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Experimental Investigation of Flow-Induced Vibration in a Parallel Plate Reactor Fuel Assembly.

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Abstract

This research aims to experimentally investigate the critical flow velocity of light-water coolant in a reactor parallel-plate fuel-assembly. The critical flow velocity is the speed at which rectangular fuel-plates will buckle and collapse onto each other as a result of flow-induced vibration and consequent asymmetric pressure distribution. Although fuel plates do not rupture during plate collapse, the excessive permanent lateral deflection (buckling) of a plate can cause flow blockage in the reactor core, which may lead to over-heating. This is an important consideration in reactor core designs with parallel plate fuel assemblies. The Replacement Research Reactor (RRR) currently under construction at the Australian Science and Technology Organisation (ANSTO) is of such a design.

A simple physical model of a parallel-plate fuel-assembly composed of two parallel plates was constructed and tested in a closed-loop water tunnel (figure 1). Plate vibration was measured at low flow speeds and the critical flow velocity was recorded. Test results show plate collapse occurring, in 25°C light water, at an average flow velocity range of 11.9 - 12.0m/s. For the first time, cavitation was observed as a result of leading-edge deformation during plate collapse. The experimental results attained support Miller's [4] critical-velocity calculation for plate collapse. However, it must be stressed that the flow characteristics of the RRR are significantly different to the results reported here due to the presence of a lateral-support comb at the RRR fuel assembly inlet. This comb greatly reduces any vibrations and increases the critical velocity for the fuel assembly.

Introduction

Plate collapse phenomenon was first observed in the Engineering Test Reactor (ETR) in the 1950s. It was noted that some fuel-plates gave warning before buckling by a slight bending or warping. Later, Miller [4] used wide-beam theory to equate the pressure differences between coolant channels with the elastic restoring force of the plate to estimate the critical-velocity (U_d) at which plates collapsed. Plate collapse is a *static-instability* type-failure occurring at a moderate velocity, identified by Kim and Davis [3] as the "critical static divergent velocity U_d". Static-instability type failure is not to be confused with the high velocity *dynamic instability* experienced at the "critical resonance velocity U_r" when flow excitation frequency coincides with the in-fluid natural frequency of the fuel plate.

Notable experimental investigations were undertaken by Groninger and Kane [2], Scavuzzo [5] and Smisseart [6] to verify Miller's critical flow velocity (critical static divergent velocity). The experiments gave mixed findings, including: (1) Plates deflecting slightly below Miller's critical-velocity and (2) an absence of Miller's predicted sudden plate collapse at or beyond the 'critical-velocity' mark. What was shown though was a gradual movement of the plates from their mean position with each incremental increase in velocity. Thus plate collapse is actually the moment at which the plates touch after a gradual movement of plates. Also, Smisseart showed that plate collapse produced alternately open and closed conduits, with plates collapsing in opposite directions.

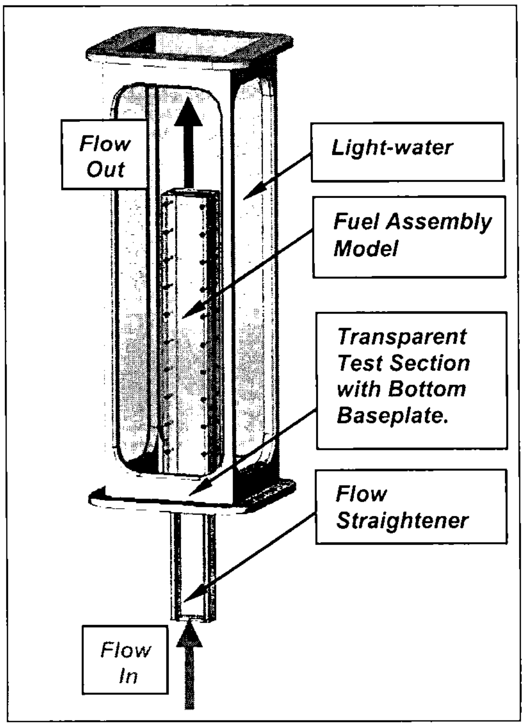

Figure 1 – Isometric view of fuel-assembly-model inside the test section.

Failure mechanism in parallel plate fuel assemblies.

The main interest of this research is the observation and recording of the plate collapse phenomenon as this data can be used to appraise the oft-quoted Miller's critical velocity, common in critical static-divergent velocity calculations.

