Experimental Study on Flow and Heat Transfer Characteristics of Nanofluids in a Triangular Tube at Different Rotation Angles

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Abstract: Because of the poor thermal performance of ordinary tubes, a triangular tube was used to replace the smooth channel in the heat transfer system, and nanofluids were used to take the place of ordinary fluids as the heat transfer medium. High stability nanofluids were prepared, and an experimental set on flow and heat exchange was established. Effects of triangular tube rotation angles (α = 0°, 30°, 60°) as well as mass fractions of nanofluids (ω = 0.1%, 0.3%, 0.5%) on heat exchange and flow performance were experimentally considered at Reynolds numbers (Re = 800–8000). It was shown that the triangular tube with a rotation angle α = 0° possesses the most excellent thermal property, followed by a rotation angle α = 60° triangular tube, and a rotation angle α = 30° triangular tube has the worst heat exchange property. Results also revealed that resistance coefficients of the triangular tube with rotation angles α = 0° and α = 30° are close to each other, and a rotation angle α = 60° triangular tube shows the minimal resistance coefficient. It could be also seen that higher nanoparticle mass fraction can augment the thermal performance. However, higher nanoparticle mass fraction can also lead to an increment in resistance coefficient. A comprehensive performance evaluation index was introduced to appraise the augment in Nusselt number and flow resistance coefficient. The experiment revealed that the highest index emerges with nanofluids (ω = 0.5%) in the triangular tube with a rotation angle α = 0°.

Keywords: Nanofluids; forced convection; heat transfer enhancement; triangular tube; rotation angle

Nomenclature

- $A_c$: sectional area of triangle tube, m²
- $c_p$: specific heat capacity of nanofluids, J·kg⁻¹·K⁻¹
- $c_{pb}$: specific heat capacity of base fluid, J·kg⁻¹·K⁻¹
- $c_{pp}$: specific heat capacity of nanoparticle, J·kg⁻¹·K⁻¹
- $d_e$: hydraulic diameter, m
- $f$: flow resistance coefficient of nanofluids
- $h$: convective heat transfer coefficient, W·m⁻²·K⁻¹
- $L$: length of triangle tube, m
- $Nu$: Nusselt number of nanofluids
- $P'$: wetted perimeter, m
- $p$: pressure drop, Pa
- $ΔP/Δl$: pressure drop per unit length, Pa·m⁻¹
- $q_m$: mass flow rate, kg/s
**Greek symbols**

- $\alpha$: rotation angle, °
- $\rho$: density of nanofluids, kg·m$^{-3}$
- $\rho_b$: density of base fluid, kg·m$^{-3}$
- $\rho_p$: density of nanoparticle, kg·m$^{-3}$
- $\omega$: nanoparticle mass fraction, %
- $\lambda$: thermal conductivity of tube, W·m$^{-1}$·K$^{-1}$
- $\lambda_f$: thermal conductivity of nanofluids, W·m$^{-1}$·K$^{-1}$
- $\mu_f$: dynamic viscosity of nanofluids, Pa·s
- $\xi$: comprehensive performance index

**Subscripts**

- b: base fluid
- f: nanofluids
- in: inlet
- out: outlet
- p: nanoparticle
- w: the wall of tube

### 1 Introduction

In the field of industry, the power of heat exchange equipment is increasing. However, due to the low thermal conductivity heat-transfer media (air, water) and the inefficient thermal performance of smooth tube, enhanced heat transfer technology is urgently needed.

Nanofluids show extraordinary thermal performance. Esfe et al. [1] indicated that the thermophysical parameters of SWCNTs-MgO/EG hybrid nanofluids augment with the volume fraction. Akhgar et al. [2] predicted the thermophysical parameters of MWCNT-TiO$_2$/water-ethylene glycol hybrid nanofluids by ANNS. Wang et al. [3] also predicted the thermal conductivity of nanofluids by artificial neural network. Hence, they are used in a multitude of heat exchange applications, such as solar thermal conversion [4,5], boiling heat exchange [6,7], and so forth. Li et al. [8] discussed the free convection of magnetic nanofluids in sinusoidal annulus. Izadi et al. [9] discussed the laminar flow of nanofluids in the two eccentric cylinders and a C-shaped cavity [10] respectively. Zhao et al. [11] investigated the CPU cooled by nanofluids and rectangular grooves, and found that the temperature of CPU is reduced by 12.5%.

