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Effect of Duct Cross Sectional Shape on the Nanofluid Flow Heat Transfer

Mohammad R. Salimpour, Amir Dehshiri

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Abstract**—**In the present article, we investigate experimental laminar forced convective heat transfer specifications of TiO_2/water nanofluids through conduits with different cross sections. we check the effects of different parameters such as cross sectional shape, Reynolds number and concentration of nanoparticles in stable suspension on increasing convective heat transfer by designing and assembling of an experimental apparatus. The results demonstrate adding a little amount of nanoparticles to the base fluid, improves heat transfer behavior in conduits. Moreover, conduit with circular cross-section has better performance compared to the square and triangular cross sections. However, conduits with square and triangular cross sections have more relative heat transfer enchantment than conduit with circular cross section.

Keywords**—**Nanofluid, cross-sectional shape, TiO_2, convection.

I. INTRODUCTION

NANOTECHNOLOGY by removing obstacles like sedimentation, clogging and erosion which are the result of solid particles dispersing, has created new heat transfer medium which is called nanofluid. Nanofluids are a new phenomenon of working fluids with high potential used for industrial applications such as construction of compact heat exchangers.

In order to construct the compact heat exchangers, the conduits with circular and non-circular cross section are used [1]. Since the size reduction in a compact heat exchanger requires a conduit with small hydraulic diameter, fluid flow is often laminar [2]. Hence the assessment of the characteristics of convective heat transferring of fully developed laminar flow through the conduits can play a significant role in the improvement of the equipment's performance.

Choi's studies on Nano fluids trades have made many researchers notice nano fluid's extraordinary characteristics such as significant increasing of conductivity in low concentrations of nano particles [3]. Wen and Ding [4] have done broad experimental researches on Nano fluids in laminar fluid flow.

In many cases metal oxides are used for preparation of stable Nano fluids. Heris et al. [5] did experiment by Al_2O_3/water Nano fluid in laminar flow with constant wall temperature and observed that Nusselt number increases with increasing volume fraction of Nano particles and Peclet number of Nano fluids.

For comparison between behaviors of metal oxides Nano particles Heris et al. [6] investigated laminar convective heat transfer of Al_2O_3 and CuO in water based Nano fluids in cupric circular conduit with constant wall temperature boundary condition.

Hwang et al. [7] studied the heat transfer behavior and flow treatment of nanofluids with volume fraction of 0.01% to 0.3%. They also measured heat transfer coefficient and pressure drop of nanofluids at fully developed laminar flow regime under uniform heat flux.

Saeedinia et al. [8] carried out experiments on laminar flow of CuO/oil nanofluid through cupric tube with constant heat flux. The maximum thermal conductivity and heat transfer coefficient enhancement of 6.2% and 12.7% were observed respectively at a weight concentration of 2%. An experimental investigation of CuO-water nanofluid flow and heat transfer inside a microchannel heat sink was performed by Rimbault et al. [9]. In a similar study, Sohel et al. [10] investigated the heat transfer enhancement of a minichannel heat sink using alumina/water nanofluid, experimentally.

Going through the literature, it is seen that most of metallic nano particles used for heat transfer augmentation are CuO and alumina and other metallic oxides are examined less. One of these nano particles is TiO_2. For example, Abbassi et al. [11] carried out an experimental investigation to study TiO_2/water nanofluid effects on heat transfer characteristics of a vertical annulus with non-uniform heat flux.

Moreover, many researchers examined turbulent convective heat transfer in conduits with different boundary conditions like works reported in [12]-[14]. Their experimental results show that adding nanoparticles to conventional fluids improves thermal characteristics of working fluids.

In order to construct compact heat exchangers, the conduits with circular and non-circular cross sections are used [15]. Since the size reduction in a compact heat exchanger requires a conduit with small hydraulic diameter, fluid flow is often laminar [16]. Hence the assessment of the characteristics of convective heat transfer of fully developed laminar flow through the conduits with different geometries and cross-sections plays a significant role in the improvement of equipment performance.