Most reactor cores have less than ideal flow conditions, characterised by turbulence, imperfect axial-flow and pressure fluctuations produced by pump and other plant equipment. As such, equal flow through each channel of a parallel plate fuel assembly cannot be assumed. Miller, one of the pioneers of flat-plate fuel stability research described fuel collapse as due to the difference in velocities of adjacent channels. This difference produces a pressure difference on either sides of a plate. When the net pressure on the plate is too large for the plate to resist, the plate buckles and deforms.

Fuel plate collapse originates from plate vibration. As flow passes through a narrowing channel, the pressure head is converted to a velocity head and creates a suction force on the wall. Should the wall be moveable as is the case for parallel fuel plates, the channel cross section can decrease to obstruct the flow. Flow obstruction increases local pressure as flow from the inlet tries to overcome the constriction. Thus pushing apart the fuel plates and increasing the channel cross section. This pushing and pulling action acts periodically, vibrating the structure which can lead to large plate deflections and localised overheating. ANSTO [1]

The theoretical collapse velocity

Miller [4] derived a theoretical expression to predict the critical flow velocity (**U_d**) at which long parallel-plate assemblies collapse. This expression is a function of the plate, channel and fluid characteristics, as shown below:

$$U_d = \left[\frac{15 \cdot E \cdot t_p^{\ 3} \cdot t_w}{\rho \cdot W^4 (1 - v^2)} \right]^{0.5} \tag{1}$$

Where:
U_d = Miller's critical velocity (m/s)
E = plate Elastic Modulus (kPa)
t_p = plate thickness (mm)
t_w = coolant channel thickness (mm)
ρ = coolant density (kg/m^3)
W = coolant channel width (mm)
v = plate's Poisson's ratio

Physical properties of parallel-plate fuel-assembly model	
Elastic Modulus of Aluminium	70.0 x 10^6 kPa
Plate thickness	1.2mm
Poisson's ratio of Aluminium plate	0.33
Channel Width	78.2mm
Channel Height	4.3mm
Coolant (H_2O) density	998.2 kg/m^3 (at 25°C)
Calculated Miller's Collapse Velocity	15.4 m/s

Table 1. Calculated Miller's critical velocity for this parallel-plate fuel-assembly.

Although Miller's theoretical collapse velocity is a basic representation of a complicated system and is known to be outmoded when compared with CFD and FEA techniques, it remains a widely used theory because of its ease in giving an approximate velocity at which plate collapse will occur. However, to allow for uncertainties, reactor designers usually place a large margin between Miller's critical-velocity and the designed operational coolant velocity. The need to impose a margin of safety was shown in an analytical investigation conducted by Kim and Davis [3], which showed plate collapse occurring below Miller's collapse-velocity, at $0.9U_m$ in the absence of a steadying-comb.

ANSTO Water Tunnel facility

The water tunnel facility used in our experiments is located at ANSTO, Lucas Heights Research Laboratories in Sydney. The water tunnel is one of only a few test facilities in Australia capable of delivering the power necessary to investigate plate collapse phenomenon. The water tunnel is a closed loop flow rig used for flow visualisation, velocity measurement and pressure loss characteristics testing of hydraulic fittings. The transparent test section is vertical, with internal measurements 0.3m x 0.3m x 1.3m. Water capacity of the rig is approximately 3000L, which is circulated by a double suction pump driven by a 75 kW AC motor and variable speed controller. The motor and pump can achieve a flow of 230 L/s with no flow impediment inside the water tunnel or a maximum head pressure of 350kPa if the exit of the pump were to be blocked.

Fuel assembly model

This physical fuel-assembly model was designed to simulate a generic light-water cooled parallel-plate fuel assembly. The model is comprised of two identical Aluminium plates dividing a single rectangular conduit into three identical channels. The plates are rigidly clamped along the two long sides, with the two shorter sides free and have a dimension of 780mm x 78mm x 1.2mm. As shown in Figure 2, the fuel-assembly-model is a sandwich structure of 40mm thick Perspex plates, 4.3mm thick Perspex lengths and 1.2mm thick Aluminium plates. The whole structure is clamped together by nuts and threaded rod equally spaced along the long edges of the model. Also, the mock fuel-assembly is mounted vertically in the water tunnel and is preceded by a plain rectangular duct mounted flush to the model.

