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Critical Velocity Experimental Assessment in Flat Plate Fuel Element for Nuclear Research Reactor

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ABSTRACT

Aluminum-coated plates, containing a uranium silicide (U3Si2) meat dispersed in an aluminum matrix, are commonly used in the fuel elements of Material Testing Reactors (MTRs). These fuel elements are typically comprised of narrow channels formed by parallel flat plates, which allow coolant flow to remove the heat of fission reactions. It is important to mention that the thickness of the plates is much smaller than their width and height. The high flow rates needed to ensure efficient fuel-element cooling may cause fuel-plate mechanical failures due to instability induced by the flow in the channels. In the case of critical velocity, excessive permanent deflections of these plates can cause blockage of the flow channels and lead to overheating. An experimental facility that simulates a plate-like fuel element with three coolant channels was developed for this work. The test-section dimensions were based on the Fuel Element design of the Brazilian Multipurpose Reactor (RMB), project being coordinated by the National Commission of Nuclear Energy (CNEN). Experiments were performed to reach Miller's critical velocity condition. This critical condition was reached at 14.5 m/s leading to consequent plastic deformation of the fuel plates.

Keywords: **critical velocity, plate fuel element, channel blockage, nuclear reactor.**

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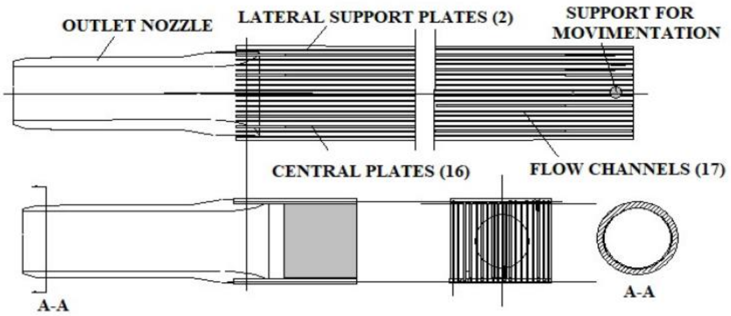
1. INTRODUCTION

Aluminum-coated plates, containing a uranium silicide (U_3Si_2) meat dispersed in an aluminum matrix, are used in the fuel elements of Material Testing Reactors (MTRs). Figure 1 [1,2] shows a typical fuel assembly where the flat plates are in parallel forming very narrow channels between them through which the coolant flows to remove the heat generated by the fission reactions. A specific characteristic of these plates is that their thickness is much smaller than their width and height.

Mechanical failure of these plates may occur due to instability induced by the high flows needed to ensure their cooling. A significant loss of coolant accident may be caused by the reduction of the coolant flow channel as a consequence of this mechanical instability. Even more, the reactor's core flow conditions are not ideal, and some distortions arise from factors such as plate roughness, manufacturing tolerances, turbulence, non-uniform axial flow and pressure fluctuations produced by the main pump or other process equipment. Therefore, there is not a uniform distribution of coolant flow through each fuel element channel.

Figure 1: *Schematic representation of a flat-plate-type fuel element.*



Source: [2]

According to MILLER [3], a pioneer study on this research topic, the fuel plates collapse originates from pressure difference between adjacent plates caused by non-uniform flow distribution. As a result, large deflections and even plastic deformation may occur in the plates.

The collapse phenomenon of nuclear research reactor fuel plates was first observed in the engineering test reactor (ETR-DOE / USA-Idaho-USA) in the 1950's. Some plates showed signs of buckling failure through verification of small torsional deformations. Later, MILLER [3] used plate theory to equate the pressure difference between the cooling channels with the resilient recovery force of the plate to estimate the critical velocity (U_d) (also called as Miller critical velocity) at which the plates collapsed. Equation (1) is a function of the plate, channel and fluid characteristics as shown below:

$$U_d = [\frac{15.E.t_p.t_w}{\rho.W^4(1-\nu^2)}]^{0.5} \tag{1}$$

where:

U_d = Miller critical velocity (m/s)
E = plate modulus of elasticity (kPa)
t_p = plate thickness (mm).
t_w = coolant channel thickness (mm)
ρ = coolant density (kg/m^3)
W = coolant channel width (mm)
ν= Poisson coefficient for the plate.

A suction force on the plates is created as the fluid flows in the narrow channels in a process of pressure energy conversion into (kinetic) velocity energy. Thus, the parallel flat plates can deflect in opposite directions reducing the channels' cross sections and obstructing the flow, CASTRO and ANDRADE [2] and CASTRO [4]. When the fluid tries to overcome the constriction, the flow obstruction increases the local pressure. Therefore, structural instability might be built when the fuel plate is pushed to widen the channel cross section by the fluid flow. This fluid-structure interaction could lead to large plate deflections and consequent localized overheating.

