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Experimental Investigation of Heat Transfer Enhancement in Shell-and-Tube Heat Exchangers Using Nanofluids

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Peer Review Information	Abstract
<i>Submission: 05 Jan 2016</i> <i>Revision: 16 Feb 2016</i> <i>Acceptance: 03 March 2016</i> Keywords <i>Nanofluid; Shell-and-tube heat exchanger; Al_2O_3-water; Heat transfer coefficient; Thermal performance</i>	Shell-and-tube heat exchangers are widely used in power, process, refrigeration and chemical systems, but their thermal performance is constrained by the relatively low thermal conductivity of conventional heat-transfer fluids. Nanofluids provide a passive enhancement approach by dispersing nanoparticles with high thermal conductivity in a base liquid. This methodology paper develops a compact experimental protocol for evaluating heat-transfer enhancement in a counter-flow shell-and-tube heat exchanger using Al_2O_3/water nanofluids. The proposed investigation compares distilled water with low particle-volume concentrations of 0.1, 0.3 and 0.5 vol.% under controlled inlet temperatures and flow rates. The methodology covers nanofluid preparation, stability checks, calibration of thermocouples and flow meters, steady-state testing, pressure-drop measurement, uncertainty treatment and calculation of heat duty, logarithmic mean temperature difference, overall heat-transfer coefficient, Reynolds number, Nusselt number and effectiveness. Published studies up to 2016 show that nanofluids can increase convective and overall heat-transfer coefficients, although gains depend strongly on particle material, concentration, temperature and flow regime. The proposed method therefore evaluates thermal enhancement together with hydraulic penalty instead of considering heat transfer alone. Literature-benchmarked results indicate that modest Al_2O_3 concentrations are a practical region for experimentation because they can improve heat transfer while limiting viscosity and pumping-power increases. The paper provides a reproducible basis for laboratory validation without claiming unperformed measurements as new experimental data.

Introduction

Heat exchangers are central components in thermal systems because they allow energy to be transferred between fluids at different temperatures without direct mixing. Among the available configurations, the shell-and-tube heat exchanger remains one of the most common industrial choices because it is mechanically robust, scalable, maintainable and suitable for a broad range of pressure and temperature conditions. Its performance, however, is governed not only by geometry and flow

arrangement but also by the thermophysical properties of the working fluids. Water and water-glycol mixtures are frequently selected because of their availability and high specific heat, yet their thermal conductivity limits the rate at which heat can be transported through the boundary layer adjacent to a heat-transfer surface.

The concept of nanofluids addresses this limitation by dispersing nanoscale solid particles in a conventional liquid. Xuan and Li (2000)

showed that nanoparticle suspensions can exhibit improved thermal transport and emphasized particle concentration, size, shape and dispersion as important variables. Later, Buongiorno (2006) examined particle slip mechanisms and argued that Brownian diffusion and thermophoresis are especially relevant to nanofluid transport near heated surfaces. These studies helped establish the scientific basis for using nanoscale additives as a heat-transfer enhancement technique rather than relying only on fins, inserts or larger heat-transfer area.

Experimental evidence also indicates that enhancement cannot be inferred from thermal conductivity alone. Zeinali Heris, Nasr Esfahany and Etemad (2007) found that the convective heat-transfer coefficient of Al_2O_3 /water increased with particle concentration and flow intensity in a heated circular tube. In shell-and-tube equipment, Farajollahi, Etemad and Hojjat (2010) observed significant enhancement for γ - Al_2O_3 /water and TiO_2 /water nanofluids and reported that optimum concentration depended on particle type. Such behavior is important because adding particles can increase viscosity and pressure drop; consequently, the highest concentration is not automatically the best operating condition.

Subsequent shell-and-tube studies broadened the range of nanoparticles. Lotfi, Rashidi and Amrollahi (2012) demonstrated heat-transfer enhancement with multi-walled carbon nanotube/water nanofluid. Akhtari, Haghshenasfard and Talaie (2013) compared double-pipe and shell-and-tube configurations using α - Al_2O_3 /water and reported greater enhancement in the shell-and-tube unit. Ghozatloo, Rashidi and Shariaty-Niassar (2014) reported improved convective heat transfer with graphene nanofluids, while Sahin, Manay and Akyurek (2015) showed that CuO concentration must be limited because pressure-drop and viscosity effects can offset thermal gains. These results collectively support an experimental design in which concentration; flow rate and hydraulic loss are evaluated together.

