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Original Article

Analytical model of transverse pressure loss in a rod array

Guillaume Ricciardi*, Jean Peybernes, Vincent Faucher

CEA, DES, IRESNE, Department of Nuclear Technology, Cadarache, F-13108, Saint-Paul-Lez-Durance, France

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ABSTRACT

The present paper proposes some new computational methods and results in the framework of flow computation through congested domains seen as porous media, as it can be found in the core of a Pressurized Water Reactor (PWR). The flow is thus mostly governed by the distribution of pressure losses, both through the porous structures, such as fuel assemblies, and in the thin fluid layers between them. The purpose of the present paper is to consider the question of the interaction of a flow and a rod bundle from an analytical point of view gathering all the contributions through a set of equations as simple and representative as possible. It aims at demonstrating a sound understanding of the relevant phenomena governing the flow establishment in the geometry of interest instead of relying mainly on a posteriori observations obtained both experimentally and numerically. Comparison with two set of experimental results showed good agreement. The model proposed being analytical it appears easily implementable for studies needing an expression of fluid forces in a rod array as for fuel assembly bowing issue. It would be interesting to test the reliability of the model on other geometry with different P/R ratios.

1. Introduction

The present paper proposes some new computational methods and results in the framework of flow computation through congested domains seen as porous media, as it can be found in the core of a Pressurized Water Reactor (PWR). The flow is thus mostly governed by the distribution of pressure losses, both through the porous structures, such as fuel assemblies, and in the thin fluid layers between them.

In this context, empirical models and correlations are mostly used to provide the head loss coefficients of interest, which theoretically depends on the inclination between the structures natural preponderant directions, and the flow. It is particularly the case when the considered structures are rod bundles such as PWR fuel assemblies mentioned above. In this latter case, some extensive work can be found in the literature to characterize the forces applied by the fluid onto the structure in the configuration of interest, separating both axial and cross flows, and adding the some specifics details regarding the grids maintaining the rod bundle together with an assembly (see for instance Refs. [1–4].

Regarding axial forces, they are mostly derived from a force balance on the full assembly, including weight, buoyancy and friction along the rods [5]. For lateral forces resulting from cross flows through a bundle, some assumptions are currently made. It is for instance proposed in Ref. [6] that the normal force on a cylinder is proportional with respect to the drag coefficient multiplied by sinus squared of the angle of incidence, which is known as the independence principle. In other words, the force is carried by the crosswise component of the incident velocity [7,8]. noticed that this assumption shows some limitations, when trying to accurately reproduce the pressure distribution around the cylinder. In terms of effort, this model was validated for angles higher than 10°, but no experiment was run below. Consequently, the model is not considered validated for quasi-axial flows.

With no additional experimental result [9], clarifies the principle for small angles. When it comes to purely axial flow, the drag force is a friction force. Considering the latter as constant for small angles, the force is projected on the cylinder normal vector and yields a term proportional to the sinus of the angle of incidence. The rod normal force is thus a sum of the independence principle term due to the lateral component of the velocity, and a frictional term. Expanding the latter model with a Taylor series shows that the normal force is to be linear for very small angles. However, it is shown in Ref. [10]; [11]; that the force is indeed linear with respect to small angles, but the slope is too low to be only due to friction. Recently [10,12], pointed out that friction only made up 10% of the

* Corresponding author.
E-mail address: guillaume.ricciardi@cea.fr (G. Ricciardi).

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normal force. The main component of the force is actually due to lift, also linear with respect to the angle. Divaret further explains that it is possible to go from one single rod to a bundle of rods with the help of the Taylor model set up for a confined rod [9,13].

The Taylor's friction term can be computed through the Darcy-Weisbach equation, while the independence principle term is more complex. It previously stood for the drag of the unconfined rod in pure cross flow. Païdoussis chose an equivalent velocity to make the most of the independence principle: he focused on a bundle traveled along by a potential flow where cylinder X is missing, then he averaged the velocity around the missing cylinder X. Divaret noted that the latter model tends toward under-estimating the measured force, and might be called into question. Finally [14], went back more recently over Divaret's works and implemented them in the TLP (Taylor-Lighthill-Païoussis) model, along with some experimental results on the FICEL mock-up (cluster of 3x3 rods), and related CFD simulations. Both experiment results and CFD simulations show good agreement, thus Joly considered that the numerical model was reliable enough to be compared with the TLP results. Aside from the rods at the bundle inlet and outlet, the simulation results validated his model.

