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Research Article

Experimental Investigation into the Forced Convective Heat Transfer of Aqueous Fe_3O_4 Nanofluids under Transition Region

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The forced convective heat transfer (FCHT) properties of nanofluids, made of Fe_3O_4 nanomaterials and deionized water, are firstly measured by a self-made forced convective heat transfer apparatus. The nanofluid flows through a horizontal copper tube in the transition region with Reynolds numbers in the range of 2500–5000. Some parameters including Reynolds number, axial distance, and mass concentration are also investigated. The preliminary results are firstly presented that the heat transfer coefficients of Fe_3O_4 nanofluids systematically decrease with increasing concentration of nanoparticles under transition region which contradicts the initial expectation.

1. Introduction

Due to restrictions of their thermal properties, traditional fluids such as water, engine oil, and ethylene glycol are inadequate for high heat flux application. Some nanofluids, made of nanoparticles and a based liquid, have been attracting much attention for they can improve the convective heat transfer and thermal conductivity of the based liquids [1, 2]. Some nanomaterials, such as Cu, Fe, TiO_2, Al_2O_3, CuO, SiO_2, and carbon tube as a main ingredient of nanofluid, have been investigated [3, 4]. Wen and Ding and Lai et al. confirmed that the heat transfer coefficient of nanofluid is increased with flow rate and nanoparticle volume fraction [2, 5]. Anoop et al. demonstrated that the heat transfer coefficient of nanofluid is enhanced with the decrease of size of nanoparticles [6]. Heris et al. found that heat transfer coefficient of nanofluid were obvious difference with different kind of nanoparticles [7]. However, some researches about heat transfer of nanofluids are often difficult to reproduce and even contrary with other relative previous research [8].

There are three modes of flow of a fluid: a fluid with Reynolds numbers below 2000 is named as a laminar flow; a turbulent flow usually refers to the fluid with Reynolds number higher than 10000; the fluid with Reynolds numbers in range from 2000 to 10000 is often called as transition region fluid. As yet, most researches about nanofluids are focused on the laminar or turbulent flow. Contrarily, the properties of nanofluid in transition region are commonly ignored or abandoned because the performances of fluid in the region are affected by many factors, and many some uncertain or irregular results are obtained even in the same conditions [9]. However, in nature a large number of significant fluids perform in transition region, such as blood passing through large arteries, which are characterized by Reynolds numbers [10]. So it is necessary to investigate fluid under the transition region for providing useful information both in academic and technological aspects.

Fe_3O_4 nanofluids, as important magnetic fluids, have been widely investigated and applied into many fields. However, according to our investigation, the study is still insufficient about the heat transfer of this nanofluid [11–13], and no report is found concerning the forced convective heat transfer (FCHT) of water-based magnetic Fe_3O_4 nanofluids under full developed transition region. Syam Sundar et al. [14] have estimated the FCHT properties of aqueous magnetic Fe_3O_4 nanofluids under turbulent flow (Reynolds number > 10000) and found that the heat transfer coefficient of the fluids was enhanced by adding the nanoparticles. Li and Xuan [15] have investigated the influence of an external magnetic field to the convective heat transfer of aqueous magnetic fluid flow over a fine wire under the laminar flow region.

In this study, Fe_3O_4 @ phenol formaldehyde resin (PFR) water-based nanofluid is constructed via a facile hydrothermal approach. The obtained black nanofluids show superparamagnetic and high stability. The FCHT properties of the water-based Fe_3O_4 and Fe_3O_4 @ (PFR) nanofluids are preliminary discussed under transition region. Some important parameters, such as particles concentration, Reynolds number, and the axial profile distance, are discussed. It is found that the heat transfer coefficients of the nanofluids systematically decrease with increasing particle concentration. This is in contradiction to the initial expectation. This investigation may provide a threshold to further exploit the peculiar heat transfer phenomena under transition region.

2. Experimental

2.1. Reagents and Materials. Iron(III) chloride hexahydrate ($FeCl_3{\cdot}6H_2O$, AR), Iron(II) sulfate heptahydrate ($FeSO_4{\cdot}7H_2O$, AR), Hexamethylene tetramine ($(CH_2)_6N_4$, AR), Sodium hydroxide (NaOH, AR), Phenol (C_6H_5OH, AR), Ethylene glycol ($C_2H_4(OH)_2$, AR), and Ethanol (C_2H_5OH, AR) were all purchased from China National Medicines Corporation Ltd. and used as received without further purification. De-ionized water used in all experiment is self-made.

