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Review

Supercritical water heat transfer for nuclear reactor applications: A review

Mohammad Mizanur Rahman [a], Ji Dongxu [b], Mehrdad Shahmohammadi Beni [c], Ho Choi Hei [d], Weidong He [e], Jiyun Zhao [d,*]

[a] Energy Institute, Atomic Energy Research Establishment, Ganakbari, Savar, GPO Box No. 3787, Dhaka 1000, Bangladesh
[b] School of Electrical and Electronic Engineering, Nanyang Technological University, Block S2.1, 50 Nanyang Avenue, Singapore 639798, Singapore
[c] Department of Physics and Materials Science, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong
[d] Department of Mechanical and Biomedical Engineering, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong
[e] School of Energy Science and Engineering, University of Electronic Science and Technology, Chengdu, Sichuan 611731, PR China

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ABSTRACT

Understanding of the heat transfer characteristics of supercritical water is one of the most important issues in Supercritical Water-Cooled Reactors (SCWRs) development. The main objective of the present study is to perform literature survey on the supercritical water heat transfer researches in order to provide the references for the SCWR researchers. Both the experimental and numerical studies related to the supercritical water heat transfer, especially for nuclear reactor applications, are reviewed. It is found that the majority researches are focusing on the supercritical water flow inside circular tubes in which first order closure models assuming isotropic behavior of turbulence are being used. However, for flow channels with different geometries such as sub-channel of fuel assembly, anisotropic behavior of turbulence and secondary flows are observed. Therefore, additional researches are needed for supercritical water heat transfer under SCWR operating conditions.

Contents

* Corresponding author.
E-mail addresses: dr.mizanrbd@gmail.com (M.M. Rahman), DJI001@e.ntu.edu.sg (J. Dongxu), mshahmoha2-c@my.cityu.edu.hk (M.S. Beni), choiheiho2-c@my.cityu.edu.hk (H.C. Hei), weidong.he@uestc.edu.cn (W. He), jiyuzhao@cityu.edu.hk (J. Zhao).

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1. Introduction

One of the critical issues for Supercritical Water-Cooled Reactor (SCWR) development is to acquire comprehensive knowledge of heat transfer under supercritical pressure in order to ensure the fuel temperature within the design limits. Under supercritical pressure, water will not experience phase change, however, a pseudo-critical point exists around which the water properties such as density and specific heat undergo drastic changes similar to the boiling process under subcritical pressure (Zhao et al., 2007, 2011). This sharp variation of the supercritical water properties results in significant difference between heat transfer characteristics of supercritical and subcritical water. It is well agreed that heat transfer deterioration would occur at upward supercritical flow under high heat flux (Cheng and Schulenberg, 2001). As a result, understand and researching of unique yet complicate heat transfer phenomena of supercritical water, would be necessary for thermal–hydraulic design of present and future nuclear reactors in which supercritical water is used as coolant. This paper tends to review and evaluate the researches related to the heat transfer of supercritical water in order to provide an easy reference point for SCWR designers.

1.1. Historical study

The first work studied the issue of supercritical heat transfer was found in 1930s. The research was purposed on developing efficient cooling system for turbine blades in jet engines, Schmidt and his associates (Schmidt et al., 1946) examined free convection heat transfer to fluids at the near-critical point. They observed relatively high free convection heat transfer coefficient (HTC) of fluid at the near-critical state. These content phenomena benefit was then applied in single phase thermosiphons with the intermediate working fluid at the near-critical point.

In order to improve the thermal efficiency of conventional thermal power plants, the concept of applying supercritical steam-water had been fascinating for steam generators in the 1950s. As there is no phase transition occurs from liquid to vapor at supercritical pressures, therefore, no critical heat flux or dry-out arise under this condition. Within a narrow range of parameters, only gradual deterioration in heat transfer would take place. In this case, no remarkable decrease in heat transfer associated with dry out in boiling fluids happens. At present, uses of supercritical water in conventional thermal power plants are the largest industrial application of fluids at supercritical pressures (Miropolsky and Shitsman, 1957; Pioro and Duffey, 2005; Dickinson and Welch, 1958; Shitsman, 1959; Schmidt, 1959; Jackson, 2013). Some investigations of possible uses of supercritical pressure water as coolant in nuclear reactor were also carried out at the end of 1950s and the beginning of 1960s (Jackson, 2013; Goldman, 1954). However, this idea was abandoned for almost 30 years, and then regained momentum in the 1990s, as means to improve the performance of water-cooled nuclear reactors. Several concepts of nuclear reactors were developed (Oka et al., 2010; Schulenberg and Starflinger, 2012).

In recent years, with the development of computer capacity, more and more numerical research has been conducted in this area by CFD tools. Compared with experimental researches, numerical simulations are more economical especially for supercritical fluids.

2. General heat transfer character of supercritical water

2.1. Thermo-physical properties of water near the pseudo-critical point

As shown in the pressure–volume diagram Fig. 1, there is large difference between water at subcritical pressure and supercritical pressure. At temperatures below the critical value, variation of pressure with volume along an isotherm exhibits discontinuities where it intersects the saturation line. Phase change takes place with horizontal, constant pressure segments; represent the presence of two distinct phases in varying proportions. Above the critical temperature, no such discontinuities occur, and from a macroscopic point of view, there is a continuous variation from a liquid-like condition to a gas-like one.

At heat transfer between surface and moving fluid, thermal boundary layer is formed across, in which variation of pressure is negligible. Therefore, in the context study of convective heat transfer inside a tube, it is appropriate to consider the manner of fluid properties vary with temperature under constant pressure. At sub-critical pressure, thermodynamic and transport properties of fluids exhibit discontinuous changes when saturation temperature is reached i.e. phase transition. At supercritical pressure, this behavior would be replaced by continuous property variation concentrated within a relatively narrow band of temperature somewhat above the critical value as shown in Fig. 2. As the result can be seen from this picture, the specific heat C_p at constant pressure achieves a peak value within the pseudo-critical region, which shows positive effect on enhancing the heat transfer coefficient. The density decreases drastically near the pseudo-critical value, which also have great influence on heat transfer ability.

2.2. Heat transfer at supercritical pressure

As indicated before, the heat capacity has a peak value near the critical value. Therefore, according to Dittus–Boelter (D–B) equation, there would be a peak of heat transfer around the pseudo-critical point (see Fig. 3) with equation listed as follow of Nu with Re and Pr.

$$\mathrm{Nu} = 0.023 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{1/3} \quad (1)$$

However, specific heat capacity is not the only factor that influence heat transfer coefficient, there are some other factors such as buoyancy, acceleration effect, gravity which may influence the heat

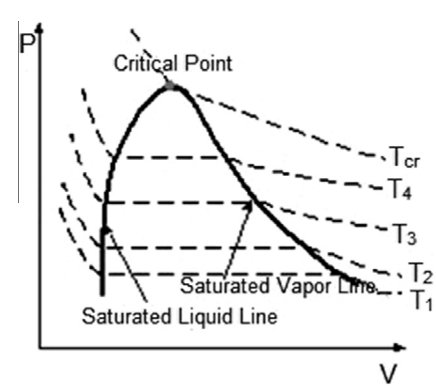

Fig. 1. Pressure–volume diagram of water (Shitsman, 1963).