The critical velocity is attained when the instability threshold is reached as a result of the flow-induced deflections and asymmetric distribution of pressures over the flat plates. Although, generally there is no plastic deformation or rupture of the fuel plates, the flow channels cross sections reduction certainly decreases the reactor core cooling efficiency leading to plates overheating.

Important investigations were carried out by GRONINGER and KANE [5], SCAVUZZO [6], and SMISSAERT [7], to verify Miller’s critical velocity. In these experiments, some non-coherent results appeared: (a) deflection of the plates at velocities slightly lower than Miller's critical velocity, and (b) absence of the sudden plate collapse predicted by Miller at or close to the critical velocity. These experiments showed a gradual movement of the plates in relation to their central position at each increment of the velocity. SMISSAERT [7] considered the collapse of the plates as a fluid-elastic instability by alternately producing opening and closing of the coolant channels with the plates collapsing in opposite directions. HO et al. [8] also observed this opening and closing of the channels between the plates through strain gauge signals in an experimental facility built to examine critical velocity of the Replacement Research Reactor (RRR) designed by the Australian Nuclear Science and Technology Organisation (ANSTO).

Although Miller’s critical velocity is a basic theoretical representation of a rather complicated phenomenology, it is widely used because of its simplicity to provide an approximate velocity at which plate collapse might occur. Due to uncertainties, designers use a good margin of safety between Miller’s velocity values and average coolant velocity inside channels. According to IAEA [9], the maximum average velocity of the coolant in the channels should be 2/3 U_d.

KIM and DAVIS [10] showed the need to impose a safety margin in their analytical investigations, which exposed the occurrence of plate collapse below Miller's critical velocity, 0.9 U_d.

The Brazilian Multipurpose Reactor (RMB) uses a core composed of fuel elements with flat plates and rectangular cross sections, [11,12]. OLIVEIRA and MATTAR NETO [13] presented a first calculation of the critical velocity in RMB fuel elements. Using core design data and Miller’s expression, a critical velocity of $U_d = 16.8$ m/s was estimated. In this same paper, they also used a modified Miller’s expression that takes into account the composite material of the fuel plates and the coating thickness (t_c), in accordance with IAEA [9]. Based on this modified expression, the estimated critical velocity was $U_{d*} = 16.0$ m/s.

JENSEN and MARCUM [14] carried out research to develop a model for critical velocity calculation on fuel plates of uranium molybdenum (U-Mo) alloy dispersed in an aluminum matrix coated with laminated aluminum, in a sandwich-like structure. They successfully developed this model by inserting a flexural stiffness term in Miller’s critical velocity formulation, where this term was determined using sandwich structure theory. The methods presented by Jensen allow simple calculations to predict the flow velocity or dynamic pressure that can cause plate collapse. The simplicity of these methods allows designers to have a very useful tool to complement other forms of analysis. It is important to notice that the JENSEN and MARCUM [14] formulation is applicable only to a sandwich-like structure as those of fuel plates of uranium molybdenum (U-Mo) alloy dispersed in an aluminum matrix coated with laminated aluminum.

This work is part of studies [1,2,4] performed to experimentally characterize these plates' instability for Miller's critical velocity condition comparing their predicted behavior with numerical simulations [15,16].

2. EXPERIMENTAL SETUP

CASTRO and ANDRADE [2] and CASTRO [4] present a detailed description of the experimental setup as well as a test section to simulate the Brazilian Multipurpose Reactor fuel element. This test section was used to study plate collapse and critical velocity detection in flat plates.

From [2]: (i) the test section model consists of two aluminum plates, six aluminum spacers and two acrylic plates mounted on a sandwich structure that divides the rectangular flow section into three identical coolant channels; (ii) an inlet length of 100 mm and a 50 mm outlet length of the channels were placed to simulate the inlet and outlet nozzles in the test section; (iii) the inlet nozzle has a reasonable amount of importance in modifying the flow at the inlet region.