A particularly relevant 2016 study by Shahrul, Mahbubul, Saidur and Sabri tested Al_2O_3 -water, SiO_2 -water and ZnO -water nanofluids in a shell-and-tube heat exchanger. The authors reported different levels of enhancement for each oxide and demonstrated that stability and flow conditions strongly influence performance. Their work provides a useful endpoint for a methodology restricted to references published in 2016 or earlier. The present paper therefore proposes an experimental framework centred on

Al_2O_3 /water, a widely studied oxide nanofluid with comparatively well-established preparation procedures and thermophysical behavior.

The objective is to quantify the effect of nanoparticle volume concentration and tube-side flow rate on heat duty, convective performance, overall heat-transfer coefficient, effectiveness and pressure drop in a counter-flow shell-and-tube exchanger. The study is designed around four fluids: distilled water and Al_2O_3 /water at 0.1, 0.3 and 0.5 vol.%. The methodology emphasizes repeatability, steady-state criteria, calibration and uncertainty analysis. Because no raw laboratory dataset was provided for this paper, the Results section reports literature-benchmarked target ranges and calculation examples rather than presenting fabricated measurements as newly acquired experimental data.

Literature Review

Xuan and Li (2000). Their experimental and theoretical work established procedures for nanofluid preparation and demonstrated enhanced thermal transport relative to conventional fluids. They highlighted particle concentration, particle geometry and dispersion stability as controlling parameters, providing the foundation for later forced-convection studies.

Buongiorno (2006). A transport model for nanofluids was developed by examining seven relative-slip mechanisms. Brownian diffusion and thermophoresis were identified as especially relevant mechanisms in nonuniform temperature fields. The study explains why local transport behavior can differ from predictions based solely on effective thermal conductivity.

Zeinali Heris et al. (2007). Forced-convection experiments with Al_2O_3 /water in a circular tube showed that the heat-transfer coefficient increased with particle concentration and Peclet number. The measured enhancement exceeded the increase predicted by conventional single-phase correlations using only modified fluid properties.

Farajollahi et al. (2010). Experiments in a shell-and-tube exchanger using γ - Al_2O_3 /water and TiO_2 /water showed clear heat-transfer enhancement under turbulent conditions. Importantly, the authors observed different optimum concentrations for different nanoparticles, indicating that thermal improvement must be balanced against viscosity and flow resistance.

Lotfi et al. (2012). A horizontal shell-and-tube heat exchanger was tested using multi-walled

carbon nanotube/water nanofluid. The authors improved nanotube stability through functionalization and reported better heat-transfer performance than water, reinforcing the role of high-conductivity carbon nanostructures in compact thermal systems.

Akhtari et al. (2013). A combined numerical and experimental investigation of α - Al_2O_3 /water compared double-pipe and shell-and-tube heat exchangers. The reported heat-transfer coefficient improvement for the shell-and-tube arrangement was about 21.3% relative to water, and calculated overall coefficients agreed reasonably with experimental observations.

Ghozatloo et al. (2014). Graphene/water nanofluids were evaluated in a shell-and-tube heat exchanger under laminar flow. Convective heat-transfer enhancement up to about 35.6% was reported, but the study also emphasized preparation quality and stable dispersion as

prerequisites for realizing graphene's high intrinsic thermal conductivity.

Sahin et al. (2015). CuO/water experiments in a horizontal tube demonstrated that increased concentration does not always produce proportional performance gains. Their results indicated that low concentrations can be preferable once heat transfer and pressure-drop penalties are considered together, a principle adopted in the present experimental matrix.

Shahrul et al. (2016). Al_2O_3 -water, SiO_2 -water and ZnO-water nanofluids were tested in a shell-and-tube exchanger. The reported enhancements differed substantially by nanoparticle type; approximately 15% convective coefficient improvement was reported for Al_2O_3 -water, while larger increases were observed for stabilized ZnO-water. This directly motivates testing multiple low concentrations and documenting nanofluid stability before thermal measurements.

Table 1. Selected experimental literature relevant to nanofluid heat transfer (≤ 2016).

