McMaster University – Marilyn Lightstone CRD

CRD Title: Improved Understanding of Intersubchannel Thermal Mixing

Overview

Nuclear safety analysis is often performed to determine the consequence of a loss of coolant accident or other event on the fuel integrity and to determine subsequent fission product release. Thermalhydraulic analyses rely on accurate modeling of the heat transfer and fluid flow within the fuel rod bundle geometries. Due to the typically long simulation times for accidents and the complex geometries of the rod bundles and their appendages, subchannel methods (such as that used in ASSERT-PV) are often in employed. With these methods, the governing equations for heat transfer and fluid flow are integrated over a subchannel and averaged quantities are determined. As a result of the spatial averaging or integration, the fine structures of the flow are not resolved. This approach therefore requires many empirical correlations to represent the complex exchange mechanisms across the gap between the subchannels. Computational Fluid Dynamics (CFD), when used with an appropriate turbulence model, provides fine resolution of the fluid flow and heat transfer within a geometry, however, requires much greater computational effort than a sub-channel method. As such, we have employed CFD as a valuable tool for studying the complex flows in rod bundle geometries and for developing physics-based correlations of fluid mixing for use in subchannel codes.

Program Results / Highlights

The majority of our previous research has been on CFD modelling of subchannel mixing for turbulent flow conditions. Two former graduate students (George Arvanitis, M.A.Sc., and Deep Home, Ph.D. , both currently employed in the nuclear industry through AMEC Foster Wheeler) studied flows in a rectangular twin-subchannel geometry. This geometry was chosen because of its relative simplicity and the availability of experimental data for validation.

An important conclusion from George Arvanitis and Deep Home's research is that the root cause of the flow pulsations is not necessarily a turbulence phenomenon but rather is more likely related to the flow instability at the gap edge arising from the inflection point in the mean axial velocity profile: the high flow resistance in the gap creates a region of low axial velocity adjacent to a higher velocities within the subchannel. That velocity profile can create an instability which allows the shear layer to roll-up and form a vortex train with associated spanwise velocities directed across the gap. Indeed, experimental work by Gosset and Tavoularis indicated that pulsations can occur under laminar conditions. As a result of this, we have directed our recent attention towards numerical simulation of laminar flows in subchannel geometries. The study of laminar flows allowed for the complexities introduced by turbulence to be removed while retaining the key elements of the flow. This work was the focus of Alan Chettle's Master's thesis.

Alan Chettle worked on modelling laminar flow in a rectangular channel containing an eccentrically placed rod with the main axial flow parallel to the rod and the eccentric placement of the rod allowing for the synthesis of a gap region (i.e., a region of diminished axial flow) directly above the rod. Flow in this geometry has been experimentally studied by Gosset and Tavoularis whose data was used for validation of the CFD results. Experimental results of this laminar flow were based on streaklines, and the simulation results (using Lagrangian methods to allow direct comparison) matched the shape and amplitude of their experimental counterparts. Predictions of Strouhal number, which is a measure of the frequency of the vortical structures, were also in good agreement with the experimental data.

The work was further studied by Gujin Wang who is currently in the final stages of completing his master's research. Gujin's work has revealed that the vortical structures initially form in both the bottom and the top gap and that, in contrast to what was expected, the bottom vortical structures are initially much stronger than those at the top with spanwise velocities of magnitudes roughly twice those at the top gap. The results indicate that the structures in the two gaps initially form vortex trains independently that progress downstream with different convective speeds. Complex flow is seen when the vortex trains interact and a form of lock-in between the vortex trains occurs. The interaction creates flows which wrap around the rod and persist as the overall flow continues to develop. The research has confirmed that the quasi-periodic structures that are responsible for the enhanced mixing seen in subchannel geometries can occur under laminar conditions. The simulations also show that, in contrast to what has been previously presumed, the flow is not a simple vortex street. This is a result of the interactions of the structures at the two gaps. As such, rotation around the rod contributes to the complexity of the flow in this geometry and thus in nuclear fuel rod bundles. It is thus concluded that this is not a turbulence phenomenon. A journal paper on this work is currently in preparation.

