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ONE-WAY FLUID-STRUCTURE INTERACTION MODEL TO STUDY THE INFLUENCE OF THE FLUID VELOCITY AND COOLANT CHANNEL THICKNESS ON THE STABILITY OF NUCLEAR FUEL PLATES

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Abstract. *In nuclear research reactors, the fuel elements are frequently composed of parallel, flat or curved plates. A major problem of that fuel element configuration is the hydraulic instability of the plates caused by high coolant velocities. Thin plates contain the fuel and they are separated by narrow channels through which the coolant flows to remove the heat generated. In this study, a numerical analysis was conducted to examine the fluid-structure interaction of a flat fuel plate bounded by two coolant channels. The loads caused by the fluid flow are calculated using a Computational Fluid Dynamics model implemented in ANSYS CFX, and the plate structural responses are determined using a Finite Element Analysis model implemented in ANSYS Mechanical. The goal of the present work is to estimate the amount of deformation of a fuel plate when there is an increment of the fluid velocity and a variation in the thickness of the coolant channels.*

Keywords: *fluid-structure interaction, flat-plate-type fuel element, nuclear research reactor*

1. INTRODUCTION

In nuclear research reactors, the fuel elements are composed of parallel, flat or curved plates. The nuclear fuel is contained in the thin plates and they are separated by narrow channels through which the fluid flows to remove the heat generated. One of the main problems of this fuel element configuration is the hydraulic instability of the plates caused by the high flow rate.

The deformation of flat-type fuel elements due to high flow rate has been analyzed for many years. In 1958, R. Doan discussed a critical flow field associated with the onset of plastic plate deflection detected during the fuel element design, development, and construction for incorporation into the Engineering Test Reactor (ETR) (Doan, 1958). The Doan's hypothesis was used by Miller who established a method for estimating the critical velocity based on the Bernoulli theory of incompressible flow and the wide beam theory (Miller, 1958). This method predicted that the flow velocities greater than a critical velocity caused the plate to collapse. This velocity is also known as "Miller's velocity".

After Miller, many researchers have studied experimentally and analytically the flow-induced deflection of stacked plates (Groninger and Kane, 1963; Jensen and Marcum, 2014; Johansson, 1959; Kim and Davis, 1995; Liu et al., 2011; Smissaert, 1968, 1969). In the last years, with the continued development of computational techniques, some studies have been performed by coupling Computational Fluid Dynamic (CFD) and Finite Element Analysis (FEA) commercial codes but with limited results due to the high complexity of this kind of problem (Curtis et al., 2013; Kennedy and Solbrekken, 2011; Kennedy, 2015).

In this work, a numerical analysis is conducted to analyze the fluid-structure interaction of a single fuel plate bounded by two coolant channels. The loads caused by the fluid are calculated using a CFD model implemented in ANSYS CFX, and the plate structural responses are determined using an FEA model implemented in ANSYS Mechanical. The goal of the present study is to calculate the amount of deformation of a fuel plate when there is an increment of the fluid velocity and a variation of the coolant channels thickness.

Considering that the future Brazilian Multipurpose Reactor (RMB by its acronym in Portuguese) will use this type of fuel assembly, this work is a first attempt to understand the fluid-structure interaction (FSI) in that element. Besides, in the near future, this study will be the base of a more exhaustive work that will help to identify the critical velocity and to establish the operational limit of that reactor.

2. METHODOLOGY

The model is developed considering the design data of the future RMB fuel assemblies. Each fuel element has 21 fuel plates, with a meat made of low-enriched (19.75%) Uranium Silicide-Aluminum dispersion (U_3Si_2-Al) clad with Aluminum. Figure 1 shows a schematic representation of the fuel element.

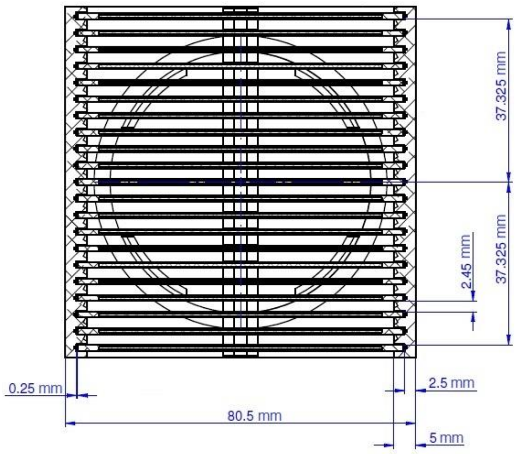

Figure 1. Top view of the fuel element.

