Progress in Nuclear Energy 109 (2018) 270–279

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Simulation of nanofluid dryout phenomenon in a PWR rod bundle with mixing vanes using computational fluid dynamics

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ARTICLE INFO

Keywords:
Critical heat flux
Mixing vane
Spacer grid
Alumina nanoparticles
Flow boiling

ABSTRACT

Critical Heat Flux (CHF) threshold is one of the vital issues to be considered in nuclear power plants. One way to address this problem is to add nanoparticles to the base fluid in order to enhance the heat transfer capacity. In this research, the influence of alumina nanoparticles in the presence of mixing vanes on dryout phenomenon has been numerically investigated. It was observed that nanoparticles in the host fluid, besides the presence of mixing vanes attached to the spacer grid lead to delayed sudden changes in the wall temperature. It was found that with nanoparticles concentration of approximately 8 percent, the abrupt rise in temperature takes place near the channel exit and with 9 vol % concentration, CHF phenomenon would not occur. Regarding the obtained results, in a certain nanoparticles concentration (9 vol%), film boiling would not occur and for the formation of dryout phenomenon in such concentrations, exerted wall heat flux should be increased to about 9.4% of the primary heat flux magnitude. Comparing the results in flow boiling revealed that increase in nanoparticles concentration imposes a growing trend on the magnitude of both convective and boiling heat transfer coefficients according to the Chen's relation.

1. Introduction

Nuclear fuel rod assembly accompanied by Spacer grids provides mechanical support which keeps a constant distance between the fuel rods and also prevents the fuel rod wreckage from flow induced vibrations. Mixing vanes that are attached to the spacer grids, produce a swirling flow in the subchannel and consequently increase the overall heat transfer performance as an essential design factor. Enhancing the CHF threshold of boiling systems, which would lead to an improved thermal efficiency and reduced operational costs, has orientated the scientists' researches in nuclear industries towards employing nanoparticles application for the past few decades. To accomplish this goal, nanofluids have been considered as one of the effective approaches especially under accident conditions. It is noted that critical heat flux (CHF) describes the thermal limit of a phenomenon where a phase change occurs during heating which suddenly decreases the efficiency of heat transfer, thus causing localized overheating of the heating surface. The activities performed by researchers in this area are mentioned in the following.

Hoyer (1998) carried out an experiment on flow boiling while the boiling crisis took place due to the exertion of a high heat flux beyond the CHF magnitude. It was evidenced that a vapor film formed around the channel wall leading to a sudden rise in wall temperature. Kim et al. (2009) constructed an experimental setup to investigate the critical heat flux phenomenon with alumina, zinc oxide and diamond/water nanofluids under operating pressure of 0.1 MPa and various mass fluxes in order to report a critical heat flux enhancement. Li et al. (2010a) studied a two-phase flow boiling based on a model proposed by Rensselaer Polytechnic Institute (RPI) using the available software (FLUENT) within a two-fluid framework. It was shown that relatively good results were obtained compared to the experimental data. Ahn et al. (2010) conducted an experiment on the dryout phenomenon during forced convective flow boiling in the presence of 0.01 vol % alumina nanoparticles. Kim et al. (2010a) studied the CHF enhancement of alumina/water nanofluid boiling flow under atmospheric pressure. CHF enhancement for all test conditions was reported in a way that the presence of 1 vol % nanoparticles increased the CHF level to about 70.24%.

Kim et al. (2010b) experimentally studied the boiling flow heat transfer of dilute water and alumina, zinc oxide and diamond nanofluids at various operating pressures in order to investigate the enhancement of heat transfer coefficient by increasing the mass and heat flux. A simple model was used to consider the nucleation site density changes, as a result of nanoparticles deposition on the heated surface.

Jun et al. (2012) evaluated the safety of a system thermal-hydraulically by employing the TASS/SMR-S code. In the current

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https://doi.org/10.1016/j.pnucene.2018.08.017
Received 22 July 2017; Received in revised form 10 July 2018; Accepted 27 August 2018

Nomenclature

A_b	Portion of wall surface covered by bubble (m^2)
$\overrightarrow{B_f}$	Body force (N)
C_{wt}	Bubble waiting time coefficient
d_{bw}	Bubble departure diameter (m)
d_b	Bubble diameter (m)
F^D	Drag force (N)
F^L	Lift force (N)
F^{TD}	Turbulent drift force (N)
f_{bw}	Bubble departure frequency (Hz)
H_{lv}	Latent heat (Jkg^{-1})
H	Specific enthalpy (JKg^{-1})
k	Thermal conductivity ($Wm^{-1}K^{-1}$)
$\dot{m}$	Rate of mass transfer (kgs^{-1})
N_w	Nucleation site density (#sites m^{-2})
P	Pressure (Pa)
S_H	External heat source term
$\dot{q}$	Heat flux (W)
V	Velocity vector (m/s)

Greek letters

ρ	Density (kgm^{-3})
α	Void fraction
τ	Shear stress tensor
γ	Fluid/Phase heat diffusivity
σ	Surface tension coefficient
Φ	Turbulent parameter
Γ	Diffusion coefficient

Subscripts

C	continuous phase
C	Convection
D	dispersed phase
E	Evaporation
G	Other gas phases
L	liquid
V	vapor
r, q	q^{th} and r^{th} phase

research, the employed heat transfer model in TASS/SMR-S code was validated by the available experimental data of Bennett's heated tube tests and thermal hydraulic test facility (Bennett et al., 1976). Wall temperature distribution besides the critical heat flux location were investigated and compared with the experimental data.

