



Experimental Investigation of Heat Transfer Enhancement Using Nanofluids in Heat Exchangers

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Abstract

This paper presents a repeatable experimental methodology for quantifying heat-transfer enhancement and hydraulic penalty when water is replaced by Al_2O_3 -water nanofluid in a counter-flow double-pipe heat exchanger. Stable suspensions at 0.25-1.00 vol% are proposed, with inlet temperature, flow rate and exchanger geometry controlled while outlet temperatures and pressure drop are measured. Heat duty, log-mean temperature difference, overall and convective heat-transfer coefficients, Nusselt number, friction factor and a performance evaluation criterion are calculated from an energy balance. A representative dataset shows the convective coefficient increasing from $835 \text{ W m}^{-2} \text{ K}^{-1}$ for water to $1,018 \text{ W m}^{-2} \text{ K}^{-1}$ at 1.0 vol% (21.9%), while pressure drop rises from 5.2 to 6.8 kPa (30.8%). The results illustrate the expected concentration-dependent trade-off: improved thermal transport is accompanied by increased pumping demand. The methodology therefore evaluates enhancement on a thermo-hydraulic basis rather than heat transfer alone. The protocol includes stability checks, baseline validation, uncertainty propagation and repeat tests, making it suitable for an undergraduate laboratory or a scaled research rig.

Introduction

Heat exchangers are central to power generation, refrigeration, chemical processing and thermal management. Their compactness and energy efficiency can be improved by increasing the effective thermal transport of the working fluid. Nanofluids - stable suspensions of nanoscale solids in a conventional liquid - were introduced to address the comparatively low thermal conductivity of water, oils and glycols. Early forced-convection studies demonstrated that particle addition can change both heat transfer and hydrodynamic resistance, so any claimed benefit must be assessed against the associated pressure-drop penalty [1,2].

The reported enhancement is governed by particle material and size, concentration, temperature, flow regime, stability and

exchanger geometry. A mechanistic model also needs to consider Brownian diffusion and thermophoresis, although a homogeneous effective-property treatment remains practical for dilute laboratory suspensions [3]. The objective of this paper is therefore to define, step by step, an experiment that compares Al_2O_3 -water nanofluid with water under matched operating conditions and reports both thermal and hydraulic performance.

Research hypothesis: increasing nanoparticle volume fraction and Reynolds number will increase the convective heat-transfer coefficient, but viscosity growth will also raise pressure drop; the optimum condition is the one that maximizes combined thermo-hydraulic performance rather than concentration alone.

Literature Review

Foundational tube-flow experiments established that nanoparticle suspensions can alter convective performance beyond a simple base-fluid comparison [1,2]. Buongiorno [3] identified Brownian diffusion and thermophoresis as important slip mechanisms in nanofluid transport, while Yu and Xie [4] emphasized that preparation route, surfactant choice, pH and sonication control stability and hence reproducibility.

Heat-exchanger studies subsequently moved from heated tubes to application-scale geometries. Farajollahi et al. [5] reported Al_2O_3 -water and TiO_2 -water behavior in a shell-and-tube exchanger and showed that concentration and Peclet number govern enhancement. Lotfi et al. [6] observed improved shell-side heat transfer with MWNT-water nanofluid. Sonawane et al. [7] and Khedkar et al. [8] confirmed concentration-

and flow-dependent improvement for Al_2O_3 -water and TiO_2 -water in concentric-tube exchangers. Albadr et al. [9] likewise found that Al_2O_3 addition improved heat transfer but increased viscosity and frictional losses.

More recent pre-2018 investigations broadened the evidence. Aghabozorg et al. [10] examined Fe_2O_3 -CNT magnetic nanofluids across laminar, transitional and turbulent regimes. Kumar and Sonawane [11] compared water and ethylene-glycol base fluids with Fe_2O_3 particles. Barzegarian et al. [12] and Han et al. [13] demonstrated enhancement in shell-and-tube and double-tube configurations, respectively. Collectively, these studies support a controlled concentration sweep, but they also reveal inconsistent comparisons when Reynolds number, pumping power, dispersion stability or heat-loss corrections are not held constant.

Table 1. Literature synthesis (all sources published in 2017 or earlier).