Complementary to this modeling and experimental work, the purpose of the present paper is to consider the question of the interaction of a flow and a rod bundle from an analytical point of view gathering all the contributions through a set of equations as simple and representative as possible. Such a methodology differs from the previous works in the way that it aims at demonstrating a sound understanding of the relevant phenomena governing the flow establishment in the geometry of interest instead of relying mainly on a posteriori observations obtained both experimentally and numerically. The proposed development obviously need validation, but no calibration if the goals are matched, and this is provided through the comparison to a relevant experiment known as EOLE tests dedicated to the flow through an inclined set of rods.

2. Pressure loss in a rod array

In this section, an analytical model for the pressure loss in a rod array will be developed.

2.1. Axial pressure loss

The axial pressure loss, along the x axis, is usually expressed as:

$$\frac{dp}{dx} = \frac{\rho \lambda U_{ax}^2}{2D_h}, \tag{1}$$

where p stands for the pressure, ρ is the fluid density, D_h is the hydraulic diameter, U_{ax} is the mean axial velocity and λ is the pressure loss coefficient.

The pressure loss is related to the friction stress τ_x:

$$\frac{dp}{dx} S_e = \tau_x P_e, \tag{2}$$

where S_e is the cross section and P_e is the perimeter.

The friction stress is usually expressed as follows:

$$\tau_x = \frac{1}{2} \rho C_f U_{ax}^2, \tag{3}$$

where C_f is the friction coefficient.

From the previous expressions and considering the particular case of a cylindrical pipe, one can relate the two coefficients λ and C_f:

$$\lambda = 2C_f. \tag{4}$$

In the following we will make the assumption that the latter equality obtained for a cylindrical pipe remains true for a rod array.

λ can be obtained by measuring the pressure decrease for various temperature and flow rate conditions. Experiments made on full scale fuel assembly at CEA Cadarache give the law:

$$\lambda = 0.19 \mathrm{Re}^{-0.19}, \tag{5}$$

where Re stands for the Reynolds number given by:

$$\mathrm{Re} = \frac{\rho U_{ax} D_h}{\mu}, \tag{6}$$

where μ is the viscosity of the fluid.

2.2. Transverse pressure loss

Let us now assume that the flow trough the rod array is not only axial but also transverse (Fig. 1). The rod array is defined by the radius of each rod R and the distance between two rods noted $2H$. The mean cross velocity on a section without any rods is noted U_t. P is the pitch of the array ($P = 2R + 2H$).

In cylindrical coordinate, the momentum equation of the fluid gives an expression of the transverse pressure gradient:

$$\frac{H}{R_m} \frac{\partial p}{\partial \theta} = \frac{1}{2} \rho C_f v \sqrt{U_{ax}^2 + v^2}, \tag{7}$$

where $R_m = H/2$ is the mean radius and v is the azimuthal velocity.

Let us make the assumption that v is constant, continuity equation therefore gives:

$$v = U_t \frac{R+H}{H}. \tag{8}$$

Injecting (8) in equation (7) and integrating the pressure over half of the rod between 0 and π, gives the expression of the transverse pressure loss for one rod Δp:

$$\Delta p = \frac{\pi \rho C_f R_m U_t}{2H} \frac{R+H}{H} \sqrt{U_{ax}^2 + \left(\frac{R+H}{H} U_t\right)^2}. \tag{9}$$

According to eq (9), the model shows that the pressure loss drastically increases as the distance between the rod is small compared to the diameter of the rod. This is due to the acceleration of the fluid induced by the restriction of the cross-section.

3. Pressure loss test

In this section, the model proposed will be compared to experimental results.

