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Nanofluids as heat transfer fluids: Hurdles to industrial application and economic considerations

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Abstract

Nanofluids have gained substantial interests over the past years due to their enhanced thermal properties. However, these dispersions remain scarcely used in industrial applications. In this work, we demonstrate how the stability of nanofluids and economic factors are the major hurdles preventing their industrial large-scale use through an economical analysis. The cost-effectiveness of multi-walled carbon nanotubes (MWCNT)-water and copper oxide-water nanofluid used in a concentric tube heat exchanger instead as substitutes for fresh water was assessed in four different scenarios. It was determined that three of the four cases were not economically viable as a deficit is generated due to a recurring annual investment for the renewal of the nanofluid as they destabilised with time. The fourth case, however, was sustainable because of the high stability (5 years) and showed a payback time on investment of less than a year. Finally, a tool illustrating the operating window for nanofluid economics in our selected heat exchanger geometry was developed.

KEYWORDS

coolants, economic impact, industrial application, nanofluids, stability.

1 INTRODUCTION

Nanofluids are colloidal dispersions of nanoparticles (of characteristic dimension 1-100 nm) in base liquids such as water, ethylene glycol etc. They were first described in 1995 by Choi et al.

and since then, there has been a tremendous amount of research on their properties for many applications.[1] Initial studies focused on the enhancement in thermal conductivity, owing to Sir Maxwell's theory that addition of solid particles to liquids would enhance its heat carrying capacity.[2] Since then, a significant amount of research has been published on both single-phase and two-phase heat transfer using nanofluids, particularly over the past two decades.[3-11] In addition to heat transfer, nanofluids have been tested for medical, tribological, and mass transfer applications.[12-20] Proof of a strong interest from the scientific community, no less than 15,000 publications on nanofluids have been written in the last ten years, many of them being detailed reviews on this tremendous literature and giving an insight of the difficulty of the subject. These reviews, which can cite over 300 publications each, present a summary of the large body of research on nanofluids, with several focusing on elements such as preparation and characterization techniques, applications (such as their use in various heat transfer devices) and on physical properties (such as viscosity).[21-30]

Surprisingly, nanofluids are still not widely used in industrial applications (notably as coolants) and the literature offers few studies on their economic impacts despite the fact their nanoparticles loading, viscosity, and especially stability in time are major characteristics that have significant cost considerations. Several studies have reported an improvement in the thermal properties of nanofluids with an increase in particle concentration. However, this improvement is usually associated with an increase of its viscosity, which generally implies a higher pressure drop and therefore an increase in pumping power.[31-34] This negative effect on pressure drop might be, depending on the system and the nanofluid used, strong enough to have a significant impact on its cost-effectiveness. Similarly, nanofluid stability can have an even greater impact, owing to the cost of replacing nanomaterials that have settled out of dispersion (retail prices reported in Table 1).

TABLE 1 Unit cost of different type of nanoparticles [35-39]

Nanoparticles	Density (kg/m^3)	Price ($USD/kg)
Cu (40-60 nm)	8900	1560
CuO (20 nm)	6400	328
Al_2O_3 (20 nm)	3890	225
TiO_2 (50 nm)	4230	238
Industrial MWCNT (20 nm)	2100	382

In this article, we aim to explain why stability, among others, strongly contributes to the timid use of nanofluids as heat transfer fluids in industrial thermal applications by making an economical analysis on four case studies where nanofluids are applied on a heat transfer system. We use the findings to establish a general operating window for cost-effectiveness.

2 STABILITY OF NANOFLUIDS

Particles smaller than 100 nm are commonly used in preparing nanofluids to take advantage of their large surface-to-volume ratio, which can help achieving a higher enhancement in thermal properties and to avoid limitations induced by larger particles such as erosion, clogging, and high pressure drops.[40, 41] However, the major problem faced in nanofluid preparation and application is the lack of stability: a colloid loses its stability when the Van der Waals force of attraction between the dispersed particles overcomes the electrostatic repulsion between them.[42] This causes the particles to stick to each other and form agglomerates; these agglomerates are no longer within the nanoparticle size regime and their desirable nano-properties (low erosion, pressure drop, clogging) are lost. Hence, preparing nanofluids that can remain stable over the long term is essential for their use in industrial applications, where maintenance and replacement costs should be kept minimum, as detailed in section 5 of this article.

