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Experimental study of laminar mixed convection in a rod bundle with mixing vane spacer grids

Lokanath Mohanta [a,*], Fan-Bill Cheung [a], Stephen M. Bajorek [b], Kirk Tien [b], Chris L. Hoxie [b]

[a] Department of Mechanical and Nuclear Engineering, Pennsylvania State University, University Park, PA 16802, USA
[b] Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, USA

HIGHLIGHTS

- Investigated the heat transfer during mixed laminar convection in a rod bundle with linearly varying heat flux.
- The Nusselt number increases downstream of the inlet with increasing Richardson number.
- Developed an enhancement factor to account for the effects of mixed convection over the forced laminar heat transfer.

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ABSTRACT

Heat transfer by mixed convection in a rod bundle occurs when convection is affected by both the buoyancy and inertial forces. Mixed convection can be assumed when the Richardson number ($Ri = Gr/Re^2$) is on the order of unity, indicating that both forced and natural convection are important contributors to heat transfer. In the present study, data obtained from the Rod Bundle Heat Transfer (RBHT) facility was used to determine the heat transfer coefficient in the mixed convection regime, which was found to be significantly larger than those expected assuming purely forced convection based on the inlet flow rate. The inlet Reynolds (Re) number for the tests ranged from 500 to 1300, while the Grashof (Gr) number varied from 1.5×10^5 to 3.8×10^6 yielding $0.25 < Ri < 4.3$. Using results from RBHT test along with the correlation from the FLECHT-SEASET test program for laminar forced convection, a new correlation is proposed for mixed convection in a rod bundle. The new correlation accounts for the enhancement of heat transfer relative to laminar forced convection.

1. Introduction

In a hypothetical loss of coolant accident following the quenching of the bundle, the heat transfer regime can be mixed convection in the lower portion of the reactor core. For long-term cooling of the reactor core, mixed convection would be the prevailing mode of heat transfer. It should be noted that the new generation of small modular reactors with passive safety cooling systems highly depend on mixed convection heat transfer. In addition to nuclear reactor applications, mixed convection heat transfer mode also occurs in other engineering fields including, for example, cooling of electronic equipment, solar energy systems, drilling of oil wells, and removal of pollutants from confined spaces (Maudou et al., 2013).

Mixed convection heat transfer has been extensively studied for vertical surfaces (Sparrow and Gregg, 1959; Lloyd and Sparrow, 1970; Wilks, 1973; Oosthuizen and Bassey, 1973; Ramachandran et al., 1985) and vertical channels (Aung and Worku, 1986; Barletta and Zanchini, 1999; Boulama and Galanis, 2004; Desrayaud and Lauriat, 2009; Gau et al., 1992). In the existing mixed convection studies (for both laminar and turbulent flows), the Nusselt number is correlated as a function of several non-dimensional parameters including Gr, Pr, Re, Ra, and Gz. Laminar mixed convection in partially blocked vertical channel was studied by Habchi and Acharya (1986). In their study, the Nusselt number was found to decrease in the streamwise direction with a local maximum at the blockage. Jackson et al. (1989) provided a detailed review of mixed convection in vertical tubes. They found that the Nusselt number correlates well as a function of Gr/Re. Jackson and Fewster (1977) correlated the enhancement factor (Nu/Nu_0) for circular tubes as a function of $Gr/(Re^{21/8})$ for opposing turbulent flows. Swanson and Catton (1987) presented an enhancement factor for vertical parallel plates in terms of the Richardson number. A later work on laminar mixed convection in a vertical circular tube with uniform heat flux for both opposed and assisted flow in the

* Corresponding author.
E-mail address: lxm971@psu.edu (L. Mohanta).

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laminar Reynolds number range of 400–1600 was presented by Mohammed (2008). They found that the Nusselt number is high at the inlet and decreases axially downstream, but the mixed convection Nusselt number was higher than the laminar forced convection. The Nusselt number was correlated for buoyancy assisted flow as a function of Gr/Re.

In addition to simple geometries, the study of mixed convection has been extended to annulus and rod bundle geometries. Maitra and Raju (1975) showed that the Nusselt number varies with $Ra^{1/4}$ in mixed convection in a vertical annulus. Maudou et al. (2013) studied mixed convection in vertical annular channels with and without eccentricity. An increase in the Nusselt number with increasing Re was observed for both concentric and eccentric channels. Dawood et al. (2015) presented a review of experimental and numerical work on mixed convection heat transfer in concentric as well as eccentric annulus geometry. Yang (1978) in a theoretical study analyzed mixed convection in both square and triangular array rod bundles, and showed that the Nusselt number increases with Gr/Re. An analytical solution was proposed by Iannello et al. (1988) for fully developed laminar mixed convection flows in an annular and in rod bundle geometries with a triangular array. They obtained a relation for the Nusselt number as a function of Gr/Re. Suh et al. (1989) correlated the subchannel pressure drop in laminar and transitional mixed convection as a function of $\ln(1 + (Gr/Re)$. Kim and El-Genk, (1989) investigated single-phase heat transfer in a triangular array rod bundle. Based on the experimental data it was concluded that the flow can be treated as forced laminar flow for $Ri < 1$ and mixed convection for $Ri \geqslant 1$. In mixed convection regime, they correlated the Nusselt number as