The initial geometry considered by Deep Home and George Arvanitis consisted of a single rectangular gap connecting two subchannels. Alan Chettle and Gujin Wang's geometry added complexity through the inclusion of a second gap between two subchannels. This added a degree of freedom not seen in the previous cases since much more complex flows, with partial and full flow circulation around the rod, developed. The next logical step is then to examine the flow structures that arise from multiple rods and gaps. This is the focus of the Master's research of Aaron Zaretsky who completed his master's degree in December 2014. This work seeks to first quantify the rate of intersubchannel mixing in a simplified fuel bundle geometry, shown in Figure 1, using a thermal trace. Experimental data obtained by Silin & Juanico was used for validation of the CFD predictions. The simulation revealed that a bias existed in the flow through the gaps associated with the central triangular subchannel. As such unequal Stanton numbers were predicted for the three gaps: the top and right gaps had similar Stanton numbers of about 15 while the left gap was approximately twice that value. The predicted Stanton number for the left gap is in excellent agreement with the experimental value. The colour contours shown in Figure 1 indicated the predicted mean temperature 0.325 m downstream of the heater outlet. The flow bias towards the left gap of the central subchannel is clearly indicated by the enhanced extent of higher temperatures in the vicinity of the left gap. Figure 1 also shows a sample of the spanwise velocities at the top rod-to-rod gap and the bottom rod-to-wall gap. Previous work has shown that the magnitude and frequency of quasi-periodic spanwise flow is strongly influenced by the pitch-to-diameter (P/D) ratio of the rods. In the current investigation, the P/D ratio is higher in rod-to-rod gaps than rod-to-wall gaps (1.20 vs. 1.12), thus leading to interesting interactions between the flow fields produced by both gaps. Spanwise flow in the rod-to-wall gap was highly periodic with a dominant frequency of 3.42 Hz. The flow through the central subchannel gaps was much less structured with no dominant frequency and a correspondingly broad energy spectra.