2.2. Preparation of Nanofluids. In a typical procedure, 15 mmol $FeCl_3{\cdot}6H_2O$ and 12 mmol $FeSO_4{\cdot}7H_2O$ were dissolved in 100 mL de-ionized water with 50 mL ethylene glycol in a three-necked bottle. The mixture was quickly stirred with a mechanical whisk at 65°C. After 30 minutes, the aqueous NaOH (1 M) 50 mL were added into the bottle and the black suspension was formed at once. The black suspension had been constantly stirred for 60 minutes, and then it is transferred into a 500 mL autoclave with Teflon lining. After that, 150 mL de-ionized water, 0.50 g C_6H_5OH, and 1.00 g $C_6H_{12}N_4$ were added into the autoclave. The autoclave was sealed and kept in a controllable temperature oven at presetting 120°C for 4 h.The autoclave was cooled naturally after the heating process. The black precipitate was washed by ethanol for several times, respectively. Finally, Fe_3O_4 @ PFR nanocomposites were redispersed into deionized water to form nanofluids. The naked Fe_3O_4 nanofluid was prepared via two steps: the naked Fe_3O_4 nanoparticles were dispersed into water by a mechanical whisk, and then the pH value of the mixture was adjusted to 9-10 by 1 M aqueous NaOH solution for preparing stable fluid.

2.3. The Measurement of the Forced Convective Heat Transfer Behavior of the Nanofluids

2.3.1. Experimental Setup. The forced convective heat transfer properties of nanofluids were measured by self-made simplified apparatus referred to the literature [16]. The schematic diagram of experimental apparatus is shown in Figure 1.

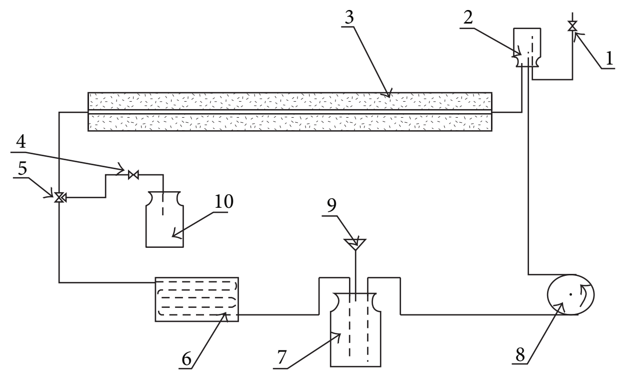

Figure 1: The schematic diagram of experimental apparatus for detecting the forced convective heat transfer of fluid. (1) Steam trap, (2) Water tank, (3) Test section, (4) Swith, (5) Vacuum valve, (6) Air cooler, (7) Reservoir tank, (8) Pump, (9) Funnel, and (10) Collection tank.

The test chamber consisted of 110 cm annular horizontal straight copper tube with 5 mm inner diameter and 1 mm thickness. Seven thermocouples are dispersedly instated on the tube, among them, five thermocouples are mounted on the test section at axial positions to measure the wall temperature distribution, and remaining two thermocouples are, respectively, inserted at the inlet and exit of the test section to measure the temperature of nanofluids there. Nanofluids flow inside the copper tube and pass through the test section for heat exchanger. The test chamber is covered by a heat-insulating shield with 10 cm thickness for blocking the heat lost. The flow rate of fluid is controlled by a peristaltic type pump. The supply heat is regulated by the resistance wires which are intertwined on the copper tube. The air cooler is used to cool fluids out of the test unit.