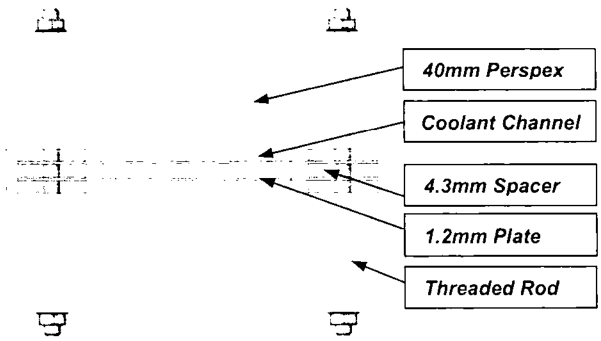

Figure 2 – Top view of the flat plate fuel-assembly-model, dimensions are in millimetres.

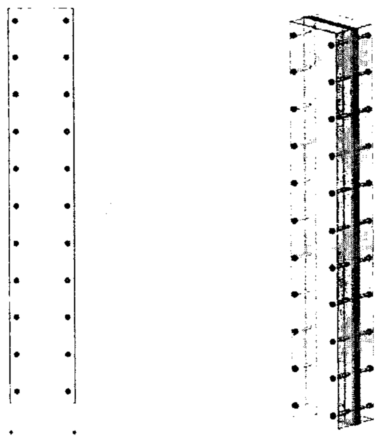

Figure 3 – Front and isometric view of the flat plate fuel-assembly-model, dimensions are in millimetres.

Most flat-plate fuel assemblies are equipped with a stabilisation comb at the plate's leading edged. This comb, mounted at the mid point of the leading edge, helps to stabilise the fuel plate against flow induced vibration mechanisms such as turbulence, vortex shedding and fluidelastic instability. For a conservative test of Miller's Critical Collapse Velocity, there was no reason to install a stabilisation comb and none was installed in this model.

As shown in figure 1, light-water at 25°C enters the flow straightener and passes into the fuel-assembly-model. A base plate at the bottom of the test section prevents any flow bypass. Thus, all flow through the closed-loop facilty must enter the fuel-assembly-model. Having passed between the plates, the flow exits the top of the fuel-assembly-model and travels through a flowmeter further downstream. Consequently, the flowmeter is able to measure the aggregate flow through the model.

Instrumentation

In the fuel-assembly model, one of the two plates is instrumented with strain gauges at three positions: the leading edge, the middle of the plate and the trailing edge. At each position two strain gauges on either side of the plate detect vibration and deflection at different flow speeds. Strain gauges serve as the primary method for plate-deflection detection because they are in direct contact with the plate. The strain gauges were epoxied into a 0.4mm ditch milled into the plate and sealed by Araldite. The analogue voltage signal produced by the strain-gauges is directly proportional to the deformation on the plate.

Figure 4 – Close-up photograph of strain gauge embedded inside an Aluminium plate and pressure tapings drilled into the side of the 40mm Perspex plate.

Data Acquisition Equipment	
Strain Gauge	Copper-Nickel alloy measuring-grid ; Measurable Strain: 2–4% max.
Strain Gauge Amplifier	RS Components No. 846-171
Data Acquisition Card	Fast Card : LabView No. NI6071E ; PCI Bus ; 1.25x10^6 Samples/Sec; Slow Card : LabView No. NI6033E ; PCI Bus ; 100x10^3 Samples/Sec
Data Acquisition Software	LabView 6.1
Data Acquisition Hardware	IBM Personal Computer, WinNT Operating System.

Table 2 : List of Equipment for plate vibration and deflection monitoring.

In addition, the mock fuel-assembly is equipped to measure static pressure at 100mm intervals along the axis of the plate. Measuring pressure drop serves as a secondary method in detecting plate collapse, as the flow-loss characteristics of the fuel assembly-model changes once the plate has deformed. Pressure loss data can also be collected and used to verify CFD simulations in the future.

As mentioned previously, aggregate flow through the fuel-assembly model is measured by an electromagnetic flowmeter mounted in the water tunnel. To validate the correct physicality of our experiment, it is necessary to check that equal flow is observed through each of the three channels before plate collapse. This was done by using Laser Doppler Velocimetry (LDV) to sample the maximum flow-velocity exiting each channel.

Vibration tests

Tests were conducted in air and quiescent water to ascertain the dynamic characteristics of this model fuel plate. To measure the in-air fundamental vibration of the Aluminium plate, stain gauges and accelerometers were used. The plucking method was used to find the in-air fundamental frequency of the model fuel plate. Examination of the accelerometer and strain gauge results show a close agreement between the two measurements, with the accelerometer measuring a fundamental frequency of 684 Hz and the strain gauge measuring a fundamental frequency of 685Hz.

