Nuclear Engineering and Design 270 (2014) 1–20

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Numerical investigation of quasi-periodic flow and vortex structure in a twin rectangular subchannel geometry using detached eddy simulation

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HIGHLIGHTS

- Dynamics of the subchannel gap vortex street was captured using the DES-SST model.
- Gap vortical structures were qualified as eddy zones with low pressure cores.
- Gap vortex formation is due to interaction between the low and high speed fluids.
- Quasi-periodic gap flow was associated with an inflectional velocity profile.

ARTICLE INFO

Article history:
Received 15 February 2013
Received in revised form 2 January 2014
Accepted 4 January 2014

ABSTRACT

The hybrid Unsteady Reynolds-Averaged Navier–Stokes (URANS)/Large Eddy Simulation (LES) methodology was used to investigate the flow dynamics and associated gap vortex structure in compound rectangular channels for isothermal flows. The specific form of the hybrid URANS/LES approach that was used is the Strelets (2001) version of the Shear Stress Transport (SST) based Detached Eddy Simulation (DES). The DES-SST model was used to study quasi-periodic flow across a gap connecting two rectangular sub-channels on which extensive experiments were conducted by Meyer and Rehme (1994). It was found that the DES-SST model was successful in predicting the characteristics of the flow field in the vicinity of the gap region. The span-wise velocity contours, velocity vector plots, and time traces of the velocity components showed the expected cross flow mixing between the sub-channels through the gap. The dynamics of the flow field were quantitatively described through temporal auto-correlations, spatial cross-correlations and power spectral functions. The numerical predictions were in general agreement with the experiments. Predictions from the model were used to identify different flow mixing patterns. As expected, the simulation predicted the formation of a gap vortex street which results in a quasi-periodic flow through the gap. Coherent structures were identified in the flow field to be comprised of eddies, shear zones and streams. Eddy structures with high vorticity and low pressure cores were found to exist near the vicinity of the gap edge region. A three dimensional vorticity field was identified and found to exist near the gap edge region. The instability mechanism and the probable cause behind the quasi-periodic fluid flow across the gap was identified and related to the inflectional stream-wise velocity profile.

1. Introduction

Nuclear safety analysis is often performed to determine the consequence of a loss of coolant accident or other event on the fuel integrity of the reactor. The analysis relies on accurate modelling 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, sub-channel methods (such as that used in ASSERT-PV and COBRA (Tóth and Aszódi, 2007)) are often employed. With these methods, the governing equations for heat transfer and fluid flow are integrated over a sub-channel and averaged quantities are determined. As a result of the spatial averaging, the fine structures of the flow are not resolved. This approach therefore requires many empirical correlations to represent the complex exchange mechanisms between the sub-channels. 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, CFD is a valuable tool for studying the complex flows in rod

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0029-5493/$ – see front matter
http://dx.doi.org/10.1016/j.nucengdes.2014.01.002

bundle geometries and for developing physics-based correlations for use in sub-channel codes.

Experimental investigations have conclusively shown that energy and momentum transport between sub-channels is greatly enhanced by large-scale, quasi-periodic vortex structures, which form across the gap (Guellouz and Tavoularis, 2000a,b; Gosset and Tavoularis, 2006). The presence of large-scale, quasi-periodic structures in the vicinity of the gap, for a range of gap widths has been demonstrated through flow visualization, spectral analysis and space-time correlation measurements. These structures, which are responsible for the quasi-periodic flow are generated in both isothermal and non-isothermal flow conditions. Indeed, in a recent review paper, Meyer (2010) concluded that flows in gaps and slots are associated with 'vortex trains'. Tavoularis (2011) recommends that these structures be referred to as a 'gap vortex street'. These large scale vortices represent a significant mixing mechanism in tightly packed rod bundle geometries. Conventional turbulence modelling such as steady-state RANS methods, based on the gradient transport mechanism has been grossly inadequate to predict the velocity and temperature fields accurately in rod bundle geometries, leading to inaccurate prediction of cross sub-channel mixing (Rock and Lightstone, 2001; Suh and Lightstone, 2004; Merzari et al., 2008a,b). Ikeno and Kajishima (2010) performed an LES study of turbulence in rod bundle geometry without heat transfer. The computational domain was comprised of four sub-channels which were large enough to capture the large-scale structures. The LES study was performed for three different values of P/D ratio, where P is the distance between rod centroids and D is rod diameter. The predictions indicated that the flow was not confined to a sub-channel, which was a direct consequence of the vortex street formed across the rod gaps between the sub-channels. The intensity of the gap flow increased as P/D decreased. The turbulence intensity profile in the rod gap suggested that the quasi-periodic flow was caused by the turbulence energy transferred from the main flow to the wall tangential direction. Merzari et al. (2008a,b) performed a detailed CFD study on assessing the applicability of unsteady turbulence modelling approaches to capture the effect of the gap vortex street in sub-channel geometries. Two different sub-channel geometries were investigated. LES was used to study flow in a rectangular duct connected by a narrow gap. The snapshots of the flow field produced from the LES results correctly revealed the presence of the large-scale vortex structure. The predicted average frequency and wavelength associated with the vortex structure was found to be in agreement with the experimental values (Lexmond et al., 2005). Proper orthonormal decomposition (POD) was used to analyze the time varying solution. The flow field was decomposed into a series of modes, and the primary modes that are responsible for mixing were found to have an oscillatory pattern. Home et al. (2009a) have assessed the applicability of predicting the quasi-periodic flow using the one equation Spalart–Allmaras turbulence model (Spalart and Allmaras, 1992) within a URANS framework. A twin rectangular sub-channel geometry was investigated and validated against the experimental data of Meyer and Rehme (1994). It was found that this modelling approach captured the characteristics of the flow field including the quasi-periodic nature of the velocity time traces, frequency and wavelength of the associated flow vortex structure. The numerical results compared reasonably well with the experiments. The important result that transpired from the work was that this modelling approach is computationally very cost effective, easy to implement and therefore is suitable for simulation of flows in more realistic sub-channel geometries formed by rod bundle arrangements. Turbulent mixing rate has subsequently been evaluated by Liu and Ishiwatari (2011) between circular channels connected by a narrow gap using a URANS approach and it was found that the mixing rate was dramatically enhanced by the cyclic and periodic flow across the gap. The numerically evaluated mixing rate compared well with the experimental data.

