THEORETICAL ANALYSIS OF THE FLUID DYNAMIC LOADS ON THE FUEL ELEMENT OF THE RESEARCH REACTOR MUNICH II

H. SPRÜNKEN, J. ADAMEK, H. UNGER

Abstract

Considering a fluid flow in narrow cooling channels, the significant loads caused by the fluid flow can be divided into static and dynamic loads. The only significant static load is the pressure difference between adjacent channels due to different boundary conditions of the channels. In the fuel element of the new research reactor Munich II (FRM-II) the pressure difference is evoked by the variation of the channel width, as a result of manufacturing tolerances. For the determination of the pressure differences a computer code has been developed, which calculates the pressure in parallel channels, whereby the interaction between the plate deflection and the fluid flow can be considered (fluid structure interaction). The results of the computation show lower pressure values in narrow channels than in wider ones. In case of the consideration of fluid structure interaction the pressure differences are lower than in the case of a rigid structure.

The significant dynamic loads are caused by vortex shedding. The vortex shedding can appear at a deflected leading edge of a plate due to the flow separation, where the deflection bases on the pressure difference between the adjacent channels. Futhermore vortex shedding occur at the end of a plate (Kármán vortex street). If the frequency at which the vortices come off is close to the plates natural vibration frequency, resonance effects are possible. This resonance effects may endanger the fatigue strength of the plates, the surrounding structure and the connection between both. In opposite to the vortex shedding, the loads due to the turbulence of the flow inside the channels can be neglected.

A finite element analysis has been performed in order to determine the deformations of the leading edge of the FRM-II fuel element plates caused by a static load. Due to the annular spacers the plates are stabilized, so the pressure differences evoke merely small deformations of the leading edges. Futhermore the edges of the plates are chamfered, so that the flow separation can be excluded.

For the investigation of the vortex shedding at the ends of the FRM-II fuel element plates the vortex shedding frequency has been calculated using the Strouhal-Number, which depends on the flow velocity, and the natural frequencies of the fuel plates by means of a finite element analysis. Conformity of the frequencies exists at flow velocities, that occur between the normal operation of the reactor and the operation of the decay heat removal system. This result has been validated by vibration measurements during transient pump operation, which have been performed for the qualification of the FRM-II fuel element at the Ruhr-University Bochum. At the calculated velocities the measurements show a higher vibration level, which is still less than the vibration level at normal operation and therefore does not endanger the integrity of the FRM-II fuel element.

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THEORETICAL ANALYSIS OF THE HYDRAULIC LOADS ON THE FUEL ELEMENT OF THE RESEARCH REACTOR MUNICH II

H. SPRÜNKEN1), J. ADAMEK, H. UNGER

Abstract

Considering a fluid flow in narrow cooling channels, the significant loads caused by the fluid flow can be divided into static and dynamic loads. The only significant static load is the pressure difference between adjacent channels due to different boundary conditions of the channels. In the fuel element of the new research reactor Munich II (Forschungsreaktor München II, FRM-II), the pressure difference is evoked by the variation of the channel width, as a result of manufacturing tolerances. For the determination of the pressure differences, a computer code has been developed, which calculates the pressure in parallel channels, whereby the interaction between the plate deflection and the fluid flow (fluid-structure interaction) can be considered. The results of the computation show higher pressure values in narrow channels than in wider ones. In case of the consideration of fluid-structure interaction the pressure differences are lower than in the case of a rigid structure.

The significant dynamic loads are caused by vortex shedding, which can appear at a deflected leading edge of a plate due to the flow separation, where the deflection bases on the pressure difference between adjacent channels with different widths. Furthermore, vortex shedding occurs at the end of a plate (Kármán vortex street) also. If the frequency, at which the vortices come off, is close to the plates‘ natural vibration frequency, resonance effects are possible, which may challenge the fatigue strength of the plates, the surrounding structure and the connection between both. In comparison with the vortex shedding, the loads due to the turbulence of the flow inside the channels can be neglected.

A finite element analysis has been performed in order to determine the deformations of the leading edge of the FRM-II fuel element plates caused by a static load. The plates are stabilized by means of annular spacers, therefore the pressure differences evoke merely small deformations of the leading edges. Furthermore, the edges of the plates are chamfered, so that the flow separation at the leading plate edges can be excluded.

For the investigation of the vortex shedding at the ends of the FRM-II fuel element plates the vortex shedding frequency has been calculated using the Strouhal number, which depends on the flow velocity, and the eigenfrequencies of the fuel plates by means of a finite element analysis. Conformity of the frequencies exists at flow velocities, that occur between the normal operation of the reactor and the operation of the decay heat removal system. This result has been validated by vibration measurements during transient pump operation, which have been performed at the Ruhr-University Bochum. In the range of the conformity of the vortex shedding frequencies and the calculated plate eigenfrequencies, the measurements show a higher vibration level, which is still lower than the vibration level at normal operation and therefore does not endanger the integrity of the FRM-II fuel element.