Salimpour [17] studied heat transfer coefficients of shell and coil tube heat exchangers experimentally and proposed a correlation for predicting Nusselt number of in-tube conventional fluid flow. He further examined the effect of

Mohammad Reza Salimpour is with Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran (phone: +983133915210, e-mail: Salimpour@cc.iut.ac.ir).

Amir Dehshiri was with Department of Mechanical Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran (e-mail: a.dehshiri@me.iut.ac.ir).

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temperature-dependency of conventional fluid properties on heat transfer characteristics of in-tube fluid [18]. The geometric optimization of an array of circular and non-circular ducts was done by Salimpour et al. [19]. They invoked constructal theory for this purpose. They further utilized this theory to optimize the microchannel heat sinks with different cross-sections [20].

In this section, the use of nanofluid in conduits with special geometries is addressed. Kumar et al. [21] carried out an experimental investigation on convective heat transfer and friction factor of alumina/water nanofluid flow in a helically coiled tube. Nassan et al. [22] conducted an experimental investigation on Al2O3/water and CuO/water in laminar flow regime through conduit with square cross-section by uniform and constant heat flux on the wall. Compared with water, both of nanofluids had substantial increase in convective heat transfer. The experimental results demonstrated that CuO/water has more enhancement than alumina/water. In another work, Heris et al. [23] studied the laminar convective heat transfer of Al2O3/water nanofluid through square cross-sectional duct under constant heat flux in laminar flow. They mentioned that a square cross section conduit has the advantage of lower pressure drop, but it has a lower heat exchange rate than that of a circular conduit and it is expected that using nanofluid as a new heat transfer media may improve the heat transfer performance of this kind of conduit.

Examining the literature, it was seen that the heat transfer characteristics of TiO_2/water nanofluid in conduits with different cross-sections has not been investigated, yet. Therefore, in the present study, an experimental set-up was designed and constructed to evaluate the laminar flow heat transfer coefficients of TiO_2/water nanofluid in conduits with circular, square and triangular cross-sections.

II. EXPERIMENTAL SET-UP

To investigate the convective heat transfer behavior of Nano fluids through conduits whit different cross-sections in laminar flow regime, the experimental set-up was designed and assembled as shown in Fig. 1. The test loop was assembled to measure convective heat transfer coefficient under constant wall temperature boundary condition. It contains a test section, a reservoir, steam generation unit, pump, precooling and cooling system, flow measuring and controlling devices, thermocouple and digital indicator. Cupric conduits with length of 1000mm whit different cross sections are used as test section. Test section is inside the vapor bath with five electrical elements to produce vapor for having constant wall temperature boundary condition. Working fluid flows inside the test section while steam bath is full of saturated vapor. Steam bath is insulated thermally to reduce heat loss from its wall to surrounding. To measure the inlet and outlet bulk temperature of nanofluids, two calibrated RTD PT100 type thermocouples of 0.1ºC accuracy with digital indicator are fixed across the fluids flow. Six K-type thermocouples are located on the test section wall at equal distances to measure the wall temperature.

In this investigation, water based TiO_2 nano fluids with two volume fraction of 0.2% and 0.5% are prepared by double-step method. The required weight of nanoparticle with average diameter of 13 nm are added to distilled water, then they are mixed.

