Nuclear Engineering and Design 339 (2018) 105–115

Contents lists available at ScienceDirect

Nuclear Engineering and Design

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

Experimental study on the heat transfer enhancement in sub-channels of 6 × 6 rod bundle with large scale vortex flow mixing vanes

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ARTICLE INFO

Keywords:
Rod
Bundle
Support grid
Mixing vane
LSVF mixing vane
Spilt mixing vane

ABSTRACT

In this study, single-phase heat transfer characteristics for downstream flow in the support grid of 6 × 6 rod bundle were investigated. It is known that turbulence generated by a support grid with split mixing vanes enhances heat transfer in a rod bundle. However, the enhancement is observed in relatively short length. Further, a support grid with large scale vortex flow (LSVF) mixing vanes enhances heat transfer over a relatively longer distance. Based on the results of previous studies, heat transfer experiments were performed at Reynolds numbers of 30,000 and 50,000, and the effects of heat transfer enhancement with both i) the split mixing vanes and ii) LSVF mixing vanes were compared in this study. The results showed that the effects of heat transfer enhancement in the rod bundle region by the split mixing vanes were maintained up to a length of 15 D_h behind the spacer grid. At a Reynolds number of 50,000, it was observed that the effects of heat transfer enhancement by the LSVF mixing vanes were approximately 3% higher than those by the split mixing vanes for a distance ranging in 1–15 D_h behind the spacer grid.

1. Introduction

A pressurized water reactor (PWR) fuel assembly consists of fuel rods, control rods, and spacer grids with mixing vanes, as shown in Fig. 1. A spacer grid in a fuel rod assembly secures the flow channel of the coolant, maintains the structural form of the fuel rod to withstand external shock, and suppresses flow-induced vibration. Further, it improves the capability of preventing critical heat flux (CHF). The occurrence of CHF in a nuclear reactor can damage fuel rods by increasing the surface temperature of the fuel rod up to the melting point. Therefore, the design of fuel rods must include a sufficient thermal margin to suppress the occurrence of CHF under normal operating conditions. For this purpose, a mixing vane is attached to the end of the spacer grid. The mixing vane increases convective heat transfer by causing a swirling and cross flow, which forces flow mixing between the reactor sub-channels and generates turbulence. If the geometric shape of the fuel rod bundle and the heat release rate are under the same condition, the overall heat transfer performance of fuel rods will be governed by the secondary flow induced by the spacer grid.

The flow inside the fuel assembly will be laminar in the case of a loss of coolant accident, whereas it will be turbulent under normal operating conditions. Turbulent flow in sub-channels is characterized by the cross-flow mixing between sub-channels, anisotropy of turbulence diffusion, and secondary flow.

Fig. 2 shows the main secondary flow phenomena in sub-channels. The cross-flow mixing between the sub-channels, which is caused by the difference in flow cross-sectional areas between the sub-channels, equalizes the temperature of the fluid. Although experimental correlations for heat transfer enhancement through cross-flow mixing have been developed in several studies, theoretical correlations have not been established yet owing to the complex turbulence structure and geometry of the sub-channels.

In general, the flow in a sub-channel is spiral, and this spiral flow is caused by the secondary flow, which generates an average shear stress to maintain the balance between the pressure gradient and Reynolds stress in the cross section of a flow channel. Compared with the main flow, the secondary flow is relatively small, but it strongly influences the mean velocity distribution, wall shear stress, and turbulence kinetic energy of the main flow (Carver et al., 1995). Rowe and Chapman (1973) studied the effect of a spacer grid on turbulence by investigating the turbulence structure of a spacer grid upstream and downstream by using Laser Doppler Velocimetry (LDV). In addition, Shen et al. (1991) concluded that the mixing ratio was strongly influenced by the angle of mixing vane by measuring the cross-flow velocity and turbulence

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https://doi.org/10.1016/j.nucengdes.2018.09.004
Received 18 December 2017; Received in revised form 28 May 2018; Accepted 5 September 2018

Nomenclature

A	area (m^2)
D	rod diameter (m)
D_h	hydraulic diameter (m)
h	convective heat transfer coefficient
k	heat transfer coefficient
Nu	Nusselt number ($\frac{hD_h}{k}$)
T	temperature (°C)
x	x axis
z	z axis

Subscripts

D	fully developed
m	measured
s	surface

intensity in rod bundle sub-channels including a spacer grid with mixing vanes by using LDV.

Yang and Chung (1996) measured the axial velocity, turbulence intensity, skewness factor, flatness factor, and spectral energy in 5 × 5 and 6 × 6 rod bundle assembly sub-channels with spacer grids by using LDV. It was found that the turbulence intensity in the main-flow direction at the end of the spacer grids was the largest, and it decreased rapidly downstream until it reached the previous level. It was also found that the turbulence in a spacer grid downstream was more isotropic than that upstream. Chang et al. (2008, 2014) measured the axial velocity and turbulence intensity for rectangular 5 × 5 and 6 × 6 rod bundles by using LDV. The pressure drop was also measured to evaluate the loss coefficient of the spacer grid and friction factor. From these data, it was found that mixing factors showed the highest values near the spacer grid and decreased rapidly up to about $x/D_h = 15$.