2.3.2. Relative Problem Calculation Formula. The de-ionized water was used as fluid to test the reliability and accuracy of the experimental system. The results were compared with the predictions of the following Gnielinski equation [17] under fully developed section in transition region:

$$\mathrm{Nu} = \frac{(f/8)(\mathrm{Re}-1000)P_r}{1+12.7\sqrt{f/8}\left(P_r^{2/3}-1\right)} \quad 2300 \le \mathrm{Re} \le 10^6. \tag{1}$$

The resistance coefficient f and Reynolds number are calculated as follows:

$$f = (1.82 \lg \mathrm{Re} - 1.64)^{-2}, \tag{2}$$

$$\mathrm{Re} = \frac{\rho \cdot v \cdot D}{\mu}. \tag{3}$$

The forced convective heat transfer coefficient (h) in this experiment is calculated as follows:

$$\overline{h_{nf}} = \frac{q}{T_w - T_f} = \frac{C_{pnf}\cdot\rho_{nf}\cdot\overline{v}\cdot A\cdot(T_{b2}-T_{b1})}{\pi DL\cdot\left(T_w-\overline{T_b}\right)}. \tag{4}$$

C_{pnf} in this experiment is calculated, respectively, as follows:

$$C_{pnf} = \frac{m_s \cdot C_{ps} + m_w \cdot C_{pw}}{m_{nf}}. \quad (5)$$

The ρ_{nf} value is given as $1\,\mathrm{g\,cm^{-1}}$ for the concentration of nanoparticles is very low, and the influence can be ignored to the dense of fluid; D and L values are 0.5 and 110 cm in turn; So (4) can be simplified into (6) as follow:

$$\overline{h_{nf}} = \frac{C_{pnf} \cdot \overline{v} \cdot (T_{b2} - T_{b1})}{880 \cdot \left(T_w - \overline{T_b}\right)}. \quad (6)$$

3. Results and Discussion

The crystal phase of as-obtained Fe_3O_4 @ PFR nanocomposites is characterized by X-ray power diffraction, and a typical XRD pattern of them is shown in Figure 2. The pattern reveals the obtained nanocrystalline product consisted of F-centered cube structure. All diffraction peaks are easily indexed as cube phase Fe_3O_4 given in JCPDS (no. 65-3107) with lattice constants $a = 8.383(9)$ Å. The average crystallite size of samples is estimated about 20 nm by the Scherrer equation autocalculated in Jade software. Concurrently, a widen peak appeared in the region between 20° and 30° of two-theta diffraction angle due to amorphous PFR. It suggests that the Fe_3O_4 @ PFR nanocomposite can be facilely synthesized via the two-step method. It is found that Fe_3O_4 @ PFR nanofluids show higher stability than naked Fe_3O_4 nanofluids after they have been statically laid aside in sealing bottle for 7 days. It should be ascribed to water-solute PFR polymer, which can catch some H_2O molecular by hydrogen bonds and increase the dispersity of Fe_3O_4 nanoparticles.

For inspecting the reliability and accuracy of the self-made experimental system, the pure water as work fluid measured the Nusselt number change with Reynolds number in the range of 2400–3300. The measurements values, which are shown in Figure 3, are compared with the calculated values via the classical Gnielinski equation [17]. From the figure, the deviations between measured and calculated values are less than 12% over the Reynolds number range, which is located in the allowable range of deviation in transition region [9, 10]. That is to say, the self-made apparatus is reliable to measure the forced convent heat transfer of as-obtained nanofluids.

The forced convective heat transfer coefficient ($\overline{h_{nf}}$) of a fluid rises with Reynolds number (Re) increasing, but the increased amplitude changes with the type of fluid. Reynolds number of fluid can be calculated by (3) according to the change of flow speed, so some examinations are measured at different flow speed of fluid controlled by a special pump. The relevancies between $\overline{h_{nf}}$ and Re of some fluids are inspected and corresponding results curves are shown in Figure 4, where $\overline{h_{nf}}$ of nanofluid is calculated by (6). The heat capacities of as-obtained nanofluids, which are lower than that of pure water, are calculated by empirical equation (5). The results clearly indicate that pure water shows the highest $\overline{h_{nf}}$ of all tested samples in transition region at a same Reynolds number. That is to say, the forced convective heat transfer capacity of water cannot be enhanced by adding tiny Fe_3O_4 nanoparticles in current investigation conditions. Fe_3O_4 @ PFR nanofluids demonstrate superior $\overline{h_{nf}}$ to the naked Fe_3O_4 nanofluids shown in Figure 4(b). The heat transfer coefficient of the naked Fe_3O_4 nanofluids is declined with the concentration increase of Fe_3O_4 nanoparticles. The above experimental results suggest that it is disadvantaged to raise the forced convective heat transfer efficiency of nanofluid by the increase concentration of the nanoparticles in the present research system. These results are contradictive with the initial expectation and some reports that the FCHT properties of the fluid may be improved by adding some nanoparticles [14, 15]. However, we also found that the result

