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Compatibility of fusion reactor materials with flowing nanofluids

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ABSTRACT

In this study, rotating experimental devices have been built to investigate the compatibility of the fusion reactor materials RAFM steel, 316L(N) stainless steel, and CuCrZr alloy with the Al_2O_3-water nanofluids. According to the ITER water-cooling program, the experimental conditions were selected as flow velocity of 1.13 m/s and 3.71 m/s, fluid temperature of 70°C, testing duration of 1224 h and 2136 h, and nanofluid mass fraction of 0.01% and 1%. Surface morphology and component analysis are characterized by SEM, EDS and XPS. The preliminary results indicate that the compatibility of RAFM steel and 316L(N) steel with nanofluids is better than that of CuCrZr alloy. Metallic oxide film with holes and cracks appears on the surface of CuCrZr alloy, and its morphology is strongly affected by the testing duration, flow velocity and mass fraction of nanofluids. The corrosion mechanism is dominated by the coupling effect of chemical corrosion and mechanical erosion.

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1. Introduction

The concept of the nanofluid was first proposed by Choi and his colleagues in U.S. Argonne National Laboratory in 1995, which was expected to exhibit high thermal conductivity and good stability by adding nanoscale metallic or nonmetallic oxide into heat transfer fluid [1]. A considerable amount of experimental and theoretical research has been focused on heat transfer of nanofluids in recent years. These studies indicate that nanofluids have important engineering values for the enhancement of 30% on the thermal conductivity and promising to increase the critical heat flux (CHF) by a factor of 2 or 3 [2–4].

High heat flux components are widely used in ITER and future commercial fusion reactor. For example, the first-wall need to withstand continuous power densities in the order of 5 MW m^{-2} and the divertor even bear high transient heat flow of 20 MW m^{-2} [5–7]. Under the circumstances, the use of nanofluids as the coolant, instead of water, promises to enhance the heat transfer performance of the high heat flux components and increase the CHF, which would contribute to the efficiency of energy use and safe operations of reactor [8,9].

The preliminary experimental investigation has been carried out on the compatibility of nanofluid coolants with structural materials for several years, which is likely to cause the pipeline corrosion and erosion that lead to equipment failure. Nguyen has developed a test (1800 h) with 5vol.% Al_2O_3-water nanofluid [10]; Routborthas conducted some tests with 0.01vol.% Cu particles in trichloroethylene glycol, and some weight loss was found in a long-term test (60 days) [11]; Different nanofluids (containing TiO_2, Al_2O_3, ZrO_2, and SiC, respectively) and different tested materials (Al, Cu, stainless steel) have been investigated by Celata [12], and the stainless steel has been little affected by the nanofluid flow. Up to now, some research about the compatibility of pipeline materials with nanofluids have been carried out, but still very few data are available from these experiments. Therefore more experimental study and further investigation on the root causes of these interactions are encouraged.

In this study, the rotating experimental devices have been built to investigate the compatibility of the fusion reactor materials RAFM steel, 316L(N) stainless steel and CuCrZr alloy with the Al_2O_3-water nanofluids. According to the ITER water-cooling program [13], the corrosion for long time has been operated in various testing conditions. The results of the experiment would improve the corrosion data of nanofluids and provide references for engineering design of candidate materials for future fusion reactor.

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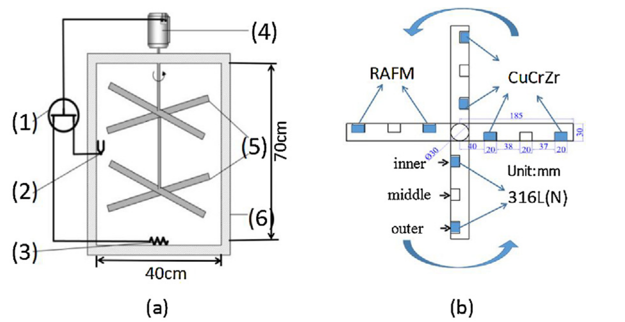

Fig. 1. The sketch of facility and specimen holder after mounted specimens. (1) Controller; (2) Thermocouple; (3) Resistive heater; (4) Motor; (5) Sample holder; (6) Thermal insulation.

2. Experiment

2.1. Experimental apparatus

The sketch of the experimental apparatus with the size and dimensions is illustrated in Fig. 1(a). It's composed of a stainless steel cylindrical insulation tank, two cross sample holders, a heating and temperature control system, and a motor of stepless speed regulator. The effective volume of the tank is approximately 70 l. The experimental system is not sealed and the fluid is direct contact with atmosphere. To allow a direct comparison of the corrosion behavior of different mass fraction nanofluids, two identical experimental devices have been designed to work simultaneously under the same conditions. Two cross sample holders composed of four mutually perpendicular vanes are mounted along the axial direction in each device. Each vane can provide three identical sample grooves (inner, middle and outer) for positioning specimens at different distances from the center of the device. The device is able to accommodate up to 24 samples, which could provide enough specimens with different flow velocities.