Various methods have been developed for the synthesis of nanofluids. The direct method of synthesis involves different steps of producing nanoparticles, their surface modification, and dispersion in a solvent all occurring in a single batch process such as the one step-nano emulsification process.[43] In this case, there is no external handling or storage of nanoparticles at any stage of its production. Another preparation technique is solution chemistry, whereby chemical precursors are added in a sequence which involves heating, cooling, and mixing of the prepared nanoparticles into the solvent.[43] This method poses the difficulty of removing residual reagents from the nanofluid. Most articles that report testing of nanofluids for different applications have employed the two-step method, that involves separate steps for nanoparticle synthesis and dispersion into base liquids. Magnetic stirring, ultrasonic agitation, ball milling or high shear mixing are common mechanical methods used to disperse the nanoparticles in the base liquid.[44, 45]

The major disadvantage of these methods, however, is that the produced nanofluids do not typically remain stable over long periods. As per DLVO theory, particles dispersed in a liquid medium interact with each other by Van der Waals force of attraction and the electrostatic repulsion offered by the double layer due to the charge on the particle surface. As the particles get closer (owing to the constant Brownian motion) both forces of attraction and repulsion increases. In those cases, when the repulsive force between the particles offered by their double layer is higher than Van der Waals attraction, they remain separate without agglomerating. Since the nanoparticles are not inherently functionalized, no electrostatic repulsion exists (beyond that of the original particle) between them and hence nanoparticles interact with each other by Van der Waals force of attraction. Due to collisions between particles that occur by Brownian motion, the particles come sufficiently close to each other that the attractive force overcomes the low repulsion thus leading to agglomeration.[46] As the agglomerates grow, they slowly start settling, leading to destabilization of the nanofluid, often in less than one day.[47] The most common method to prevent the particles from agglomerating is by using surfactants or to functionalize the nanoparticles.

Surfactants are amphiphilic molecules which contain hydrophobic or hydrophilic ends that physisorb to the nanoparticles and provide compatibility with solvent molecules. The connection with surfactant molecules increases the surface charge on the nanoparticles, increasing repulsion between nanoparticles and thus preventing agglomeration. However, the long-term stability of surfactant-stabilised nanofluids is either not reported or shown to degrade over time. The reason for this is the surfactant molecular motion brought about by ion exchange and ion pairing.[48] This process causes surfactant molecules to disconnect from one nanoparticle and connect with another nanoparticle, at different instants. This movement between adjacent particles leaves nanoparticles devoid of surface charge, thus initiating agglomeration. In addition, surfactants have been reported to desorb at temperatures as low as 60 °C and hence the method of surfactant addition for stabilising nanofluid dispersion is not suitable for their use in heat transfer applications at high temperatures.[49] This important point is rarely considered in the reported results and explains the controversy of enhancement or deterioration of heat transfer that exists in the nanofluid literature owing namely to the poor stability of nanofluids.[43, 50-52]

Another method to prepare stable nanofluids is to functionalize the nanoparticles. Surface functionalization is the process of chemically attaching functional groups either by solution chemistry or by solvent-free methods such as plasma enhanced chemical vapor deposition (PECVD) or photo-initiated CVD (PICVD). Whereas wet chemistry methods suffer from issues of residual reagent separation, gas-phase functionalization such as PE- and PICVD have shown promise to prepare functionalised nanoparticles.[53-56] The functional groups on the nanoparticles either undergo hydrolysis when interacting with the base liquid molecules or causes variations in polarity that lead to strong hydrogen bonding with the base liquid molecules.[57] Such nanofluids prepared using functionalized nanoparticles have been reported to remain stable for more than five years. In addition, another important point to consider for the application of nanofluids as coolants is their stability when boiled and in the presence of metals, since heat exchangers are metallic structures. Researchers have developed nanofluids containing functionalised MWCNT that remain stable for more than 1 year after being boiled and in the presence of copper metal coupons.[57]