Many researchers have conducted many studies in compulsive convection. Sheikholeslami et al. discussed the compulsive convection of nanofluids in a lid drive 3D enclosure [12] and a solar system [13] respectively. Results indicated that high lid velocity, permeability and revolution cause an increase in $\text{Nu}$, but the high Lorentz force reduces it. Karimipour et al. studied the forced convection of water, carbon nanotubes-water nanofluids [14] and copper-water nanofluids [15] in a microchannel respectively. They discovered that the magnetic field is beneficial to the heat flux at the thermally developing region, and the...
wall slip velocity is also a favorable factor for the heat exchange. Sun et al. analyzed the heat exchange of nanofluids in a channel under magnetic field [16] and also studied the convection impinging jets [17]. It was indicated that the magnetic field has a beneficial effect on the thermal property, and the swirling impinging jets has more superiority than common impinging jets. Mei et al. discussed the forced convection of nanofluids in a circular tube under horizontal magnetic field [18]. Results showed that the enhanced tubes can contribute to the thermal performance, but the paralleled magnetic field has a negative effect.

From above references, the enhanced technologies and nanofluids not only promote the thermal performance but also magnify the flow resistance. Hence, it is necessary to develop a comprehensive assessment method. Some investigators used comprehensive assessment methods to analyze these, such as entropy generation [19]. In addition, compared to the smooth tube, the triangular tube has a smaller hydraulic diameter under the same sectional area, which can increase the disturbance in the channel to enhance the heat exchange. Besides, considering the stable structure of triangle, triangular tube can be applied in various fields. Hence, the target of the article is to systematically research the turbulent flow of nanofluids in a triangular tube at diverse rotation angles. Since the triangle is not completely symmetrical structure, different angles may affect the flow resistance and heat transfer. Different parameters, such as triangular tube rotation angles ($\alpha = 0^\circ, 30^\circ, 60^\circ$), mass fractions of nanoparticle ($\omega = 0.1\%, 0.3\%, 0.5\%$) and Reynolds numbers ($Re = 800–8000$), are considered to explore the mechanisms of the heat and flow performance. Also, a comprehensive performance evaluation index is introduced to appraise the thermal-hydraulic performance of nanofluids in enhanced tubes, which can contribute to the design and operation of heat-exchange equipment. The innovations of this paper are as below: (1) Triangular tubes with different rotation angles are considered to explore the mechanisms of the heat and flow performance. (2) The comprehensive performance is studied by a comprehensive evaluation performance index.

2 Methods
2.1 Nanofluids

In this paper, TiO$_2$-water nanofluids are adopted as the working medium, since the high sterilization, stability and excellent thermal conductivity of TiO$_2$ nanoparticles. The diameter of the TiO$_2$ nanoparticle is around 10 nm, because the nanofluids with nanoparticles of this size have high stability and thermal conductivity, which can reduce the deposition and agglomeration in tube and enhance the heat exchange. The working medium is produced by a two-step method. Firstly, a proper dose of dispersant agent is mixed into the pure water to ensure the stability of nanofluids. After being stirred for some time, TiO$_2$ nanoparticles with certain mass fractions are added. Then some NaOH is added to regulate the pH value and fluid continues to be stirred. At last the ultrasonic vibration is used to prepare the nanofluids. The prepared TiO$_2$-H$_2$O nanofluids with three mass fractions of nanoparticle ($\omega = 0.1\%, 0.3\%, 0.5\%$) are shown in Fig. 1. In this paper, precipitation method is introduced to examine the stability of TiO$_2$-H$_2$O nanofluids, results demonstrate that TiO$_2$-H$_2$O nanofluids still remain well stability after standing seven days, thus illustrating the nanofluids prepared have well stability.

