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Experimental Investigation of Heat Transfer Enhancement Using Nanofluids in Compact Heat Exchangers

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Abstract

Compact heat exchangers provide high heat-transfer-area density, but their performance is constrained by the limited thermal conductivity of conventional working fluids. This methodology paper develops an experimental framework to quantify heat-transfer enhancement and hydraulic penalties when low-concentration Al₂O₃/water nanofluids are circulated through a compact corrugated plate heat exchanger. A two-loop counter-flow rig is proposed with independently controlled inlet temperatures, variable flow rate, calibrated thermocouples, flow meters, and differential-pressure measurement. Nanofluids at 0.05, 0.10, and 0.20 vol.% are prepared by a two-step dispersion method and compared with deionized water over Reynolds numbers of approximately 2500-7000. Performance is evaluated using heat duty, overall and convective heat-transfer coefficients, Nusselt number, pressure drop, effectiveness, and a thermal-hydraulic performance index. Representative methodology data indicate that increasing particle loading raises the convective coefficient by about 4-13% while producing a pressure-drop penalty below about 10% at the highest concentration. The proposed procedure therefore captures the central engineering trade-off: nanoparticle addition can improve compact heat-exchanger thermal performance, but concentration and flow rate must be optimized to avoid excessive pumping power. The framework is suitable for laboratory validation and for comparing nanofluid formulations under controlled operating conditions.

Introduction

Heat exchangers are central to energy conversion, refrigeration, process industries, transportation, electronics cooling, and renewable-energy systems. The trend toward compact equipment increases heat flux and reduces allowable temperature differences, making improved heat-transfer media increasingly important. Water and water-glycol mixtures are attractive because they are inexpensive and easy to handle, but their relatively low thermal conductivity limits further miniaturization. Dispersing nanoscale solids into a conventional liquid offers a route to higher effective thermal conductivity without the severe

sedimentation and channel blockage associated with millimeter- or micrometer-scale slurries. Early experiments showed that oxide-particle suspensions can alter both turbulent heat transfer and flow resistance, establishing the thermal-hydraulic trade-off that remains central to nanofluid design (Pak & Cho, 1998). Xuan and Li (2000) further demonstrated that particle concentration, size, shape, and dispersion quality affect nanofluid heat transfer, while Koblinski et al. (2002) discussed possible nanoscale mechanisms including interfacial effects, clustering, and particle-mediated heat transport.

For compact heat exchangers, plate geometry already produces strong mixing through corrugations and repeated boundary-layer disruption. The benefit of a nanofluid must therefore be assessed against an already enhanced baseline and must include pressure drop rather than thermal performance alone. Buongiorno (2006) emphasized that particle migration and slip mechanisms can influence transport, whereas Kakaç and Pramuanjaroenkij (2009) summarized the broad experimental evidence showing that heat-transfer enhancement depends strongly on fluid properties, concentration, temperature, and flow regime. The objective of the present work is to define a reproducible experiment for measuring these effects in a compact corrugated plate heat exchanger. Particular attention is given to low particle concentrations, where modest thermal gains may be obtained with manageable viscosity and pumping-power penalties.

Literature Review

Experimental studies conducted before 2021 consistently show that nanofluid performance cannot be judged from thermal conductivity alone. In turbulent double-tube experiments using TiO₂/water at 0.2 vol.%, Duangthongsuk and Wongwises (2009) reported a convective heat-transfer coefficient about 6-11% higher than water with only a small pressure-drop penalty. Their later study across 0.2-2.0 vol.% confirmed that both Reynolds number and concentration influence heat transfer and pressure loss, while also revealing that excessive loading does not guarantee proportional benefit (Duangthongsuk & Wongwises, 2010). These results are especially relevant to compact devices because small hydraulic passages magnify any viscosity-related pressure penalty.