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1 Introduction

At the Technical University of Munich (TUM), Germany, the research reactor Munich II (Forschungsreaktor München II, FRM-II) is being built. This efficient high flux neutron source provides a maximum neutron flux density of $8 \cdot 10^{14}$ n/(cm^2·s) at a thermal power of 20 MW. For this reactor a new compact core was designed, consisting of a single fuel element. Figure 1 shows a longitudinal and a cross section of the FRM-II fuel element, consisting of two concentric tubes between which 113 involutely bent fuel plates placed rotationally symmetric. Each plate has a thickness of 1.36 mm and a length of 720 mm. The plates are separated by cooling channels with a width of 2.2 mm. In order to reinforce the inlet and the outlet of the plate zone, at each end of the fuel plates an annular spacer is located.

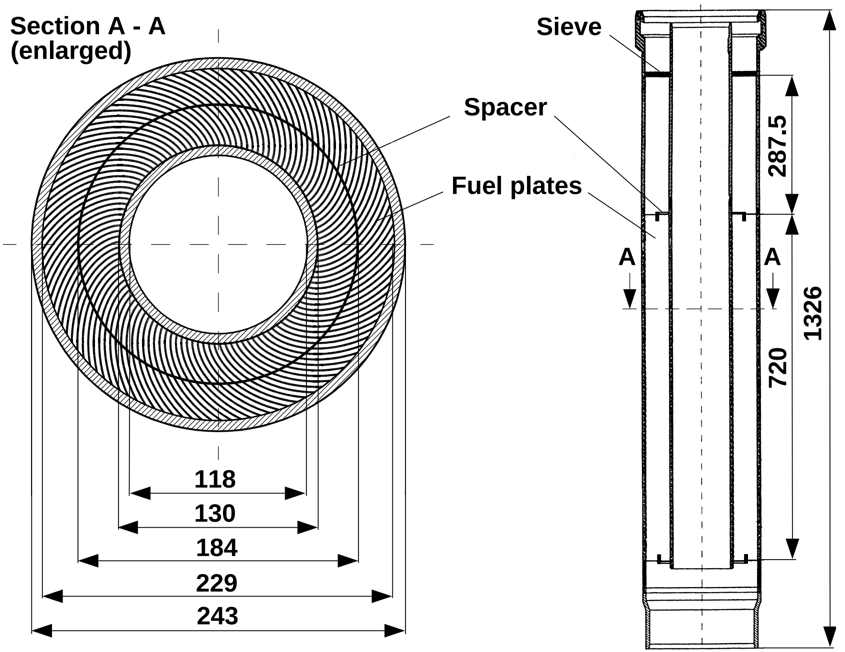

Fig. 1: Longitudinal and cross section of the FRM-II fuel element.

During normal reactor operation the thermal power is removed by a water mass flow of 300 kg/s, which flows downwards through the cooling channels of the fuel element. The velocity of the light water during this mode of operation is maximal 17.4 m/s. After a shut down of the reactor, the cooling pumps of the decay heat removal system are started, which provide a mass flow of 60 kg/s, reducing the velocity in the cooling channels to 3.2 m/s.

The experiments for the hydraulic and mechanical testing of the FRM-II fuel element have been performed at the Ruhr-University Bochum, at the Department for Nuclear and New Energy Systems [1, 2]. After finishing the tests, theoretical analyses are performed now, concerning the mechanical behaviour of the fuel element plates in the fluid flow, using the data base, which has been received by the experiments. The coolant flow causes different loads on the fuel element leading to deflections and vibrations of the plates. So the analysis of the stability and the long-term integrity of the fuel plates is of major importance with respect to the reactor safety.

2 Static Loads

2.1 Determination of the Significant Static Loads

The significant static loads are caused by pressure differences between adjacent channels. While Miller [3] developed an analytical criterion for the velocity endangering the plate stability due to large deformations, Swinson et al. [4] gave an empirical correlation for the static pressure difference load acting on the plates.