Figure 1: Nanofluids prepared by two-step method, (a) before standing, (b) after standing for 7 days.
2.2 Experimental System

An experimental set for nanofluids forced convection is established, which is shown in Fig. 2. The core section is the triangular tube which is presented in Fig. 3. For the purpose of preventing the entrance effect, a length of 100 mm at two ends of tube is left respectively. A DC power connected to a heating wire supplies the heat for the triangular tube, and the application of eleven thermocouples is adopted to record the outside wall temperature of the triangular tube, besides, the pressure drop is measured by a pressure difference sensor. The cooling bath thermostat is adopted to control the temperature of the nanofluids. To maintain the insulation and prevent the heat dissipation, mica layer, silicate insulation wool and aluminum insulation are adopted, and the details can be seen from Fig. 3(a). The size of the triangular tube is presented in Fig. 3(b). Three rotation angles ($\alpha = 0^\circ, 30^\circ, 60^\circ$) are adopted in this experiment, and the details can be seen from Fig. 3(c).

Figure 2: Schematic diagram of experimental system

Figure 3: Triangle tube, (a) internal diagram, (b) size dimension, (c) rotation angle
2.3 Data Processing

The hydraulic diameter of the triangle tube can be computed as below:

\[ d_e = \frac{4A_c}{P} \]  (1)

Reynolds number is:

\[ Re = \frac{\rho ud_e}{\mu_f} \]  (2)

DC power heating power is:

\[ Q_j = UI \]  (3)

Heat absorption of the fluid is:

\[ Q_r = c_p q_m (T_{out} - T_{in}) \]  (4)

Convective heat transfer coefficient is:

\[ h_f = \frac{Q_r}{\pi d_e L (T_{wi} - T_j)} \]  (5)

Average temperature of the external wall of the triangle tube can be computed:

\[ T_{wo} = \frac{\sum_{i=1}^{11} T_{wo}(i)}{11} \]  (6)

Average temperature of the internal wall of the triangle tube can be computed:

\[ T_{wi} = T_{wo} - \frac{Q_j \ln(r_o/r_i)}{2\pi\lambda l} \]  (7)

Average temperature of the fluid is presented as below:

\[ T_f = \frac{T_{in} + T_{out}}{2} \]  (8)

Nusselt number can be defined as follows:

\[ Nu = \frac{h_f d_e}{\lambda_f} \]  (9)

Resistance coefficient is:

\[ f = \frac{2d_e \Delta p}{\rho u^3 \Delta t} \]  (10)

Specific heat and density are presented as below respectively [20]:

\[ c_p = (1 - \varphi)c_{pb} + \varphi c_{pp} \]  (11)

\[ \rho = (1 - \varphi)\rho_b + \varphi\rho_p \]  (12)

Comprehensive performance index for flow and heat exchange is [21]:

[ ... ]
\[ \xi = \left( \frac{Nu}{Nu_{bf}} \right) / \left( \frac{f}{f_{bf}} \right)^{1/3} \]  

(13)

2.4 Uncertainty Analysis

For the purpose of guaranteeing the reliability of the experimental system, uncertainty analysis is essential. The uncertainties of thermal-hydraulic performances (\(Nu\) and \(f\)) are defined as follows [21]:

\[ \frac{\delta Nu}{Nu} = \sqrt{\left( \frac{\delta Q_r}{Q_r} \right)^2 + \left( \frac{\delta T}{T} \right)^2} \]  

(14)

\[ \frac{\delta f}{f} = \sqrt{\left( \frac{\delta q_m}{q_m} \right)^2 + \left( \frac{\delta L}{L} \right)^2 + \left( \frac{\delta p}{p} \right)^2} \]  

(15)

Based on Eqs. (14) and (15), the uncertainties of thermal-hydraulic performances (\(Nu\) and \(f\)) are obtained which can be seen in Tab. 1. All the data of temperature and pressure drop are recorded about 60 minutes until stable to guarantee the precision of the experiment.

| Physical quantity | DC power | Temperature | \(Nu\) | Pressure drop | Tube length | Mass Flow | \(f\) |
|-------------------|----------|-------------|-------|--------------|-------------|-----------|-------|
| Uncertainty       | ±1.0%    | ±1.0%       | ±1.4% | ±0.5%        | ±0.1%       | ±1.1%     | ±1.1% |

3 Results and Discussion

3.1 Experimental Verification

The experimental verification, which is prior to the formal experiment, is carried out. The experiment results of this paper are compared with those of other references [22,23] and those calculated by Eq. (16) in Fig. 4. The figure illustrates good agreement between the results, whose max errors are less than 6.6% and 1.4% for Nusselt number and flow resistance coefficient respectively, thus demonstrating that the experiment system has well reliability.