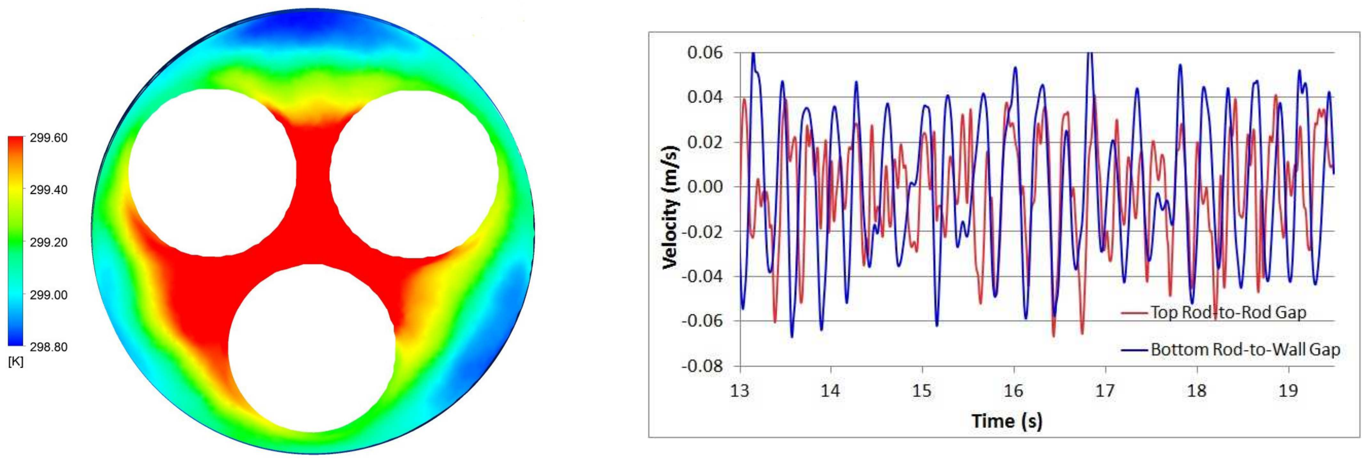


Figure 1: Cross-section of the multi-rod geometry (left) with time-averaged temperature contours resulting from the thermal trace. The flow bias in triangular subchannel is clearly illustrated. Samples of spanwise velocities at the top rod-to-rod gap and the bottom rod-to-wall gap are shown in the figure on the right. The spanwise velocities are approximately 15% and 18% of bulk axial velocity in the rod-to-rod and rod-to-wall gaps respectively.

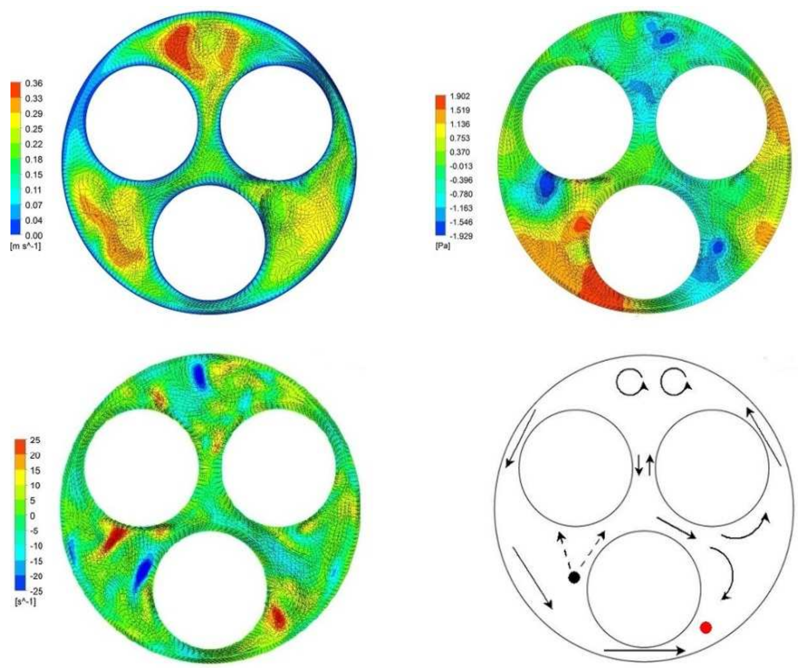
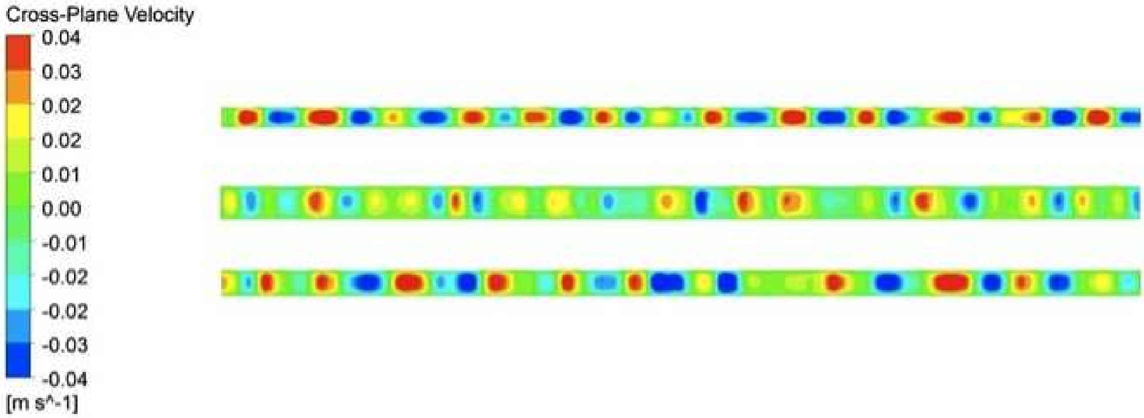


Figure 2: Instantaneous spanwise velocity vectors. The colour contours represent axial velocity (top left), pressure (top right), and axial velocity gradient (bottom left). A representation of the flow is also shown.

