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Analysis of inter-channel sweeping flow in wire wrapped 19-rod bundle

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ABSTRACT

Helical wire spacers are widely used in sodium cooled fast reactors. One of the main effects of wire spacers is enhancing the inter-channel cross flow in triangular arrayed rod bundles. To study the characteristic of sweeping flow rate across the gaps between the sub-channels, the computational fluid dynamics (CFD) method is used in the present study to analyze the flow field in a 19-rod bundle with wire wraps. This CFD work only considers the fluid zone of one section of the rod bundle. The height of the CFD model with periodic inlet and outlet boundary conditions is one wire pitch. The $k-\omega$ SST model is used as the turbulent model. The wire effect on the velocity distribution of the flow across the interface between two sub-channels is investigated in the CFD study. Based on the force balance equation between the wire wake force and the surface friction force of rods in the circumferential direction, a theoretical model for estimating the average swirling flow rate driven by one single wire is proposed. The simulation shows that the ratio of rod pitch (P) to rod diameter (D) has a strong effect on the velocity of the sweeping flow. The flow rate increases with the P/D ratio. The simulation agrees well with the proposed model. In addition, the effect of the ratio of wire pitch (H) to rod diameter has also an influence on the cross flow rate: A small H/D ratio leads to higher cross flow rate. A correlation as a function of both P/D ratio and H/D ratio is proposed to predict the sweeping flow velocity by the present study.

1. Introduction

Helical wire wrapped rod bundle is used as the main component of fuel assembly in sodium cooled fast reactors. The main functions of the wire spacers are supporting the fuel pins to keep the space between each other, and enhancing the flow mixing in the sub channels of the fuel assembly. The sweeping flow induced by the wires enhances the inter-channel energy exchange, therefore the temperature distribution in the cross section of the flow path of the fuel assembly is smoothed. Since it is a crucial design criterion to keep the cladding and fuel temperatures lower than their upper limits, the effect of the wire on the thermal hydraulic behavior of the sub-channels is very important to the safety analysis. Due to the complexity of the flow passage geometry of a hexagonal arranged rod bundle with wire spacers, the accurate prediction is still a great challenge to engineers. Figuring out the inter-channels sweeping flow distribution in axial direction is one of the key points of the present study.

In the fuel assembly of fast reactors, the fuel rods are usually arranged in a triangular array. The aim of this arrangement is to obtain a small volume ratio of coolant to fuel compared with the quadrilateral arrangement. The flow passage of the sub assembly can be divided into sub channels by the narrow gaps between the fuel pins. The width of the gap is very close to the diameter of the wire, and the wires of two fuel rods next to each other come into the gap alternately, while the inter-channel cross flow direction also changes periodically. The magnitude of the sweeping flow could be affected by the geometry parameters and flow condition. The sweeping flow influenced by the complicated geometry of the flow passage plays an important role in the thermal hydraulic analysis of fuel assembly. So a deeper understanding of the mechanism, and a good prediction of the sweeping flow rate will have a practical engineering value to get a more accurate core thermal hydraulic prediction result.

In the last 45 years, a lot of numerical approaches and experimental studies were carried out, and many models were proposed for the sub-channel analysis. For the sub-channel code COBRA, a model named "forced flow inter-channels mixing" was proposed by Ginsberg (1972). In this model, the transverse flow rate is purely based on the geometric consideration, and the flow velocity is presumed maximum where the wire cross the gap. The cross flow distribution is expressed as a cosine function. A comparison of forced flow and turbulent mixing model reveals the turbulent mixing model is an inadequate representation of the inter-channels flow characteristic of fuel assembly with wire spacer system. In the sub-channel code ORRIBLE, an approximate correlation was proposed by Wantland (1974) to predict the cross flow due to the wire wrap. In this model, the turbulent mixing and the transverse thermal conduction were considered. In this kind of sub channel

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Nomenclature

English alphabets and Greek symbols

α	wire position angle
γ	flow velocity to axis angle
ω	specific dissipation
ρ	density
τ	shear stress
θ	wire incline angle
φ	starting wire position angle
C	coefficient
c	width of gap
D	rod diameter
F	force
H	wire pitch
k	turbulent kinetic energy
n	surface normal
P	rod pitch, pressure
U	velocity
u	velocity
$y+$	dimensionless wall distance
z	wire axial position

Subscripts

$*$	normalized
a	axial
$circ$	circuit
D	drag
f	friction
gap	gap
r	rod
t	transverse, turbulent
w	wire

approach, the investigation assumes the flow direction goes with the helical wire, and the maximum velocity is also assumed to occur on the position where the wire is in the gap between two adjacent rods, and the wire is assumed to occupy no flow area. With this assumption, the ratio of transverse flow velocity to axial velocity is obtained with the geometry input of H/D ratio. Where the wire is more than 60 degrees away from the gap, the influence is assumed negligible. For less than 60 degrees, the influence is assumed to obey a correlation. This model is also based on geometric consideration. Ninokata et al. (1987) proposed the "distributed resistance model" as an alternative model of the "forced flow inter-channel mixing model". The force exerted on the fluid by the wall is called the distributed resistance term. It includes the friction and the form drag from the surfaces of rods and wires.

