On Coherent Structures, Flow-Induced Vibrations, and Migratory Flow
in Liquid Metal Nuclear Reactors

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Extended summary

Flows in rod bundles are common to many industrial applications such as heat exchangers or some types of nuclear reactors. The core of many classes of nuclear reactors can be easily sketched as a bundle of rods, the fuel pins, immersed in an axial flow of coolant that removes the heat produced by the fission reaction. Coupling this geometry to an axial flow can trigger periodical vortices, known as large coherent structures or gap vortex streets, that move on both sides of the gaps between the rods. By crossing the gap (cross-flow), these vortices may enhance the heat removal mechanism, thus improving the performance of the reactor.
However, coherent structures cause velocity oscillations in the flow that may induce vibrations of the fuel rods, leading to their long term damage. The length (or wavelength) of coherent structures is a key parameter for understanding the interplay between these vortices and the vibrations that may be triggered on the rods. Their wavelength determines the frequency of the velocity oscillations in the fluid, hence of the external force imposed on the rods.

One of the reactor designs belonging to the next generation (Gen-IV) of nuclear reactors is the Liquid Metal Fast Breeder Reactor (LMFBR). This reactor has the fuel rods in the core arranged in a hexagonal matrix. In this design, a wire is helicoidally wrapped around each fuel rod to keep them separated from each other. The presence of the wire diverts part of the more turbulent flow from the bulk towards the gap between the rods, where the flow would be otherwise less turbulent. This enhances the heat exchange and avoids hot spots on the fuel cladding. A phenomenon known as migratory flow has been observed in rod bundles with wire spacers. In the presence of migratory flow, the fluid is diverted from the gap towards the main subchannel and it bends against the helicoid path of the wire, thus leading to a very complex flow, where part of the fluid follows the wire direction and part moves against it, away from the gap. Although this behaviour was first observed years ago, the governing mechanism is not clear yet. Explaining migratory flow is thus a fundamental step towards a general understanding of the mixing and mass transfer phenomena in rod bundles in the presence of helicoid wires.

This research considers several aspects of the flow inside rod bundle geometries. The aim is to study coherent structures to understand their role in inducing vibrations of the rods, and to provide a model that explains migratory flow caused by helicoid wire spacers.

To these purposes, three experimental facilities are designed and built that work in isothermal conditions, ambient pressure and with water as working fluid. The first is a rectangular channel hosting two half-rods whose distance can be adjusted. A second hexagonal bundle containing seven rods has the central rod made of flexible silicone to study vibrations induced by the flow. The third facility is a hexagonal bundle with seven rods, each of them equipped with a wire helicoidally wound around them in order to measure and explain migratory flow.
The measurements are carried out with non-intrusive optical systems. Laser Doppler Anemometry (LDA) is used to measure the flow components in the rectangular channel with half-rods and in the hexagonal bundle without wire spacers. For the latter, a high speed camera is also used to measure the amplitude and frequency of the vibrations induced on the flexible rod by the flow. In the hexagonal bundle hosting wire spacers, planar (i.e. two dimensional) Particle Image Velocimetry (PIV) is used to measure the flow near to the wire of the central rod of the bundle. For all the three experiments, optical access is achieved by replacing part of the material of the rods with Fluorinated Ethylene Propylene (FEP), a Refractive Index-Matching (RIM) polymer that nearly matches the refractive index of plain water. In this way, optical distortion of the light rays is greatly reduced.

The measurements of the flow inside the channel hosting two half-rods show that cross-flow of coherent structures across the gap decreases in frequency if the distance between the rods is increased.
This research shows that the wavelength of coherent structures becomes independent of the flow rate above a certain value of the Reynolds number, and that it is affected solely by the geometry of the channel. Performing

dimensional analysis of the problem, and supporting the reasoning with experimental evidence, has increased our understanding of what determines the length of the structures. This appears to be a function of only the hydraulic diameter of the gap region close to which they form. This finding is presented in the form of a novel correlation that predicts the length of coherent structures. This correlation is applicable to a number of different geometries, ranging from channels with few rods to full rod bundles. The flow measurements in the hexagonal bundle (without wire spacers) show that the frequency of passage of coherent structures in the axial direction increases with the Reynolds number. If this frequency becomes equal to twice the first natural frequency of rod, a drastic increase in the amplitude of oscillation is observed, which can be ascribed to the synchronization between the rod and coherent structures carried by the flow.

It is experimentally shown that for hexagonal rod bundles with helicoid wires, the flow very close to the rod follows the helicoid path of the wire.
However, if the measurement region is shifted closer to the main subchannel surrounding the rod, the flow bends towards the wire, against the helicoid path, suggesting the presence of migratory flow. A model to reconstruct the pressure gradient caused by the wire, and responsible for the bending of the flow, is derived from the steady-state, two-dimensional, inviscid Navier-Stokes equations applied to the flow streamlines. Following a theoretical approach, an equation is derived from this model to estimate the bending angle of the flow at any point inside the measured area, based on the time-averaged flow fields. This equation has the form of an integral evaluated along the path followed by a streamline. It shows how the bending of a streamline at an arbitrary point is the result of the interaction between the transversal pressure gradient, trying to bend the fluid, and the inertial forces, trying to straighten it towards the direction of the main flow.
A possible correlation for estimating the bending angle of the flow is obtained with dimensional analysis and with the support of the experimental results. Contrarily to the theoretical model, this correlation relies on macroscopic variables, being the bundle dimensions and the geometry of the subchannel.
Finally, this thesis suggests possible topics of interest for future research.