

Experimental Investigation in Enhancement of Heat Transfer in a Straight Tube Heat Exchanger Using Twisted Tape Inserts and Nano Fluids-Effect of Turbulent and Laminar Flow Characteristics

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ABSTRACT

To measure convective heat transfer and hydraulic penalty of a straight circular tube heat exchanger equipped with twisted-tape inserts and run using the Al_2O_3 water nanofluids, an experimental study was carried out. Reynolds numbers between 500 and 15,000 with three twist ratios ($y/w = 3.0, 4.5, 6.0$) and nanoparticle volume concentrations of 0.1 to 0.5 percent by volume were tested. Nusselt number and friction factor were measured and compared to plain tube with pure water. A combination of the twisted-tape inserts and nanofluids resulted in a synergistic rise in heat transfer at a penalty of a quantifiable pressure-drop. Net benefit was measured by thermal performance factor η , assuming constant pumping-power. It was found that the optimum improvement can be achieved at low twist ratios and moderate nanoparticle concentration where 2 indicates net system-level advantage. Significant implications to the design of compact heat exchanger are discussed.

Keywords

Insert twisted-tape; nanofluid of Al_2O_3 ; Nusselt number; friction factor; thermal performance factor; heat transfer enhancement.

1. Introduction

Enhancement of heat transfer has continued to be the focus of the enhancement of compactness and energy efficiency of heat exchanger in industrial processes. Passive techniques like twisted-tape inserts can be used to enhance convective coefficients by causing swirl and secondary flows that break the thermal boundary layer. Nanofluids are produced by dispersing nanoparticles in a base fluid and enhance effective thermal conductivity and may enhance additional enhancement of convective heat transfer. Synergism effects of twisted-tape inserts and Al_2O_3 water nanofluid have been demonstrated to be promising, though limited data have been obtained across laminar and turbulent regimes and twist ratios. In this experiment the authors experimentally measure the augmentation of heat transfer and hydraulic penalties of the combined approach and assess performance in terms of a thermal performance factor. It has been established in literature that twisted tapes are very effective in improving Nu through vortex generation and mixing, whereas Al_2O_3 nanofluids is effective in increasing thermal conductivity and minimally raising viscosity; both of which improve Nu and pressure drop respectively.

2. Literature review

Twisted-tape inserts have been widely studied; they create a better mixing and long-term vortices that increase local heat transfer coefficients. Review papers suggest that the improvement is heavily reliant on twist ratio, tape width and geometry changes like perforations or multiple tapes.

Al₂O₃ nanofluids are some of the best characterized nanoparticle suspensions; increases in thermal conductivity can be reported to range between a few percent and tens of percent with respect to particle size, volume fraction, and temperature; increases in viscosity are typically smaller yet non-negligible. There is a significant influence of stability and dispersion method (ultrasonication, surfactants) on properties.

Numerical and experimental results of the combined twisted tapes and Al₂O₃ nanofluids show a general tendency: Nu rises significantly with the reduction of twist ratio and rise of nanoparticle concentration, and pressure drop rises with both. Research gives performance metrics like PEC or η to equalize between heat transfer gains and pumping penalties.

3. Experimental design and procedure.

3.1 Apparatus

The closed-loop test rig consists of a storage tank, centrifugal pump having variable speed drive, calibrated magnetic flow meter, heater assembly, test section and differential pressure transducer. The copper tube ($D_i = 14.0$ mm, $D_o = 16.0$ mm) with the length $L = 1200$ mm is used to test section where electrical resistance heating is applied to offer a near-uniform heat flux to the test section. T-type thermocouples are placed at inlet and outlet and at the same axial distance on the tube wall; a thermocouple is in the flow to measure bulk fluid temperature.

3.2 Preparation of inserts and nanofluid.

The 1.0mm thick aluminum strips were twisted into tapes, with width of the strips $w = 13.5$ mm, and twist ratios $y/w = 3.0, 4.5, 6.0$. Al₂O₃ nanoparticles (nominal $d_p = 40$ nm) were suspended in deionized water (volume fraction of 0.1, 0.3, and 0.5). The test durations were maintained by ultrasonic agitation of 4 hours and mild addition of surfactants to maintain the stability of the suspension. Density, viscosity and thermal conductivity of each nanofluid were determined before flow testing using calibrated property tools.

3.3 Test procedure and data acquisition.

In every setup, the steady-state tests were conducted with Reynolds number 500 Re and 15,000 Re . The values of flow rate and temperature were measured once the steady-state had been achieved.

Across the test section, pressure drops were measured. The average of three or more constant measurements is the experimental point.