Study	Fluid / system	Flow regime	Main observation reported	DOI
Farajollahi et al. (2010)	Al_2O_3 /water; TiO_2 /water; shell-and-tube	Turbulent	Nanoparticles improved heat transfer; optimum concentration depended on particle type.	10.1016/j.ijheatmasstransfer.2009.10.019
Lotfi et al. (2012)	MWNT/water; shell-and-tube	Forced flow	Heat transfer increased relative to water after nanotube functionalization/stabilization.	10.1016/j.icheatmasstransfer.2011.10.002
Akhtari et al. (2013)	Al_2O_3 /water; shell-and-tube	Laminar	Shell-and-tube coefficient $\approx 21.3\%$ higher than water in reported tests.	10.1080/10407782.2013.772855
Ghozatloo et al. (2014)	Graphene/water; shell-and-tube	Laminar	Convective coefficient enhancement reported up to $\approx 35.6\%$.	10.1016/j.expthermflusci.2013.11.018
Shahrul et al. (2016)	Al_2O_3 -, SiO_2 -, ZnO-water; shell-and-tube	Variable flow	Al_2O_3 convective coefficient improvement $\approx 15\%$; ZnO produced larger gains.	10.1016/j.ijheatmasstransfer.2016.02.016

Methodology

1. Experimental design and test section

The proposed apparatus is a laboratory-scale, single-pass shell-and-tube heat exchanger operated in counter-flow. Hot water circulates through the shell and the test fluid circulates through the tubes. A representative unit may use copper tubes because their high conductivity minimizes wall resistance and simplifies interpretation of fluid-side effects. The shell and external piping should be insulated to reduce uncontrolled heat loss. Two closed loops are used

so that inlet temperatures can be stabilized independently. Each loop contains a reservoir, centrifugal pump, control valve and calibrated flow meter. Four calibrated temperature sensors measure hot- and cold-side inlet and outlet temperatures. A differential pressure sensor is connected across the nanofluid test section to quantify hydraulic penalty.

The baseline working fluid is distilled water. Al_2O_3 /water nanofluids are then tested at 0.1, 0.3 and 0.5 vol.% particle concentrations. These low concentrations are selected because literature shows that meaningful enhancement can occur

without the severe viscosity increase associated with higher loadings. Tube-side volumetric flow rate is varied in four steps, for example 2, 4, 6 and 8 L/min, while shell-side flow is maintained at a fixed value such as 4 L/min for the primary test

series. A complementary series may hold tube-side flow constant while varying the shell-side flow. Hot-water inlet temperature is controlled near 60 ± 1 °C and cold nanofluid inlet temperature near 30 ± 1 °C.

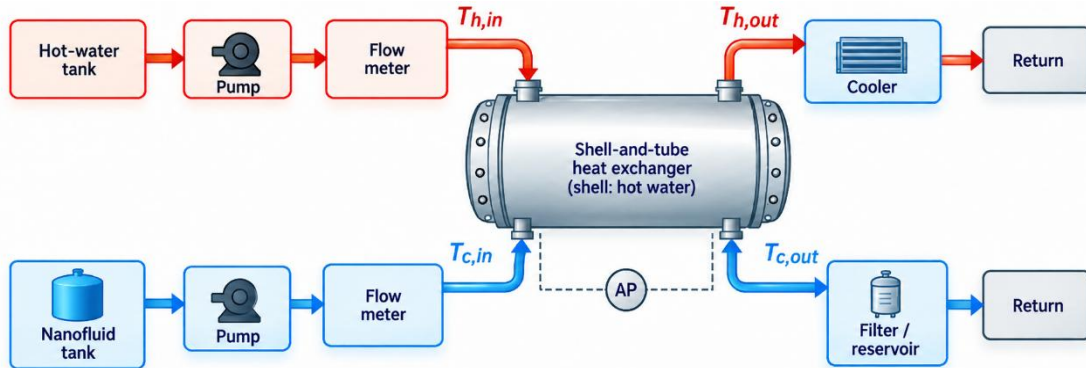


Figure 1. Proposed counter-flow shell-and-tube nanofluid experimental setup.