2.1 CFD model

A simplified CFD model of the flat-plate fuel element, considering two coolant channels and one fuel plate centered (see Fig. 2), was created using ANSYS CFX (ANSYS Inc., 2017). In Fig. 2 the cyan region is the position where the plate is located. Flow direction is indicated by the dark blue arrows. The fluid domain is divided into three regions: inlet plenum, coolant channels, and outlet plenum. Geometric data and fluid properties are listed in Tab. 1.

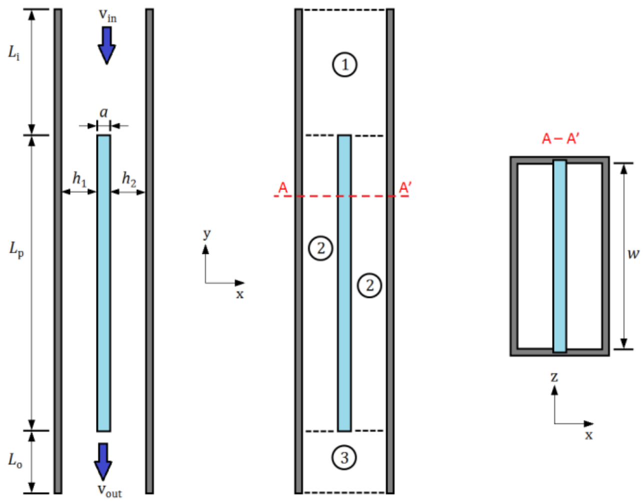

Figure 2. Fluid domain: (1) inlet plenum, (2) coolant channels and (3) outlet plenum.

The average fluid velocity through the channels is v_0 = 8.2 m/s and hereinafter is called the “fluid velocity”. It is the minimum coolant velocity required in the channels in order to meet the design criteria and it was taken from the RMB project (INVAP, 2013). Equation (1) was used for the flow rate at the inlet, taking into account an incompressible fluid and the law of mass conservation:

$$v_{inlet} = \frac{h_1 + h_2}{h_1 + h_2 + a} v_0 \tag{1}$$

Table 1. Geometric data and fluid (water) properties.

Parameter	Value
Coolant channel 1 thickness, h_1 [mm]	2.45
Coolant channel 2 thickness, h_2 [mm]	2.45
Plate thickness, *a* [mm]	1.35
Wetted plate/ Channels width, *w* [mm]	70.5
Inlet region length, L_i [mm]	190.0
Plate length, L_p [mm]	655.0
Outlet region length, L_o [mm]	70.0
Fluid density, ρ [kg/m^3]	997.561
Fluid dynamic viscosity, μ [Pa·s]	8.871 e-4

Since the coolant flow through the fuel element is turbulent, a turbulence model must be utilized to generate precise flow predictions. In this work, the k-ε model was used, which has proven to be stable and numerically robust (ANSYS Inc., 2017). In ANSYS CFX, the k-ε model uses the scalable wall-function approach to improving robustness and accuracy when the near-wall mesh is very fine. For that approach, it is typically recommended values of y^+ close to the lower bound (≈ 30), and it was considered here.

Figure 3 depicts the mesh used in the CFD modeling. To capture the contraction/expansion effects at the leading/trailing edges of the plate, a bias factor 4:1 was set up for spacing the cells along inlet, outlet and plate lengths. Equal bias factor was used to reduce the element size near the plate walls parallel to fluid direction. This factor is defined as the ratio of the longest division and the shortest division. The total number of elements of the fluid mesh is 657280.