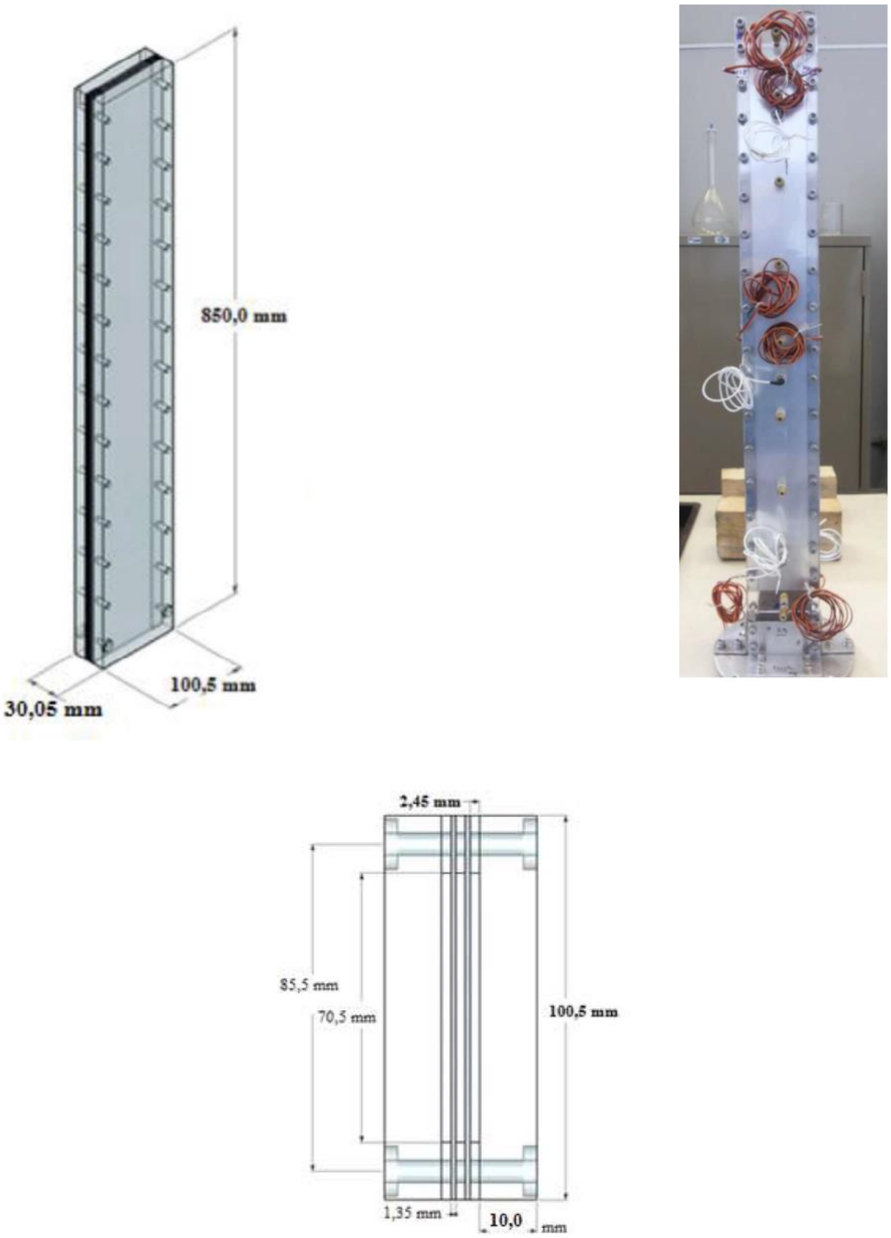
The test section, Figure 2 [2,4], has open top and bottom sections. One of its aluminum plates is instrumented with strain gauges of 350 Ohm in three different positions: inlet (SG1, SG2), center (SG3, SG4) and outlet (SG5, SG6). The signals from the attached strain gauges serve as the primary source to assess the plate deflections.

Figure 2 shows the test section sandwich structure, the model cross section and a model photo. The cross section dimensions of the three coolant channels are 70.5 mm x 2.45 mm and can also be observed in this figure.

It is important to note that this work was focused in the study of arising sudden changes in strain gauge signals due to controlled induced flow variation inside these channels. The stress or strain measurements were considered less relevant.

The secondary method used for plate instability assessment was the static pressure measurement. The channel load losses related to deflection of the plates alter the pressure measurements. Static pressure taps at axial intervals along the acrylic plates were installed to measure the static pressure. Four piezo-resistive micro sensors were used on the external acrylic plate of the flow channel next to the strain-gauge sensors [2,4].