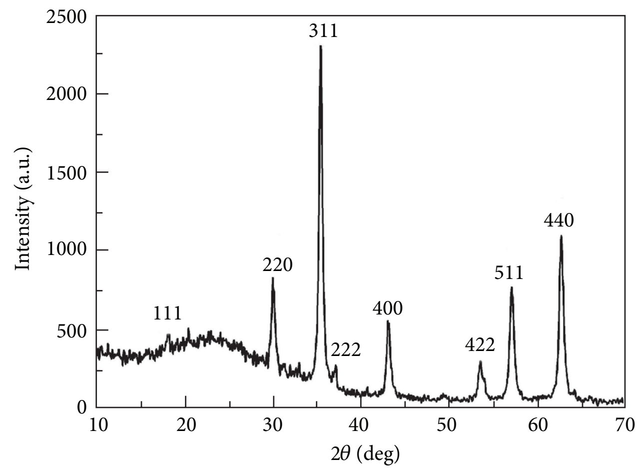

FIGURE 2: The typical XRD Pattern of the as-obtained Fe_3O_4 nanoparticles coated by PFR.

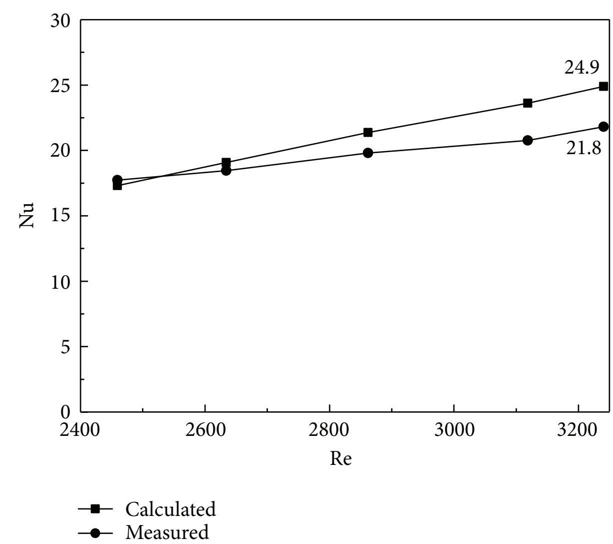

FIGURE 3: Comparisons between the calculated value by Gnielinski equation and measured value by the self-made apparatus in the deionized water system.

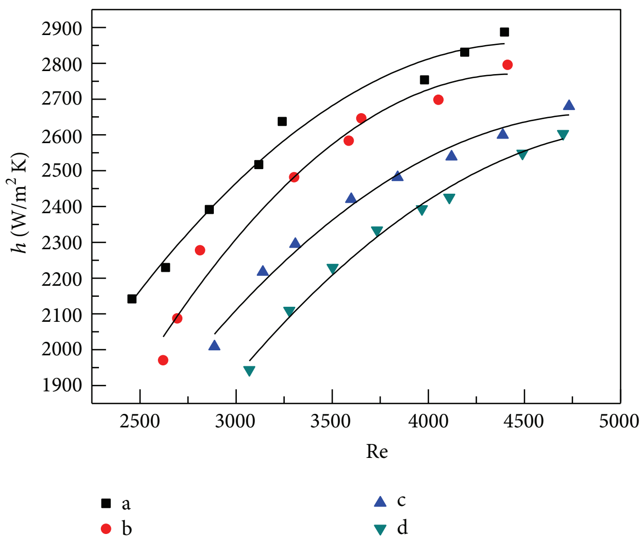

FIGURE 4: Dependence of heat transfer coefficient of samples on Re. (a) Deionized water, (b) 0.16% (m/m) Fe_3O_4 @ PFR nanofluid, (c) 0.05% Fe_3O_4 nanofluid, and (d) 0.24% Fe_3O_4 nanofluid.