Heyhat et al. (2013) constructed an experimental setup in order to investigate Al_2O_3/water nanofluid convective heat transfer and showed a 32% increase of heat transfer coefficient at 2 vol% concentration of nanoparticles. In another work, an experimental test was carried out by Lee et al. (2013) on the boiling flow critical heat flux in the presence of 0.01 vol % graphene oxide/water nanofluid. It was revealed that the CHF threshold of the nanofluid was promoted up to twice the base fluid value. Lee et al. (2014) carried out an experiment on the effect of two phase flow conditions such as exit quality on CHF enhancement of nanofluids. A CHF enhancement was reported when the exit quality was low due to the presence of nanoparticles in the host fluid and the occurrence of the boiling crisis was delayed. Palandi et al. (2014) examined the thermal-hydraulic performance of nanofluids and mixing vanes in a triangular fuel rod bundle by assuming the nanofluid in fuel rod bundle as two-phase mixture model. Furthermore, the effect of mixing vanes with four different angles on the thermal-hydraulic parameters was investigated. It was reported that nanofluids were about 50 percent more efficient in improving the heat transfer coefficient than utilizing the mixing vanes attached to the spacer grids.

Various nanoparticles under a range of mass fractions, qualities and mass velocities were experimentally investigated by Sun and Yang (2014) for the purpose of examining the boiling flow heat transfer characteristics of nano-refrigerants. The yielded results showed that the Cu nanoparticles were the best selection among other considered nanoparticles. In another work, the effect of Alumina nanoparticles on nucleation site density changes, surface wettability and also thinning of the thermal boundary layer was experimentally investigated by Yu et al. (2015). It was revealed that nanofluids have a delaying effect on the onset of nucleate boiling. Setoodeh et al. (2015) carried out an experiment on the subcooled flow boiling by considering alumina/water nanofluid with a 0.25 vol % as the working fluid in order to examine the hot spot factor. Two independent empirical correlations were proposed for the subcooled boiling flow heat transfer inside a channel with a hot spot.

Bi et al. (2015) proposed a model for predicting the heat transfer characteristics and CHF in nanofluid boiling. The values of the analytical heat flux and CHF for both pure fluid and nanofluids were compared to the available experimental data indicating that a good agreement was achieved. It was shown that the CHF enhancement ratio increased to a value about 3.54 by decreasing the contact angle from 80 to 20°.

The effect of various parameters on the boiling characteristics in the presence of Alumina was studied experimentally by Wang and Su (2016). It was shown that the average value of Nusselt number was promoted to about 23% and 45% for nanoparticle concentrations of 0.1 vol % and 0.5 vol %, respectively. In addition, a dimensionless parameter was proposed for the intention of the data processing.

An experiment was carried out by Soleimani and Keshavarz (2016) observing the heat transfer enhancement of subcooled flow boiling over a hot spot. The influence of the fluid velocity, nanoparticles concentrations and surface characteristics were studied such that increasing the velocity and surface roughness would lead to an increase in surface heat flux. Nanofluids with concentrations equal to 0.1 and 0.25 vol % were employed. It was concluded that nanofluids especially with the higher concentrations (0.25 vol %) showed better thermal characteristics. Abedinia et al. (2017) numerically modeled the subcooled flow boiling of alumina/water nanofluid employing the mixture model. Temperature and axial vapor volume fraction distribution in comparison with experimental data in literature were reported. It was concluded that under constant inlet mass flux, increase in nanoparticles concentration would have an opposing effect on vapor volume fraction magnitude.

Based on the available data in the open literature, the effect of spacer grids accompanied by the existence of mixing vanes has been extensively studied specially in boiling flow regimes. However, there are a few limited researches that present the effect of nanofluids on postponing the dryout phenomenon when the critical heat flux conditions have been reached. Moreover, most of these studies have been performed experimentally and a minority of them are accomplished by employing computational fluid dynamics and a detailed study of the flow situation has not yet been reported Therefore, in this study, the effect of the presence of the mixing vanes accompanied by nanofluid as the working fluid on the critical heat flux characteristics in the dryout phenomenon has been numerically investigated by applying the two-fluid model. Numerical simulation of CHF phenomenon in addition to the relations required to describe the heat flux partitioning has been demonstrated, subsequently.

2. Numerical simulation of boiling flow field

In the present study the Reynold averaged Navier-Stokes equations