3.4 Data reduction and equations. Reynolds number:

Rate of heat transfer to fluid:

Convective heat transfer coefficient:

where T_f is average temperature of the fluid. Nusselt number:

Friction factor of measured pressure drop ΔP :

Thermal performance factor with a constant pumping-power assumption:

where subscript 0 refers to plain tube with base fluid.

3.5 Uncertainty analysis

Standard propagation was used to combine measurement uncertainties. Representative uncertainties: flow (10-percent), temperature (0.3 C), pressure (0.5). The uncertainty in Nu is determined as -6%, and in f -8%.

4. Results

4.1 Thermophysical properties

Observed rises in effective thermal conductivity and viscosity as a function of volume fraction were in line with literature values of Al 2 O 3 nanofluids. The thermal conductivity increased with the concentration and temperature and the viscosity also increased slightly at the greatest concentrations. These changes in the property are behind the trend in Nu and f.

4.2 Heat transfer enhancement

All configurations have been plotted in figure plots (to be included in final manuscript) of Nu versus Re. Table 1 provides the key observations in the representative turbulent regime (Re = 8000).

Table 1: Experimental Data Summary (Representative at Re 8000)

Configuration Concentration (ϕ)

Nu f

Nu/Nu₀ f/f₀

η

Plain Tube (Water) 0.0%

68.2

0.032

1.00

1.00

1.00

Plain Tube (Nanofluid) 0.5%

84.5

0.036

1.24

1.12

1.19

Tape y/w = 6.0 (Water) 0.0%

112.4

0.078

1.65

2.43

1.23

Tape $y/w = 3.0$ (Water) 0.0%

135.0

0.095

1.98

2.96

1.38

Tape $y/w = 3.0$ (Nanofluid) 0.5%

162.8

0.110

2.38

3.43

1.58

The combined case ($y/w = 3.0$, 0.5% Al_2O_3) gives the largest Nu as well as the largest friction factor. These findings are consistent with the trends in previous experimental and numerical studies which indicate high Nu increase when twist ratio is low and higher frictional losses with particle concentration.

4.3 Friction factor and pressure drop.

Insert presence enhances pressure drop because of decreased flow area, and increased swirl. There is also an increase in the viscosity of nanofluid. The pressure-drop scale is proportional to the twist tightness and nanoparticle concentration. The data corroborate the anticipated trade-off: optimum Nu is associated with optimum f. This is in agreement with the previous reported increase in friction of the helical or twisted inserts in conjunction with Al_2O_3 nanofluids.

4.4 Thermal performance factor

The combination of these results is that given a constant pumping-power assumption, the net performance gain is obtained with η as the figure of merit. As an illustration, $y/w = 3.0$ with 0.5 percent Al_2O_3 created $\eta = 1.58$, which suggested a good trade-off at the operating point tested. These types of PEC or η analysis are typically used in literature to measure practical viability.

5. Discussion

Mechanisms: On twisted tapes, swirling flow and secondary vortices develop that thin the thermal boundary layer and homogenize temperature distributions. Nanoparticles enhance thermal conductivity and have the ability to modify micro-convectional effects by particle movement in strong swirl flows; the combination of both can augment the

overall heat transfer.

Design implication: The tight twist (low twist ratio) gives maximum Nu, however, it raises pumping power. In the case of compact heat exchangers, the designers have to maximize the twist ratio and concentration of the nanoparticles with a target operating Re and a reasonable pressure-drop budget. This optimization is assisted by multi-criteria measures like η and PEC.

Limitations: The stability of nanofluid during long-term circulation and erosion or fouling by nanoparticles should be further long-term investigated. The measurements in this case are steady and short term, long term durability tests are recommended. At the higher concentrations, property measurement accuracy and slip effects necessitate a more refined two-phase model, which would accurately predict these effects.

6. Conclusions

In the case of using a combination of twisted-tape inserts along with Al₂O₃-water nanofluid, the convective heat transfer increases tremendously in comparison to a simple plain tube using water.

The highest gains in the Nusselt number were realized at tight twist ratios ($y/w = 3.0$) and also with increased nanoparticle concentrations up to approximately 2.38 times the plain tube at $Re = 8000$.

The penalties based on friction factors cannot be overlooked and should be taken into account; the optimal integrated case yielded $\eta =$ about 1.58, which means that the net performance of the chosen operating points is favourable.

Recommendations: To implement in practice prefer geometry and concentration that maximise η at the desired Re range; test long-term stability of nanofluids and adopt filtration or treatment to control possible agglomeration of particles.

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