The Filonenko formula [24]:

\[ f = (1.82 \log Re - 1.64)^2 \]  

(16)
6.4 6.6 6.8 7.0 7.2 7.4 7.6 7.8 8.0
1.5
1.6
1.7
1.8
2.0
2.1

Experimental result
Theoretical result of Eq.16

\ln(100f)
\ln(Re)

(c)

Experimental result
Theoretical result of Eq. 16

\ln(100f)
\ln(Re)

(d)

Figure 4: Experimental verification, heat transfer characteristics: (a) laminar flow, (b) turbulent flow; flow characteristics: (c) laminar flow, (d) turbulent flow

3.2 Effects of Rotation Angles

Nusselt numbers of the triangular tubes with rotation angles (\(\alpha = 0^\circ, 30^\circ, 60^\circ\)) for laminar and turbulent conditions are investigated in Figs. 5 and 6 respectively. Results indicate that the triangular tube with a rotation angle \(\alpha = 0^\circ\) shows the maximal Nusselt number, followed by the triangular tube with a rotation angle \(\alpha = 60^\circ\), and the minimum one is the triangular tube with a rotation angle \(\alpha = 30^\circ\). A comparison between the triangular tubes with rotation angles \(\alpha = 0^\circ\) and \(30^\circ\) illustrates that the maximum ratios on enhancing heat transfer are 6.2% and 5.3% for laminar and turbulent conditions respectively. It may be because the triangular tube with a rotation angle \(\alpha = 0^\circ\) has the greatest impact on the reduction in laminar boundary layer, and the rotation angle \(\alpha = 30^\circ\) shows the minimal influence. A bigger enhancement ratio in Nusselt number for laminar condition is obtained compared to the turbulent condition, due to reasons that the rotation angle has a significant impact on enhancing the heat exchange for laminar condition, however, the effect of the rotation angle can be weakened by the disturbance for turbulent condition, and when the flow state changes from laminar flow to turbulent flow, the enhancement ratio reduces.

The flow resistances of different rotation angles for laminar and turbulent conditions are researched in Figs. 7 and 8 respectively. It is obtained that the resistance coefficients of the triangular tube are close to each other, especially the rotation angles \(\alpha = 0^\circ\) and \(30^\circ\), and the triangular tube with a rotation angle \(\alpha = 60^\circ\) behaves the minimal resistance coefficient. In addition, compared with a rotation angle \(\alpha = 60^\circ\), the maximal increments of resistance coefficients are 4.1% and 3.2% in the triangular tube with a rotation angle \(30^\circ\) for laminar and turbulent conditions respectively. This demonstrates that the resistance coefficients relate to the rotation angles directly as well.
Figure 5: Effects of different rotation angles on Nusselt numbers at laminar flow, (a) 0.0%, (b) 0.1%, (c) 0.3%, (d) 0.5%

Figure 6: Effects of different rotation angles on Nusselt numbers at turbulent flow, (a) 0.0%, (b) 0.1%, (c) 0.3%, (d) 0.5%
Figure 7: Effects of different rotation angles on the flow resistance at laminar flow, (a) 0.0%, (b) 0.1%, (c) 0.3%, (d) 0.5%

Figure 8: Effects of different rotation angles on the flow resistance at turbulent flow, (a) 0.0%, (b) 0.1%, (c) 0.3%, (d) 0.5%
3.3 Effects of Nanoparticle Mass Fractions