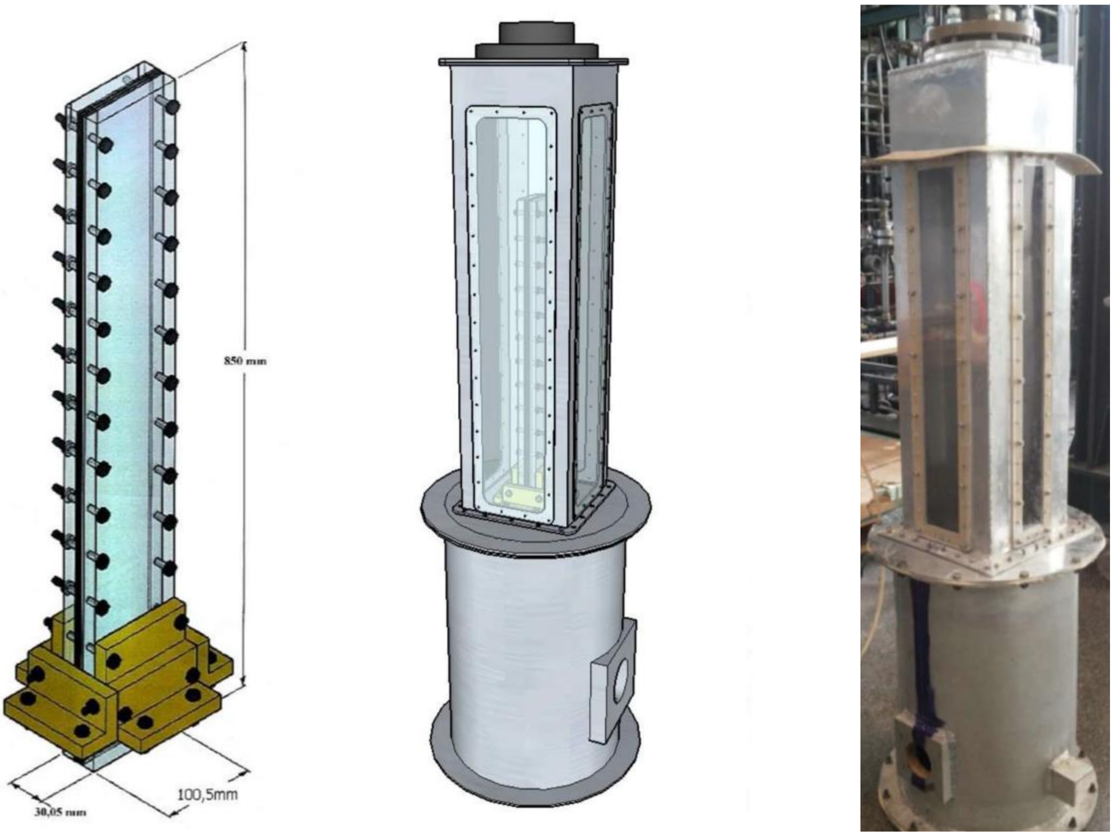
Figure 2: *Diagrams and photograph of the instrumented plates.*



Source: [2,4]

Figure 3 presents a scheme and a photograph of the test section [2,4]. The fuel element model was vertically mounted inside the test section. It was fixed to the top of the inlet chamber (D = 500 mm, h = 635 mm). This aluminum inlet chamber forms a plenum to produce an inlet flow through the three coolant channels with uniform velocities. Outside, there is an aluminum channel, with square cross section (250 mm x 250 mm) and a height of 940 mm with polycarbonate windows, whose main function is to allow the return of the flow to the circuit of the experimental setup. This aluminum channel also works as outlet, as a sealing device for the instrumentation, and as a visualization chamber.

Figure 3: *Diagrams and photograph of the test section.*

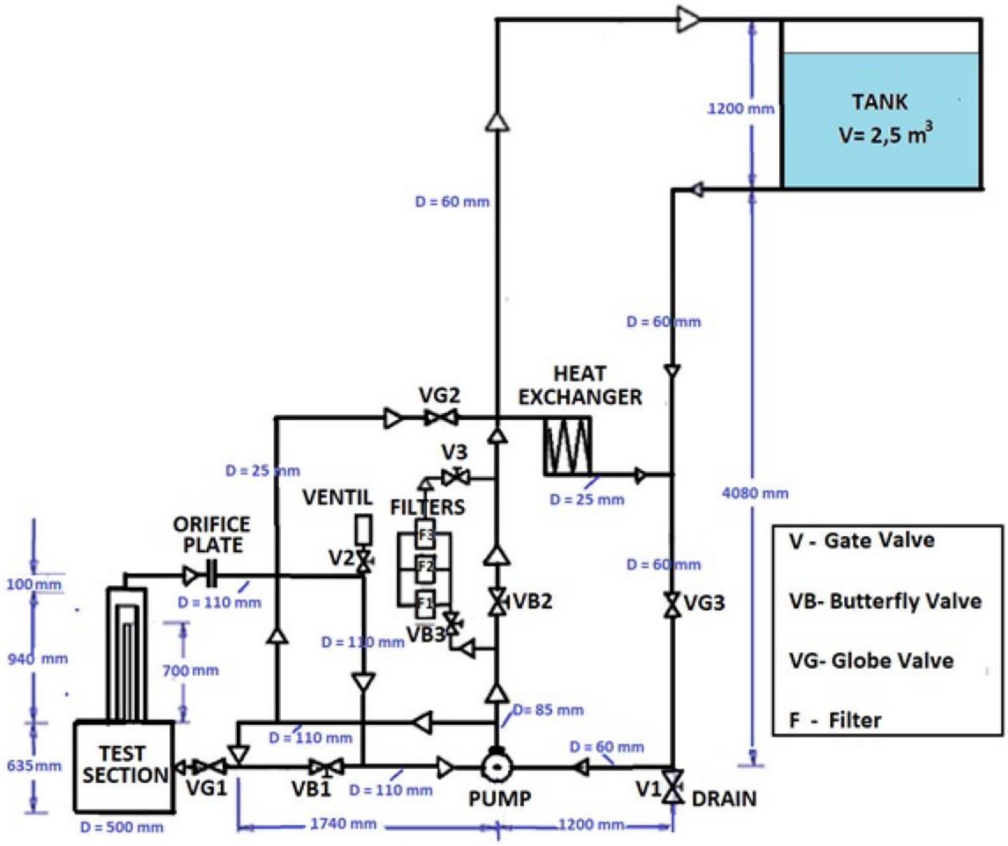


Source: [2,4]

