Annals of Nuclear Energy 118 (2018) 154–164

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

A new dimensionless thermal hydraulics parameter for the heat exchangers

Muhammad Ilyas, Fatih Aydogan *

Center for Advanced Energy Studies (CAES), Idaho State University, Idaho Falls, ID, USA

ARTICLE INFO

Article history:
Received 7 September 2017
Received in revised form 29 March 2018
Accepted 6 April 2018

Keywords:
Dimensionless thermal hydraulics parameter
Heat exchangers of nuclear power plants

ABSTRACT

Thermal and hydraulic considerations are crucial for the design of an efficient heat exchanger (HX) which allow boiling. Steam generator is one of the biggest and most expensive components of most nuclear power plants. Therefore, design perfections of heat exchangers can lead to improved design of steam generators. Two-phase heat transfer coefficient (HTC) strongly depends on the prevailing flow regime for a given surface pattern as well. The enhancement in HTC is associated with an increase in frictional pressure drop. A single parameter for characterization of heat transfer surfaces based on thermal and hydraulic consideration doesn't exist. A new dimensionless number for thermal and hydraulics characterization (DITCH) of the heat exchanger surface has been derived for evaluation of heat transfer surfaces. It captures the hydraulic behavior of coolant due to phase change and wall friction. Its value characterizes different flow regimes of two phase flow. Analysis of a selected data reveals that DITCH increases with quality 'x' and the mass flow rate '$\dot{m}$'. A steep increase up to $x = 0.4$ is followed by lesser slope. It is also observed that bubbly flow regime has a least value of this parameter whereas slug flow regime has a value less than 1. This ratio is nearly equal to one or higher for the annular flow region. It is therefore concluded that in annular flow regime, compared to the other flow regimes, heat transfer coefficient is getting significant and pressure drop is getting insignificant.

1. Introduction

Heat exchangers are utilized in the primary and secondary coolant systems of nuclear power plants Fig. 1).

A steam generator (SG) is one of the most expensive and biggest components of a pressurized nuclear power plant. The SG of a typical PWR employs vertical U-tube bundle such that hot primary coolant flows through inside of the U-tubes whereas feedwater flows around outside of the tubes. The Westinghouse and Combustion Engineering recirculation steam generators are shown in Figs. 2 and 3 respectively. In both these designs, water from the steam separators mixes with the main stream secondary coolant and rises over the U-tube bundle as it is partially converted to steam. The steam-water mixture passes through multiple levels of steam separation equipment which returns the water to the U-tube bundle for further heating and evaporation. Steam generators by the Pressurized Water Reactor vendors differ slightly in their designs and operations. The process of moisture separation and steam drier is so efficient that the water content in the outlet steam is less 0.25%.

Heat transfer enhancement is crucial in the new design of the heat exchangers, such as steam generators. In most of the heat transfer systems, boiling of the coolant is allowed to increase heat transfer. Phase change enhances heat transfer drastically as latent heat of vaporization is considerably larger compared to sensible heat. Heat transfer coefficient (HTC) can be enhanced significantly by changing smooth surface channel to one with a surface having small-scale geometric patterns. The modification in surface offers high density of nucleation sites, more surface area, increased turbulence and disruption of the boundary layer thereby contributing to more heat transfer. However, the modified surfaces are associated with an increase in the fractional pressure drop as well. So, in essence, there is a trade-off between heat transfer coefficient and frictional pressure drop.

A formidable body of research work has been done for investigation of thermal and hydraulic behavior of single-phase and two-phase flow under varied flow conditions and geometries. The purpose of the present work is not to attempt a comprehensive review of the previous for which the reader is referred to (Asadi et al., 2014; Attinger, 2014; Wu and Sundén, 2014). However, a brief review of the relevant literature is presented here.

The earliest reported work on fluid dynamics dates back to the work of Archimedes (287–212 BCE) who introduced some basic

---

* Corresponding author.
E-mail address: aydofati@isu.edu (F. Aydogan).

https://doi.org/10.1016/j.anucene.2018.04.011

Nomenclature

Abbreviations

HX	Heat Exchanger
HTC	Heat transfer Coefficient
DITCH	DImensionless number for Thermal and hydraulics CHaracterization of the heat exchanger
BWR	Boiling Water Reactor
PWR	Pressurize Water Reactor
SG	Steam Generator
CHF	Critical Heat Flux
ONB	Onset of Nucleate Boiling
EHT	Enhanced Heat Transfer
Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number