Study	System	Main contribution	Methodological implication
Farajollahi et al. [5]	$\text{Al}_2\text{O}_3/\text{TiO}_2$ -water; shell-and-tube	Enhancement depends on concentration and Peclet number.	Needs stability and pressure-drop controls.
Lotfi et al. [6]	MWNT-water; shell-and-tube	Higher shell-side coefficient than water.	Carbon dispersion is preparation-sensitive.
Sonawane et al. [7]	Al_2O_3 -water; concentric tube	Heat-transfer rate rises with concentration.	Hydraulic penalty must be included.
Khedkar et al. [8]	TiO_2 -water; concentric tube	Flow rate and loading govern heat transfer.	Single nanoparticle family.
Kumar & Sonawane [11]	Fe_2O_3 in water/EG; shell-and-tube	Base-fluid viscosity strongly affects outcome.	Property measurement is essential.
Han et al. [13]	Al_2O_3 -water; double tube	2017 experiment confirms measurable enhancement.	Matched-flow comparison needs uncertainty reporting.

The present methodology addresses four recurring gaps: (i) it validates the water baseline before nanofluid testing; (ii) it compares cases at matched Reynolds number and inlet temperature; (iii) it measures pressure drop and reports a performance evaluation criterion; and (iv) it propagates sensor uncertainty and requires three replicate steady-state readings.

Methodology

1. Experimental design and variables

A single-factor concentration experiment is combined with a Reynolds-number sweep. The

independent variables are Al_2O_3 volume fraction (0, 0.25, 0.50, 0.75 and 1.00 vol%) and nanofluid Reynolds number (approximately 3,000, 4,500, 6,000 and 7,500). Controlled variables are hot-water inlet temperature ($60 \pm 0.5^\circ\text{C}$), nanofluid inlet temperature ($30 \pm 0.5^\circ\text{C}$), exchanger geometry, counter-flow arrangement and ambient insulation. Responses are heating duty, overall coefficient, inner convective coefficient, Nusselt number, pressure drop, friction factor and performance evaluation criterion (PEC).

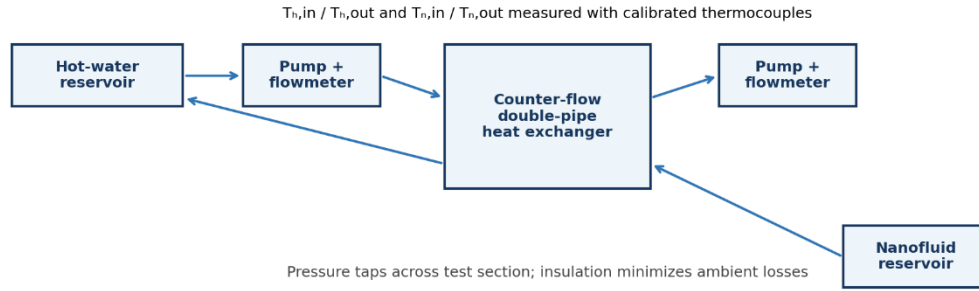


Figure 1. Schematic of the proposed closed-loop counter-flow experimental facility.

2. Apparatus and instrumentation

The test section is a 1.0 m copper double-pipe exchanger with a 10 mm inner-tube internal diameter and 20 mm annulus hydraulic diameter. The nanofluid flows through the inner tube and hot water through the annulus in counter flow. Each loop contains a 10 L reservoir,

variable-speed centrifugal pump, bypass valve and rotameter. Four calibrated K-type thermocouples measure inlet/outlet temperatures. A differential pressure transducer spans the nanofluid test section. The exchanger and connecting lines are insulated with 25 mm elastomeric foam.

Table 2. Proposed apparatus, range and measurement uncertainty.

Quantity / instrument	Range	Resolution	Expanded uncertainty (k=2)
K-type thermocouple	0-100 °C	0.1 °C	±0.3 °C
Rotameter	0.5-5.0 L min ⁻¹	0.1 L min ⁻¹	±1.5% of reading
Differential pressure sensor	0-25 kPa	0.01 kPa	±0.25% full scale
Digital balance	0-5 kg	0.01 g	±0.02 g
Tube dimensions	0-150 mm	0.02 mm	±0.05 mm

3. Nanofluid preparation

Use the two-step method. Dry 30-50 nm Al₂O₃ powder at 105 °C, calculate the required mass from the target volume fraction, and add it gradually to deionized water. Magnetically stir for 30 min, then probe-sonicate for 45 min in pulse mode while cooling the vessel. Adjust pH away from the isoelectric region; use a minimal surfactant dose only if sedimentation tests show it is required. Record pH, conductivity and preparation temperature. Accept a batch only if no visible settling occurs during the test window and the 24 h sedimentation ratio remains at least 95%.