Miller [3] considered plates, which are homogeneous, isotropic, elastic and uniform in spacing and surrounded by an equal mass flow in every channel. Furthermore, Miller assumed a negligible modification of the cross-section area of the channels, what is in contrast to Miller‘s aim to determine the collapse velocity of a channel. The expression for the critical velocity v_{crit}, which bases on the integrated deflection curve of a plate and the Bernoulli Theorem, is

$$v_{crit} = \left(\frac{15\,E\,s^3\,h}{2\,\rho\,b^4\,(1-\nu^2)}\right)^{1/2} \tag{1}$$

for a flat plate, with the Young's modulus of elasticity E, the plate thickness s, the cooling channel height h, the fluid density ρ, the channel wideness b and Poisson's ratio of the material ν. But the collapse of a channel at the critical velocity could not be verified in several experiments [5, 6] concerning the stability of plates in a fluid flow; at fluid velocities reaching the critical velocity they merely showed the beginning of plate deformations. So Miller's critical velocity did not appear to be a suitable base for further analyses of the effect of static loads causing large plate deformations. Therefore an other criterion has been chosen.

Swinson et al. [4] correlated the fluid velocity with the static pressure difference load Δp acting on the plates. The investigations have been performed at just one prototype element of the former planed Advanced Neutron Source, from which merely two channels have been observed. This leads to a specific empirical relation, which is given by

$$\Delta p = 0,04\ \rho\ v^2 \left(\frac{\rho v\, h}{\eta}\right)^{0,177}, \qquad (2)$$

with the fluid density ρ, the fluid velocity v, the flow channel height h and the dynamic viscosity of the fluid η. The cause of the pressure differences is not explained in [4]. In [7] the measured pressure differences between adjacent channels in futher experiments [5, 6] were led back to imperfections of the channels, caused by manufacturing tolerances leading to small deviations from the nominal channel width. Due to the fact, that parallel connected flow paths have equal pressure loss [8], a pressure difference between adjacent channels can merely caused by different boundary conditions such as different channel widths. Equation 2 describes just the measured pressure difference between the two adjacent channels of the prototype fuel element and is therefore not transferable to further fuel elements or geometries.

The analysis of the literature leads to the conclusion, that merely the pressure differences due to different boundary conditions is the significant static load caused by the fluid flow.

2.2 Effect of the Static Load on the FRM-II Fuel Element

In case of the FRM-II fuel element, the pressure differences base mainly on the deviations from the nominal channel width of 2.2 mm. The tolerance for the local channel width deviation of the FRM-II fuel element is set to ± 0.3 mm, i.e. the channel width can vary by ± 13.6 %.

For the investigation of the effect of the pressure differences, a computer code has been developed to calculate the pressure distribution in narrow channels. It has following features:

- Calculation of the fluid velocities, pressures and temperatures by means of a mass and an energy balance considering the losses due to friction and the change of the geometry, especially at the inlet and the outlet of the plate zone.
- Consideration of the effects due to bypass flows in the fuel element and the flow division at the inlet of the plate zone.
- Implementation of a module for the calculation of the temperature and pressure depending thermohydraulic water properties, such as density, kinematic viscosity, internal energy and enthalpy.

The verification of the program has been performed by comparing the measured pressure distribution in the FRM-II fuel element with those calculated.

The measurements have been performed in the framework of the hydraulic and mechanical testing of the FRM-II fuel element at the Ruhr-University Bochum [1, 2]. Figure 2 shows the pressure measurement points at the FRM-II fuel element, which is positioned in the central channel pipe. Point 1 is above the element. Points 2 and 3 are used for the pressure drop caused by the sieve. Point 4 is above the plate zone, points 5 to 10 are in a channel of the plate zone, Point 11 is below the plate zone and Point 12 is located below the fuel element. Figure 3 shows the comparison of the measured and calculated pressure at the measurement points 4 to 11 in the FRM-II fuel element. The results concern the mass flows of the operation of the decay heat removal system (60 kg/s), the normal operation (300 kg/s) and an overload test with 350 kg/s. For the calculation, the mass flow, the pressure at the pressure measuring point number 4, the fluid temperature, the channel width and the roughness of the plates are given as boundary conditions. The good agreement of the results from the calculations and the measurements for different mass flows can be seen in Figure 3.

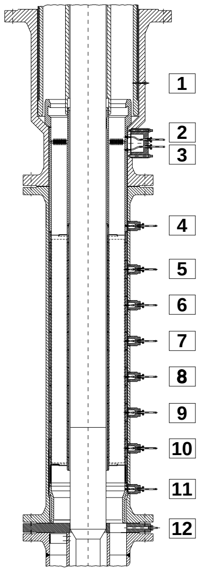

Fig. 2: Pressure measurement points in the FRM-II fuel element.

