Annals of Nuclear Energy 38 (2011) 1023–1032

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Unsteady Reynolds Averaged Navier–Stokes simulation of the turbulent flow pulsation and coherent structures in a tight lattice in rolling motion

B.H. Yan [a,*], H.Y. Gu [b], L. Yu [a]

[a] Department of Nuclear Science and Engineering, Naval University of Engineering, 717 Jiefang Street, Wuhan 430033, China
[b] School of Nuclear Science and Engineering, Shanghai Jiao Tong University, 800 Dong Chuan Road, Shanghai 200240, China

ARTICLE INFO

Article history:
Received 6 May 2010
Received in revised form 18 December 2010
Accepted 6 January 2011
Available online 3 February 2011

Keywords:
Rolling motion
Turbulent flow
Tight lattice
Coherent structure

ABSTRACT

The flow in a tight lattice is strongly affected by the quasi-periodic lateral flow pulsations caused by large scale vortices. This kind of large scale vortices is largely responsible for the momentum and heat exchange across the gaps. In rolling motion, the coherent structure and flow oscillation are affected by an additional force. The coherent structure in rolling motion is more significant than that in no rolling motion. The oscillation period in rolling motion is about 10% bigger than that in no rolling motion. The rolling motion can affect the coherent structure. However, the effect of rolling motion on the thermal hydraulic parameters, i.e. wall temperature and bulk temperature, is very limited. The wall temperature and wall shear stress in rolling motion and no rolling motion are nearly the same. The additional force due to rolling motion can change the moving characteristics of coherent structures, but its effect on the turbulent flow and heat transfer is weak.

1. Introduction

Rod bundles are essential elements of pressurized water nuclear reactors. They consist of tightly packed arrays of rods, which contain the nuclear fuel and are surrounded by flowing liquid coolant. Flow phenomena in the sub-channels bounded by adjacent rods or outer rods and the containing pressure tube walls are quite complex and exhibit patterns not present in pipe flows. In particular, rod–rod and rod-wall gap regions are characterized by strong transverse flow pulsations, which are largely responsible for momentum and heat transfer across the gaps.

It has been found that secondary flows in rod bundle geometries are very small. Further, they do not contribute significantly to the mixing between sub-channels of the rod bundles for small pitch to diameter ratio, since secondary flow vortices are expected to move within the elementary cells of the sub-channels. Experimental investigations have conclusively shown that cross sub-channel mixing is greatly enhanced by transport due to large-scale, quasi-periodic pulsations, which form across the gap (Guellouz and Tavoularis, 2000a,b; Gosset and Tavoularis, 2006). A thorough understanding of these coherent structures and their role in inter-sub-channel mixing would be of benefit to safety analysis of nuclear reactors and to the design of future, improved rod bundles.

Several experimental studies have examined heat and momentum transport in rod bundles, particularly near the narrow gaps between rods and between rods and the surrounding duct, with the general conclusion that flow in these regions is dominated by quasi-periodic transverse flow pulsations (Rehme, 1992; Guellouz and Tavoularis, 2000a,b; Moller, 1991; Wu, 1995; Chang and Tavoularis, 2005). It has been accepted that these flow pulsations are caused by large scale vortices, which form in pairs on either side of each gap. These vortices meet the definition of "coherent" structures, as flow modules with instantaneous phase-correlated vorticity (Hussain, 1983).

The use of Reynolds Averaged Navier–Stokes model in an unsteady simulation (URANS) has the potential of resolving large scale flow oscillations, where the length scales of these macroscopic structures are much larger than the typical turbulence scales (as it is the case for the flow pulsations). The implementation of URANS approach in comparison to DNS and LES permit much coarser grids for the simulation, which consequently leads to larger time stepping resulting in orders of magnitude difference in computing time (Merzari et al., 2008).

Chang and Tavoularis (2005) used URANS approach with a Reynolds stress model to simulate isothermal axial flow in a rectangular channel containing a cylindrical rod. The unsteadiness in the flow field due to the flow pulsations was reproduced (quasi-periodic character of the time history of the span-wise velocity in the centre of the gap) and the coherent structures near the narrow gap region were identified. It was observed from the study that coherent components were significant in the gap region and accounted for 60% of the total kinetic energy.

* Corresponding author. Tel.: +86 21 34204917.
E-mail address: binghuoy@163.com (B.H. Yan).