In addition to the different rotation angles, Figs. 9 and 10 give the impacts of mass fractions on Nusselt numbers and resistance coefficients. Results of Fig. 9 explain that Nusselt number and the nanoparticle mass fraction are positively related. A comparison between nanofluids ($\omega = 0.5\%$) and pure water illustrates that the growths of the Nusselt number are 20.3% and 16% for laminar and turbulent conditions respectively. The whole thermal conductivity of fluid can be increased with TiO$_2$ nanoparticles whose thermal conductivity is higher. Besides, nanoscale nanoparticles have the greatest Brownian force compared with other interaction forces [25], which can augment the heat exchange. Besides, a bigger enhancement ratio for the laminar condition is present, compared to the turbulent condition. This reason is similar to Figs. 5 and 6. In laminar regime, the influence of nanoparticle has a positive role in the enhancement ratio, however, the disturbance reduces the impact of nanoparticle in turbulent regime.

Figure 9: Effects of nanoparticle mass fractions on Nusselt numbers, $\alpha = 0\degree$: (a) laminar flow, (b) turbulent flow; $\alpha = 30\degree$: (c) laminar flow, (d) turbulent flow; $\alpha = 60\degree$: (e) laminar flow, (f) turbulent flow
Changes of flow resistances with nanoparticle mass fractions are researched in Fig. 10. It can be seen that the addition of nanoparticles increases the resistance coefficient. A comparison between nanofluids ($\omega = 0.5\%$) and pure water illustrates that the growths of the resistance coefficient are 4.7% and 3.3% for laminar and turbulent conditions respectively. The drag force between water molecules and nanoparticles is caused by the mass differences between them [25], and the drag force is an unbenefficial factor and can increase the viscosity, lastly reduces the heat transfer. Hence, with the increase of nanoparticles, the resistance coefficient shows an increase trend. Results also present that the enhancement in laminar regime is prior to that in turbulent regime, due to reasons that the drag force plays a great role in resistance coefficient in laminar regime, however, the disturbance begins to dominate the flow resistance in turbulent regime.

**Figure 10:** Effects of nanoparticle mass fractions on flow resistance, $\alpha = 0^\circ$: (a) laminar flow, (b) turbulent flow; $\alpha = 30^\circ$: (c) laminar flow, (d) turbulent flow; $\alpha = 60^\circ$: (e) laminar flow, (f) turbulent flow
In order to clearly compare these data, Tabs. 2 and 3 present the Nusselt numbers in laminar and turbulent conditions respectively. Tabs. 4 and 5 show the resistance coefficients in laminar and turbulent conditions respectively.

**Table 2:** Nusselt numbers in laminar condition

| Re  | α  | ω = 0% | ω = 0.1% | ω = 0.3% | ω = 0.5% |
|-----|----|--------|----------|----------|----------|
| 0   | 8.0152 | 8.89687 | 9.13732  | 9.29763  |
| 30  | 7.61444 | 8.37588 | 8.68046  | 8.83274  |
| 60  | 7.85489 | 8.64038 | 8.95458  | 9.11167  |
| 800 | 0   | 8.47403 | 9.40617  | 9.66039  | 9.82987  |
| 1200| 0   | 9.01995 | 10.01215 | 10.28274 | 10.46314 |
| 1600| 0   | 9.48324 | 11.3640  | 11.9509  | 12.16056 |
| 2000| 0   | 10.48324| 12.32347 | 12.6563  | 12.87858 |
| 2200| 0   | 11.1022 | 12.32347 | 12.6563  | 12.87858 |

