was examined, whereby due to the high heat flux densities, that were considered during the tests, breakdowns of the downwards directed flow were observed in every case. After the breakdown of the flow boiling processes appeared generally before dry outs were observed. During one measurement a dry out occured spontaneously without previous boiling processes. Here the minimum critical heat flux density of 21.49 W/cm^2 appeared, which is still more than twice the value occuring at a complete loss of the active decay heat removal system in the FRM-II.

In the last test series, which has been finished in March 1999, critical heat flux densities at the transition from forced to natural convection have been determined. These critical heat flux densities have been found to be independent of the downwards directed starting velocity, because the earliest dry out appeared 54 s after the transition from forced to natural convection where the conditions in the test section are independent of the starting conditions.The lowest critical heat flux density occuring during the tests is 27.39 W/cm^2, which is about 28% higher than the value of mixed convection due to the undisturbed development of free convection. The maximum pressure amplitude recorded is 1.81 bar.

All results prove the possibilty to remove the decay heat of the FRM-II by natural convection, even in case of a complete loss of the active decay heat removal system. Above this, large safety margins concerning pressure pulsations, beginnig of boiling and dry out could be verified.

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