A Pitot tube was installed in the outlet-nozzle center to measure the average velocity in the fuel-element channels. The Pitot tube signal is directly connected to a diaphragm-type pressure gauge. The Plenum of the test section was also instrumented with a K-type thermocouple and a bourdon manometer (0 - 6 kgf/cm2 scale). The closing square channel of the test section is instrumented with an accelerometer, a K-type thermocouple, and a bourdon manometer (scale 0 - 4 kgf/cm2). The inlet pressure in the test section is obtained by using a piezoelectric pressure transducer (scale 0-10 bar). The purpose of the pressure gauges in the test section is to measure quickly and visually the pressure drop (ΔP) throughout the test section, and to check the tightness between the inlet Plenum and the test section outlet box.

Figure 4 [2,4] shows the flow diagram of the experimental test loop. This loop was developed, assembled, and installed at the Nuclear Engineering Center of the Instituto de Pesquisas Energéticas e Nucleares IPEN-CNEN. It comprises a 2.5 m^3 tank, a pump (B1) (capacity of 100 m^3/h of volumetric flow rate and 60 meters of manometric height), a test section, an orifice plate (PO) flow meter, filters, a heat exchanger, a deaerator, a globe valve, butterfly valves, manometers and industrial PVC (polyvinyl chloride) pipes (D = 110 mm, D = 85 mm and D = 60 mm).

Figure 4: *Experimental test loop*



Source: [2,4]

This experimental setup provides operating conditions required for the critical velocity and plate instability tests highlighting that the three-channel flow model with two aluminum flat plates simulates the RMB fuel element.

A data acquisition program was developed by using LabVIEW10 platform (from National Instruments) to monitor and record the process signals of pressure, temperature, volumetric flow rate, pitot velocity and the test section accelerometer. The developed program allows the user to select the sampling frequency, the number of samples to update the data, the choice between monitoring and data recording, and the selection of the file where the recorded data will be stored. The Quantum-X system of HBM was used for the monitoring and recording of the strain gauge signals. The two data acquisition computers were synchronized in order to enable monitoring and analyzing the signals over time.

2.1. Experiments

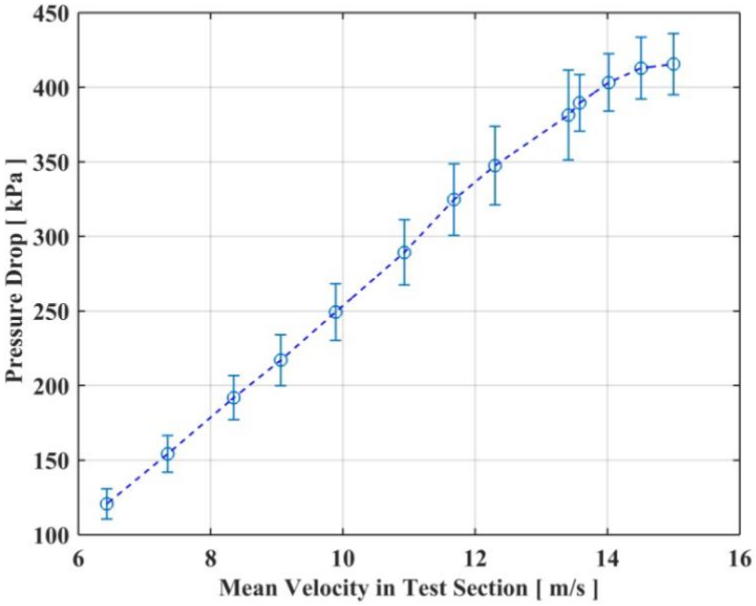
First, to verify the reproducibility of the signals from strain gauge and pressure sensors, the range of the mean velocities in the test section varied from 7.0 m/s to 12.0 m/s. The obtained signals showed reliability and reproducibility and were not affected by spurious noise from the power supply. After each operational on/off cycle, the strain gauges signals returned to the initial condition, i. e., no plastic plates deformations.