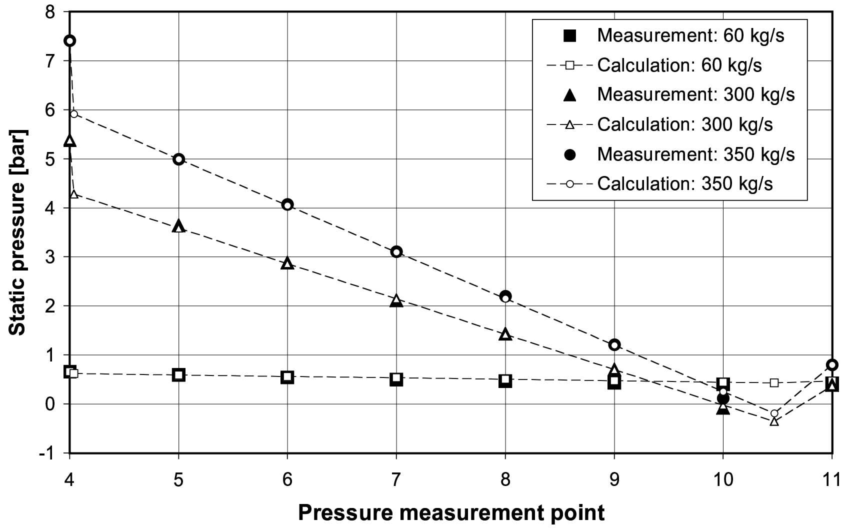

Fig. 3: Comparison of the measured and calculated static pressure at the measurement points 4 to 11 in the FRM-II fuel element for different mass flows.

For the further analyses the normal reactor conditions of the FRM-II are given for the calculations, i.e. a mass flow of 300 kg/s, an inflow water temperature of 35 °C and a thermal power transfered to the water of 18.8 MW. With these boundary conditions the pressure and the velocity in channels of different width have been computed. In Figure 4, the pressure distrubutions in a FRM-II cooling channel as a function of the channel length are depicted for the widths of 1.9 mm, 2.2 mm and 2.5 mm. The pressure in the narrowest channel is higher than in the other channels, whereby the largest differences between the pressures appear in the inlet zone of the channels. Furthermore, Figure 5 shows how the calculated pressure decreases and the velocity increases in the inlet zone of the plates as the channel width increases.

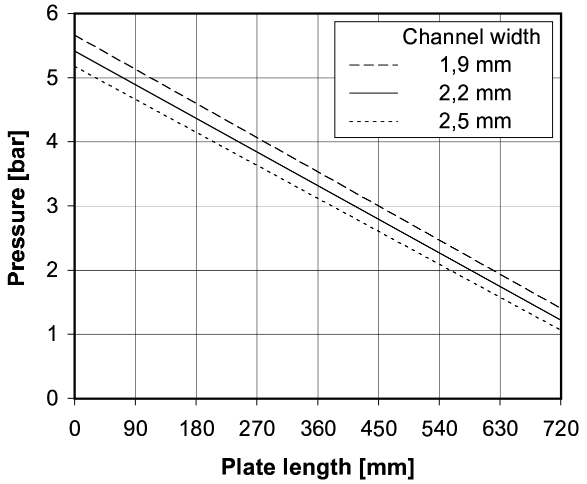

Fig. 4: Pressure in cooling channels for different widths as a function of the channel length (normal reactor conditions).

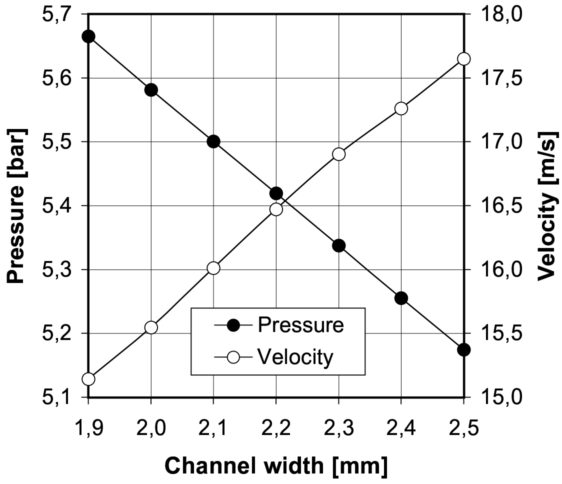

Fig. 5: Pressure and velocity in the inlet of the plate zone as a function of the channel width (normal reactor conditions).

As a result of the variation of the channel width, pressure differences occur between adjacent channels of different widths, which cause a deflection of the plate in between, accompanied by consequent channel width changes and modifications of the original pressure differences.