In this experiment, only one cross sample holder was mounted in each device due to a small number of specimens for test. There were 2 specimens of RAFM steel, 2 of 316L(N) stainless steel and 4 of CuCrZr alloy. The specimen positions of different materials are described in Fig. 1(b).

2.2. Preparation of the specimens and nanofluids

The materials used in this study were RAFM steel produced by IMR (Institute of metal research, Chinese Academy of Sciences), 316L(N) stainless steel and CuCrZr alloy of which the composition and properties meet the requirements of the ITER standards [14]. The chemical composition of experimental specimens is presented in Table 1.

The specimen size was 20 mm × 10 mm × 2.5 mm. Before testing, the surfaces of specimens were polished using #180, #240, #320, #400, #500, #600, #800, #1000 SiC paper to achieve a mirror finish, respectively. After cleaned in acetone, the specimens of RAFM steel, 316L(N) stainless steel and CuCrZr alloy were mounted on the sample holders at the same time.

Table 1
Chemical composition of experimental specimens (unit: wt%).

RAFM	C	Cr	W	V	Ta	Mn	Si	Fe
	0.09	8.93	1.43	0.19	0.10	0.48	0.05	Bal.

316L(N)	C	Cr	Mn	Ni	Mo	N	Fe
	0.02	17.50	1.80	12.2	2.50	0.07	Bal.

CuCrZr	Cr	Zr	O	Cu
	0.75	0.11	0.03	Bal.

Table 2
Experimental parameters for corrosion test.

Parameters	Number
Rotating speed/rpm	215
The flow medium/wt%	Al_2O_3-water/0.01%,1%
Temperature/°C	70
Pressure/Mpa	0.1
Duration/h	2136

A two-stage nanofluid preparation method was followed for the experiments. Al_2O_3 nanopowder with a diameter of about 10 nm was mixed with deionized water and placed in an ultrasonic bath. The mixture was placed in a sonic bath for at least 60 min in order to ensure that most/all of the agglomerates formed were broken up and good suspension qualities were reached. According to the previous experimental result, the mass fraction of 0.01% Al_2O_3-water nanofluid could show a better heat transfer performance [15], so mass fraction of 0.01% and 1% Al_2O_3-water nanofluids were prepared to perform a direct comparison of the corrosion behavior in this study.

2.3. Experimental scheme and sample characterization

The specimens were fixed on sample grooves. Then the sample holders were submerged in nanofluids. The fluid may have co-rotation according to the rotation of the sample holder. The specimens of RAFM steel, 316L(N) stainless steel and CuCrZr alloy were corroded for 2136 h in mass fraction of 0.01% and 1% Al_2O_3-water nanofluids, respectively. Table 2 presents the experimental parameters of corrosion tests.

After the corrosion tests, the specimens were taken out and cleaned by ultrasound in deionized water to remove the adherent nanoparticles from the specimen surface, and then washed the specimens in acetone. The specimens were analysed using analytical methods such as Scannning Electron Microscope (SEM), Energy Dispersive x-ray Spectroscopy (EDS) and X-ray Photoelectron Spectroscopy (XPS).

3. Experimental results and discussion

3.1. Erosion-corrosion of RAFM steel and 316L(N) stainless steel in flowing nanofluids

The results of the tested samples by SEM analysis are shown in Fig. 2. The surfaces of the RAFM and 316L(N) steel continue to present metallic luster and have insignificant corrosion products. The observable scratch was caused by the process of preparing metallographic specimen. It is found that flow velocity, testing duration and nanofluid mass fraction present few effects on RAFM and 316L(N) steel, which shows a good compatibility of RAFM steel and 316L(N) stainless steel with nanofluids in the test period.

3.2. Erosion-corrosion of CuCrZr alloy in flowing nanofluids

There was remarkable corrosion of CuCrZr alloy in mass fraction of 0.01% and 1% Al_2O_3-water nanofluids. As shown in Fig. 3, the untested samples with metallic luster surface have changed into dark after corrosion.

The composition of oxide film of CuCrZr alloy was studied by EDS and XPS. EDS analysis shows that all the oxide films consist of Cu, O and C. As shown in Fig. 4, the outer groove sample tested in mass fraction of 0.01% Al_2O_3-water nanofluid for 2136 h was detected by XPS. By Fig. 4(a), it could be further confirmed that the specimen

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