0306-4549/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.anucene.2011.01.010

Nomenclature

General symbols

a	acceleration (m^2/s)
F	additional force (N)
p	pressure (Pa)
S	rate of strain tensor
T	period (s)
t	time (s)
U,W	velocity (m/s)
x	coordinate (m)

Greek letters

β	angle acceleration (rad^2/s)
δ	constant
μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
ω	angle velocity (rad/s)
Ω	rotation tensor

Superscripts

$^-$	time averaged
$'$	fluctuation variable
$\rightarrow$	vector
+	dimensionless variable

Subscripts

i	x, y, z directions
m	maximum
c	coherent component
nc	non-coherent component

In recent years, there has been a growing interest in a barge mounted floating nuclear desalination plant to provide potable water in coastal areas. Such plants are cost effective when compared to land-based nuclear power plants, have lesser construction periods and the potential to shift to any place, and have simplified anti-seismic design measures and decommissioning technology (Panov et al., 1998).

The main difference from a fluid mechanics point of view between a land-based and barge-mounted equipment is the influence of sea wave oscillations on the latter. The thermal hydraulic behaviour of barge-mounted equipment is influenced by different motions such as rolling, pitching and heaving motions (Figs. 1 and 2). Oscillations change the effective forces acting on the fluid and induce flow fluctuations, which result in a change in momentum, heat and mass transfer characteristics (Pendyala et al., 2008a,b). A series of single-phase natural circulation experiments were carried out by Murata et al. (2002) and Ishida and Yoritsune (2002), for analyzing the effect of rolling motion on the thermal hydraulic characteristics of reactor. Tan et al. (2009) carried out a series of experiments to study the single-phase natural circulation flow and heat transfer under rolling motion condition. Yan et al. (2010a,b,c) also investigated the laminar flow in rolling motion with theoretical methods.

In engineering application, the tube diameter is usually very small (less than or next to 10 mm). In this case, the flow in ship movement could be restricted by the wall (Yan et al., 2010d). As a result, the effect of ship movement on the flow and heat transfer characteristics of turbulent flow in tubes or rectangular channels is limited. But the tight lattice is one kind of open channel. The turbulent mixing between the sub-channels should not be neglected. In ship movement, the transverse flow within the lattice may be affected by the additional forces due to ship motions. Thus the turbulent mixing and heat transfer may also be changed.

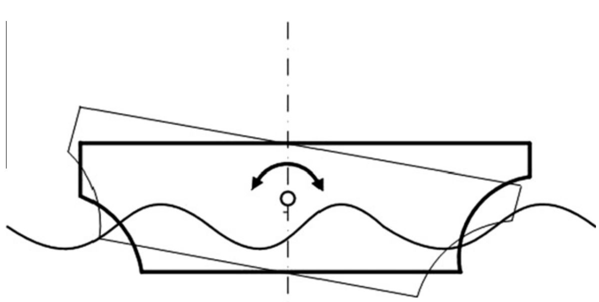

Fig. 1. Schematic of rolling motion.

In the present paper, the flow and heat transfer characteristics of turbulent flow in triangular rod bundles in ship motions is investigated theoretically with CFD code FLUENT. The effects of ship movement and other parameters on the flow and heat transfer characteristics of turbulent flow in tight lattice are also analyzed. The calculation results were firstly validated with experimental data in no rolling motion. Then the effect of rolling motion on the turbulent flow and the coherent structure was analyzed. It is hoped that the present work will contribute to the understanding of these important flow phenomena and will facilitate the prediction and design of rod bundles and other complex engineering systems.

2. Theoretical models

2.1. Analysis of ship motions

The ship movement mainly includes rolling, heaving and heeling motions (Lewis, 1967), which are shown in Figs. 1 and 2. In heeling motion (transverse inclination), there is no additional acceleration and force. The force affect on the flow is similar with that in steady state. The momentum and energy equations are also the same with that in steady state. There is no difference between the parameter characteristics of heeling motion and steady state. All the equations in steady state are applicable for heeling motion (Yan et al., 2010a,b). In fact, the heeling motion could be considered as a quasi-steady state. In the present paper, only the effect of rolling and heaving motions on flow in tight lattice is investigated.

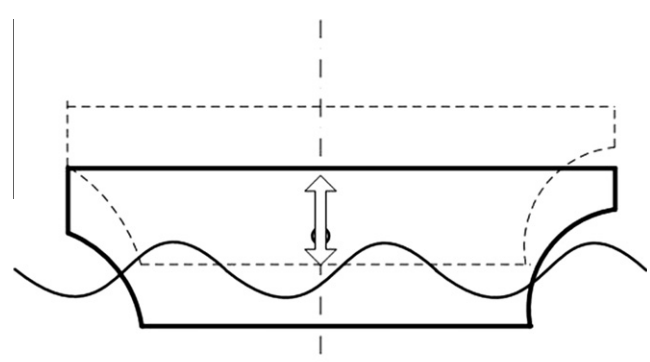

Fig. 2. Schematic of heaving motion.