The stability of a colloid should be quantitatively assessed since visual inspection alone, is misleading, especially for high concentration colloids. Quantitative techniques used to determine colloidal stability include measuring the zeta potential, monitoring particle diameter over time, and assessing absorption spectra. The electrokinetic (zeta) potential is a measure of the stability of a colloidal dispersion; its magnitude indicates the degree of electrostatic repulsion between adjacent similarly charged particles in dispersion.[58] When the potential is small (in absolute value), the attractive force exceeds the repulsion force, thus leading to nanoparticle agglomeration. Hence the larger the absolute value of the potential, the greater the repulsion and better the stability. As per ASTM (American Society for Testing and Materials) standards, zeta potential value higher than 40 mV indicates a stable dispersion [59]. Another important indicator is the variation of particle size with time, which is typically measured using dynamic light scattering (DLS) technique. An increase in particle size over time indicates the agglomeration of the nanoparticles. Note that this DLS presents limitations when monitoring highly polydisperse suspension – in such cases, alternate methods such as SMPS (scanning mobility particle sizer) or obscuration should be retained.[53] The stability of nanofluids can also be confirmed through measurements of absorption spectra in the UV-Visible range. This method, however, depends on the absorption range of the nanoparticles used. For a stable nanofluid, the UV-Vis absorption spectra should remain the same as that immediately after preparation and after long storage.[60] Despite the huge increase in research on nanofluids, the stability assessment of nanofluids is rarely reported. Overlooking nanofluid stability while estimating their physical properties is a significant hurdle preventing industrial application.

3 DETAILS OF CASE STUDIES

Nanofluids in each case will be used to replace fresh water as a coolant in a heat transfer system, which consists of a counterflow, concentric tube heat exchanger (hereafter Hex), a pump with 75% efficiency and a 100 L reservoir tank (FIGURE 1, TABLE 2). This simple configuration was chosen to emphasize the economic trends we observe when using nanofluid in a retrofitted Hex. These trends can be extrapolated to more complex systems by applying a correction factor in the calculations.[61] The Hex allows the cooling of ethylene glycol which is fed through the annulus at 180 °C and at a rate of 5.00 kg/s. Fresh water (or the nanofluid) is used in the inner tube where higher velocities are possible to reduce fouling and for ease of cleaning.[62]

TABLE 2 Heat exchanger specifications

Specification	Inner Tube	Outer shell
Diameter (m)	D_i = 0.04	D_o = 0.07
Length (m)	30.61 (100 ft)	
Internal heat transfer surface area (m^2)	3.85	

(A) (B)