$$Nu = aRi^b Re^c \tag{1}$$

The values of a, b and c depend on the pitch to diameter ratio of the bundle. A similar study was conducted by El-Genk et al. (1993) in a nine-rod square array rod bundle. They concluded that the mixed convection regime is significant when $Ri \geqslant 2$ for a square array rod bundle. The Nusselt number in the mixed convection regime was obtained by superimposing the correlations for forced and natural convection. Kim (1979) presented a Nusselt number for infinite rod bundle with square pitch of 1.33 as given below

$$\frac{Nu}{Pr^{0.33}} = 7.86 \tag{2}$$

In the FLECHT-SEASET test program (Wong and Hochreiter, 1981), steam cooling tests were conducted in a 161-rod unblocked bundle with square array having pitch to diameter ratio of 1.33. A minimum Reynolds number for transition to turbulent flow was observed to be 2500 from the test data. They recommended the Nusselt number given in Eq. (2) for laminar forced convection.

Previous studies demonstrated that in mixed convection the Nusselt number is a function of Gr/Re^n, with the value of n being different from different studies. The effect of mixed convection is found to be important in the range of $0.3 < Ri < 5$ for a vertical plate (Venugopal et al., 2008). Sudo et al. (1990) defined the mixed convection regime to be in the range of $0.0001 < Gr/(Re^{21/8}) < 0.01$. For a rod bundle having a uniform heat flux, El-Genk et al. (1993) concluded that the flow can be treated as forced laminar for $Ri < 2$ in a square array. In the present work, experiments were conducted in a 7×7 rod bundle that has mixing vane type spacer grids. The rod bundle has linearly increasing heat flux. Experimental data obtained in the present work shows that mixed convection is important even at very low Ri ($\sim$0.3). The local Nusselt numbers are found to be higher than those reported by El-Genk et al. (1993). An enhancement factor has been developed in this study to account for the effect of mixed convection in the form of $\ln(1 + (Gr/Re^2))$.

2. Experimental method

2.1. Test facility description

The Rod Bundle Heat Transfer (RBHT) test section consists of 7×7 full-length electrically heated rods with a diameter of 9.5 mm (0.374 in) and pitch of 12.6 mm (0.496 in) with seven spacer grids placed in a square flow housing of 90.2 mm (3.55 in) Rosal et al. (2010), Hochreiter et al. (2012). The test section simulates a portion of a commercial size 17×17 rod bundle. There are 45 electrically heated rods and 4 support rods in the corners. The length of the heated portion of the rod bundle is 3.66 m (144 in) with a top-skewed axially linear power profile. The peak power is 1.5 times the average power at 2.74 m (108 in) elevation, and 0.5 times of the average power at both ends. A schematic of the flow loop and a 3-D drawing of the facility is shown in Fig. 1. The flow loop consists of a water supply tank, injection line with a centrifugal pump with the capacity of 0.946 m^3/min, a flow meter having a range 0–454 kg/min, lower plenum, test section, upper plenum, carryover tanks, and pressure oscillation damping tank connected to the exhaust line.

To measure the temperature in the rod bundle, 256 K-type thermocouples are located on the inside surface of the cladding with a distribution that covers the entire length of the test section. The bundle has seven mixing vane spacer grids with a design prototypical of a commercial fuel bundle. Fig. 2(a) shows an actual photograph of the spacer grid with a few rods and a traversable temperature probe. An isometric view of the spacer grid used in the rod bundle is shown in Fig 2(b). The first spacer grid is located at a distance of 0.102 m from the inlet and the second spacer grid is at a distance of 0.588 m from the first spacer grid. The other spacer grids are separated by 0.522 m subsequent to Grid 2. These spacer grids have the same blockage ratio of 36.22%, when viewed from the top. Several thermocouples are mounted on the spacer grid. In order to measure the centerline temperature, 13 traversable probes having three thermocouples each (as shown in Fig. 2(a)) are installed at various axial locations. The RBHT facility has 23 differential pressure (DP) cells mounted on the flow housing. Sixteen DP cells having a span length of 76.2–127 mm (3–5 in) are used to provide a detailed axial pressure drop near the middle of the bundle. High-resolution digital cameras along with an infrared laser are used to observe the flow field in the bundle. There is also appropriate instrumentation to measure the input power, inlet flow rate, exhaust steam flow rate, inlet liquid temperature, upper plenum pressure, flow housing temperature, and liquid level.

2.2. Test procedure

Several level swell tests were carried out in the RBHT facility using deionized water (Hochreiter et al., 2016; Welter et al., 2006). The system pressure, regulated using a Nitrogen line connected to the supply tank, was varied from 138 to 414 kPa (20 to 60 psia). To carry out a test, water was fed to the test section through the lower plenum having a flow straightener, which ensures a uniform flow distribution in the test section. The power was applied to the bundle using a DC power supply. Inlet velocities were varied from 2.5 to 40.6 mm/s. When the flow rate was varied the bundle was allowed to reach steady state, which took few hundred seconds; then temperature measurements were recorded for more than 100 s at a frequency of 1 Hz. The inlet liquid subcooling was varied from 11 to 56 K. The power of the bundle was varied from 54 kW to 144 kW.

In all the level swell tests, the lower portion of the bundle exhibited single-phase cooling. However, to evaluate mixed convection effects, only tests in which single-phase convection was

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