International Journal of Heat and Mass Transfer 98 (2016) 738–745

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental investigation of hypervapotron heat transfer enhancement with alumina–water nanofluids

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A R T I C L E I N F O

Article history:
Received 6 June 2015
Accepted 23 March 2016

Keywords:
Alumina–water nanofluids
Hypervapotron
Heat transfer performance
High heat flux
Plasma facing components

A B S T R A C T

In order to meet the cooling needs of high heat flux (HHF) internal plasma facing components (PFC) of fusion reactor, experimental investigations of hypervapotron (HV) heat transfer enhancement with the alumina–water nanofluids were carried out. Pressure water hypervapotron loop-II (PWHL-II) has been constructed to implement the high heat flux HV heat transfer correlative experiments for PFC. The triangular fins in HV test section of chromium–zirconium–copper alloy were processed similar to the International Thermonuclear Experimental Reactor like (ITER-like) divertor targets and the Neutral Beam Injector (NBI) cooling components. 200 KW high frequency induction heating equipment was developed to use as the power source of HHF. Alumina–water nanofluids of four different mass fractions were prepared by ultrasonic dispersion technology. The experiments of heat transfer enhancement measurement have been completed. Real-time temperature data of the four specified positions at the root of HV fins were acquired by the temperature sensors and used to analyze the heat transfer performance enhancement under each of the corresponding conditions. Experimental results show that the HV heat transfer performance enhancement with the mass fraction 0.01% alumina–water nanofluids is better than that of the mass fraction of 0.005%, 0.05% and 0.10% alumina–water nanofluids as well as deionized water under HHF and different flow velocities. In the cases of high flow velocity at different heat flux, the heat transfer enhancement of the 0.01% alumina–water nanofluids in HV increases by 17% on average and 31% at most in comparison with deionized water. In the case of HHF, the heat transfer enhancement of the 0.01% alumina–water nanofluids in HV increases by 21% on average and 30% at most in comparison with deionized water. The results in question can function as a reference for design optimization and improvements of the ITER-like devices' water cooling structure of the HHF plasma facing components for future fusion reactors.

1. Introduction

International thermonuclear experimental reactor (ITER) and future commercial fusion power plants have many plasma facing components (PFC), such as the first wall (FW) of blanket and divertor, the residual ion dumps (RIDs) of neutral beam injector (NBI) auxiliary heating system, which needs to withstand 1–10 MW m^{-2} normal high heat flux (HHF) [1,2], while divertor targets have to withstand the impact of 20–30 MW m^{-2} instantaneous HHF [3]. In order to enhance the performance of these components under HHF and improve the heat exchange capacity of coolant for efficient use of energy, the study of heat transfer enhancement is thus of great significance. A number of HHF devices have therefore been developed specifically for this application. One of the most promising candidates is the hypervapotron (HV), which is a water cooled device with internal fins orientated perpendicular to the flow with a fin temperature profile bounded by the Leidenfrost temperature at the root and allowed to exceed incipient boiling temperature at the fin tip. The water cooled device relies on internal fins and subcooled boiling heat transfer to maximize the heat transfer capability. Fig. 1 shows an example of the details of the FW HV configuration in the finger or triangular fins geometry for ITER PFC [4]. Fig. 2 is NBI HV design which has been built and tested at the Joint European Torus (JET) facility at the Culham centre for Fusion Energy (UK) [5]. Over the past 30 years, numerous variations of the HV have been built and tested at fusion research centers across the globe resulting in devices that can now sustain heat fluxes up to 10–20 MW m^{-2} [5–10]. The multiphase flow model of

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.03.089
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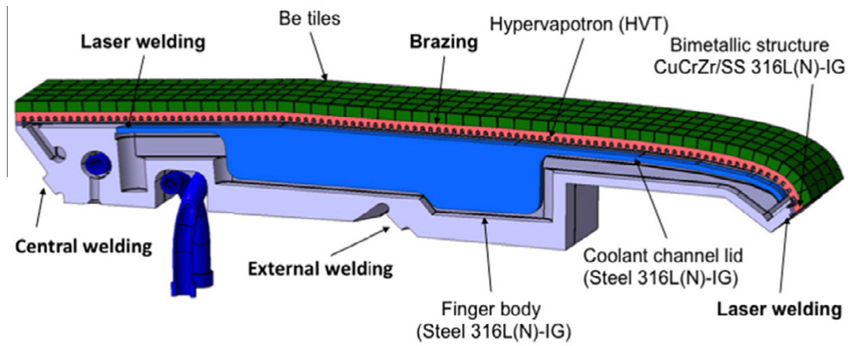

Fig. 1. Details of enhanced heat flux FW 14 showing the HV configuration in the finger (high neutron heating and surface heat flux).