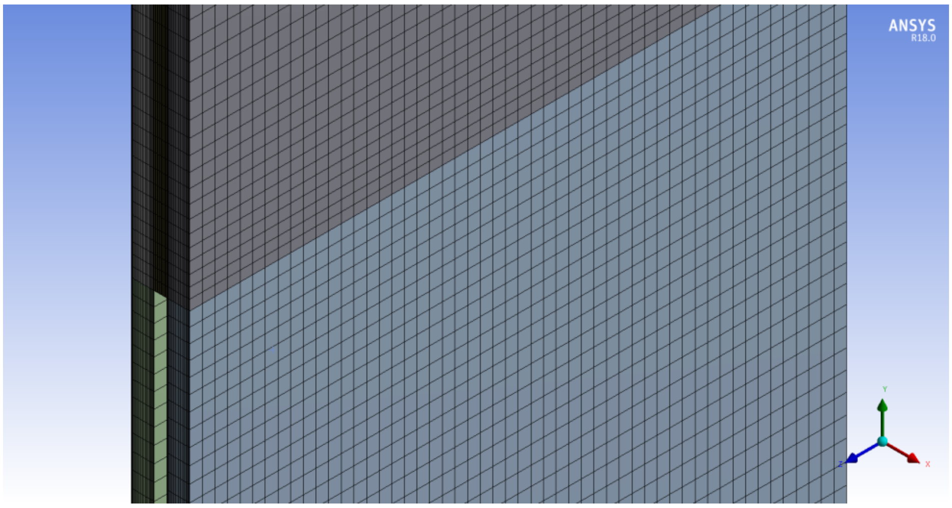

Figure 3. CFD mesh – leading edge region.

The residual is one of the most used criteria assessing CFD solution convergence. In this study, residual values of six variables (i.e. continuity, *x*, *y* and *z* velocities, turbulent kinetic energy *k* and the turbulence dissipation ε) are monitored during the simulation. Residual values of 1e-5 are used, usually sufficient for the majority engineering applications. Other important criteria to confirm the solution convergence is the net mass imbalances. The net mass imbalance to be deemed converged should be less than 0.1%.

2.2 FEA model

The FEA model of the flat plate was built using ANSYS Mechanical (Static Structural module). The major part of the flat plate dimensions is listed Tab. 1; the plate width (*b*) is 75.00 mm. Figure 4 shows the plate geometry. In the figure, dark gray surfaces (2.25 mm each one) are the regions used for fixing the plate. The applied boundary condition (BC) on front and back surfaces are set to $x = y = z = 0$. As these surfaces are fixed, the plate was restricted from rotating and so creating a clamped BC. The leading and trailing edges are free, and with the remaining surfaces form the loaded surfaces, which are where pressure loadings are applied.

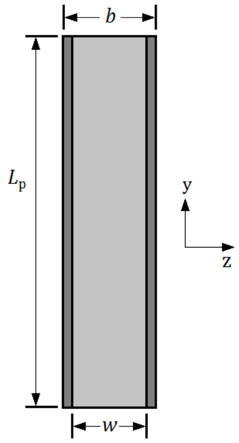

Figure 4. Plate geometry.

The plate was discretized using structured mesh with SOLID186 elements. SOLID186 is a higher-order 3-D 20-node solid element that exhibits quadratic displacement behavior. It is defined by 20 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyperelasticity, creep, stress stiffening, large deflection, and large strain capabilities. The structural mesh is shown in Fig. 5. The total number of elements is 149600.

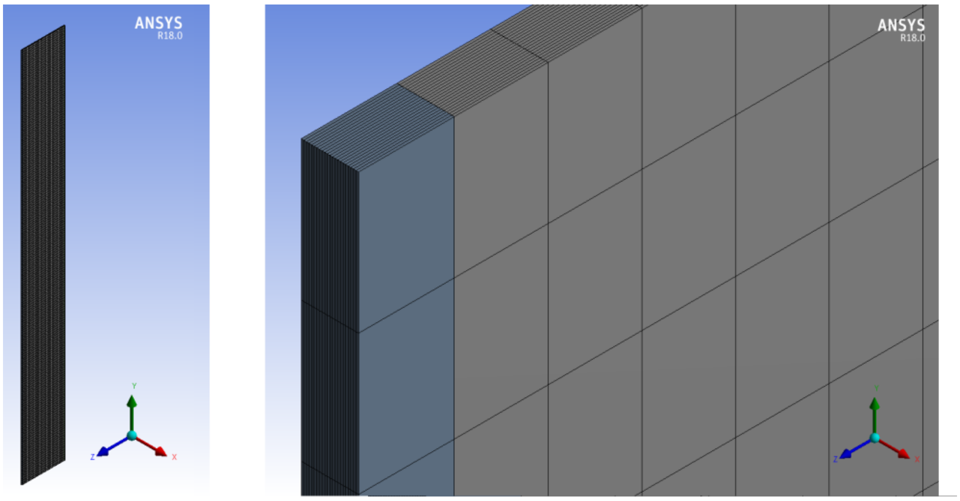

Figure 5. Structural mesh: plate (left) and close view at the leading edge (right).

The plate material is Aluminum Alloy 6061-T6 and has the properties given in Tab. 2. Note that only elastic properties are considered.