Examples of instanteous spanwise velocity vectors are shown in Figure 2 with the colour contours representing axial velocity, pressure, and axial velocity gradient. An illustration of the flow pattern is also shown. The red dot illustrates a point of extraction of the flow from the cross-plane due to the axial velocity increasing. The black dot shows a source of mass into the cross plane as a result of the axial velocity decrease. The flow has a clear counter-clockwise rotation around the periphery of the rods through the rod-to-wall gaps. The flow is highly synchronized and correlated with a clear periodic behaviour consistent with the Fourier analysis. The flow through the central triangular subchannel is far less structured. The odd number of gaps in that subchannel creates an interruption to the flow thus reducing flow coherence.

Case #	P/D Ratio	W/D Ratio	D_{cyl} (mm)	Re
1	1.20	0.12	26.45	1400
2	1.20	0.20	27.98	1650
3	1.152	0.152	26.45	1400

To explore the impact of the gap spacing, two additional geometries were simulated. Details of the geometry are given in the table above. Case 1 is the geometry used by Silin and Juanico in their experiments which was used for the validation study described. Cases 2 and 3 explored the impact of equal gaps but varied the magnitude of P/D. The mean axial velocity was kept constant for all cases which resulted in a variation in the Reynolds number due to the geometrical changes.



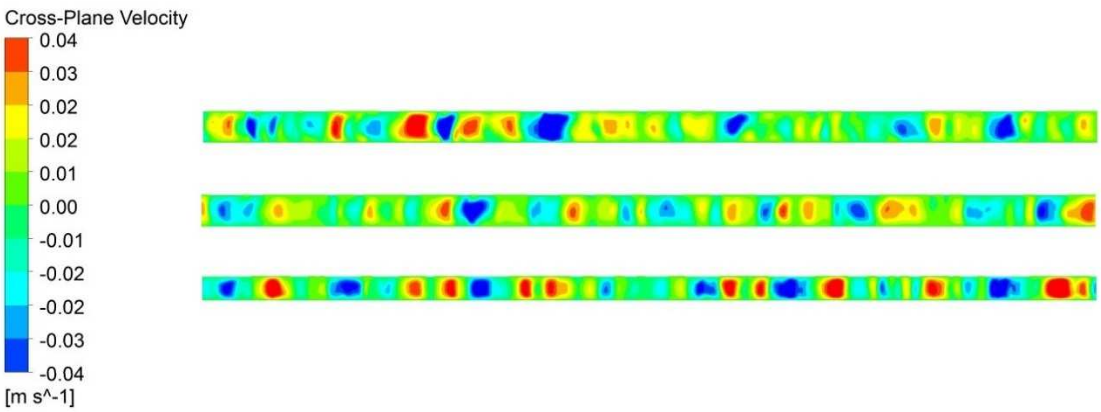


Figure 3: Snapshots of cross-plane flow through the rod-to-wall gaps (top) and rod-to-rod gaps (bottom) for Cases 1, 2, and 3. Axial flow is from left to right.

The topmost figure in Figure 3 shows the highly periodic nature of the flow through the rod-to-wall gap for Case 1. As previously discussed, the flow through those gaps is highly synchronized and alternates between a clockwise and counter clockwise rotation. For Case 1, the rod-to-wall geometry is tighter which allows a dominance of the rod-to-wall gap flow over the central subchannel gap flows. When the gaps in the central subchannel increase (Case 2) such that the rod-to-wall and rod-to-rod gaps are the same, the rod-to-wall gap flow is less structured (see the second contour from the top) than for Case 1. Reducing the gap spacing, while keeping the rod-to-rod gap and the rod-to-wall gap the same size, acts to increase the magnitudes of the cross-flows and increase coherence. The cross-plane flows through the central subchannel gaps are shown in the bottom three contours for each case. It is clear the flow is far more irregular and lacks a clear periodicity as was seen in the rod-to-wall gaps in Case 1. This work clearly shows the complexity and interactions of the gap flows within a bundle geometry even under laminar conditions.