Reproducing the operations description showed in [2,4], to reach the plates instability condition and the detection of the critical velocity, the experiments started with 6.5 m/s average velocity inside the test section. The signals from the process sensors in steady state condition were monitored and recorded at a sampling frequency of 1200 Hz for 10 seconds at each globe valve actuation to increase the flow of the circuit and consequently the average velocity in the test section. Strain sensors were monitored and recorded with the same frequency, but with a longer sampling rate. This velocity was increased by 1.0 m/s at each step. From the average velocity around 13.0 m/s, 0.5 m/s increases were promoted, and signals were recorded during the transient operation of the globe valve for a period of 30 seconds for the process signals and at least of 60 seconds for the strain gauge signals. The maximum flow condition was reached with an average velocity of 15.0 m/s in the channel. Flow increase and average velocity control was performed through ΔP signal monitoring using the diaphragm-type sensor display situated on the orifice plate.

3. RESULTS AND DISCUSSION

The pressure drop (ΔP) between test-section inlet and outlet as a function of the average fluid velocity through the channels is depicted in Figure 5. An approximate linear relationship between ΔP and the fluid velocity up to 14.0 m/s can be observed. From 14.0 m/s onwards, the test-section hydraulic resistance decreases because of plates' deformation.

Figure 5: *Pressure drop (ΔP) for different fluid velocities*

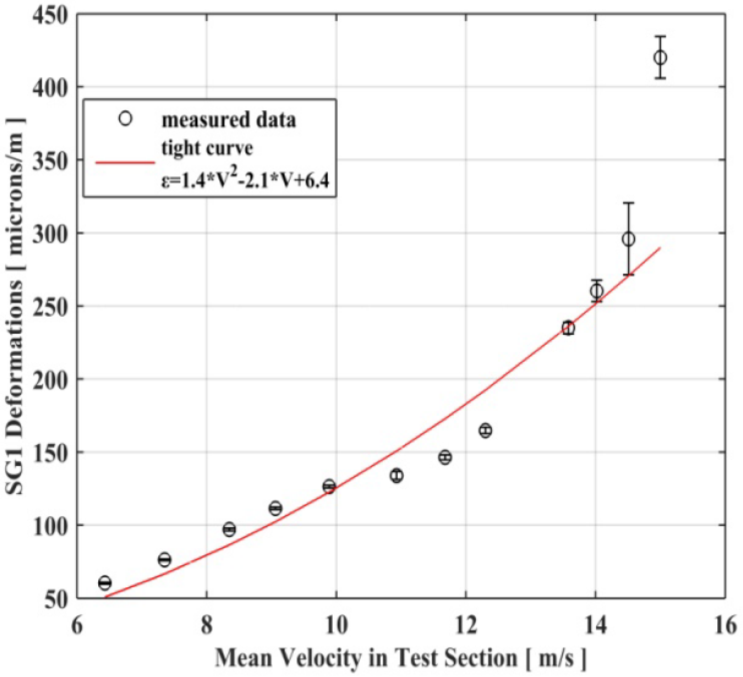


Source: [2,4]

Figures 6 to 8 show the collected deformations with the strain gauges. A continuous deformation increment with fluid velocity increase can be observed. Larger deformations occurred at the plate center (SG3). A sharp deformation increment was recorded by SG3 for velocities above 14.0 m/s. For fluid velocities from 14.0 to 14.5 m/s, there was a deformation increment of 219% at the plate midpoint. In addition, instability and plastic deformation of the plates have occurred.

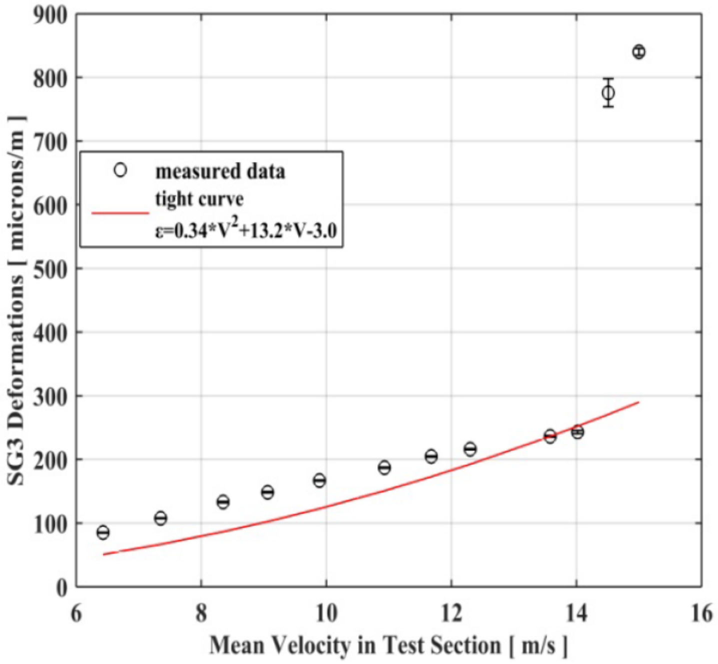
Figure 9 presents a picture of the channels/plates after the critical velocity experiments. The plates' deformation can be clearly seen, collapsing away from each other. Consequently, the central channel expanded, and lateral channels' thickness was considerably reduced.