In recent years, the CFD technology was widely used in the reactor core thermal hydraulic simulation. Hu and Fanning (2013) developed a momentum source model to simulate the anisotropic flow in wire wrapped pin bundle without the need to resolve the geometric details of the wire. The source term is only dependent on the local velocity profile. Both CFD model of complex geometry and bare bundle with momentum source term are evaluated in the study from them. Raj and Velusamy (2016) performed RANS simulations on a 217-rod bundle. They reported the friction factor, Nusselt number, and transverse flow rate. An empirical correlation based on CFD simulation results was given by them. The correlation gives a more accurate prediction on the position of maximum transverse velocity compared with Wantland correlation. Although the maximum velocity position has been figured out with the CFD results, the transverse flow rate is estimated in a similar way as the sub channel approach, with a linear regression to the ratio of wire pitch to rod diameter and the axial mean velocity.

Generally, the sweeping flow distribution in axial direction should be a function of P/D ratio, H/D ratio, and Re number. All previous studies assume that it only depends on the H/D ratio. As a key design parameter, the P/D ratio effect still needs a further study. The motivation of this paper is to give a more accurate correlation for sweeping flow velocity with a physical explanation of the effects of the main geometry parameters.

2. A wake effect driving force model

In Fig. 1, the crucial geometry parameters for the study of sweeping flow are shown. The pitch of rods refers to the distance between the center points of two rods, while the wire pitch refers to the length of one section. Usually, the gap width is very close to the diameter of wire. The P/D ratio is the most important parameter in the design of fuel and rod. The axial position of the flow cross section in the fuel assembly can also be represented by the wire position angle. In this paper, it is assumed that the wires locate exactly in the rod gaps at the inlet plane, where the wire position angle $\alpha = 0$. Since the cross section of the helical wire rotates in the axial direction of the rod, the wire position angle also refers to the angle between the wire and the gap.

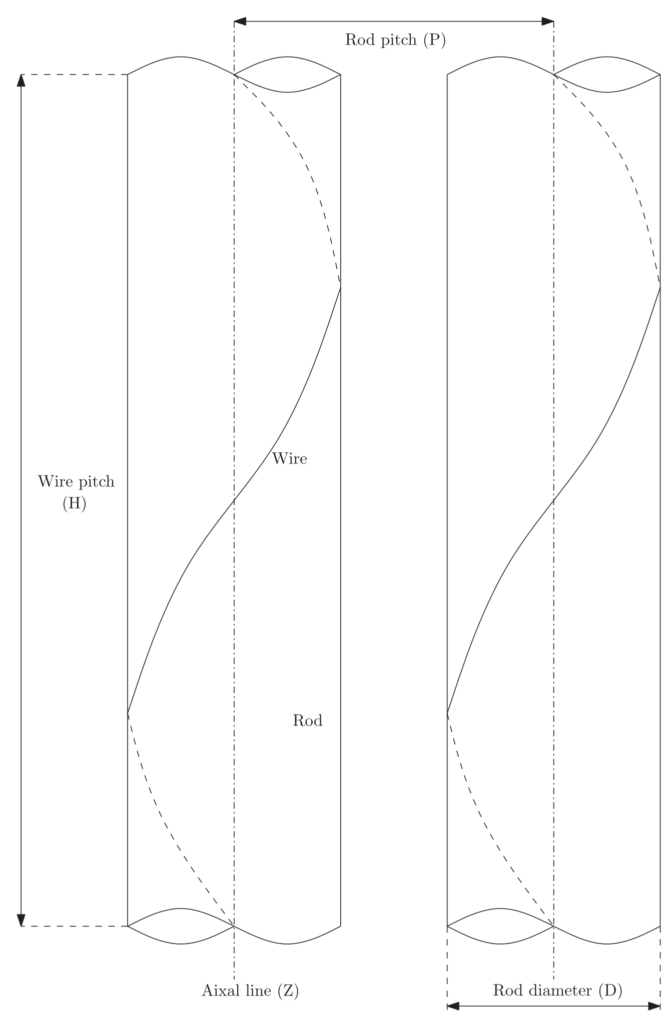

Fig. 1. Schematic diagram of rods and wires.