In order to assess the theory that the underlying cause of the vortical flow structures is due to an instability, a postdoctoral fellow (Mobin Khakbazbaboli) was hired to explore the relationship between frequency of flow structures to that for canonical flows that can result in vortex-trains such as wakes behind cylinders. The analytical work was compared to predictions from CFD simulations of a compound rectangular channel with a single gap. The research has indicated that the analytically determined dominant frequency from the perturbation analysis is in approximately 20% agreement with the CFD simulations. This provides confidence that the underlying phenomenon is again due to an instability in the flow.

<u>Cases with Realized Outcomes to Industry</u>

The ultimate goal of the research is to develop improved models of thermal fluid mixing for subchannel codes such as ASSERT-PV. Much of the work by Home and Arvanitis has direct application to the increased mixing that occurs with the gap vortical flows, and this knowledge transfer has occurred through technical meetings with representatives of Bruce Power, OPG and AECL/Candu. Additional knowledge transfer has occurred through the direct employment of both Home and Arvantis by AMEC-NSS and Zaresky by Bruce Power. The lower Re number work has a more indirect outcome to industry through a more basic understanding of the phenomena, although the stability work has application to Reynolds numbers up to the full-scale fuel channels, and is important in determining the development time of this enhanced mixing/heat-transfer within the real bundles and fuel channels.

The complex nature of the underlying flow indicates that further studies should be performed to assess the impact of subchannel shape, appendages, number of fuel pins and flow rates. Directly based on the results from this UNENE/CRD project, additional work is being done by our group with Candu Energy on the effect of appendages and fuel pins on the enhancing mixing.

Research Facilities and Equipment

All numerical simulations are performed on local workstations within the CFD Laboratory at McMaster and on Sharcnet computer clusters. Sharcnet provides infrastructure for high performance computing to a consortium of Canadian academic institutions.

Current HQP Enrolled in the Programs: 2 M.A.Sc. students, 1 PDF

For the period January 1, 2014 to December 31, 2014 we had two master's students and one postdoctoral fellow working on this project. These students are listed below:

- Gujin Wang
- Aaron Zaretsky
- Mobin Khakbazbaboli (PDF)

HQP Graduated: 2 M.A.Sc.

Three students have completed their graduate studies on this topic. Their names, degrees, and current occupation are listed below:

- Alan Chettle, M.A.Sc., Currently enrolled as a Ph.D. student at University of Manchester, United Kingdom.
- Aaron Zaretsky, accepted a position with Bruce Power.

Publications

- Chettle, A., Wang, G., Lightstone, M.F., and Tullis, S. 'Numerical study of the development of a gap vortex street for laminar flow in a rectangular channel containing a rod', in preparation.
- Zaretsky, A., Lightstone, M.F., and Tullis, S. 'Simulation of Intersubchannel mixing in a triangular nuclear fuel bundle geometry', in preparation.
- Home, D. and Lightstone, M.F., 'Numerical investigation of quasi-periodic flow and vortex structure in a twin rectangular subchannel geometry using using detached eddy simulation', *Nuclear Engineering and Design,* Vol. 270, pp. 1-20, 2014
- Zaretsky, A., Lightstone, M.F., and Tullis S., 'Improved Understanding of Nuclear Subchannel Mixing, Proceedings of the 22st Annual Conference of the CFD Society of Canada (CFD2014), Toronto, June 1-4, 2014.

Interactions / Consultations with Industry

The work has been presented to the UNENE community through the student poster session on December 15, 2014 and at the UNENE workshop on December 16, 2014.