Table 2. Aluminum Alloy 6061-T6 properties.

Properties	**Value**
Elasticity Modulus, E [GPa]	68.9
Poisson's Ratio, ν	0.33
Density, ρ_p [kg/m^3]	2700

2.3 One-way fluid structure interaction

Fluid-structure interaction is a two field problem: one fluid flow and one structural field. The fields are interfaced via the so-called wet surface where the pressure and friction forces produced by the fluid are acting on the structure. In one-way FSI, the fluid field is solved only for the pressure forces, and these pressure forces are later applied on the plate as load boundary conditions. Afterward, the FEA model is used to calculate the structural responses of the plate (displacements and stresses).

2.4 Analysis procedure

This study is divided into two parts. In the first case, the influence of the fluid velocity on the plate deflection is studied. Initially, the design fluid velocity was used and the plate deformation was calculated. Afterward, static deflections were obtained at velocity ratios v_0/v_M equal to 0.8, 0.9 and 1.0. The Miller's velocity (v_M) of the assembly is given by:

$$v_M = \sqrt{\frac{30Ea^3h}{\rho w^4(1-\nu^2)}} \tag{2}$$

The parameters involved in the previous equation are presented in Tab. 1 and Tab. 2. In this study, the Miller's velocity is 23.82 m/s.

In a second part, an offset of 0.05 mm of the plate was imposed. As a result, the coolant channels adjacent to the plate have different thicknesses, 2.40 mm and 2.50 mm. The influence of the thickness variation on the plate deformation was also studied.

3. RESULTS AND DISCUSSION

Starting at 8.2 m/s, and considering equal coolant channels, the fluid velocity was increased according to the relationship mentioned in Section 2.4. Figure 6 shows pressure and plate deformation contour plots for fluid velocities of 8.2 m/s, 19.06 m/s, and 23.82 m/s. As it can be seen, the maximum pressure and the maximum deformation occur at the leading edge of the plate.