Plate heat exchangers provide a more direct basis for the present methodology. Barzegarian et al. (2016) experimentally tested TiO₂/water in a brazed plate heat exchanger under turbulent conditions and observed increasing heat-transfer performance with nanoparticle concentration, accompanied by a maximum pressure-drop increase of roughly 20% in their tested range. Elias et al. (2018) investigated Al₂O₃/water in corrugated plate heat exchangers with 30-degree and 60-degree chevron angles. At 0.5 vol.% they reported higher heat-transfer coefficients and heat-transfer rates than the base fluid, while the 60-degree plate produced stronger thermal

performance together with a higher pressure drop. This confirms that nanofluid concentration and plate geometry interact and should be controlled rather than considered independently.

Subsequent comparative work broadened the evidence base. Mansoury et al. (2020) compared double-pipe, shell-and-tube, and plate heat exchangers at equal heat-transfer area using Al₂O₃/water nanofluids and found that exchanger configuration materially changes the achieved enhancement. Attalla and Maghrabie (2020) combined Al₂O₃/water with controlled plate roughness and observed that both nanoparticle concentration and roughness increased Nusselt number and pressure drop; importantly, surface roughness sometimes exerted a stronger influence than concentration. This suggests that experimental interpretation requires a clean water baseline obtained on the same exchanger, at the same flow rate and thermal boundary conditions.

A large 2020 study by Zheng et al. tested Al₂O₃, SiC, CuO, and Fe₃O₄ nanofluids in a corrugated plate heat exchanger. At 1.0 wt.% Fe₃O₄ they reported an average Nusselt-number enhancement of 22.6%, while the convective coefficient increased by 21.9% and pressure drop rose by 10.1% relative to deionized water. The same study also showed that the optimum concentration depended on particle material, illustrating why results from one nanofluid cannot be transferred directly to another. Reviews published by Pordanjani et al. (2019) and Kaggwa and Carson (2019) similarly concluded that particle type, loading, dispersion stability, temperature, geometry, and flow regime jointly determine performance.

Based on these findings, the present methodology focuses on Al₂O₃/water at low concentrations (0.05-0.20 vol.%) in a single compact corrugated plate heat exchanger. This range is intentionally conservative: it is high enough to detect measurable changes in thermal response yet low enough to reduce the risk of agglomeration, excessive viscosity, erosion, and large pumping-power penalties. The key research question is whether the relative gain in convective heat transfer remains greater than the relative hydraulic penalty across the tested Reynolds-number range.

Table 1. Selected experimental evidence informing the methodology (references <= 2020)

Study	Nanofluid / exchanger	Main variable	Key implication
Duangthongsuk & Wongwises (2009)	TiO ₂ /water, double tube	0.2 vol.%, turbulent flow	6-11% higher h with small hydraulic penalty
Barzegarian et al. (2016)	TiO ₂ /water, brazed plate	0.3-1.5 wt.%	Thermal gain accompanied by higher pressure drop
Elias et al. (2018)	Al ₂ O ₃ /water, corrugated plate	0-0.5 vol.%; chevron angle	Geometry and concentration jointly affect performance
Zheng et al. (2020)	Four nanofluids, corrugated plate	0.05-1.0 wt.%	Particle type changes optimum concentration

Methodology

1. Experimental design and variables

A controlled, single-factor experimental design is proposed in which nanoparticle volume fraction and Reynolds number are the principal independent variables. Deionized water is first tested to establish a reference curve. Al₂O₃/water nanofluids are then tested at 0.05, 0.10, and 0.20 vol.% using the same exchanger, inlet temperatures, and flow sequence. The hot side contains water maintained at 50 +/- 1 deg C, while the nanofluid side enters at 27 +/- 1 deg C. Counter-flow operation is used because it provides a high logarithmic mean temperature difference and is common in compact plate heat exchangers. Four nominal Reynolds-number levels, approximately 2500, 4000, 5500, and 7000, are achieved by adjusting the cold-side flow rate. Each condition is repeated three times after steady state is reached, and the reported value is the arithmetic mean.