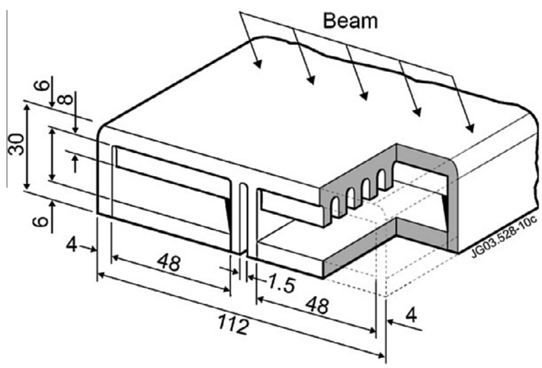

Fig. 2. Section through the JET MkI HV (figs. in mm).

the HV heat transfer enhancement has been developed by customized commercial computational fluid dynamics software [11–13]. Under the plasma off-normal conditions (such as disruptions and vertical displacement events (VDEs)) or in the edge localized mode (ELM), the unexpected heat flux of divertor targets will become very high. Take the example of the major disruption and VDEs of ITER, the plasma thermal quench and current quench are within ~26 m s with an energy density on the wall is about ~1 GJ m^{-2} s^{-1} [14,15]. The PFC cooling may then evolve from the regular subcooled nucleate boiling regime to the critical heat flux (CHF, the departure from nucleate boiling with sudden reduction in heat transfer efficiency) at the cooling flow channel wall, and cause its burnout. Strong material damages can result, up to a very detrimental water leakage in the vacuum vessel which would lead to costly damages and long break for repairing [16]. So, the FW of PFC using HV boiling heat transfer mechanism is inherently limited by their CHF during plasma off-normal conditions. The use of nanofluids as the coolant, instead of water, promises to enhance the heat transfer performance of the HVs and increase the CHF by a factor of 2 or 3 [17], which would lead to a step-change improvement in the power handling capability. Based on this objective, the novel cooling way of HVs over subcooled boiling integrate with alumina–water nanofluids is proposed, to be an alternative for cooling solutions of HHF for ITER and future fusion power plants PFC. This method can be used as the most promising candidate cooling scheme for the success of a safe and reliable operation of divertor targets in ITER.

With respect to the improvement of heat transfer performance by combining HVs and nanofluids technologies, only Sergis et al. [17] discussed the HV mechanism of water-based nanofluids using a numerical simulation of molecular dynamics. They also observed the flow fields and vortex structures of alumina–water nanofluids in the groove under cold conditions, and described the nanofluids synthesis and quality assessment, and the fluid sample analysis methods [18]. Currently, the measurement experiments on HVs heat transfer enhancement of nanofluids are still rare. The mechanisms of heat transfer enhancement are not yet well understood, and there is thus a need for further underlying experiment research to allow the design of nanofluids for fusion applications.

In face of HHF cooling needs of PFC in a fusion reactor, this paper carried out the heat transfer enhancement experimental study of the water-based nanofluids in HV, aimed at exploring and verifying the heat transfer improvement of HHF components when both enhanced heat transfer technologies were combined, so as to provide a reference for engineering solutions. Therefore, pressure water hypervapotron loop-II (PWHL-II) has been constructed to implement the HV heat transfer correlative experiments for PFC. Triangular fins in HV test section of chromium zirconium copper were processed, which are similar to the ITER divertor targets and the NBI components. 200 KW high frequency electromagnetic induction heating equipment was developed; alumina–water nanofluids of four different mass fractions were prepared by ultrasonic dispersion technology. The experiment of heat transfer enhancement measurement has been completed. Real-time temperature data of the four specified positions at the root of fins were acquired by the temperature sensors and used to analyze the heat transfer enhancement performance under each of the corresponding conditions. Experimental results will function as a reference for efficient cooling PFC of ITER and future fusion power plants.

2. Experimental facility and methods

2.1. Nanofluids synthesis

Nanofluids are a uniform, stable suspension, which improve thermal conductivity, obtained by the addition of nanoscale particles into the base fluid [19]. Compared with conventional solid particle suspension, the specific surface area of the nanoparticles significantly increases. Therefore, there is a larger heat transfer area between the fluid and the particles [20,21]. However, precisely because of the large surface area and high surface energy of nanoparticles, they often develop into an aggregate and sink in base fluid, affecting the flow and heat transfer characteristics of nanofluids. Therefore, it is a necessary condition for the application to the heat transfer enhancement to prepare nanofluids featuring good uniformity, good dispersion, high stability and long lifetime.

In these experiments, γ phase alumina particles with $10 \sim 20$ nm in diameter on average are selected as nanoparticles, with deionized water as base fluid, and a two-step method of synthesis [22] is used to employ for the uniform and stable nanosuspension. At the first step, the nanoparticles are diluted to 1% volume deionized water. Secondly, the fluid is agitated and homogenized by an ultrasonic