**Table 3:** Nusselt numbers in turbulent condition

| Re  | α  | ω = 0% | ω = 0.1% | ω = 0.3% | ω = 0.5% |
|-----|----|--------|----------|----------|----------|
| 0   | 22.85134 | 25.13588| 26.05053 | 26.50756 |
| 3000| 21.70878 | 23.87908| 24.748   | 25.18218 |
| 60  | 22.39432 | 24.63316| 25.52952 | 25.97741 |
| 4000| 32.52524 | 35.78177| 37.07977 | 37.72928 |
| 5000| 30.89898 | 33.99268| 35.22579 | 35.84282 |
| 60  | 31.87474 | 35.06613| 36.33818 | 36.97469 |
| 6000| 41.76444 | 45.93988| 47.60946 | 48.44675 |
| 5000| 39.67622 | 43.64289| 45.22899 | 46.02441 |
| 60  | 40.92915 | 45.02109| 46.65727 | 47.47781 |
| 6000| 50.69103 | 55.75914| 57.78878 | 58.8016  |
| 7000| 48.15648 | 52.97118| 54.89934 | 55.86152 |
| 60  | 49.67721 | 54.64395| 56.633   | 57.62557 |
| 8000| 55.48214 | 61.02835| 63.25064 | 64.35928 |
| 7000| 52.70803 | 57.97694| 60.08811 | 61.14132 |
| 60  | 54.3725  | 59.80779| 61.98563 | 63.0721  |
| 8000| 65.36175 | 71.89813| 74.5094  | 75.81963 |
**Table 4:** Resistance coefficients in laminar condition

| $f$ | $\alpha$ | $\omega = 0\%$ | $\omega = 0.1\%$ | $\omega = 0.3\%$ | $\omega = 0.5\%$ |
|-----|-----------|-----------------|-------------------|-------------------|-------------------|
| 800 | 0         | 0.07614         | 0.0769            | 0.07767           | 0.07844           |
|     | 30        | 0.07738         | 0.07805           | 0.07883           | 0.07962           |
|     | 60        | 0.07421         | 0.07536           | 0.07611           | 0.07687           |
| 1200| 0         | 0.06428         | 0.06482           | 0.06547           | 0.06623           |
|     | 30        | 0.065           | 0.06565           | 0.06631           | 0.06728           |
|     | 60        | 0.0627          | 0.06353           | 0.06426           | 0.0649            |
| 1600| 0         | 0.05678         | 0.05735           | 0.05792           | 0.0585            |
|     | 30        | 0.05698         | 0.05806           | 0.05834           | 0.05902           |
|     | 60        | 0.05564         | 0.0561            | 0.05686           | 0.05733           |
| 2000| 0         | 0.05213         | 0.05265           | 0.05318           | 0.05371           |
|     | 30        | 0.05243         | 0.05306           | 0.05359           | 0.05412           |
|     | 60        | 0.05109         | 0.0516            | 0.05212           | 0.05264           |
| 2200| 0         | 0.05196         | 0.05248           | 0.053              | 0.05353           |
|     | 30        | 0.05216         | 0.05268           | 0.05321           | 0.05374           |
|     | 60        | 0.05012         | 0.05143           | 0.05204           | 0.05246           |

**Table 5:** Resistance coefficients in turbulent condition

| $f$ | $\alpha$ | $\omega = 0\%$ | $\omega = 0.1\%$ | $\omega = 0.3\%$ | $\omega = 0.5\%$ |
|-----|-----------|-----------------|-------------------|-------------------|-------------------|
| 3000| 0         | 0.04548         | 0.04594           | 0.0464            | 0.04686           |
|     | 30        | 0.04567         | 0.04613           | 0.04659           | 0.04705           |
|     | 60        | 0.04458         | 0.04502           | 0.04547           | 0.04593           |
| 4000| 0         | 0.04367         | 0.04411           | 0.04455           | 0.04499           |
|     | 30        | 0.04385         | 0.04429           | 0.04473           | 0.04518           |
|     | 60        | 0.0428          | 0.04323           | 0.04366           | 0.04409           |
| 5000| 0         | 0.04102         | 0.04143           | 0.04184           | 0.04226           |
|     | 30        | 0.0412          | 0.04161           | 0.04203           | 0.04245           |
|     | 60        | 0.0402          | 0.0406            | 0.04101           | 0.04142           |
| 6000| 0         | 0.03717         | 0.03754           | 0.03791           | 0.03829           |
|     | 30        | 0.03744         | 0.03781           | 0.03819           | 0.03857           |
|     | 60        | 0.03684         | 0.03731           | 0.03758           | 0.03796           |
| 7000| 0         | 0.03552         | 0.03587           | 0.03623           | 0.0367            |
|     | 30        | 0.03609         | 0.03625           | 0.03681           | 0.03708           |
|     | 60        | 0.03497         | 0.03532           | 0.03568           | 0.03603           |
| 8000| 0         | 0.0338          | 0.03413           | 0.03448           | 0.03482           |
|     | 30        | 0.03396         | 0.0343            | 0.03464           | 0.03499           |
|     | 60        | 0.03313         | 0.03347           | 0.0338            | 0.03414           |
3.4 Comprehensive Evaluation