English Alphabets with the SI units

P	pressure (Pa)
G	mass flux (kg/m^3-s)
x	quality
X	Martinelli parameter
D	diameter (m)
f	friction factor
z	elevation (m)
V	velocity (m/s)
h	heat transfer coefficient (W/m^2-K)
L	characteristics length (m)
k	thermal conductivity (W/m-K)
C	Chisholm constant
A	surface area (m$^{2)}$
T	temperature (K)
Q	heat quantity (W)
H	enthalpy of the fluid (J)

Greek letters

υ	specific volume (m^3/kg)
ρ	density of the fluid (kg/m^3)
μ	dynamic viscosity of the fluid (N-s/m^2)
Δ	change in a given parameter

Superscripts/Subscripts

TP	Two-phase
acc	Acceleration
fric	Frictional
grav	Gravitational
h	hydraulic
f, L	liquid phase
V, g, G	vapor phase

Miscellaneous

υ_{fg}	difference of liquid and vapor specific volume (m^3/kg)
H_{fg}	difference of liquid and vapor enthalpy (J)
ϕ^2_{lo}	Lockhart-Martinelli multiplier for liquid only
c_p	specific heat at constant pressure (J/kg)
$\dot{m}$	mass flow rate (kg/s)

ideas in fluid statics. Then the progress on the understanding of fluid flow halted for centuries until observation/explanation of complex flows over objects in streams by Leonardo da Vinci (1452–1519). However, a quantitative understanding of the physics of fluid flow started with examination of fluid statics/dynamics by Isaac Newton (1642–1727). This was followed by the work of Daniel Bernoulli (1700–82), Jean le Rond d'Alembert (1717–83), and Leonhard Euler (1707–83) leading to a profound physical understanding and mathematical formulation of fluid flow. It took another century when Claude-Louis Navier in 1822 modified Euler equations to a system of even more elaborate nonlinear partial differential equations now called the Navier–Stokes equations (Anderson, 2005).

Since then, extensive research has been carried out for prediction and measurement of thermal and hydraulic parameters for single/two-phase flow under varied conditions and geometries by many researchers. For the purpose of generality, these parameters are represented in dimensionless groups. Numerous interesting dimensionless groups have been defined as a result of dimensional analysis of fluid mechanical problems. The most important of these is the Reynolds number (Re) defined as the ratio of inertial forces to viscous forces. Reynolds (Reynolds, 1884) established through careful experimentation that the nature of the flow can be predicted in a convenient way on the basis of Re number for the given flow conditions. For flow in a circular tube of diameter D at an average velocity V, the Reynolds number Re is defined in Eq. (1).

$$\mathrm{Re} = \frac{DV\rho}{\mu} \tag{1}$$

where μ is the dynamic viscosity of the fluid, and ρ is the density of the fluid.

Then the concept of boundary layer in a fluid flow over a surface introduced by Ludwig Prandtl in his publication in 1905 (Prandtl, 1928) revolutionize the understanding of fluid dynamics. The effectiveness of the boundary layer on momentum diffusivity as compared to thermal diffusivity is represented by the Prandtl number defined as the ratio:

$$\mathrm{Pr} = \frac{c_p\mu}{k} \tag{2}$$

where c_p is the specific heat and k is the thermal conductivity of the fluid.

In 1915, Wilhelm Nusselt derived a set of dimensionless numbers by dimensional analysis of the partial differential equations of fluid flow and heat transfer in turbulent pipe flow. Out of these, the number that represents the ratios of convective heat transfer to the fluid to the thermal energy conducted within the fluid is now known worldwide as the Nusselt number (Martin, 2014) given by:

$$\mathrm{Nu} = \frac{hL}{k} \tag{3}$$

where L is the characteristic length.

As of the present time, a large number of dimensionless groups have been defined on the basis of experimental and theoretical studies by numerous investigators, the reader is referred to (Grigull, 1982; Morton, 2006) for more details.

Thermal and hydraulic characteristics for two-phase flow in channels imprinted/carved with surfaces patterns under varied flow condition has been reviewed in this paper. A comparison of two-phase flow heat transfer characteristics (Bergman, 2011; Chamra and Webb, 1995; Choi et al., 1991; Eckels and Pate, 1991; Ergu, 2009; Kawahara et al., 2002; Longo et al., 2004; Thors and Bogart, 1994) and pressure drop (Longo et al., 2004; Gao et al., 2002; Hahne and Grigull, 1977; Lee et al., 2002;