For the investigation of the influence of the interaction between the flow and the plates – the so-called fluid-structure interaction (FSI) – a module has been added to the program in order to analyse this effect. Concerning the fluid flow, the major consequence of the pressure load acting on the plate is the change of the channel cross-section area. The consideration of the fluid-structure interaction in the program has been realized by coupling the pressure load and the resulting change of the channel cross-section area. This correlation has been received by the evaluation of the pressure dependend plate deformations, which have been computed by means of a finite element analysis of the complete FRM-II fuel element.

Figure 6 shows the pressure difference caused by the channel width variation of two adjacent channels with and without consideration of the fluid-structure interaction. If the channel widths have the same value, the pressure difference is zero. Due to the influence of the fluid-structure interaction, the pressure difference between two adjacent channels is reduced, e.g. in the case of channel widths of 1.9 mm and 2.5 mm from 0.498 bar to 0.423 bar, corresponding to a decrease of the pressure load of about 15 %. The reduction of the pressure load leads to a decrease of the strain in the same order of magnitude. The maximum strain appears in the welding spots, which connect the plates with the inner and outer tube. The calculated maximum tension in the welding spots amounts to 55.6 N/mm^2 with and 65.5 N/mm^2 without considering the fluid-structure interaction, whereby both values are lower than the yield strength of aluminum, which has a value of 80 N/mm^2.

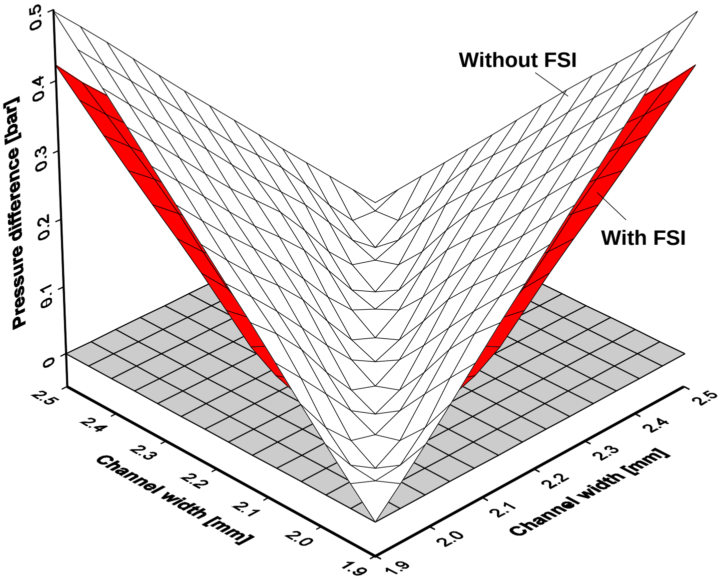

Fig. 6: Pressure difference caused by the channel width variations of two adjacent channels with and without consideration of the fluid-structure interaction (FSI).

3 Dynamic Loads

3.1 Determination of the Significant Dynamic Loads

The determination of the significant dynamic loads includes an experiment concerning the vibration of fuel plates and the hydroelastic stability analysis of a plate in a fluid flow.

Stromquist and Sisman [9] examined the vibration behaviour of fuel element plates for the High Flux Reactor in a fluid flow. The analysis of the vibration showed a relation between the fluid velocity and the measured vibration frequencies. The vibration excitation is caused by the vortex shedding with the frequency f at the end of the plates. The relation between the frequency f and the fluid velocity v can be expressed by the Strouhal number Sr, which is defined as:

$$Sr = \frac{f\, l_{ch}}{v} , \tag{3}$$

with the characteristic length l_{ch}, which is the thickness of the plates. The Strouhal number Sr resulting from the experiments amounts to 0.21. The phenomenon described is called Kármán vortex street and can be observed behind a body in a fluid flow. Figure 7 shows the Kármán vortex street behind a plate in a fluid flow, whereby the flow direction is from the left to the right [10].

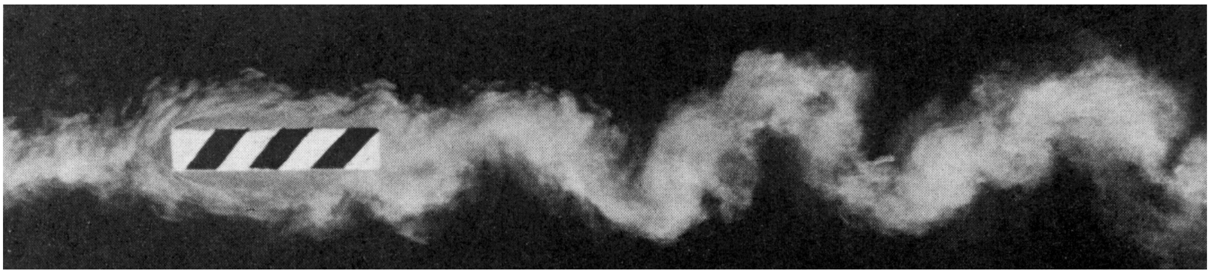

Fig. 7: Kármán vortex street behind a plate in a fluid flow (flow from left to right).