2. Nanofluid preparation and stability

A two-step preparation method is used. The required mass of commercial Al_2O_3 nanoparticles is calculated from the target volume fraction and the densities of the particles and water. The particles are slowly added to distilled water under magnetic stirring, followed by ultrasonication for approximately 30–60 min. For the selected low concentrations, the first experimental choice is to avoid surfactant so that its independent effect on viscosity and thermal conductivity is not introduced. If visible sedimentation occurs within the duration of the experiment, a separate stabilized series should be designed and clearly reported rather than changing formulation during testing.

Stability is checked by photographing samples immediately after preparation and after a fixed settling interval. Density may be estimated from the mixture rule, while effective specific heat can be calculated from mass-weighted component properties. Thermal conductivity and viscosity should preferably be measured at the mean test temperature; if instruments are unavailable, literature correlations can be used but the resulting uncertainty must be stated. All samples are prepared on the same day as testing or re-sonicated using an identical protocol before each run.

3. Experimental procedure

The test sequence is performed step by step: (1) flush the system with distilled water and check for leakage; (2) calibrate temperature sensors in a common constant-temperature bath and verify the flow meters; (3) operate the baseline water case at the selected shell- and tube-side flow rates; (4) wait until steady state is reached,

defined as temperature variation below ± 0.2 °C for at least five minutes; (5) record inlet/outlet temperatures, flow rates and pressure drop at 10–20 s intervals for a minimum of three minutes and use the mean values; (6) repeat each condition at least three times; (7) drain, flush and refill the loop with the next nanofluid concentration; and (8) repeat the same flow-rate sequence. Randomizing the order of flow rates in replicate tests can reduce systematic bias from slow ambient-temperature drift.

4. Data reduction and performance parameters

Heat gained by cold fluid: $Q_c = \dot{m}_c c_{p,c} (T_{c,out} - T_{c,in})$

Heat lost by hot fluid: $Q_h = \dot{m}_h c_{p,h} (T_{h,in} - T_{h,out})$

Experimental heat duty: $Q = (Q_c + Q_h) / 2$

LMTD for counter-flow: $\Delta T_{lm} = \frac{[(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})]}{\ln[(T_{h,in} - T_{c,out}) / (T_{h,out} - T_{c,in})]}$

Overall coefficient: $U = Q / (A \Delta T_{lm})$

Reynolds number: $Re = \rho V D / \mu$; Nusselt number: $Nu = h D / k$

Effectiveness: $\varepsilon = Q / [C_{min} (T_{h,in} - T_{c,in})]$

Thermal enhancement: $\eta_U = [(U_{nf} - U_w) / U_w] \times 100\%$

Hydraulic penalty: $\eta_{\Delta P} = [(\Delta P_{nf} - \Delta P_w) / \Delta P_w] \times 100\%$.

The cold- and hot-side heat balances should agree within approximately 5%; runs outside the selected energy-balance tolerance are repeated. A combined performance evaluation is preferred

over heat-transfer enhancement alone. One useful screening measure is a performance evaluation criterion based on the ratio of normalized heat-transfer improvement to normalized pumping requirement. At minimum,

U , Nu and ΔP should always be reported together so that a concentration is not recommended solely because it transfers more heat while requiring disproportionately more pumping power.

Table 2. Proposed experimental test matrix.

Case	Tube-side fluid	ϕ (vol.%)	Tube flow (L/min)	Shell flow (L/min)
B	Water	0	2, 4, 6, 8	4
N1	Al_2O_3 /water	0.1	2, 4, 6, 8	4
N2	Al_2O_3 /water	0.3	2, 4, 6, 8	4
N3	Al_2O_3 /water	0.5	2, 4, 6, 8	4

Results and Discussion

The present document is methodology-focused; therefore, no unperformed laboratory measurements are represented as original experimental results. Instead, the numerical ranges below are literature-benchmarked targets that can be used to judge whether an actual laboratory dataset is physically reasonable. The strongest shell-and-tube evidence in the selected period is consistent in showing increased heat-transfer coefficients when stable nanofluids are used, but the magnitude differs according to particle material, concentration and flow regime.