3.1. Experimental apparatus

The experimental apparatus EOLE involves a 8 by 8 rod array representative in terms of diameter and pitch of a PWR fuel assembly with a water flow at a temperature of 20 °C (Fig. 2). Four inclinations α of the rod arrays are possible by changing the inner components of the test section (0°, 22.5°, 45° and 60°), 0° stand for a full transverse flow. The total pressure drop is measured with differential pressure sensors, with an accuracy of about 0.1%, for various values of the velocity inlet U_b up to 1 m/s. The flow rate in the test section is measured with a vortex flow meter with an accuracy of about 2%. Tests are performed with 8 and 6 rows of rods as

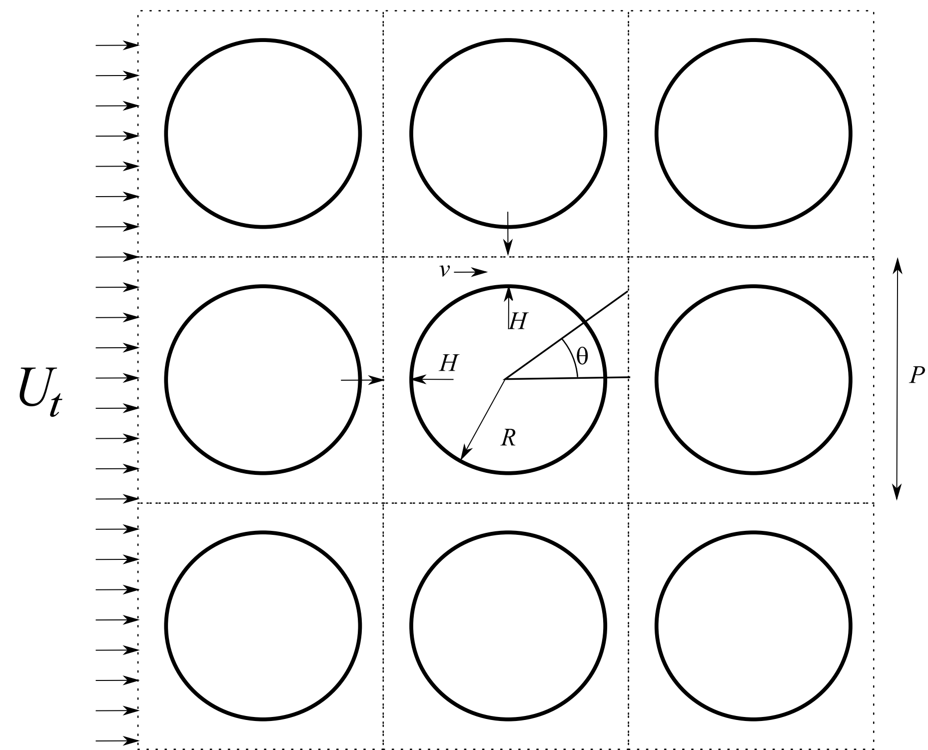

Fig. 1. Rod array notation.