If the frequency at which the vortices come off is close to the plates natural vibration frequency, resonance effects are possible. These resonance effects may endanger the fatigue strength of the plates, the surrounding structure and the connection between both.

Smissaert [6, 7] investigated the plate stability experimentally and theoretically. In the experiments the vortex shedding frequencies were about 5 times higher than the plates natural vibration frequencies, whereby resonance effects could not be observed. The oscillation frequency of the plates was noticeably lower than the eigenfrequency of the plates.

In a further hydroelastic stability analysis, the fuel element plate zone and the leading edge of the plates were considered. The analysis of the plate zone showed, that the effect due to the turbulent fluid flow inside the channels can be neglected. From the examination of the leading edge of the plates it can be concluded, that vortex shedding can appear at a deflected leading edge of the plates caused by flow separation. Figure 8 shows an example for the vortex shedding caused by flow separation at the leading edge of an airfoil profile [11]. The deflection of the plates bases for instance on the static pressure difference between adjacent channels evoked by the variation of the channel width. So the consideration of the fluid-structure interaction is essential for the analysis of the vortex shedding at the leading edge of the fuel plates.

It can be stated, that the significant dynamic loads due to the fluid flow are caused by vortex shedding at the leading edge and at the end of the plates.

Fig. 8: Vortex shedding caused by flow separtion.

3.2 Effect of the Dynamic Load on the FRM-II Fuel Element

In order to investigate the vortex shedding at the leading edge of the fuel plates a finite element analysis has been performed. The finite element analysis considered the complete FRM-II fuel element including the 113 fuel plates and the annular spacer at the inlet and the outlet of the plate zone. The pressure difference caused by variation of the channel widths has been taken as the load for the plates with a value of 0.423 bar, being the result of the calculation of two adjacent channels with a width of 1.9 mm and 2.5 mm under consideration of the fluid-structure interaction. The computed deflections of the leading edge of the plate are shown in Figure 9. The largest deflection appears between the first and second welding spot at the side with the smaller radius of the involutely bent plate. The welding spots are located at the plate length of 24 mm and further on every 56 mm; at this positions no deflections occured. The influence of the spacer on the deflection of the leading edge can be seen, too. The deflection at the position of the spacer is nearly zero, whereas the maximum deflection of the leading edge obtains about 53 µm. The edges of the FRM-II fuel plates are chamfered, so that, considering the small deflections, the appearance of vortex shedding and consequently the vibration excitation is not to be expected at the leading edge of the FRM-II fuel element plates.

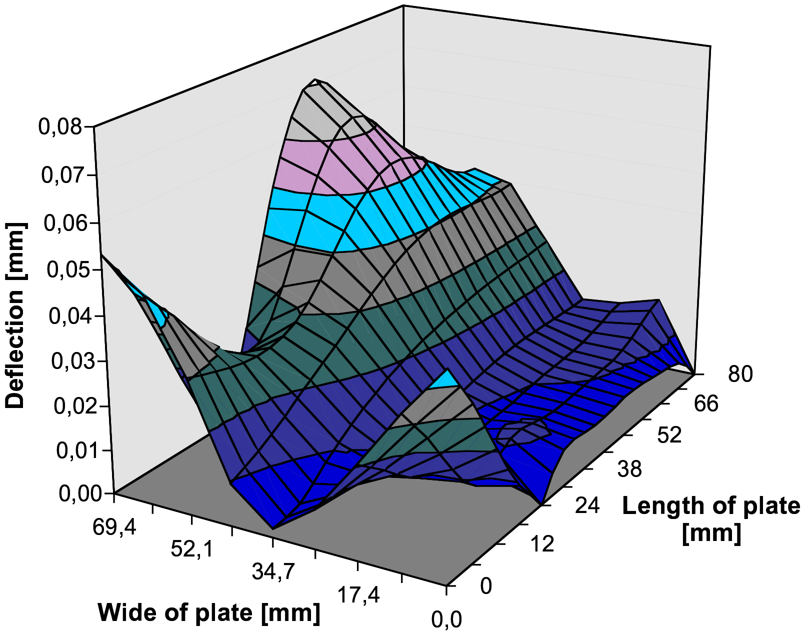

Fig. 9: **Deflection of the leading edge of the FRM-II fuel element plate caused by a pressure difference of 0.423 bar.**

The investigation of the vortex shedding at the end of the fuel plates is looked at in the following. The frequency at which the vortices come off is determined by Equation 3, with the Strouhal number $Sr = 0.21$ resulting from the experiments performed by Stromquist and Sisman [9]. The characteristic length l_{ch}, which corresponds to the plate thickness has got a value of 1.36 mm and the fluid velocity of normal operation of the reactor and the operation of the decay heat removal system of 16.5 m/s and 3.2 m/s, respectively. The calculated excitation frequencies are 2586 Hz for normal reactor operation and 494 Hz for operation of the decay heat removal system.