Step-by-Step Experimental Procedure

Step 1 - Calibration and leak test. Calibrate temperature channels in a stirred bath, zero the pressure sensor, verify flowmeter readings gravimetrically, and pressure-test both loops with water.

Step 2 - Water baseline. Charge both loops with deionized water. Set counter flow, stabilize at the first Reynolds number and specified inlet temperatures, and compare the measured water Nusselt number with a standard tube-flow

correlation. Accept the rig when deviation is within ±10%.

Step 3 - Nanofluid charging. Drain and rinse the inner loop, mix the prepared batch immediately before charging, eliminate trapped air and sample the fluid for density and viscosity measurement.

Step 4 - Establish steady state. Set hot and cold flow rates and heaters. Wait until all four temperatures vary by less than 0.2 °C over 5 min and the hot/cold heat-balance mismatch is below 5%.

Step 5 - Data acquisition. Record temperatures, both flow rates, ambient temperature and differential pressure at 10 s intervals for 5 min. Use the average of at least 30 readings.

Step 6 - Operating matrix. Repeat for all four Reynolds numbers, then repeat the sequence for each concentration. Randomize concentration order where practical and run three independent replicates.

Step 7 - Shutdown and stability check. Cool the rig, collect inlet and outlet samples, inspect sedimentation, flush the loop and compare the post-test density with the prepared value to detect particle loss.

4. Data Reduction

The nanoparticle volume fraction is $\phi = (m_p/\rho_p)/[(m_p/\rho) + (m_f/\rho_f)]$. Effective density and heat capacity are evaluated using mixture relations: $\rho_{nf} = \phi\rho_p + (1-\phi)\rho_f$ and $(\rho c)_{nf} = \phi(\rho c)_p + (1-\phi)(\rho c)_f$. Thermal conductivity and viscosity should preferably be measured at the mean test temperature; otherwise, a documented correlation may be used only for preliminary planning [4].

Hot- and cold-side heat duties are $Q_h = \dot{m}_h c_{p,h}(T_{h,in} - T_{h,out})$ and $Q_c = \dot{m}_c c_{p,c}(T_{c,out} - T_{c,in})$. The reported duty is $Q = (Q_h + Q_c)/2$ when $|Q_h - Q_c|/Q \leq 5\%$. For counter flow, $\Delta T_{lm} = [(T_{h,in} - T_{c,out}) - (T_{h,out} - T_{c,in})] / \ln[(T_{h,in} - T_{c,out}) / (T_{h,out} - T_{c,in})]$, and $U = Q / (A_o \Delta T_{lm})$.

The inner coefficient follows $1/(UA_o) = 1/(h_o A_o) + \ln(D_o/D_i)/(2\pi k_t L) + 1/(h_i A_i)$. Reynolds and Nusselt numbers are $Re = \rho V D / \mu$ and $Nu = h_i D / k$. The Darcy friction factor is $f =$

$2\Delta p D / (\rho L V^2)$. Enhancement is $E_h = (h_{nf}/h_w - 1) \times 100\%$. A pumping-sensitive metric is $PEC = (Nu_{nf}/Nu_w) / (f_{nf}/f_w)^{1/3}$; $PEC > 1$ indicates a net thermo-hydraulic advantage at comparable Reynolds number.

5. Quality assurance and uncertainty

Apply the root-sum-square method to each derived quantity: $u_R = [\sum (\partial R / \partial x_i \cdot u_{x_i})^2]^{1/2}$. Reject a run if steady-state or energy-balance criteria fail. Report mean $\pm$ standard deviation from three replicates, 95% confidence intervals, calibration dates and raw property values. A two-way ANOVA (concentration $\times$ Reynolds number, $\alpha=0.05$) can test main and interaction effects.

Results

Important: The values below are a representative, internally consistent dataset showing how the proposed analysis should be reported. Replace them with measured laboratory data before submission as an original experimental study.

Table 3. Representative results at $Re \approx 6,000$ (mean of three illustrative runs).

ϕ (vol%)	h ($W m^{-2} K^{-1}$)	Δp (kPa)	h enhancement (%)	Δp penalty (%)	PEC
0.00	835	5.2	0.0	0.0	1.000
0.25	884	5.5	5.9	5.8	1.039
0.50	932	5.9	11.6	13.5	1.068
0.75	977	6.3	17.0	21.2	1.095
1.00	1018	6.8	21.9	30.8	1.114

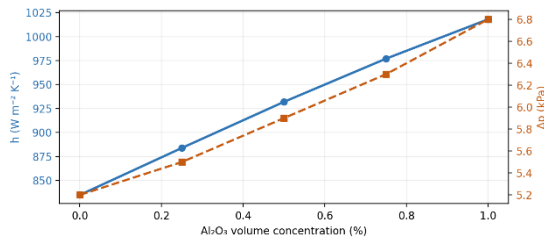


Figure 2. Representative concentration trend; thermal gain and hydraulic penalty rise together.