Park (2002) compared the effects of heat transfer enhancement with split mixing vanes and Large Scale Vortex Flow (LSVF) mixing vanes in a rod bundle spacer grid. Blum and Oliver (1996) confirmed that internal flow with a swirling flow showed greater heat transfer enhancement than that without a swirling flow. Yao et al. (1982) developed two correlations for the local heat transfer characteristics in a spacer grid downstream of a rod bundle: the correlation between the redevelopment of the boundary layer and the change in flow channel cross-sectional areas in a spacer grid and the correlation between the heat transfer downstream in a spacer grid with mixing vanes and the boundary layer effect.

Karoutas et al. (1995) analyzed the structure of turbulent flow in a rod bundle with mixing vanes through experiments and a numerical analysis. Imaisumi et al. (1995) suggested the computational flow analysis method to evaluate the three-dimensional flow characteristics due to mixing vanes.

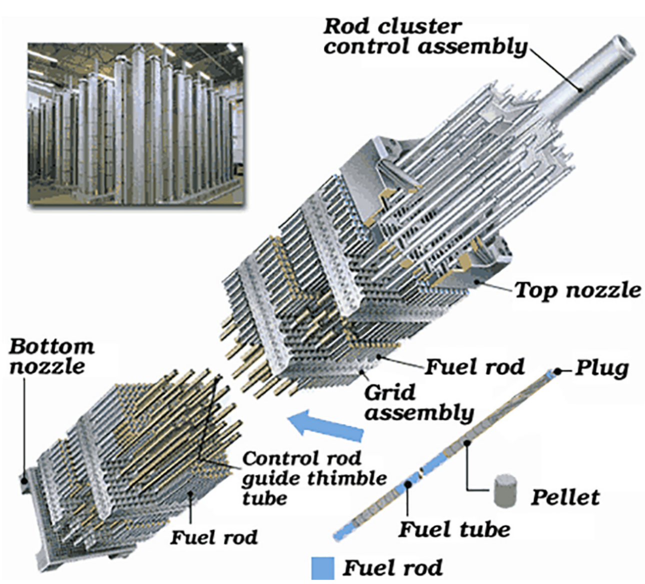

Fig. 1. Typical fuel rod assembly of pressurized light water nuclear reactor.

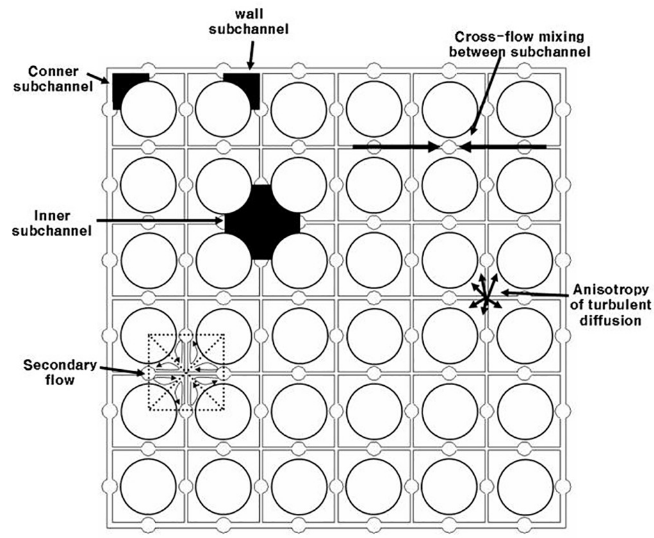

Fig. 2. Configuration and secondary flow phenomena in sub-channel.

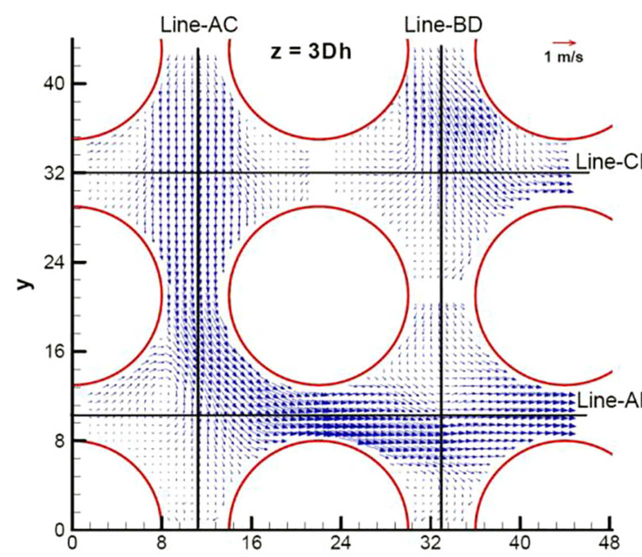

Fig. 3. Lateral vector profile, measured using LDV measurement, in the sub-channels with LSVF mixing vanes (Seo, 2009).

In et al. (2000, 2001) suggested several types of mixing vanes through a numerical analysis and compared the flow mixing ratio and pressure drop according to the angle of the split mixing vane and twisted mixing vane.

Cui and Kim (2003) numerically analyzed the effect of the twist angle of a mixing vane on heat transfer. Kim and Kim (2002) and Kim and Seo (2005) studied the shape optimization of a PLUS7 mixing vane. An and Choi (2006) numerically analyzed the heat transfer