The eigenfrequencies of the plates have been determined by means of a finite element analysis. The complete FRM-II fuel element has been used for the calculations, whereby the water in the cooling channels, which damps the vibration, has been simulated by a fictitious density of the plates containing additionally the water mass of each channel. The first eigenfrequencies of the FRM-II fuel plates computed are 574 Hz, 775 Hz and 1018 Hz. These frequencies calculated have now to be compared with the measured ones. In Figure 10 the measured acceleration level of the FRM-II fuel element is depicted as a function of the frequency for the normal reactor operation and for the operation of the decay heat removal system. Neither the curve for the normal operation nor for the operation of the decay heat removal system show any peaks in the region of the eigenfrequencies. Merely the acceleration level rises slightly in the closeness of the frequencies at which the vortices come off.

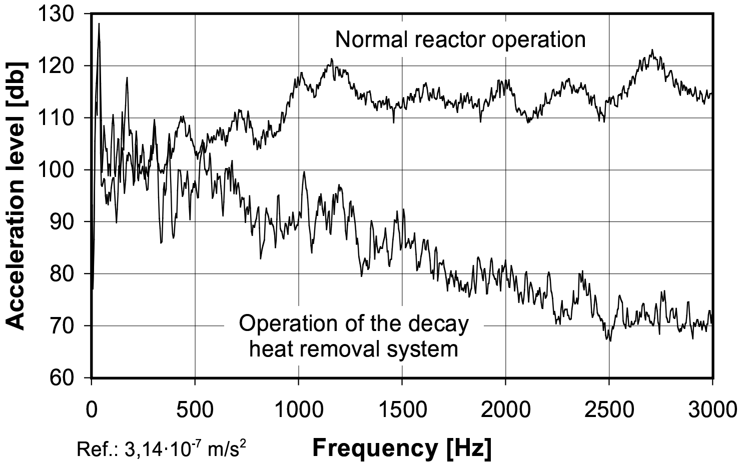

Fig. 10: **Acceleration level of the FRM-II fuel element as a function of the frequency for the normal reactor operation and the operation of the decay heat removal system.**

Furthermore, the transient operation is considered, i.e. the starting and the coast down of the pump. In Figure 11 the coast down of the pump is depicted, showing the time history of the acceleration and the volume flow. After the shut down of the pump, the volume flow and the acceleration decrease, whereas the acceleration level increases in the volume flow range of 120 l/s down to 80 l/s. Considering the frequencies and the acceleration level at different time steps in this volume flow range, significant peaks of the acceleration level could be observed, which are lead back to the vortex shedding at the end of the plates. The according frequencies at these peaks are 610 Hz, 784 Hz and 916 Hz, and correspond to velocities in the FRM-II cooling channel of 4.4 m/s, 5.3 m/s and 6.4 m/s, respectively. It has to be emphasized, that the measured acceleration in the range of 120 l/s down to 80 l/s is by a factor of 2 lower than the acceleration in case of normal operation of 300 l/s, therefore the vibration excitation of the plate‘s eigenfrequencies caused by vortex shedding has no relevancy for the stability and long-term integrity of the FRM-II fuel element.

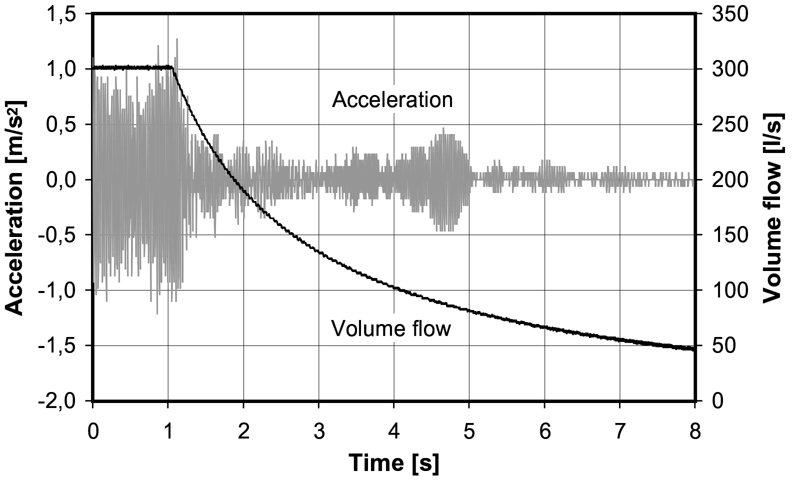

Fig. 11: Time history of the acceleration of the FRM-II fuel element and the volume flow for the coast down of the pump.

