International Journal of Heat and Mass Transfer 126 (2018) 493–507

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical investigation of heat transfer and pressure drop in nuclear fuel rod with three-dimensional surface roughness

Amitav Tikadar [a], Umair Najeeb [b], Titan C. Paul [c], Saad K. Oudah [a], Azzam S. Salman [a], Ahmed M. Abir [a], Leo A. Carrilho [d], Jamil A. Khan [a,*]

[a] Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA
[b] Arclin, Columbia, SC, USA
[c] Department of Mathematical Sciences and Engineering, University of South Carolina Aiken, Aiken, SC, USA
[d] Westinghouse Electric Company, 5801 Bluff Road, Hopkins, SC, USA

ARTICLE INFO

Article history:
Received 12 March 2018
Received in revised form 25 May 2018
Accepted 28 May 2018

Keywords:
Turbulent flow
Friction factor
Surface roughness
Heat transfer

ABSTRACT

The paper focuses on the numerical studies of heat transfer and pressure drop in a simulated nuclear fuel rod with three-dimensional surface roughness. Two-dimensional numerical simulations utilizing SST $k-\omega$ turbulent model were performed to evaluate heat transfer and pressure drop on the smooth and rough section of the heater rod. The numerical results were compared with experimental data obtained from a heater element which simulates a single Inconel-Nickel fuel rod for pressurized water reactor (PWR). The length of the rod was 2152.6 mm, and an outer diameter 9.5 mm, of which the outer surface of a 304.8 mm long section of the Inconel fuel rod was modified with three-dimensional (Diamond-shaped blocks) surface roughness. The angle of corrugation for each diamond block was 45°, and the length of each side of the diamond block was 1 mm. The numerically computed local heat transfer coefficient, overall Nusselt number, and pressure drop across the test rod shows good agreement with the corresponding experimental results. For the simulated rough surface, heat transfer coefficient was enhanced by 86% at $Re = 4.18 \times 10^5$ as compared to the smooth surface, and pressure drop was found to increase by 15.75% within Re range of $4.50 \times 10^4 - 1.07 \times 10^5$. Plausible reason of the heat transfer enhancement of the three-dimensional surface roughness was discussed in the paper.

1. Introduction

Electricity utility companies face an ever-growing demand for electricity due to continuous industrial expansion and growing residential and commercial power needs. Due to it's constant electricity generation capacity, lower operating cost, and zero carbon emission compared to the conventional power plants [1,2], nuclear energy plays an important role in the electricity generation techniques throughout the world. For single phase flow regime of the working fluid, pressurized water reactor (PWR), and for two-phase flow regime (liquid-gas), boiling water reactor (BWR) are commercially used in nuclear industries. In the case of modern nuclear fuel rod bundle in a pressurized water reactor (PWR), maximization of heat extraction from the fuel rod to increase the bulk fluid temperature and to eventually augment the power generation rate of the nuclear power plant is a major challenge for the thermal engineers. Therefore, an optimally designed nuclear fuel rod bundle in a PWR reactor is preferred to meet the continuously increasing electrical load and allow the system to operate at near maximum efficiency.

Steinke et al. [3] studied heat transfer enhancement techniques for single-phase conventional flow channels and compact heat exchangers. These techniques include flow transition, the breakup of the boundary layer, entrance region, vibration, electric fields, swirl flow, secondary flow, and mixers. Bergles et al. [4] presented a more detailed and well-categorized heat transfer enhancement techniques. According to them, the heat transfer enhancement techniques for single phase can be categorized in two ways such as active techniques, and passive techniques. The active techniques require an external input in the form of electricity, radio frequency (RF) signals, and power. Some of the popular techniques in this regard are flow pulsation, electric field exposure, synthetic-jet, and vibration. Effect of pulsation frequency on the heat transfer behavior was analytically examined by Moschandreou et al. [5]. Kim et al. [6] experimentally studied the effect of ultrasonic vibration on heat transfer performance in natural convection, sub-

* Corresponding author at: Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208, USA.
E-mail address: khan@cec.sc.edu (J.A. Khan).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.141
0017-9310/

Nomenclature

Q''	heat flux, W m^{-2}
T	temperature, K
k	thermal conductivity, W m^{-1} K^{-1}
y	local length, m
L	rod length, m
D, d	diameter of the rod, m
Re	Reynolds number
v	velocity of the fluid, ms^{-1}
D_h	hydraulic diameter, m
ΔP	pressure drop, Pa
Nu	Nusselt number (dimensionless)
f	friction factor (dimensionless)
h	convection heat transfer coefficient, W m^{-2} K^{-1}
A	area
CL	center line
S	smooth
R	rough

Greek letters

ρ	density, kg m^{-3}
μ	dynamic viscosity, Pa s

Subscript

in	inlet
out	outlet
eff	effective
m	mean
b	bulk
o	outer
i	inner
w	wall of the rod
f	fluid
ave	average

cooled boiling, and saturated boiling regime and reported a significant augmentation of heat transfer especially in natural convection regime. The effect of the micro-synthetic jet and micro-nozzle on the thermal performance of the micro-channel heat sink had also been studied [7–9].