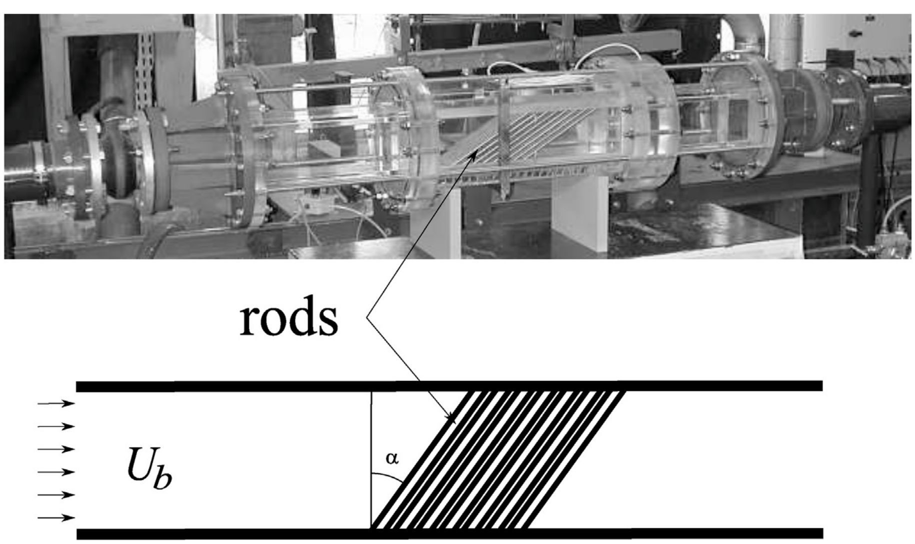

Fig. 2. EOLE experimental apparatus.

it was possible to remove some rods from the test section. Taking the difference allows us to isolate the pressure loss of one row of rods ignoring the singularities effect due to inlet and outlet of the rod array. The pressure drop was measured far from the inlet and outlet to have a fully developed flow.

3.2. Results

Axial and transverse velocities seen by the rod depend on the angle α:

$$U_t = cos\alpha U_b, \tag{10}$$

$$U_{ax} = sin\alpha U_b \frac{P^2}{P^2 - \pi R^2}. \tag{11}$$

Experimental results are compared to the model proposed in the previous Section (Fig. 3). One can see that the model gives a satisfactory estimation of the pressure loss and its variation with angle and flow rate.

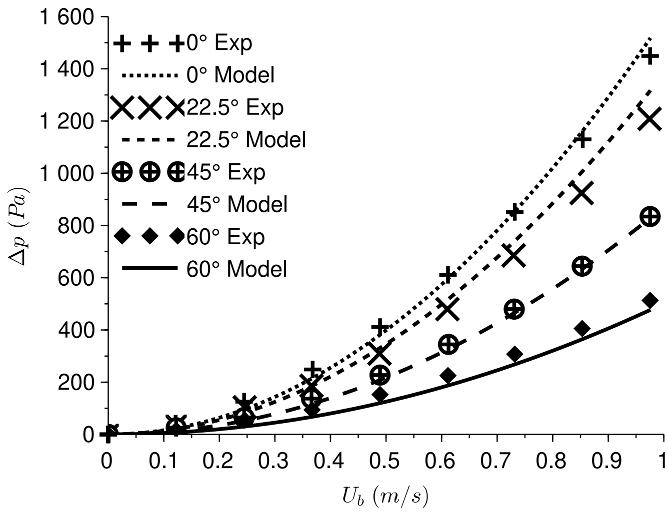

Fig. 3. Pressure loss for various angle.

It can be useful to consider the effect of the angle as a correction factor ϕ:

$$\Delta p = \phi(\alpha)\Delta p_0, \tag{12}$$

where Δp_0 is the pressure loss for $\alpha = 0$.

From the model proposed (9) and expression of U_{ax} in (10) and U_t in (10) one can obtain the expressions:

$$\phi = cos\alpha\sqrt{\frac{16H^2(R+H)^2}{(P^2-\pi R^2)^2}sin^2\alpha + cos^2\alpha}, \tag{13}$$

$$\Delta p_0 = \frac{\pi\rho C_f R_m}{2H}\left(\frac{R+H}{H}\right)^2 U_b^2. \tag{14}$$

Fig. 4 compares the model proposed for correction with the experimental results. As for the transverse pressure loss one can observe that the model gives a reasonable estimation of the correction angle.

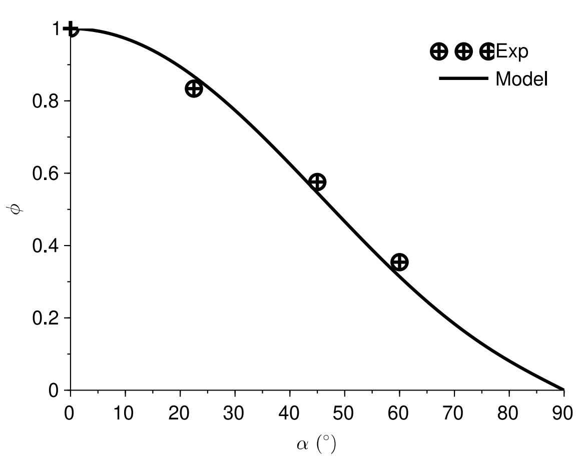

Fig. 4. Correction angle.