Figure 6: *Deformations at the inlet (SG1) of the plate*



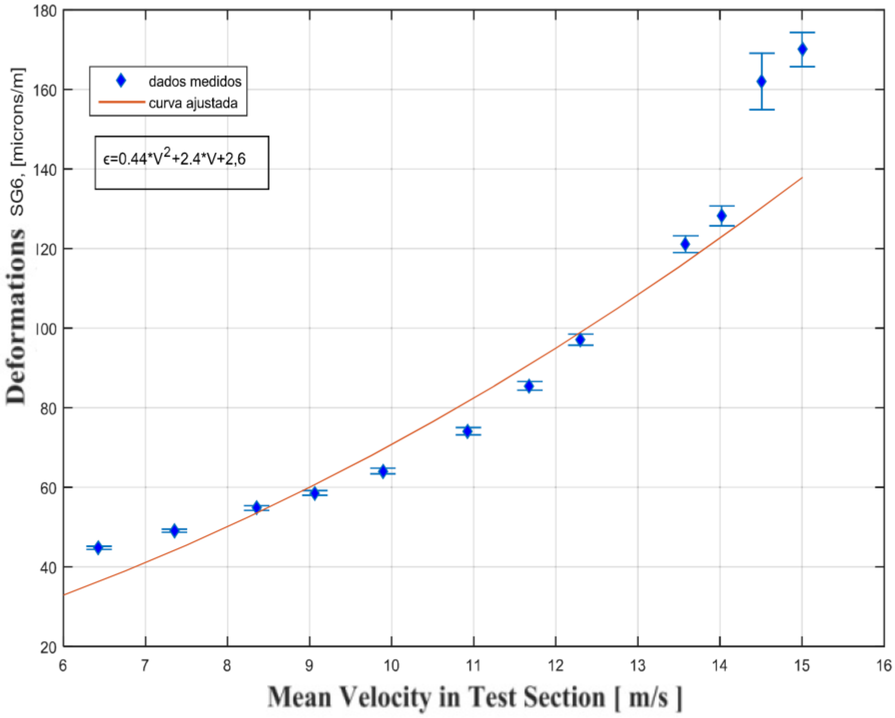
Source: [2,4]

Figure 7: *Deformations at the middle (SG3) of the plate*



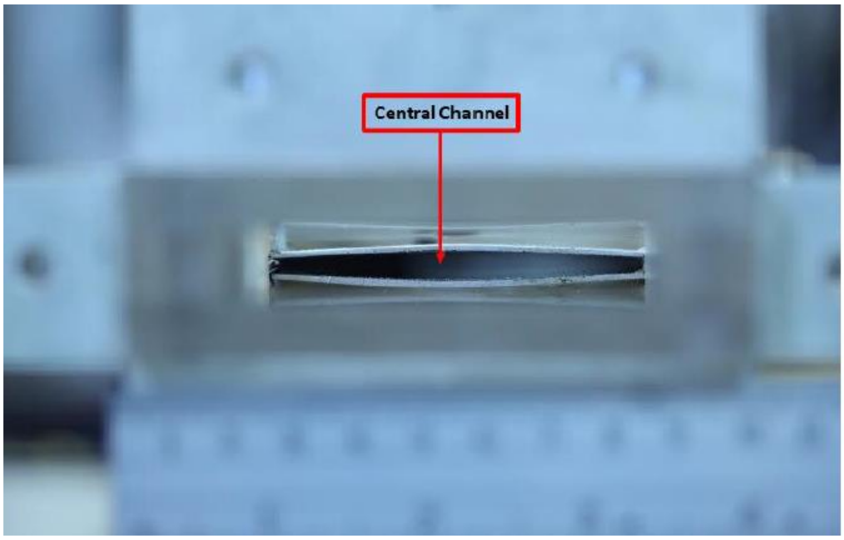
Source: [2,4]

Figure 8: *Deformations at the outlet (SG6) of the plate*



Source: [2,4]