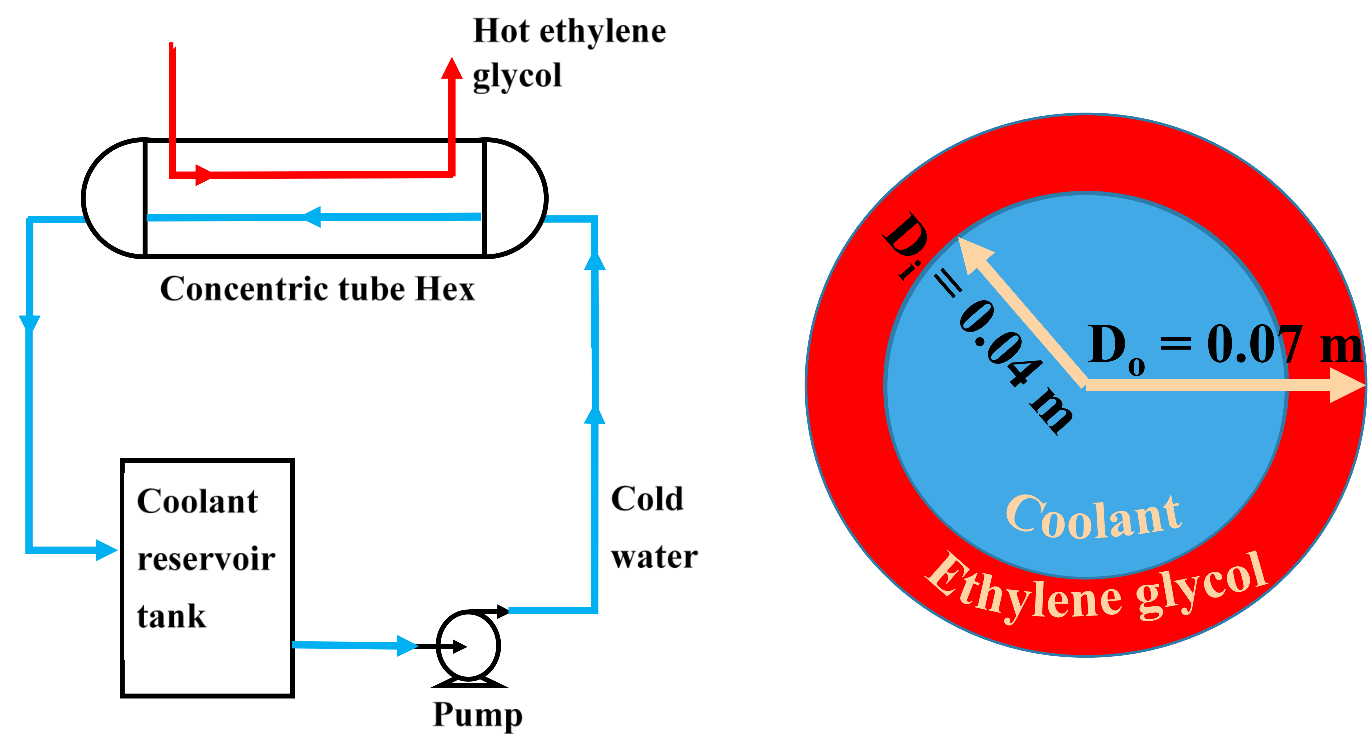

FIGURE 1 (A) Schematic of heat transfer system, (B) cross-section of concentric tube Hex

3.1 Case study 0 (CS0)

This scenario represents the base case of our heat transfer system where fresh water is used as the coolant.

3.2 Case study 1 (CS1)

In CS1, water is replaced by a multi-wall carbon nanotubes (MWCNT)/water nanofluid stabilized with a surfactant, specifically gum arabic (GA), as described by Ismail et al.[63]. CNT-based nanofluids exhibit great potential for heat transfer enhancement because of the material's very high thermal conductivity (k ≈3000 W/mK for MWCNTs and ~6000 W/mK for single walled CNTs). Secondly, this nanofluid has been reported to remain stable for nearly 180 days through the addition of GA.[64-66] This composition was retained as it is considered as a "best-case scenario" for heat transfer enhancement in nanofluids. According to Ismail et al.[63], a 0.5 wt% MWCNT suspension with a CNT:surfactant weight ratio of (1:0.5) will have the best potential for a thermal application, as it exhibits a 38%, 25%, and 50% increase in viscosity μ, thermal conductivity k, and specific heat capacity C_p, respectively, compared to water.

CS1 is divided into 3 different sub-scenarios:

- CS1A: the system operates for 360 days a year but the nanofluid is renewed after 180 days.
- CS1B: the system operates for 360 days a year, the nanofluid is not renewed and there is fouling in the pipes after 180 days.
- CS1C: The system operates for 360 days a year and the nanofluid is stable for 5 years.

In CS1B, the nanofluid is used beyond its stability period and we assume that all the nanoparticles will agglomerate and settle in the pipes. To compensate, additional fresh water will be added after the 180-day cut-off, thus increasing pumping costs back to their original level. The agglomeration of nanoparticles leads to a complete loss of enhanced thermal properties of the coolant and fouling. This hypothesis is validated by several studies in the literature which have shown that random collisions of particles within the fluid (strongly limited by agglomeration and sedimentation) were one of the main reasons for their thermal properties' enhancements.[8, 10, 67, 68] The effect of fouling on the other hand gives way to great debates in the scientific community, some studies even suggesting that an enhancement of the heat transfer coefficient could rather take place due to changes occurring in the fluid at the walls. These changes may overcome the thermal resistance generated by the deposits depending on its thickness.[69, 70] Because of these discrepancies, the authors chose to look at the case where the fouling thermal resistance is negligible and consider the coolant, after 180 days, to have the same parameters as CS0 (i.e., fresh water).

CS1C is used to evaluate the potential payback time (amount of time required to recover the cost of investment) the nanofluid would have in CS1A and CS1B if it had the longest stability found in the literature (5 years). The investment here would be the purchase cost of nanofluid.

3.3 Case study 2 (CS2)

In this scenario, a copper oxide (CuO)/water nanofluid with an estimated stability period of 30 days was selected as representative of metal oxide-based nanofluids. In this case, CuO is much heavier and has a lower thermal conductivity than the MWCNT-based nanofluid. ($\rho \approx$ 6500 kg/m^3, k $\approx$ 33 W/mK).[71-73] According to values available in the literature, a nanofluid with a 9 wt% dispersion of CuO will have a thermal conductivity of 0.6768 W/mK, specific heat capacity of 3858 J/kgK and viscosity of 0.0007 Ns/m^2. These values represent a 5% increase in k, an 8% decrease in C_p and a 21% increase in μ compared to water respectively.[72, 74]