Satisfied with our in-air plucking test, the strain gauge and accelerometer can be confidently used to examine the in-water response of the model-fuel-plates. The fuel-assembly-model was placed horizontally and covered with water. A set of strain gauge and accelerometers were fixed on the same location on the plate and the plucking method was used to obtain the plate's dynamic response. Examination of the accelerometer and strain gauge results for the quiescent water test shows near-identical results. The model fuel plate in quiescent water has a fundamental frequency of 100Hz, a first harmonic at 225Hz and second harmonic at 430Hz.

Vibration monitoring of fluid-elastic instability.

Following the in-air and in-water plucking test, the fuel-assembly-model was flow tested in the water tunnel. Before a model fuel plates was tested to destruction, it was vibration tested from 0 m/s to 8 m/s at 1m/s intervals to observe fluid-elastic instability effects. Monitoring was performed via the use of a LabView data acquisition card & software. The analogue voltage signal was passed through a low-pass filter, recorded then processed using Fast Fourier Transform (FFT) method. Results were averaged over 50 samples to reduce the effects of white noise.

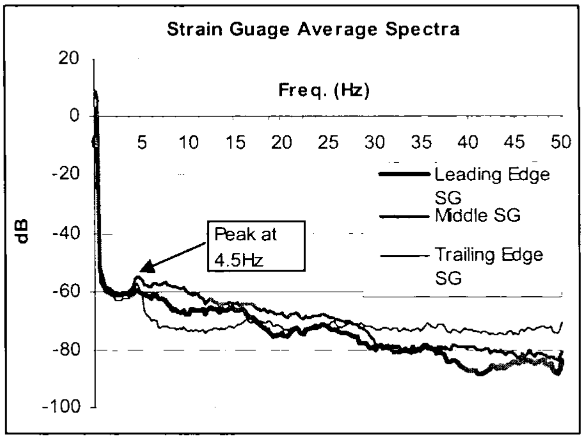

Figure 5 – Average spectra of strain gauges with flow velocity at 6.0m/s (Re 48,360). Results show a distinct peak at 4.5Hz.

Results attained agree with the push-pull fluid-elastic effect described in The Preliminary Safety Analysis Report prepared by ANSTO [1]. The vibration is low in frequency and appears to remain constant at 4.5Hz in turbulent flow. Also, the graphs show that the amplitude of the vibration increases with flow velocity, which supports the notion that an increase in flow speed is accompanied by increasing plate exacerbation until plate collapse is brought about.

Plate collapse flow tests.

To detect the plate collapse phenomenon, the model was gradually subjected to higher flows at average-velocity increments of 0.5m/s until plate collapse occurred.

Plate collapse was observed in a variety of ways. The most accurate method was by recording the voltage output of the strain gauge at the leading edge of the plate where plate collapse was most severe. As the plate catastrophically buckled out, the voltage would change sharply as the resistance changed in the strain gauge - until it was out of the ±5V range of the data acquisition card.

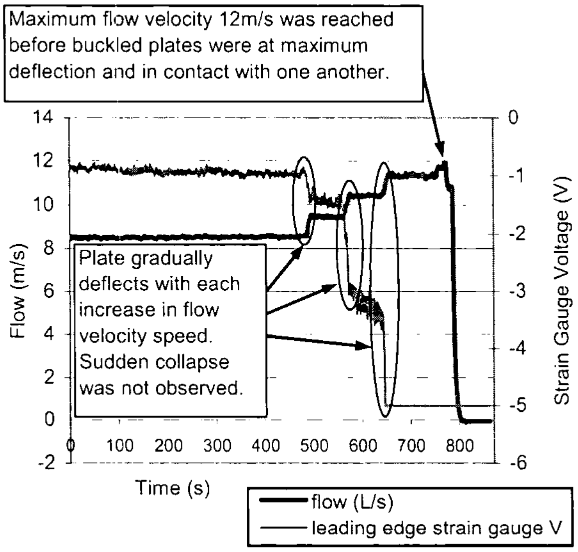

Fig. 6 Flow velocity and pump head pressure versus time.

As shown in figure 6, the leading edge of the plate experienced a gradual buckling outwards as observed by Smissaert [6]. A maximum flow velocity of 12m/s (Re 108,716) was reached before the plates buckled far enough to be in contact with one another and thus achieving "plate collapse".