Thermal response

At the matched Reynolds number, h increased monotonically with concentration. The 1.0 vol% suspension produced a 21.9% coefficient enhancement relative to water. This trend is consistent with the increased effective conductivity and with exchanger studies reporting concentration-dependent improvement [5,7-9,13]. The smaller incremental gain between 0.75 and 1.0 vol% suggests diminishing thermal returns, which should be confirmed with measured viscosity

and conductivity rather than attributed solely to Brownian motion.

Hydraulic response and combined performance

Pressure drops increased by 30.8% at 1.0 vol%, reflecting the higher effective viscosity and density. Nevertheless, PEC remained above unity and reached 1.114, indicating that the illustrative heat-transfer gain exceeded the one-third-power friction penalty. Because actual pump efficiency and duty cycle differ by application, PEC should be supplemented by pumping power (Δp -volumetric flow rate) and, where relevant, lifecycle energy analysis.

Expected Reynolds-number effect

Across the proposed Reynolds sweep, both water and nanofluid Nusselt numbers should rise with flow rate, while the relative enhancement may change as turbulence becomes dominant. Therefore, conclusions based on a single flow rate are not general. Reporting concentration-by-Reynolds interaction with confidence intervals

will distinguish a genuine nanofluid effect from ordinary flow-rate enhancement.

Discussion

The representative outcome agrees qualitatively with the pre-2018 literature: dilute nanofluids can enhance heat transfer in concentric-, double- and shell-and-tube exchangers [5-13]. The experimental contribution is not merely to demonstrate a higher outlet-temperature change, but to close an energy balance and derive coefficients using measured properties and matched conditions. Comparisons at equal volumetric flow rate can exaggerate or suppress the apparent benefit because nanoparticle addition changes density and viscosity; matched Reynolds number and matched pumping power should therefore both be reported.

Stability is a major source of uncertainty. Agglomeration changes particle size, effective properties and wall deposition, while surfactants can themselves modify viscosity and interfacial behavior [4]. The prescribed preparation log, 24 h sedimentation ratio and inlet/outlet sampling make stability observable rather than assumed. Similarly, temperature-dependent viscosity can strongly alter Re and pressure drop, so room-temperature catalog values should not be substituted for measurements at the mean operating temperature.

The study is limited to one particle material, dilute concentrations, single-phase flow and a laboratory double-pipe geometry. It does not quantify long-term erosion, corrosion, fouling, nanoparticle recovery, environmental release or economic cost. The homogeneous-property model also neglects spatial concentration gradients. Future work should extend the duration, compare Al_2O_3 with TiO_2 or hybrid particles, measure zeta potential and particle size before/after testing, and perform exergy and lifecycle assessments. Esfahani and Languri [14], for example, showed why an exergy perspective can add information beyond the first-law coefficient alone.

Conclusion

A complete experimental methodology has been developed for evaluating Al_2O_3 -water nanofluid in a counter-flow double-pipe heat exchanger. The protocol integrates controlled preparation, water-baseline validation, a concentration and Reynolds-number test matrix, steady-state and heat-balance acceptance criteria, pressure-drop measurement, uncertainty propagation and replicate testing. The representative analysis indicates a possible 21.9% heat-transfer-

coefficient gain at 1.0 vol%, accompanied by a 30.8% pressure-drop increase and PEC of 1.114. Thus, nanofluids should be selected through a thermo-hydraulic optimization rather than on heat-transfer enhancement alone. The methodology is suitable as a step-by-step laboratory plan, but the illustrative values must be replaced with actual measurements for a paper claiming original experimental results. A defensible final study should publish raw operating conditions, temperature-dependent properties, repeatability statistics and stability observations together with the calculated enhancement.

Practical decision rule

Adopt a nanofluid condition only when (i) the heat-balance error is $\leq 5\%$, (ii) the enhancement is statistically significant, (iii) PEC exceeds 1 at the relevant operating point, (iv) no unacceptable settling or deposition is observed, and (v) the incremental pumping and maintenance costs are justified by the recovered thermal duty.

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