Figure 12 shows the summary of the analysis of the vortex shedding at the end of the fuel plates by depicting the frequency as a function of the flow velocity in the FRM-II cooling channels. The exciation frequencies due to the vortex shedding for Strouhal numbers of 0.17 to 0.21 are marked by a gray area. This range corresponds to the Strouhal numbers for plates [12]. The comparison of the calculated eigenfrequencies shows a good agreement with the measured frequencies at significant acceleration. These frequencies do not appear at a reactor operation flow velocity, but during the starting and coast down of the pump.

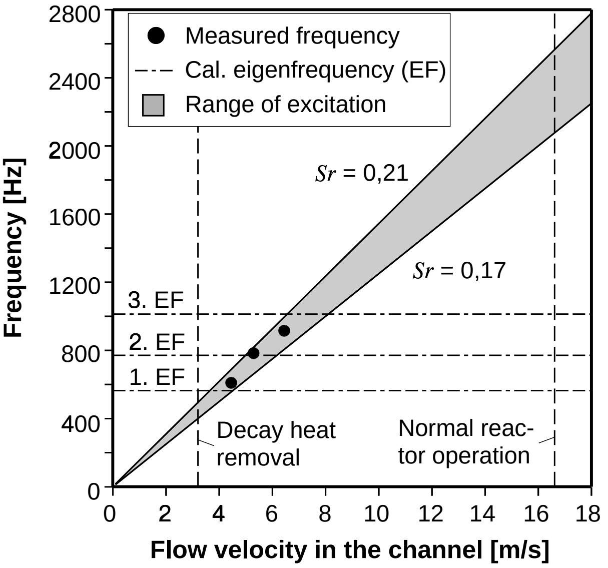

Fig. 12: Comparison of the calculated and measured eigenfrequencies of the FRM-II fuel plates and the excitation frequency range calculated with the Strouhal number Sr.

4 Conclusion

At the Ruhr-University Bochum analyses have been performed to examine the significant loads due to the water flow in the fuel element of the new research reactor Munich II (FRM-II). The significant static load is the pressure difference between adjacent channels caused by their width variation. The different channel widths are due to manufacturing tolerances, whereby the maximum allowed tolerance amounts to ± 0.3 mm of a nominal channel width of 2.2 mm. To perform the analysis of the influence of the significant load on the mechanical integrity, a computer code has been developed, considering the thermohydraulics of the fluid flow in narrow channels, the flow division, bypass flows and – optional – the fluid-structure interaction. The verification of the computer code has been performed by the comparison of calculated and measured pressures, which shows a good agreement. Concerning the channel width variation, the largest pressure difference between adjacent channel results in case of the smallest channel of 1.9 mm and the widest channel of 2.5 mm at the inlet of the plate zone. The calculated pressure differences are

0.498 bar without and 0.423 bar with the consideration of the fluid-structure interaction. In both cases the maximum tension is considerably below the yield strength of aluminium.

The significant dynamic load is caused by vortex shedding, on the one hand at the deflected leading edge of the fuel plates and on the other hand at the end of the plates. If the frequency, at which the vortices come off, is close to the plates natural vibration frequency, resonance effects are possible.

In order to investigate the leading edge of the plates, a finite element analysis has been performed by simulating the complete FRM-II fuel element. The deformations of the leading edge of the plate caused by a pressure load of 0.423 bar show merely small deflections, hence the flow separation due to the deflected edge can be excluded. The major reason for the small deflections is the annular spacer, which stabilizes the plates.

The eigenfrequencies of the FRM-II fuel element have been calculated by a finite element analysis in order to assess the influence of the vortex shedding at the end of the plates. Furthermore, the frequencies have been determined from vibration measurements, which show a higher level of the acceleration at destined fluid velocities. The comparison of the measured and calculated frequencies with the excitation frequencies caused by vortex shedding shows a good agreement. The effects of the conformity of excitation and eigenfrequency are negligible, because the acceleration level is less than the half of the level at normal reactor operation. Furthermore, the fluid velocity, at which the vortex shedding appears, is lower than the velocity of normal operation and higher than the velocity of operation of the decay removal system.

Therefore the investigated significant static and dynamic loads caused by the fluid flow do not endanger the integrity of the fuel plates or the fuel element of the FRM-II.

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