An indirect method of observing plate collapse was by recording the aggregate flow speed through the fuel-assembly model as plate collapse occurred. With the pump delivering a steady pressure, the aggregate flow speed through the fuel-assembly model dropped by approximately 1m/s after the plates collapsed as shown in figure 7. This drop in flow speed was due to the increased flow resistance of the plates as it flexed out into the path of the flow (figure 8). Also, as a consequence of plate collapse, cavitation bubbles in the form of a fine mist were observed departing the coolant channel exit.

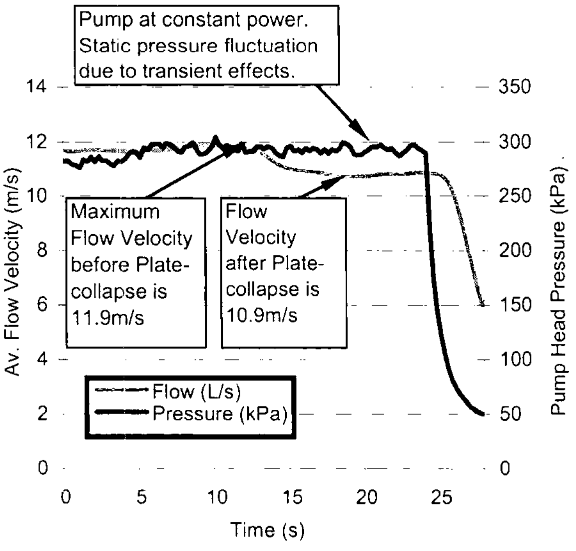

Fig. 7 Flow velocity and pump head pressure versus time.

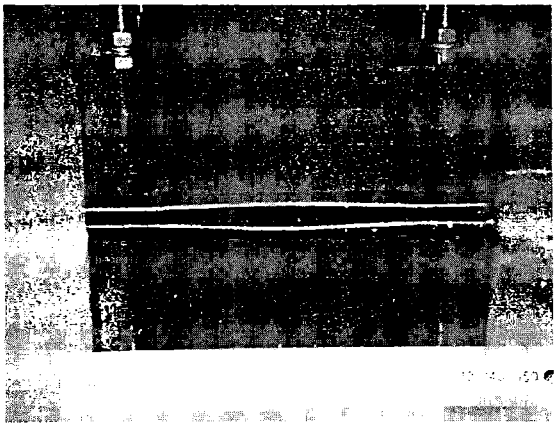

Figure 8 – Post-failure end view of the flat plate fuel-assembly-model. Note: both plates' leading edges have buckled and plastically deformed away from each other.

Conclusion

Preliminary results show plate collapse occurring at an average flow velocity between 11.9m/s to 12m/s in 25°C light-water, which is 78% of Miller's critical velocity. It is lower than the collapse velocities reported in past experiments conducted with light-water at 50°C. The shape of the plate collapse seems random, either with both plates collapsing onto each other or with both plates collapsing away from each other. In the case of the plates collapsing away from each other, cavitation was observed. The results attained in the experiment compare well with the calculated Miller's [4] Critical-velocity of 15.4m/s, keeping in mind that analytical analysis by Kim and Davis [3] predicts plate collapse at $0.9U_d$. As such, this experimental undertaking has shown the relevance and usefulness of Miller's Critical Velocity for the safe design of flat plate type research reactors.

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References

[1] ANSTO, Summary of the Preliminary Safety Analysis Report (PSAR) for the ANSTO Replacement Research Reactor Facility, **1** and **2**, Sydney, ANSTO, 2002.

[2] Groninger, R. D. and Kane, J. J., Flow Induced Deflections of Parallel Flat Plates, *Nuclear Science and Engineering*, **16**, 1963, 218-226.

[3] Kim, G. and Davis, D. C., Hydraulic Instabilities in Flat-Plate-Type Fuel Assemblies, *Nuclear Science and Engineering*, **158**, 1995, 1-17.

[4] Miller, D. R., Critical Flow Velocities for Collapse of Reactor Parallel-Plate Fuel Assemblies, *Journal of Engineering for Power*, **April**, 1960, 83-95.

[5] Scavuzzo, R. J., Hydraulic Instability of Flat Parallel-Plate Assemblies, *Nuclear Science and Engineering*, **21**, 1965, 463-472.

[6] Smissaert, G. E., Static and Dynamic Hydro-elastic Instabilities in MTR-Type Fuel Elements Part I. Introduction and Experimental Investigation, *Nuclear Engineering and Design*, **7**, 1968, 535-546.