4. Force measurement test

4.1. Experimental apparatus

The experimental apparatus MISTRAL (Fig. 5) handles a reduced scale fuel assembly of 8 by 8 rods, 4 grids and 1.9 m long. The grid design is close to the one of a fuel assembly. Two circuits allow to impose an axial velocity U_{ax} up to 5 m/s (which is representative of a PWR flow condition) and a transverse velocity U_t up to 0.2 m/s on the second span between grids 2 and 3. Top and bottom nozzles are instrumented to measure the total lateral force F induced by the traverse flow. Both nozzles are mounted with linear-motion bearing devices with a force sensor immersed in the fluid. The overall accuracy of the sensors is about 4%. Boundary conditions are stiff enough to avoid contact between the fluid assembly and the test section. Flow rates are adjustable in axial and transverse directions by means of manual vanes, and measured with vortex flow meters with an accuracy of about 2%.

4.2. Results

The force induced by the transverse flow can be easily obtained from the pressure drop:

$$F = 2(R+H)L_s\Delta p N_r^2, \tag{15}$$

where L_s is the length of the span N_r is the number of rods on a row.

Fig. 6 shows the force induced by a fully transverse flow, meaning $U_{ax} = 0$. One can see that the model slightly over estimate the lateral force but agrees well with the experiment.

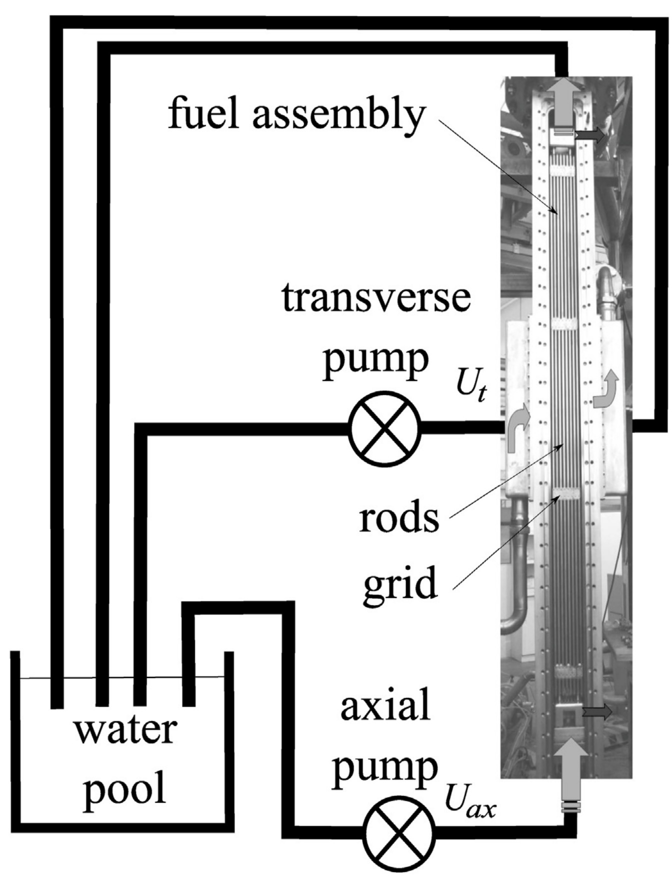

Fig. 5. MISTRAL experimental apparatus.

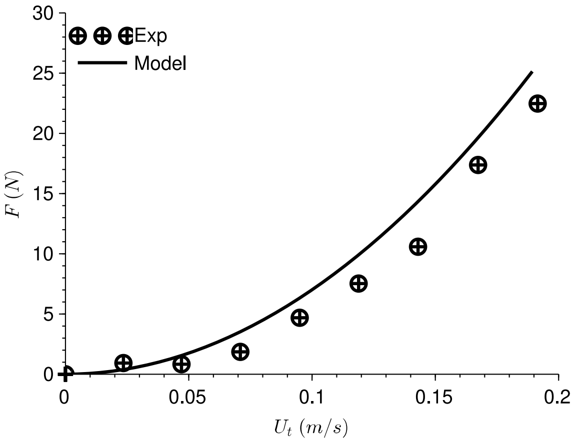

Fig. 6. Fluid forces induced by a cross flow.

