Thermoelastic Oscillations of FBR Fuel Pins

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1. SUMMARY, INTRODUCTION

In recent years, there has been growing concerns that the wear marks observed in a number of fast breeder subassemblies might have a thermoelastic origin. This paper attempts to clarify the underlying mechanism, as well as to find the governing parameters.

Two basic mechanisms are considered (Fig. 1), on a simplified geometry. The first one considers the feed back of the rod thermal bowing on the flow distribution. It is used to demonstrate that, in certain circumstances, limit cycle oscillations can occur. Non-dimensional parameters are extracted from the model, which correlate extremely well with observed marks in actual reactors. Also, it is demonstrated that the situation can be greatly improved with misaligned spacer grids.

The second model includes an additional mechanism, which accounts for the fact that oscillations have often been related to open gaps between the fuel and the cladding (at BOL, or during transients). Accordingly, it is assumed that thermal deformations not only feedback on the flow distribution, but also on the heat transfer properties between the fuel and the clad. With this model, violent oscillations can be generated during transients, which disappear when steady state conditions are recovered. A simple experiment is used to prove the plausibility of the reorganization mechanism.

Due to space constraints, most of the equations have been omitted in this paper, to concentrate on the physics. They are included in the full paper [1].

The models consist of a plane geometry involving a single rod (Fig. 2) separating two channels between which flow can be exchanged. The temperature is assumed uniform in each cross-section. The cladding heat capacity is neglected, and its temperature is equal to that of the coolant. The intermediate supports involve clearance. The linear power is assumed constant along the length of the rod. This model is believed to be the simplest for the purpose. A more elaborated 3-D version of model n°1, involving cladding heat capacity and non-uniform linear power, is presented in [2]. The main advantage of simple models like the present one is that they allow to extract non-dimensional parameters governing the phenomenon, and also to perform easily extensive parametric studies.
2. MODEL N°1

The first model considers only the feedback of the rod bowing on the thermohydraulic and assumes uniform heat transfer coefficients. This corresponds to closed gaps inside the rod. The governing PDE involve flow and energy conservation equations for each channel, and an energy equation for each part of the fuel. Using the length of the system, $L$, and the nominal residence time $\tau_0$ (travel time from the inlet to the outlet), the governing equations can be non-dimensionalized. Then, there appears a set of reduced parameters, amongst which the following have been found of particular interest in understanding the physics:

- $j/g$, the ratio of the clearance at the spacer grid to the size of the flow channel (Fig. 2). It measures the pin mobility.
- $\beta/n_a$, the axial temperature rise per active span. It is the driving mechanism.
- $\sigma = \frac{\alpha L^2}{gd}$ represents the sensitivity of the flow cross-section to the thermoelastic deformations of the pin ($\alpha = \text{thermal expansion coefficient}$).

Fig. 3 shows the diagram of $j/g$ vs. $\sigma \beta/n_a$ for actual PBR assemblies. It is striking to see that these parameters provide an extremely good separation between marked and unmarked subassemblies.

Extensive parametric studies have been conducted on various geometries. They reveal that when there is clearance at the supports, limit cycle oscillations do occur for certain conditions. During the oscillations, the rod deformations look like a wave propagating downstream. The amplitude never exceeds the clearance at the supports. The period is always between once and twice the residence time, $\tau_0$. Note that this latter observation agrees with experimental evidence in KKN-II.

3. INSTABILITY ALLEVIATION

We have investigated the effect of using misaligned supports, as shown in Fig. 4. The results indicate a considerable improvement. In all cases investigated, the instability has been removed by using an eccentricity equal to the clearance (Fig. 4b).

4. MODEL N°2

The foregoing model does not include the possibility of a non-uniform heat transfer between the pellets and the cladding. It cannot account for all the experimental evidence which, in many cases, tends to relate the oscillations to the opening of the gap between the clad and the pellets (at BOL, or during transients). Model n°2 is based on the following concepts:

a. When the gap is open, the fuel column takes, inside the clad, a more or less helical shape, which corresponds to a configuration of minimum energy.

b. The shape of the column, relative to the clad, depends on the bowing shape of the rod. In other words, the warping of the rod is accompanied by a reorganization of the fuel column inside the clad. This mechanism has been confirmed by a simple experiment on a plexiglass tube (see paragraph 5).

c. The heat transfer properties between the fuel and the clad depend on the local distribution of the gap.

The details of the model are given in [1].
The foregoing mechanism introduces an additional feedback in Fig. 1, between the rod deformations and the heat transfer properties. With this model, we have been able to reproduce oscillations very similar to those observed during the transient experiments CARNI. On the contrary to the previous model, limit cycle oscillations can be generated even without clearance at the supports. They disappear when steady state conditions are recovered.

As an example, Fig. 5 corresponds to a transient in which the flow rate is suddenly reduced to 80% of its nominal value. The upper part of the figure shows the output temperature of the two channels, the middle part displays the heat transfer properties at 3/4 of the length, while the bottom part shows the transverse displacement at the same location. After the flow has been reduced, the gap opens itself and any inlet perturbation induces a difference between the heat transfer properties of the two sides; the rod starts to oscillate. Later, when the rod reaches its new thermal equilibrium, the gap vanishes and the heat transfer coefficients recover their nominal value. The oscillations disappear. There is a small steady state thermal deformation, due to the input perturbation. As expected, the 20% drop in the flow rate leads to a temperature rise of 25% at the output.

5. EXPERIMENT ON THE REORGANIZATION MECHANISM

This experiment is aimed at checking that, when the gap is open, the warping of the rod is followed by a reorganization of the fuel column inside the clad. The experimental set up is sketched in Fig. 6. It consists of a 2 m long plexiglass tube of internal diameter 12 mm, filled with silver pellets of diameter 9 mm and height 10 mm. The large value of the gap allows a visual observation of the experiment. The pellets are loaded with a spring via a ball. The tube can rotate freely in supports which are misaligned by an amount of a few millimeters, to simulate thermal bowing. The supporting structure is subjected to high frequency, low amplitude vibrations, to relax friction during the experiment (as would be the case in an actual reactor environment).

The observations are as follows:

(1) When the preload of the spring increases, the column buckles and takes on a more or less helical shape.
(1) When the bowed plexiglass tube is rotated (manually) about its vertical axis, the helical column remains fixed in an absolute co-ordinate system (as seen by an observer in the lab), as the bowing shape does.

This demonstrates that there is a definite equilibrium pattern which depends on the bowed shape of the tube. More on this is given in [1].

REFERENCES

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Figure 1: Block diagrams of the basic mechanisms

Figure 2: System geometry
Figure 3 : Mobility vs. driving mechanism diagram for actual FBR subassemblies.

Figure 4 :  a. Nominal support configuration
b. Alternating one way supports
Figure 5: Behaviour during transient with non-uniform heat transfer properties
(N = 3, \( \lambda = 0.2 \), \( \beta = 100 \), \( \sigma = 0.5 \), one grid without clearance)

Figure 6: Experiment on the reorganization mechanism
Experimental set up.