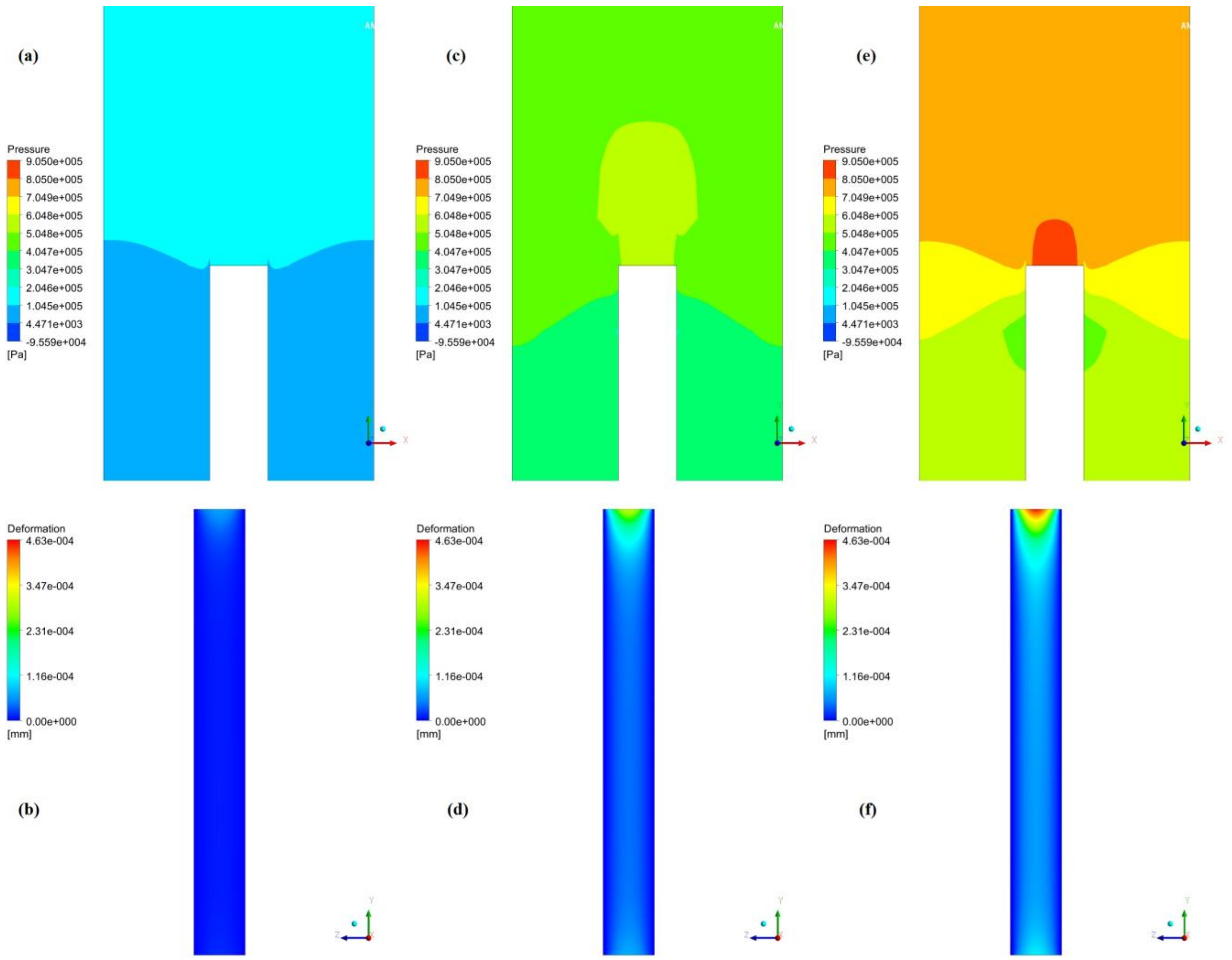

Figure 6. Pressure contours from the CFD analysis (lateral view) and plate deformation from the FEA analysis (front view): (a) - (b) for v_0 = 8.2 m/s, (c) - (d) for v_0 = 19.06 m/s, and (e) - (f) for v_0 = 23.82 m/s

Figure 7 shows the leading edge deflection along the plate width. It can be observed that the rise of fluid velocity leads to increment the plate deformation (Fig. 7-left) and the maximum value is obtained at the center point of the leading edge. On the right-hand side of the figure is shown how the maximum leading edge deflection behaved as the fluid velocity was increased. The plot includes a curve that fits the points. This curve suggests that the deflection increases with the square of fluid velocity, and this result is in agreement with the theory developed by Miller. Furthermore, the results demonstrate that very small deformations can occur below the Miller's velocity as has been predicted by other researchers (Groninger and Kane, 1963; Kim and Davis, 1995; Smissaert, 1968).

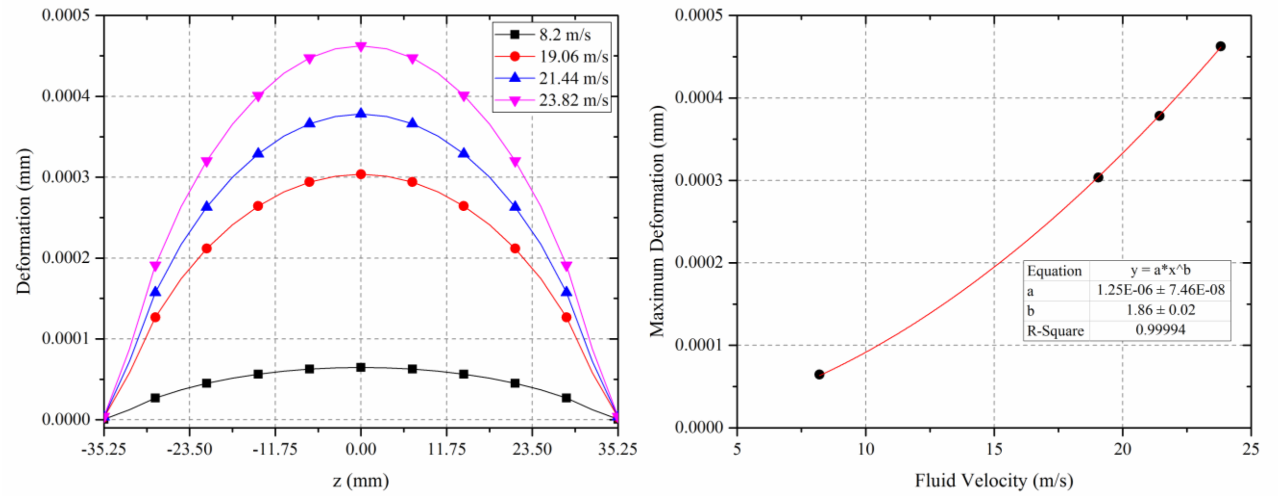

Figure 7. Deformation profile at leading edge along the plate width (left). Maximum static deformation at the leading edge (right).