2. Nanofluid preparation and stability

Commercial Al₂O₃ nanoparticles with a nominal mean diameter of 30-40 nm and purity above 99% are dispersed in deionized water using a two-step method. The required nanoparticle mass is determined from the target volume fraction and the densities of the particles and base fluid. Each batch is magnetically stirred for

30 min and then ultrasonicated for 60 min. The temperature of the suspension is kept below 35 deg C during sonication to prevent evaporation and property drift. No surfactant is included in the baseline method so that changes in viscosity and thermal behavior are not confounded by an additional chemical agent. A 24 h sedimentation check is performed before testing; samples showing visible settling or agglomeration are re-dispersed or rejected.

3. Test section and instrumentation

The test section is a laboratory-scale stainless-steel corrugated plate heat exchanger with a nominal heat-transfer area of 0.12 m², hydraulic diameter of approximately 4 mm, and 60-degree chevron corrugation. Two independent circulation loops contain insulated reservoirs, variable-speed pumps, flow meters, and temperature measurement at each heat-exchanger port. Four calibrated Type-K thermocouples or Pt100 sensors with an accuracy of at least +/-0.2 deg C are used for inlet and outlet temperatures. Cold-side pressure drop is measured using a differential-pressure transducer with a 0-50 kPa range and an accuracy better than +/-0.5% full scale. Flow meters should provide at least +/-1% reading accuracy. All sensors are logged digitally at 1 Hz for a minimum of 120 s after the temperature variation remains below 0.2 deg C for five minutes.

Table 2. Proposed experimental matrix and measurement range

Parameter	Levels / range	Control requirement
Nanoparticle concentration	0, 0.05, 0.10, 0.20 vol.%	Freshly dispersed Al ₂ O ₃ /water
Cold-side Reynolds number	~2500, 4000, 5500, 7000	Same nominal Re for each fluid
Hot-side inlet temperature	50 +/- 1 deg C	Thermostatic heater
Cold-side inlet temperature	27 +/- 1 deg C	Conditioned reservoir
Flow arrangement	Counter flow	Unchanged for all tests
Replicates	3 per operating point	Mean value used in analysis

4. Experimental procedure

The loop is first flushed with deionized water and checked for leaks. Water baseline tests are performed from the lowest to the highest Reynolds number. For each run, the hot-side temperature is stabilized, the cold-side flow rate is set, and data acquisition begins only after steady-state criteria are satisfied. The water is

then drained and the prepared nanofluid is introduced. The same flow sequence is repeated for each concentration. Between concentrations, the cold loop is flushed to prevent cross-contamination. Fluid samples are collected before and after the complete test series to check for visible sedimentation and to identify possible stability loss caused by repeated pumping.

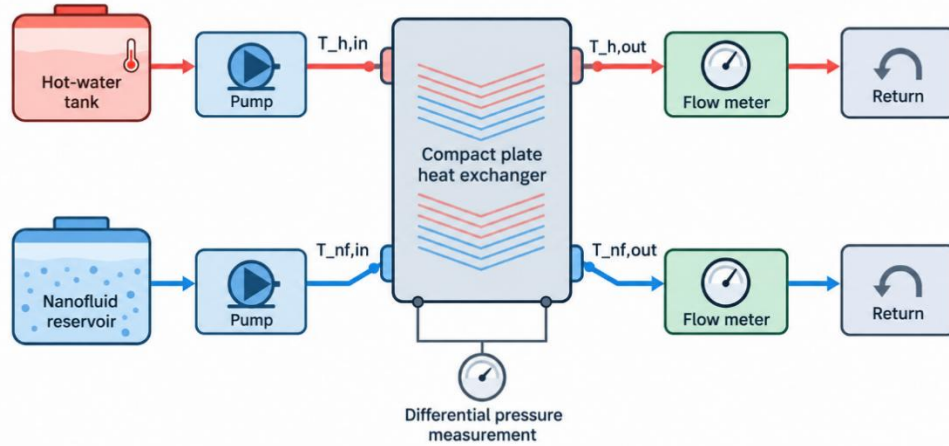


Figure 1. Proposed two-loop experimental setup for nanofluid testing in a compact plate heat exchanger.