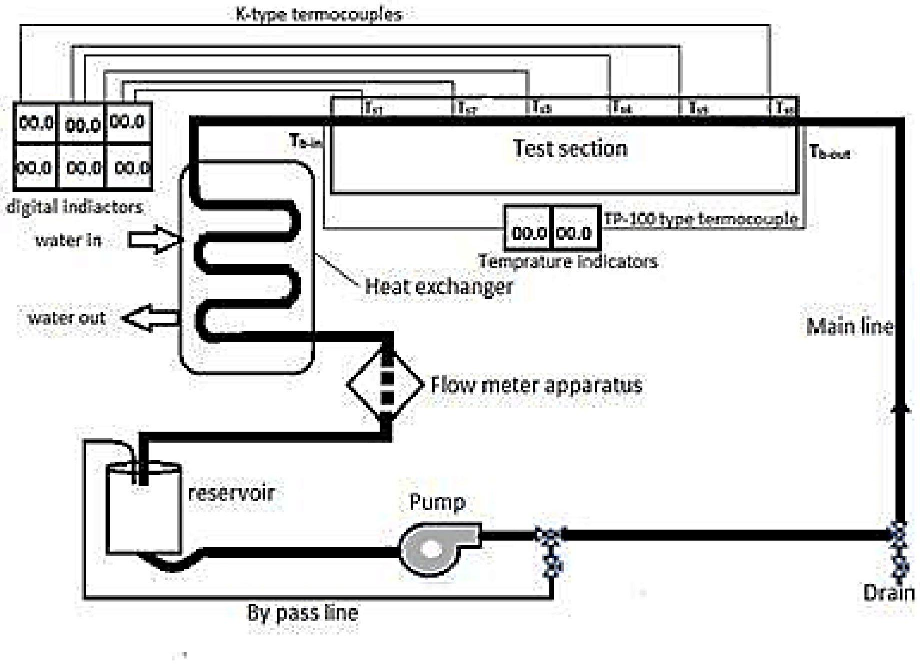

Fig. 1 Schematic of the experimental set-up

III. NANO FLUID PREPARATION

In this investigation, water based TiO_2 nanofluids with two volume fractions 0.2% and 0.5% were prepared by double-step method. The required weight of nano particles with average diameter of 13 nm were added to distilled water, then they were mixed mechanically and at the end they were sonicated in an ultrasonic apparatus that generates ultrasonic pulses of 400w at 24kHZ for 5 hours to produce stable suspension. Our observation showed that there is not a visible sedimentation in suspension in 14 hours.

IV. DATA ANALYSIS

With energy balance in conduits, the experimental convective heat transfer coefficient and Nusselt number of laminar flow that indicate heat transfer performance of water and Nano fluid are obtained:

$$h = \frac{m^{\circ} C_p \left(T_{b-out} - T_{b-in}\right)}{A_{sur}\Delta T_{lm}} \tag{1}$$

$$Nu = \frac{h_{ex} D_h}{k} \tag{2}$$

where $\left(T_{b-out} - T_{b-in}\right)$, A_{sur} , ΔT_{lm} and D_h are the mean temperature difference between outlet and inlet working fluid, surface area, logarithmic mean temperature and hydraulic diameter, respectively.

Specific heat capacity, conductivity, density and viscosity of nanofluids are calculated from Pak and Cho [24], Einstein [25], Pak and Cho [24] and Maxwell [26] relations, respectively.

$$C_p = \varnothing C_p + (1-\varnothing) C_{bf} \tag{3}$$

$$\mu_{nf} = \mu_{bf}(1+2.5\varnothing) \tag{4}$$

$$\rho_{nf} = \varnothing \rho_p + (1-\varnothing)\rho_{bf} \tag{5}$$

$$k = \frac{k_p + 2k_{bf} - 2\varnothing(k_{bf} - k_p)}{k_p + 2k_{bf} + \varnothing(k_{bf} - k_p)} k_{bf} \tag{6}$$

V. RESULTS AND DISCUSSION

In order to make sure about proper and accurate operation of set-up in laminar flow with different Reynolds numbers, at first experiments were conducted on distilled water. After collection of experimental data, the convective heat transfer coefficient and Nusselt number are calculated.

Tests were conducted by the use of three cross sections (circle, square and triangle), with two volume fractions of TiO_2, i.e. 0.2% and 0.5%.

Figs. 2-4 present Nusselt number variations versus Reynolds number for circular, square and triangle cross sections by base fluid and Nano fluids, respectively. As observed, Nusselt number increases with increment of Reynolds number and volume fraction of TiO_2 nanoparticles. For specific Reynolds numbers, the Nusselt number of Nano fluid is higher than that of the base fluid in all cross sections. This illustrates that adding a few amount of Nano powder can improve convective heat transfer coefficient in conduits. For example at Reynolds number about 2000, the increment of Nusselt number with volume fraction of 0.2% and 0.5% are 3% and 6.3% for circle, 3.2% and 7.1% for square, and 3.4 and 7.2 for triangle, respectively.