When channels with different thickness are considered, 2.40 and 2.50 mm, it is expected a growth of the pressure difference due to the variation in cross-sectional area. In Fig. 8 the maximum Von Mises Stress value from the simulations is presented. It should be noted that the maximum stress increased more rapidly when different channels are considered. The pressure on the plate surface bounded by the smaller channel is higher immediately following the leading edge because of the smaller cross-sectional area and the increment of the friction loss factor in that channel. As result, the deformation of the plate increases and the plate tends to deflect into the higher channel.

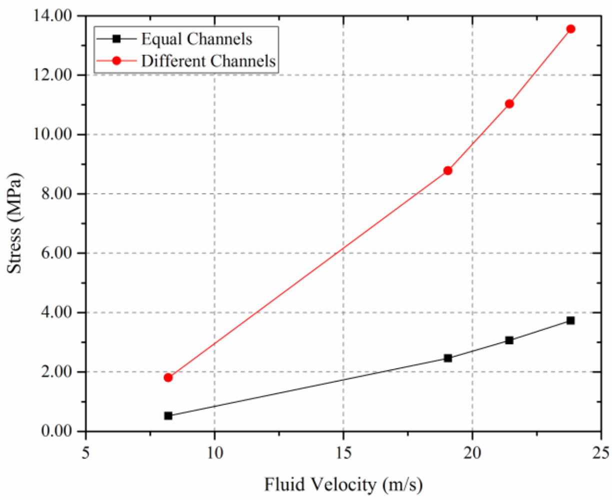

Figure 8. Maximum stress in the plate.

Figure 9 shows the total plate deformation from the 21.44 m/s simulation. It is confirmed the increment of the deflection when the channels are dissimilar. This figure deserves the reader's attention because the scales are not equal. A simple calculus reveals that there is a noticeable rise of the plate deformation at the leading edge, approximately one hundred times if compared with equal channels. It has been observed in this work that the increment of the fluid velocity and a little difference between the dimensions of the coolant channels can increase the plate deformation.

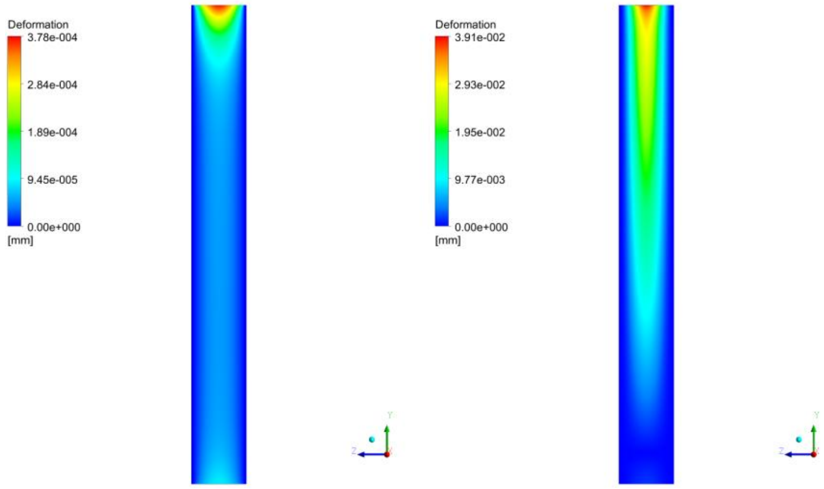

Figure 9. Total plate deformation for v_0 = 21.44 m/s with equal (left) and different (right) coolant channels.

4. CONCLUSIONS

In this work, a fluid-structure interaction model for plate-type fuel element has been established by coupling Computational Fluid Dynamics and Finite Element Analysis. The coupling strategy is based on one-way method, in which the fluid loads calculated by CFD modeling are sent to the FEA model as load boundary conditions. The following conclusions can be drawn from the present study:

1) The results suggest that the plate maximum deformation increases with the square of the fluid velocity.
2) The maximum plate deformation occurs at the leading edge.
3) For coolant channels with different dimensions, the plate deformation is higher due to the increment of the pressure difference.

The main limitation of this model is that the effect of the structure deformation on the fluid distribution is neglected. Currently, continuing studies are being carried out to understand this effect by using the two-way coupling method, which is a more precise method for this type of problem but demands more computational resources and simulation time.

5. ACKNOWLEDGMENTS

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