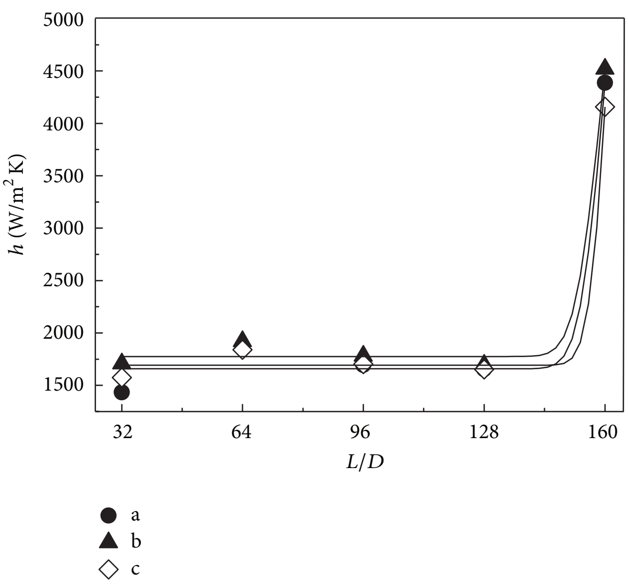

FIGURE 5: The effect of axial profile length/diameter (L/D) to the forced convective heat transfer coefficient (h) of some typical samples (Re = 2650 ± 50). (a) 0.16% (m/m) Fe_3O_4 @ PFR nanofluid, (b) 0.05% Fe_3O_4 nanofluid, and (c) 0.24% Fe_3O_4 nanofluid.

is similar with the research results about CuO and TiO_2 nanofluid and Al_2O_3 nanofluid under natural convective heat transfer conditions [18, 19]. The reasons of deterioration should be attributed to the effects coming from particle-fluid slip, sedimentation of nanoparticles [18], and the change of fluid parameters with nanoparticles self-characters [19].

The curve shown in Figure 5 indicates the relationship of the local heat transfer coefficients against the axial distance/diameter (L/D) from the test starting point to exit of the test section at Reynolds numbers around 2650 ± 50. The experiments are given at the fully developed section and exit section because of the ratio between axial distance and inner diameter of tube beyond 60. From the trend of the curve, it can be found that the influence from the entrance sector can be neglected at the fully developed section for the heat transfer coefficient keeps identical value at different positions in the L/D range from 32 to 140. This result suggests that the heat transfer coefficient keep stable in the fully developed sector for the temperature of fluid at different position are almost same in the fully developed sector. On the contrary, when the fluid flows into exit region, the heat transfer coefficients of all kinds of fluid are boosted. This phenomenon should be attributed to the obvious difference in temperature which existed in the exit sector and the outer cooling-sector fluid. Compared to the $\overline{h_{nf}}$ values at exit sector of two Fe_3O_4 nanofluids with different concentration, it indicates that the increased concentration of nanoparticles is disadvantage to improve the forced heat transfer coefficient under transition region with present investigated conditions. These results are coincident with the results shown in Figure 4.

4. Conclusions

This paper is concerned with the forced convective heat transfer of the Fe_3O_4 @ PFR nanofluids. Experiments were carried out under transition region conditions. The following conclusions were obtained.

(1) The pure water shows the highest $\overline{h_{nf}}$ of all tested samples in transition region at a same Reynolds number. This is in contradiction to the initial expectation. This may be attributed to the complex factors that affected the forced convective heat transfer properties of nanofluids.

(2) The Fe_3O_4 @ PFR nanofluids can enhance the convective heat transfer with the increases of the Reynolds number in transition region. However, the increased concentration of Fe_3O_4 nanoparticles is disadvantage to raise nanofluid the forced convective heat transfer efficiency in transition region.

(3) The enhancement is particularly significant in the outlet region and gets steady in the developed region.

Some important factors are investigated and some valuable results are obtained, but many other factors, such as the viscosity, the concentration of nanomaterials, and test temperature are still waiting for investigation. The part of research is on the way.