Recent computational advances have shed more light into the important physics of flow mixing in sub-channel geometries, with emphasis on methodologies to identify the gap vortex street and to study the sub-channel flow problem in terms of vortex dynamics. Yan (2011) and subsequently Yan et al. (2012) identified quasi-periodic large-scale vortex structure in rectangular channels with a URANS approach in a two volume and three volume rectangular duct with different surface roughness. The periodic large-scale vortex structure was found to exist in the presence of a transverse vorticity gradient in the rectangular channels without a narrow gap or slot. The presence of an unstable velocity profile is a necessary condition for large-scale vortex structure to exist. Vortex structure was found to be more significant for the channel with three volumes than in the channel with two volumes. The quasi-periodic vortex structure was observed to vanish with a decrease in channel length. Chang and Tavoularis (2012) performed three dimensional, unsteady simulations for developing turbulent flows in a rectangular channel containing a cylindrical rod and have clearly identified the core vortex street which is representative of classical sub-channel flows and responsible for inter sub-channel mixing. Different turbulence models (URANS, SAS, IDDES, LES) were tested and it was found that URANS simulations provide acceptable results for approximate tightly packed rod bundle CFD analysis, with LES providing the most accurate predictions for the mean flow, turbulence and gap vortex street. An important conclusion derived from this study was that developing flow simulations are preferable and more representative of the actual flow scenario in a CANDU 37 rod fuel bundle than simulations conducted with stream-wise periodic boundary condition.

Tavoularis (2011) in his pioneering note on rod bundle flows described flow across sub-channel gaps with representative terminologies that are synonymous with the physics of the problem. The hydrodynamic instability mechanism in the gaps connecting larger sub-channels was referred to as "gap instability". The counter-rotating vortices on either side of the gap were referred to as "gap vortex street" and the so called cross-gap flow pulsations are a result of interaction between these vortex sequences. Large-scale motions in rod bundle geometries were identified as "rod bundle vortex network".

Analysis of the literature indicates that unsteady turbulence modelling approaches are required for accurate prediction of the dynamics of the vortex street and cross-flow in sub-channel geometries. In this regard, both URANS and LES approaches have been successful at predicting the effects of the gap vortex street. URANS approaches are computationally cost effective, however, LES allows for more detailed information to be captured. LES is thus, suitable for providing fundamental insights of the complex flow and hence can be used for subsequent development of physics based constitutive models for sub-channel flows. However, computational cost is a major issue for LES especially for fully wall bounded flows that occur in sub-channel flows for rod bundle geometries (Home et al., 2009b; Merzari and Ninokata, 2009). Indeed the CPU effort required to simulate a complete rod bundle arrangement (rather than twin sub-channels) at the actual reactor flow conditions using LES is likely to be prohibitively expensive. This leads to an important question as to what could be an appropriate modelling approach for sub-channel flows in rod bundle geometries, which would correctly predict the underlying physics while remaining computationally cost effective. In this regard, the hybrid URANS-LES methodology which has the ingredients of both URANS and LES, combined into one approach, could be a suitable choice (Home et al., 2009b). For sub-channel flows, the region of interest are the gaps where large-scale coherent vortical structures are formed, which induce the quasi-periodic flow across the gap. The