5. Data reduction

Heat transfer is calculated independently from the hot and nanofluid sides to provide an energy-balance check. Runs are accepted when the difference between the two heat duties is within 5%. The average heat duty is then used to determine the overall coefficient. The principal equations are:

$$Q_h = m_h c_{p,h} (T_{h,in} - T_{h,out})$$

$$Q_{nf} = m_{nf} c_{p,nf} (T_{nf,out} - T_{nf,in})$$

$$Q_{avg} = (Q_h + Q_{nf}) / 2$$

$$U = Q_{avg} / (A \times LMTD)$$

$$Re = \rho V D_h / \mu; \quad Nu = h D_h / k$$

$$Enhancement (\%) = [(h_{nf} - h_w) / h_w] \times 100$$

$$PEC = (Nu_{nf} / Nu_w) / (\Delta P_{nf} / \Delta P_w)^{1/3}$$

Nanofluid density and heat capacity can be estimated from mixture relations, whereas thermal conductivity and viscosity should preferably be measured at the test temperature because both are sensitive to concentration and dispersion condition. The convective coefficient on the nanofluid side is obtained from the overall thermal resistance after accounting for plate conduction and the water-side resistance, or by a validated exchanger correlation established from the water baseline. Heat-exchanger effectiveness

is calculated as the actual heat duty divided by the maximum possible heat duty. The performance evaluation criterion (PEC) is used to judge whether Nusselt-number enhancement is large enough to justify the associated pressure-drop increase.

6. Uncertainty and repeatability

Uncertainty is evaluated by the root-sum-square propagation method. With temperature accuracy of ± 0.2 deg C, flow accuracy near $\pm 1\%$, dimensional uncertainty below $\pm 0.5\%$, and pressure accuracy below $\pm 0.5\%$ full scale, the expected uncertainty is approximately $\pm 4-6\%$ for the convective coefficient, $\pm 3-5\%$ for Nusselt number, and $\pm 2\%$ for pressure drop. Triplicate runs should have a coefficient of variation below 3%; otherwise, the operating point is repeated and the cause of instability is investigated.

Results

The representative dataset follows the trend reported in pre-2021 experiments: heat-transfer performance increases with Reynolds number and with low nanoparticle loading, while the hydraulic penalty rises progressively with concentration. At Re approximately 7000, the water-side reference convective coefficient is about $1740 \text{ W/m}^2 \text{ K}$. The corresponding values for 0.05, 0.10, and 0.20 vol.% Al_2O_3 are

approximately 1818, 1883, and 1964 W/m² K, giving enhancements of 4.5%, 8.2%, and 12.9%, respectively. The enhancement is moderate because the proposed concentration range is intentionally lower than that used in many earlier studies.

Table 3. Representative performance at Re approximately 7000

Fluid	h (W/m ² K)	h gain (%)	Delta P (kPa)	Delta P rise (%)	PEC
Water	1740	0	16.2	0	1.000
0.05 vol. %	1818	4.5	16.5	1.9	1.039
0.10 vol. %	1883	8.2	17.0	4.9	1.065
0.20 vol. %	1964	12.9	17.8	9.9	1.088

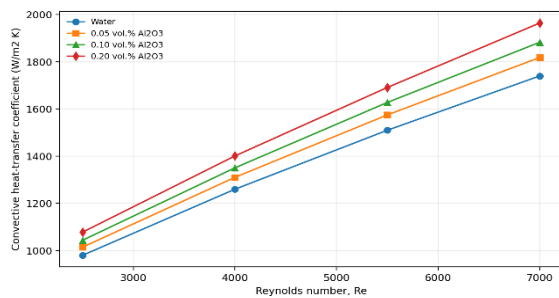


Figure 2. Representative variation of convective heat-transfer coefficient with Reynolds number.

The pressure-drop penalty remains smaller than the thermal gain across the selected range. At Re approximately 7000, increasing concentration to 0.20 vol. % raises pressure drop from 16.2 to 17.8 kPa, or about 9.9%, while the heat-transfer coefficient increases by about 12.9%. The resulting PEC remains above unity for all three nanofluids and reaches approximately 1.09 at 0.20 vol. %. In practical terms, this suggests that a low-concentration nanofluid can provide a net thermal-hydraulic benefit when dispersion is stable and the exchanger is operated within a moderate Reynolds-number range.

