Annals of Nuclear Energy 63 (2014) 409–416

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Experimental study on the convective heat transfer enhancement in single-phase steam flow by a support grid

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ARTICLE INFO

Article history:
Received 3 January 2013
Received in revised form 30 July 2013
Accepted 2 August 2013
Available online 3 September 2013

Keywords:
Support grid
Single-phase steam flow
Convective heat transfer

ABSTRACT

Single-phase flow occurs in the fuel rod bundle of a pressurized water reactor, during the normal operation period or at the early stage of the reflood phase in a loss-of-coolant accident scenario. In the former period, the flow is single-phase water flow, but in the latter case, the flow is single-phase steam flow. Support grids are required to maintain a proper geometry configuration of fuel rods within nuclear fuel assemblies. This study was conducted to elucidate the effects of support grids on the convective heat transfer in single-phase steam flow. Experiments were made in a square array 2 × 2 rod bundle. The four electrically-heating rods were maintained by support grids with mixing vanes creating a swirl flow. Two types of support grids were considered in this study. The two types are geometrically similar except the blockage ratio by different mixing vane angles. For all test runs, 2 kW power was supplied to each rod. The working fluid was superheated steam with Re = 2,301–39,594. The axial profile of the rod surface temperatures was measured, and the convective heat transfer enhancement by the presence of the support grids was examined. The peak heat transfer enhancement was a function of not only the blockage ratio but also the Reynolds number. Given the same blockage ratio, the heat transfer enhancement was sensitive to the Reynolds number in laminar flow, whereas it was nearly independent of the Reynolds number in turbulent flow.

1. Introduction

The nuclear reactor core of a pressurized water reactor is composed of fuel rod bundles arranged by square support grids. The support grids are not only to maintain a constant distance between rods within nuclear fuel assemblies, but also to secure the flow passage. They also enhance the convective heat transfer from the fuels to the coolant at a cost of pressure loss. Owing to the reduced flow area by the grids, flow undergoes contraction and expansion, and as a result, the flow is highly disturbed and convective heat transfer is improved. Chang and Dhir (1995) attributed the heat transfer enhancement in a swirling pipe to two mechanisms. The radial pressure gradient in the swirling flow leads to increased axial velocities near the pipe wall, and thus enhances the convective heat transfer from the wall to the fluid. In addition, high turbulent levels enhance the mixing and improve the heat transfer.

The nuclear core experiences single-phase liquid flow during the normal operation period of nuclear reactors. While it becomes exposed to single-phase steam flow at the early stage of the reflood phase in a loss-of-coolant accident scenario. In both circumstances, the heat transfer from the fuel to the coolant is significantly affected by the support grids. Therefore, it is important to investigate the effect of the support grids on the convective heat transfer.

The single-phase heat transfer enhancement by a support grid has been studied intensively for a long time. Marek et al. (1973) conducted heat transfer measurements in 3 × 3 and 4 × 4 rod bundles arranged in square arrays to provide relations between the pressure drop and the convective heat transfer. The working fluid was Helium between heating rods. The Reynolds number (Re) was in the range of 10^4 to 3×10^5. They found that the pressure loss could be correlated with the square of the blockage ratio of a support grid and suggested the upper limit of the enhanced Nusselt number (Nu). The detailed geometry of the test grids was not described in that study. Rehme (1973) performed a variety of experiments for grids and wire wraps in a water loop. The pressure drop was successfully correlated with the square of the blockage ratio. The Reynolds number ranged from 10^3 to 3×10^5. Rehme (1977) and Marek and Rehme (1979) carried out experiments regarding pressure loss and heat transfer in smooth and roughened rod bundles. It was revealed that the pressure drop across the grid

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http://dx.doi.org/10.1016/j.anucene.2013.08.013

Nomenclature

A	open flow area, heating surface area of four rods (m^2)
D_h	hydraulic diameter (m)
K_g	pressure loss coefficient for the test grid (–)
K_s	pressure loss coefficient for the strap (–)
Q	power (W)
T_s	steam temperature (°C)
T_w	rod wall temperature (°C)
V	average steam velocity (m/s)
a	parameter associated with the peak heat transfer enhancement (–)
b	heat transfer enhancement attenuation rate (–)
h	average convective heat transfer coefficient (W/(m^2 K))
k	steam thermal conductivity (W/(m K))
m_s	stream flow rate (kg/s)
x	downstream distance from the grid (m)
z	axial distance from the starting point of the heating region (m)
Nu	Nusselt number (–)
Nu_0	Nusselt number at the undisturbed region (–)
Re	Reynolds number (–)
SG	support grid
Greeks	
ε	blockage ratio (–)
ρ	steam density (kg/m^3)
μ	steam viscosity (Pa s)

and the maximum heat transfer enhancement could be correlated with the square of the blockage ratio. The working fluid was water.