From above analysis, high nanoparticle and a rotation angle $\alpha = 0^\circ$ not only increase the thermal performance but also increase the flow resistance, to scientifically evaluate them, a comprehensive evaluation performance index is introduced. The comprehensive index can be calculated by Eq. (13), and the corresponding results are given in Fig. 11. Fig. 11 illustrates that the Reynolds number has a significant impact on the comprehensive evaluation performance index, and the nanoparticle mass fraction has the same effect. The triangle tube with $\alpha = 0^\circ$ shows the biggest comprehensive index, followed by the triangle tube with $\alpha = 60^\circ$, and the triangle tube with $\alpha = 30^\circ$ is the minimal one. Nanofluids with $\omega = 0.5\%$ in the triangle tube with $\alpha = 0^\circ$ perform the biggest comprehensive evaluation performance index and it can reach 1.26, thus demonstrating that the influence of nanoparticles and Reynolds number on the ratio of enhancing heat exchange is bigger than that on the flow resistance.

![Figure 11: Comprehensive evaluation performance](image)

4 Conclusions

The forced convection of TiO$_2$ nanofluids is experimentally discussed in a triangular tube at various rotation angles. The main results are as below:

(1) The triangular tube with a rotation angle $\alpha = 0^\circ$ reveals the maximal Nusselt number, followed by the triangular tube with a rotation angle $\alpha = 60^\circ$, and the triangular tube with a rotation angle $\alpha = 30^\circ$ has the lowest Nusselt number. A comparison between triangular tubes with rotation angles $\alpha = 0^\circ$ and $30^\circ$ illustrates that the maximum ratios on enhancing heat transfer are 6.2% and 5.3% for laminar and turbulent conditions respectively. The reason is that the triangle tube with a rotation angle $\alpha = 0^\circ$ has the greatest impact on the reduction in laminar boundary layer.

(2) Resistance coefficients of the triangular tubes are close to each other, especially the rotation angles $\alpha = 0^\circ$ and $30^\circ$, and the triangular tube with a rotation angle $\alpha = 60^\circ$ behaves the minimal resistance coefficient. Compared with a rotation angle $\alpha = 60^\circ$, the maximal increments of resistance coefficient are 4.1% and 3.2% in the triangular tube with a rotation angle $30^\circ$ for laminar and turbulent conditions respectively. This demonstrates that the resistance coefficients relate to the rotation angles directly as well.

(3) Nusselt number behaves an increment with the enlarged nanoparticle mass fraction. Compared with pure water, the maximal increments of the Nusselt number are 20.3% and 16% for nanofluids ($\omega = 0.5\%$) at laminar and turbulent conditions respectively. It is because the whole thermal conductivity of fluid can be increased after adding the TiO$_2$ nanoparticles. Besides, nanoscale nanoparticles have the greatest Brownian force compared with other interaction forces, which can augment the heat exchange performance.

(4) Addition of nanoparticles increases the resistance coefficient. Compared with pure water, the maximal increments of the resistance coefficient are 4.7% and 3.3% for nanofluids ($\omega = 0.5\%$) at laminar conditions.
and turbulent conditions respectively. The reason is that the drag force between water molecules and nanoparticles can increase the viscosity.

(5) The Reynolds number has a significant impact on the comprehensive evaluation performance index, and the nanoparticle mass fraction has the same effect. The triangle tube with $\alpha = 0^\circ$ shows the biggest comprehensive index, followed by the triangle tube with $\alpha = 60^\circ$, and the triangle tube with $\alpha = 30^\circ$ has the smallest one.

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