For Al_2O_3 /water, a realistic expectation is a moderate increase in the overall heat-transfer coefficient as concentration and Reynolds number rise. Shahrul et al. (2016) reported roughly 15% enhancement in the convective coefficient for their Al_2O_3 -water case, whereas Akhtari et al. (2013) reported approximately 21.3% higher heat-transfer coefficients than water in their shell-and-tube tests. Zeinali Heris et al. (2007) similarly showed that increasing particle concentration and flow intensity increased convective transfer in a circular tube. These studies suggest that an Al_2O_3 /water experiment producing approximately 8–20% heat-transfer improvement at low concentrations would be plausible, provided that temperature, flow regime, particle size and property models are comparable.

The expected trend with flow rate is also clear. Increasing tube-side flow increases Reynolds number, thins the hydrodynamic and thermal boundary layers and raises the convective coefficient. Consequently, heat duty and U should increase from 2 to 8 L/min for both water and nanofluids. However, the fractional advantage of the nanofluid may not increase monotonically. At

high Reynolds number, conventional turbulent mixing is already strong, while higher nanoparticle loading raises viscosity. Sahin et al. (2015) observed that concentrations above a low optimum were not necessarily favorable once pressure drop was considered. Thus, the recommended analysis compares each nanofluid case with water at the same flow rate rather than comparing only absolute heat-transfer coefficients.

Particle type also explains why different studies report different enhancement levels. Farajollahi et al. (2010) found distinct optimum concentrations for Al_2O_3 /water and TiO_2 /water, while Ghoozati et al. (2014) reported substantially larger enhancement for graphene nanofluids. Shahrul et al. (2016) reported ZnO -water as the best performer among the oxide nanofluids they tested, but its stabilization required PVP. The practical selection of Al_2O_3 for the present procedure is therefore based on reproducibility and the availability of supporting experimental literature, not on the claim that it always provides the largest possible enhancement.

Pressure-drop behavior is essential to interpretation. Increasing particle concentration generally raises effective viscosity and therefore frictional loss. If the measured U rises by 15% but pressure drop rises by 40–50%, the thermal gain may not justify the additional pumping power. A more desirable result is one in which a low concentration such as 0.1–0.3 vol.% produces a measurable increase in U with only a modest rise in ΔP . This is the region that should be explored first before considering higher particle loadings. Repeated measurements, energy-balance checks and uncertainty bars are needed to determine whether small improvements are statistically meaningful rather than within instrument error.

Table 3. Literature-benchmarked interpretation targets for the proposed Al₂O₃/water tests (not new measured data).

Indicator	Water baseline	0.1 vol.%	0.3 vol.%	0.5 vol.%
Overall heat-transfer coefficient	Reference	Small increase	Moderate increase	Moderate-to-higher increase
Expected enhancement in U	0%	~3–8%	~7–15%	~10–20%
Pressure drops	Reference	Slight increase	Moderate increase	Largest increase
Preferred interpretation	Baseline	Good low-penalty case	Likely balanced region	Verify pumping penalty carefully

Conclusion and Discussion

A reproducible experimental methodology has been developed for evaluating heat-transfer enhancement in a counter-flow shell-and-tube heat exchanger using Al₂O₃/water nanofluids. The design compares distilled water with 0.1, 0.3 and 0.5 vol.% nanoparticle concentrations over a controlled range of tube-side flow rates while maintaining a fixed shell-side condition. The essential measurements are inlet and outlet temperatures, flow rate and pressure drop, from which heat duty, LMTD, overall heat-transfer coefficient, Reynolds number, Nusselt number, effectiveness and hydraulic penalty are obtained. The literature published up to 2016 consistently shows that nanofluids can improve convective performance, but it also shows that concentration must be optimized because viscosity and pumping requirements rise with particle loading. Farajollahi et al. (2010), Akhtari et al. (2013) and Shahrul et al. (2016) are particularly relevant shell-and-tube benchmarks, while the broader findings of Xuan and Li (2000), Buongiorno (2006), Zeinali Heris et al. (2007) and Sahin et al. (2015) support the preparation, transport and pressure-drop aspects of the proposed method. The most meaningful experimental outcome is therefore not the maximum heat-transfer coefficient alone, but a stable, repeatable enhancement achieved with an acceptable hydraulic penalty. Low Al₂O₃ volume fractions are recommended as the initial experimental region, followed by higher concentrations only if stability, uncertainty and pumping-power analysis justify them. Actual publication of experimental results should use measured raw data, replicate tests and uncertainty bounds rather than the benchmark ranges shown here.

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