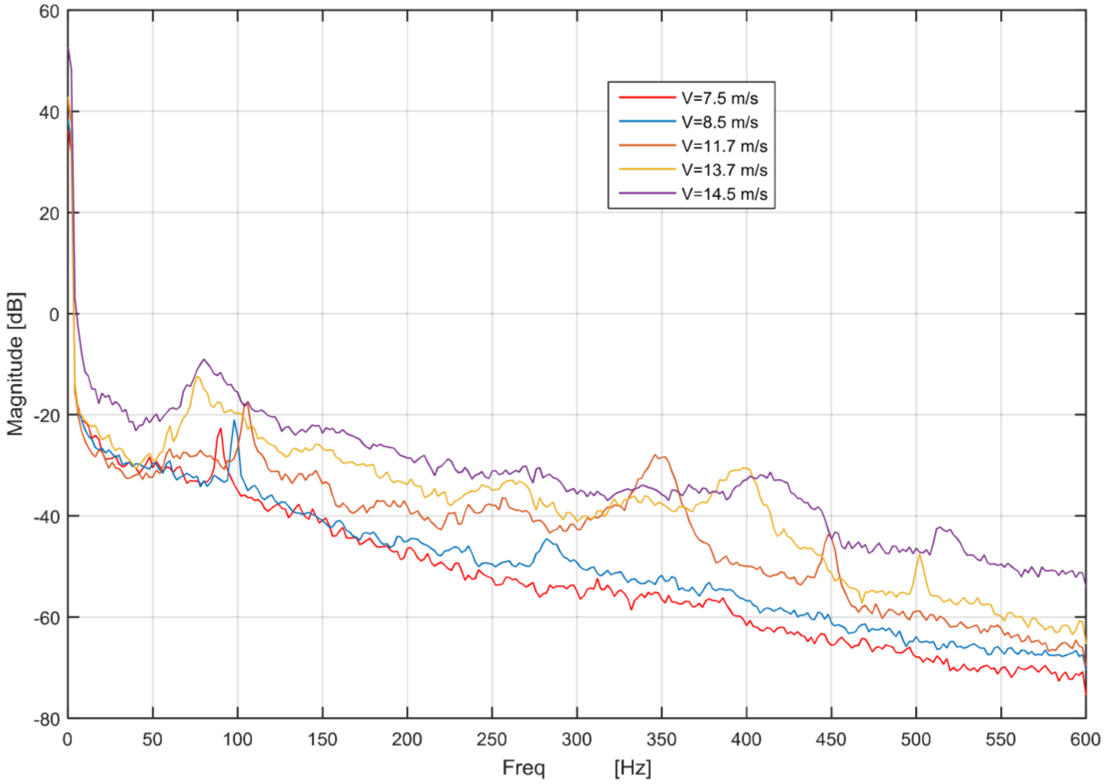
Figure 9: *Photograph of the plates after the critical velocity experiment*



Source: [2,4]

A power spectral density was taken from signals obtained with the strain gauge positioned at the middle of the test section (SG3) for different mean velocities in the channel. No probable component of elastic fluid instability was observed in Figure 10 through the frequency analysis of the strain-gauge signals near the moment of critical velocity occurrence.

Figure 10: *Power spectral density SG3*



Source: [4]

With the velocity growth in the channel, a fluid-bound excitation (broadband) was noticed in the frequency range from 90 to 130 Hz. This excitation might be linked to cavitation in the middle of the channel of the test section. Thus, the deformation at the center of the plate was much larger than that at the inlet, causing great resistance to flow, high fluid velocities and very low pressures. The second mode of natural frequency vibration was identified in the 74 Hz range, especially in the mid-section signals (SG3).

Resonances were also observed in the frequency range from 300 to 500 Hz. They may be caused by plates' vibrations and fluid vortices. These vortices are most likely produced at the exit of the test section. Therefore, to mitigate possible influences of fluid phenomena (resonances, cavitation in the flow-control valve and pressure pulses in the pump) in the results, a plenum chamber in the test section is present.

4. CONCLUSION

An average fluid velocity of 14.5 m/s, Miller critical velocity condition, was achieved resulting in plates instability and consequent plastic deformation forming the flow channel.

Considering that critical velocity by Miller equation is 17.0 m/s, the experimental one is 85.5% of this calculated value showing good agreement with Ho et al. [8].

Strain gauge signals showed that plate deformations were proportional to the squared velocity up to 14.0 m/s. This behavior is in accordance with Miller's model hypotheses [3] which apply Euler-Bernoulli equation to the wide beam theory. For speeds higher than 14.0 m/s the plate deformation proportionality no longer occurs. Based on this last finding, the occurrence of plates instability was characterized to arise at the 14.5 m/s critical velocity. The plate instability characterization technique is unique for critical velocity detection experiments.

This behavior was also observed in numerical simulations for configurations of the same fuel plates in MANTECÓN and MATTAR NETO [15,16].

The occurrence of plate collapse was visually confirmed during the disassembly of the test section as was illustrated and discussed in the analysis of the results (see Figure 9). The channels´ blockage was also observed utilizing the pressure drop (ΔP) behavior for different fluid average velocities in the test section. A hydraulic resistance drop of the test section was observed due to a cross-section increase in the central channel of flow.

Concerning the performed frequency domain analysis, the occurrence of a probable component in strain-gauge signals related to fluid elastic instability near critical-velocity conditions was not observed.

So, based on the experimental results, it can be noticed that for RMB fuel elements a design velocity of 2/3*14.5 = 9.7 m/s can be used with adequate safety margins [9].

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