Although significant augmentation of heat transfer can be achieved through active cooling techniques, nevertheless it requires additional cost. Therefore, passive cooling technique is getting more attention as the method of choice for heat transfer enhancement. It requires no external power and can be achieved by modifying the geometry, flow disruption, secondary flows, and by changing the fluid thermo-physical properties. Numerous studies have been conducted by various scholars to enhance the heat transfer passively. Firth et al. [10] conducted an experimental investigation of heat transfer and friction factor performance in the fully developed turbulent flow region with four different types of artificial roughness, among them three were two-dimensional roughness. The two-dimensional roughened surfaces were square transverse ribbed surface, helically ribbed surface, and trapezoidal transverse ribbed surface. Among these three roughened surfaces, square transverse ribbed surface and helically ribbed surface shows better thermal performance than the trapezoidal transverse ribbed surface. Han and Park [11] experimentally studied the combined effect of the angle-of-attack and the channel aspect ratio on the distribution of local convection heat transfer coefficient in the developing flow region for a Reynolds number range of 10,000–60,000. Experimental result illustrated strong dependency of heat transfer performance on both the angle-of-attack and the aspect ratio, and each aspect ratio corresponds to a particular angle-of-attack for best thermal performance. The effects of two-dimensional surface roughness on turbulent convection heat transfer were experimentally examined by Li et al. [12]. The results illustrated that to get best heat transfer enhancement, roughness height should be three times of the viscous sublayer thickness.

Also, Kandlikar et al. [13] experimentally investigated the effect of surface roughness on heat transfer and pressure drop in commercially available 316 stainless steel tubes which had an inner diameter of 1.067 mm, and 0.62 mm respectively. In the case of large diameter pipe, the authors observed less sensitivity of thermo-hydraulic behavior on surface roughness than a small diameter pipe. The effects of three different kinds of surface roughness along with the interconnector as a passive cooling technique in a mini-channel heat exchanger were numerically studied by Hossain et al. [14]. Oudah et al. [15] experimentally investigated the thermo-hydrodynamic performance of sandblasted micro-channel heat sink and reported significant heat transfer augmentation with a negligible penalty of pumping power. Carrilho [16] used a two-dimensional roughness to enhance heat transfer from a single pressurized water reactor heater rod. In that study, a square-transverse ribbed surface was used to compare the heat transfer, and pressure drop with a smooth surface as the coolant flows over the roughened heater/fuel rod. The author reported approximately 50% enhancement of heat transfer coefficient in the rough region compared to the smooth region.

Three-dimensional surface roughness is also a commonly used passive cooling technique for heat transfer augmentation. Meyer [17] conducted an experimental investigation of friction factor and thermal performance of a three-dimensionally roughened rods. The results showed three-dimensional surface roughness results in a higher increment of the friction factor, and Stanton number $(Nu/RePr)$ than the two-dimensional surface roughness. Three-dimensional corrugated channels are widely used in rotary regenerators, and plate-type heat exchangers. Groehn et al. [18] conducted an experimental investigation on two knurled roughness tubes with a cross flow in an inline tube bank. It was observed that, at low Reynold's number, heat transfer augmentation was negligible but at higher Reynolds's number such as $Re = 100,000$, heat transfer enhancement was about 50% for both tubes. Garcia et al. [19] experimentally studied the effect of three roughness shape, e.g., corrugated tubes, dimpled tubes, and wire coils on the thermo-hydraulic performance with respect to the smooth tubes in laminar, transition, and turbulent flow regimes. The effect of corrugation angle with the overall flow direction was experimentally investigated by Focke et al. [20]. The results strongly suggest that swirl in a furrow was produced due to the velocity component of the fluid moving along the opposite furrows in a direction perpendicular to the furrow and the maximum heat transfer rate can be achieved when corrugation angle is equal to 80°. Friction factor, and heat transfer characteristics of viscous oil $(125 < Pr < 525)$ in rectangular, and square ducts with wire coils, and transverse rid were experimentally studied by Saha [21,22] in both laminar and turbulent flow regimes. The effect of surface roughness as a turbulent promoter at Reynold's number less than 2000, was visually investigated by Ravigururajan et al. [23] and Li et al. [24]. Kang Liu [25] compared the effect of two-dimensional surface roughness (square transverse ribbed surface),