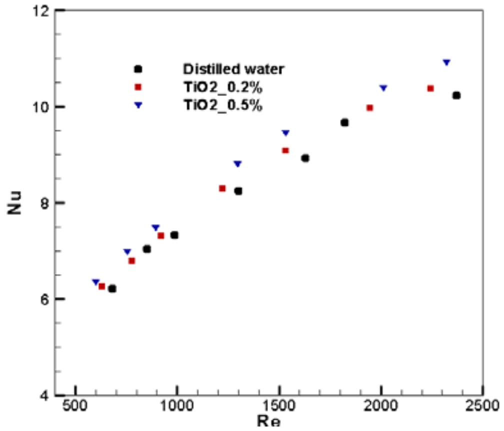

Fig. 2 Nusselt number versus Reynolds number for flow through circular cross section

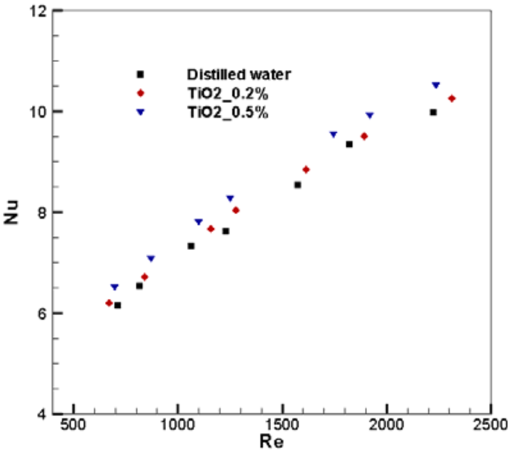

Fig. 3 Nusselt number versus Reynolds number for flow through square cross section

Average enhancement of 6.74%, 7.17% and 7.22 for volume fractions of 0.5% and of 2.84%, 3.05% and 3.2% for volume fraction of 0.2% are observed in conduits with circular, square and triangle cross sections, respectively. The enhancements of Nusselt number in square and triangular cross sections are more than that in circular cross sections that indicates the decreasing of lost heat near acute angles by non-circular cross sections.

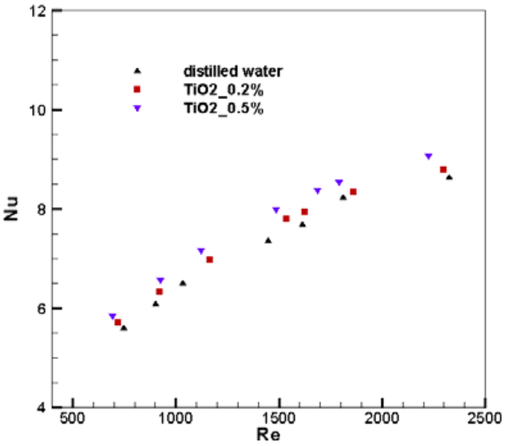

Fig. 4 Nusselt number versus Reynolds number for flow through triangular cross section

VI. Conclusion

For a specific range of Reynolds number and volume fraction of TiO_2 nanoparticles, the Nusselt number of fluids flow through conduits with circular cross section is more than those in conduits with square and triangular cross sections. The relative enhancement of Nusselt number of working fluids flow through conduit with circular cross section is less than those in conduits with square and triangular cross sections. This behavior indicates that heat lost in sharp angles is reduced.

Nomenclature

A_{sur}	External surface area of ducts(m^2)
C_p	Specific heat (J Kg^{-1} K^{-1})
D_h	Hydraulic diameter(m)
h	Average heat transfer coefficient of Nanofluids (Wm^{-2} K^{-1})
k	Thermal conductivity (W m^{-1} K^{-1})
$\overset{\circ}{m}$	Mass flow rate (Kg s^{-1})
Nu	Nusselt number
ΔT_{lm}	Log-mean temperature difference(K)

Greek letters

$\varnothing$	Nanoparticle volume fraction(dimensionless)
μ_{nf}	Viscosity (Pa s)
ρ	Density (Kg m^{-3})

Subscript

bf	Base fluid
in	Input
nf	Nanofluid
out	Output
p	Nanoparticle

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