Nomenclature

h: Heat transfer coefficient
q: Heat flux
$\overline{T_w}$: Tube wall temperature
$\overline{T_b}$ Average bulk temperature
C_p: Specific heat capacity

w: Water
nf: Nanofluid
f: Resistance coefficient
Re: Reynolds number
L: Tube length
A: Tube cross-section area
v: Fluid velocity
μ: Viscosity
ρ: Density
k: Coefficient of thermal conductivity
Nu: Nusselt number
D: Tube diameter.

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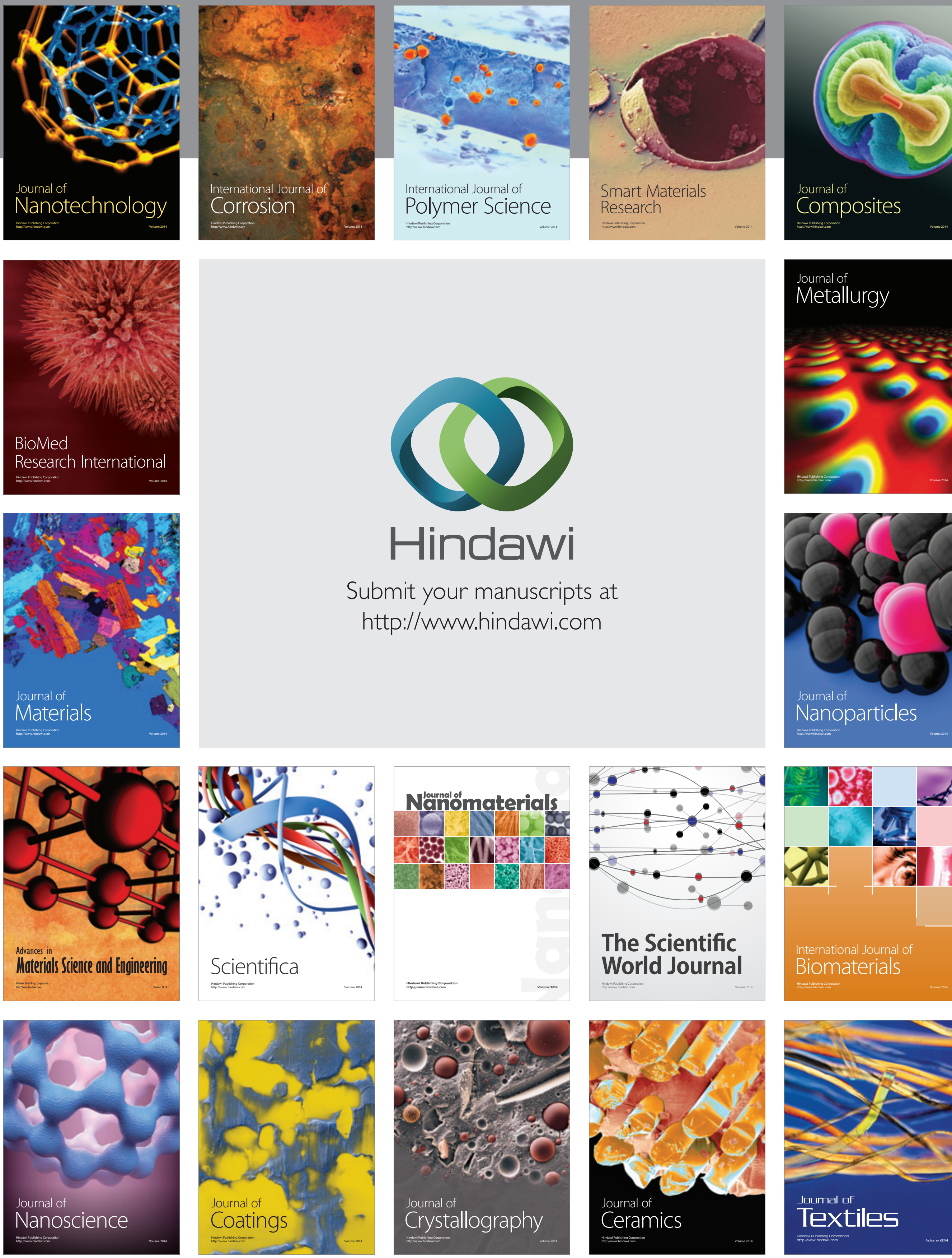
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