Yao et al. (1982) developed a correlation to predict the Nusselt number downstream of a standard grid, utilizing the results by Marek and Rehme (1979). The correlation is a function of the blockage ratio and the normalized axial distance as follows:

$$\mathrm{Nu}/\mathrm{Nu}_0 - 1 = 5.55\varepsilon^2 \exp(-0.13x/D_h) \tag{1}$$

where Nu and Nu_0 are the Nusselt numbers in the disturbed region behind the grid and in the undisturbed region ahead of the grid, respectively. The variables of ε, x and D_h are the blockage ratio, the downstream distance from the grid, and the sub-channel hydraulic diameter, respectively. Note that the above correlation is applicable for high Reynolds numbers greater than 10^4, and is independent on the Reynolds number.

The above correlation states that the heat transfer enhancement decays exponentially when going downstream. Yao et al. (1982) compared the correlation with six types of previous experimental data and concluded that the heat transfer augmentation downstream of the grids was well predicted by the suggested correlation. The maximum heat transfer, however, was not well predicted as expected. Yoder (1985) discussed intensively the effects of support grids, looking into existing experimental data. He stated that the correlation developed by Hassan and Rehme (1981) includes the Reynolds number, Graetz number, and blockage ratio dependence.

More recently, Cui and Kim (2003) analyzed the turbulent heat transfer behind a support grid with mixing vanes using RANS simulations. They showed numerically that the Nusselt number decays when going downstream. Holloway et al. (2004) conducted experiments in a 5 × 5 rod bundle. A total of seven types of support grids were considered. The working fluid was water, with a range of Re = 2.8×10^4–4.2×10^4. They reported the pressure loss factor for each grid type and related it to the heat transfer as follows:

$$\mathrm{Nu}/\mathrm{Nu}_0 - 1 = \left(6.5\varepsilon^2 + 3.2(K_g - K_s)/K_g\right) \exp(-0.8x/D_h) \tag{2}$$

where K_g is the pressure loss coefficient for the test grid, and K_s is the pressure loss coefficient for the strap. Holloway et al. (2008) performed experiments in a 5 × 5 rod bundle heated in a facility

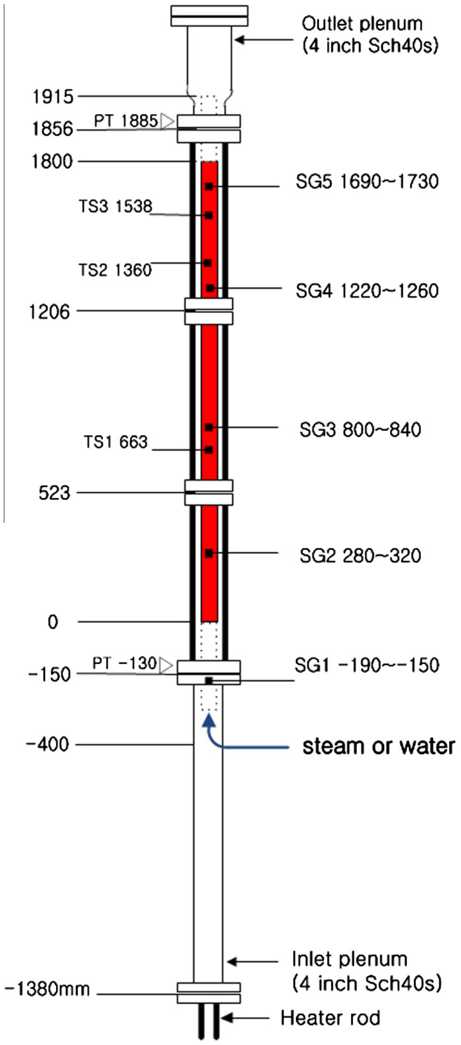

Fig. 1. Schematic diagram of the experimental setup.

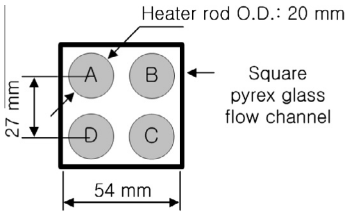

Fig. 2. Cross-sectional view of the 2 × 2 rod bundle.