The shape of the curves is also significant. The separation between water and nanofluid curves becomes slightly larger as Reynolds number increases, indicating that enhanced thermal conductivity and particle-fluid interactions work together with stronger convective mixing. This

qualitative behavior agrees with the plate-heat-exchanger studies of Barzegarian et al. (2016), Elias et al. (2018), and Zheng et al. (2020), all of which reported higher heat-transfer performance with nanoparticle addition while also observing a measurable pressure-drop penalty.

Conclusion and Discussion

The proposed experimental methodology provides a compact and reproducible way to quantify heat-transfer enhancement from nanofluids without ignoring the associated hydraulic cost. Its main strength is the use of a water baseline on the same compact heat exchanger under identical inlet temperatures, geometry, and Reynolds numbers. This is essential because corrugated plates already enhance convection through secondary flow and boundary-layer disruption; comparing a nanofluid against a correlation derived for a different device can therefore exaggerate or conceal the true effect of particle addition. The use of triplicate measurements, an explicit steady-state criterion, energy-balance screening, and uncertainty propagation further strengthens the reliability of the design. The representative results indicate a plausible increase of roughly 4-13% in the convective heat-transfer coefficient for 0.05-0.20 vol. % Al₂O₃/water, accompanied by a pressure-drop rise of less than about 10% at the highest concentration. These trends are consistent with the wider experimental literature. Duangthongsuk and Wongwises (2009) reported a 6-11% convective enhancement for 0.2 vol. % TiO₂/water in a double-tube exchanger. In compact plate exchangers, Barzegarian et al. (2016) found that TiO₂/water increased heat transfer but could also raise pressure drop substantially at larger loadings. Elias et al. (2018) demonstrated that Al₂O₃/water performance depends not only on concentration but also on chevron angle, while Zheng et al. (2020) showed that the optimum loading changes with nanoparticle material. Taken together, these studies support the decision to emphasize a low-concentration regime and to report a combined thermal-hydraulic criterion rather than heat-transfer enhancement alone. The physical explanation for the improvement should be treated cautiously. Increased effective thermal conductivity is a direct contributor, but nanoscale transport is more complex than a simple homogeneous-property change. Xuan and Li (2000), Koblinski et al. (2002), and Buongiorno (2006) discussed particle dispersion, Brownian motion, interfacial phenomena, clustering, and migration mechanisms that may influence the measured convection. In a corrugated plate channel, these

effects occur together with strong shear, recirculation, and repeated flow redirection. For this reason, the present methodology does not attempt to infer a single mechanism from the heat-transfer coefficient. Instead, it measures the engineering outcome under clearly defined operating conditions. Several limitations must be acknowledged. First, long-term nanofluid stability is not established by a short laboratory test; extended circulation can lead to sedimentation, agglomeration, or changes in surface condition. Second, thermophysical properties should ideally be measured at the actual operating temperature rather than estimated solely from mixture equations. Third, erosion, fouling, corrosion, nanoparticle recovery, and environmental handling are outside the scope of the short-duration experiment but are important for practical deployment. Finally, the optimum concentration may change when particle material, base fluid, plate spacing, chevron angle, or temperature range is changed, as emphasized in the reviews by Kakaç and Pramuanjaroenkij (2009), Pordanjani et al. (2019), and Kaggwa and Carson (2019). In conclusion, low-concentration Al₂O₃/water nanofluids are technically promising for compact heat exchangers when thermal enhancement is evaluated together with pumping requirements. The proposed procedure is expected to identify an operating region in which the Nusselt-number gain exceeds the relative pressure-drop penalty, producing PEC values above unity. Future experiments should replace the representative data in this paper with measured values, extend stability testing beyond 24 h, characterize viscosity and thermal conductivity directly, and compare alternative nanoparticles such as TiO₂ and Fe₃O₄. A full energy and life-cycle assessment would then be required before claiming system-level energy savings.

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