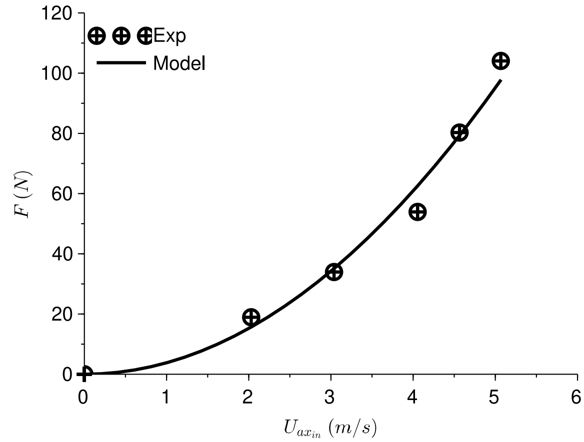

Fig. 8. Fluid forces induced by axial and cross flow with fixed ratio $U_{ax_{in}}/U_{t_{in}} = 25$.

Although the experimental apparatus was designed to generate a combined axial and cross flow, some uncertainties remain on the flow rate at the outlet of the cross flow device when both axial and cross flow are imposed. This is due to the fact that the two circuits are linked by the water pool. In the following we will make the assumption that this outlet flow rate is negligible. We therefore assume a linear distribution for the transverse velocity:

$$U_t = U_{t_{in}} \frac{y - w}{w}, \tag{16}$$

where $U_{t_{in}}$ is the transverse velocity at the inlet and w is he width of the fuel assembly.

By continuity the axial velocity linearly increases along the middle span:

$$U_{ax} = U_{ax_{in}} + U_{t_{in}} \frac{x}{L_s} \frac{L_s w}{(P^2 - \pi R^2) N_r^2}, \tag{17}$$

where $U_{ax_{in}}$ is the axial velocity at the bottom of the fuel assembly.

Figs. 7 and 8 compare experimental results to the model accounting for the distribution proposed in (16) and (17). The model agrees well with the experimental results reproducing effect of axial and transverse velocities.

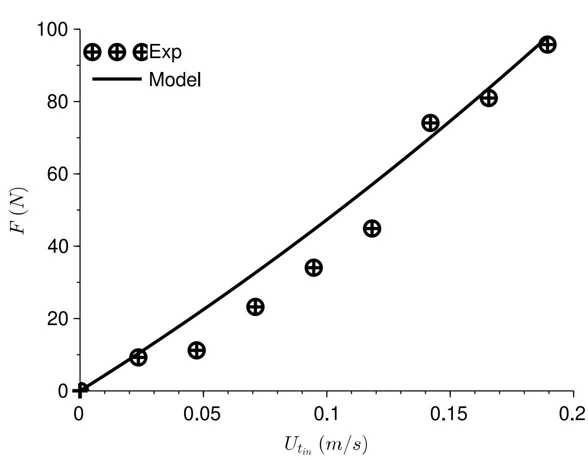

Fig. 7. Fluid forces induced by axial and cross flow with fixed axial flow rate of $U_{ax_{in}} = 5$ m/s.

4.3. Conclusion

A simplified analytical model for pressure loss and fluid forces in a rod array subjected to a inclined flow, has been proposed. Comparison with two set of experimental results showed good agreement. The model proposed being analytical it appears easily implementable for studies needing an expression of fluid forces in a rod array as for fuel assembly bowing issues. It would be of interest to test the reliability of the model on other geometry with different P/R ratios ranging from 1.1 to 1.4, for square and triangular arrays to cover geometries encountered in fuel assemblies and steam generators.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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