4 SIMPLIFIED HEAT TRANSFER MODEL

4.1 Evaluation of initial heat transfer and operational parameters

In this work, the analysis will be performed in the tube side of the Hex to evaluate the flow of coolant required to remove the heat Q based on the boundary conditions from the ethylene glycol which will allow us to calculate the pumping power. The initial heat exchange capacity and the water flow rate are calculated using known ethylene glycol data (TABLE 3) with Equation (1):

$$Q = \dot{m}_h Cp_h \Delta T_h = \dot{m}_c Cp_c \Delta T_c \tag{1}$$

The subscripts *h* and *c* represent the hot and cold stream, respectively. Assuming the Hex has negligible heat loss to its surroundings, the fluid's properties are deemed constant and there is negligible tube wall thermal resistance, Q remains constant throughout the Hex and it is possible to calculate the overall heat transfer coefficient with Equation (2):

$$U = \left(\frac{1}{h_i} + \frac{1}{h_o}\right)^{-1} \tag{2}$$

where h_i and h_o represent the convection heat transfer coefficient of water and ethylene glycol respectively and are calculated using Equation (3), (4), (5), and (6): [61]

$$Re = \frac{\rho v d}{\mu} \tag{3}$$

$$Pr = \frac{C_p \mu}{k} \tag{4}$$

$$Nu = 0.023 Re^{0.8} Pr^{0.4}, Re > 10^4, 0.6 \leq \mathrm{Pr} \leq 160 \tag{5}$$

$$h_i = \frac{Nuk}{D} \tag{6}$$

The pressure drop Δp generated by the fluid in the pipes can be calculated using Equation (7), (8), and (9): [61, 75]

$$\Delta p = \frac{f \rho v^2 L}{2D} \tag{7}$$

$$f = (0.79 \ln Re - 1.64)^{-2}, 3000 \leq Re \geq 5 \times 10^6 \tag{8}$$

$$v = \frac{4\dot{m}}{\rho \pi D^2} \tag{9}$$

The pumping power is calculated with Equation (10):

$$P_p = \frac{\dot{m} \Delta p}{\eta \rho} \tag{10}$$

The pumping cost ($/year) can then be calculated with Equation (11):

$$P_c = P_p \tau C_e \tag{11}$$

Where τ is the number of operating hours and C_e is the average electrical cost (in $/kWh).

4.2 Economic calculations

The economical comparison of the system before and after application of the nanofluid presented in the different case studies is done by the relative cost approach, where the incomes and expenses of the initial condition are considered to be zero.

The use of nanofluids in these case studies can be compared to a retrofit of an existing process where the operating conditions need to stay constant and the geometry of the Hex is fixed. Based on this assumption, the heat transfer rate Q of the Hex will not change between the base case and the case studies (ethylene glycol and water must come out of the Hex at 65 °C and 70 °C) and the heat transfer coefficients U, h_i, and h_o stay constant. A new pumping cost can then be estimated by evaluating the changes in Nusselt and Reynolds numbers. The thermal conductivity enhancement will be compensated by a decrease in the coolant mass flow rate. The income (IC) is then simply estimated with Equation (12) by considering the difference between the pumping cost (P_c) of the base case and the pumping cost of the various case studies. As for the additional operating costs (EX), we assume here that the operating costs of the system is equivalent to the amount of maintenance necessary to renew the nanofluid because it has lost stability over time (i.e. acquisition cost of the nanofluid, which depends entirely on the unit cost of the nanoparticles as its dispersion cost is negligible).[45] The total cash flow for the current year is then calculated as the difference between the income and the operating costs.

$$IC = P_{c_0} - P_c \tag{12}$$

$$EX = C_{nf} \frac{stability\ period\ of\ nf}{Operating\ hours} \tag{13}$$

$$CF = IC - EX \tag{14}$$

The stability period of the nanofluid in Equation (13) is in hours.

5 RESULTS AND DISCUSSION

5.1 Initial parameters of the heat transfer system

TABLE 3 shows the initial conditions and parameters of the heat transfer system. Note that friction factor, velocity, pressure drop, pumping power and pumping cost are not calculated for the outer shell, as the economic analysis is focused only on the coolant in the inner tube. The electrical cost is assumed to be the industrial average cost in the United States during Spring 2021, which is approximately 0.07 $/kWh.[76]

TABLE 3 Initial conditions and parameters of the heat exchanger

Parameters	Inner Tube	Outer shell
Type of fluid	Water	Ethylene glycol
Mass flow rate (kg/s)	4.24	5.00
Inlet temperature (°C)	20	130
Outlet temperature (°C)	70	65
Mean temperature (°C)	45	98
Specific heat (J/kgK)	4180	2728
Density (kg/m^3)	989	1067
Viscosity (Pa.s)	0.000577	0.002280
Reynold number	234 022	93 073
Prandtl number	3.77	73.50
Thermal Conductivity (W/mK)	0.640	0.262

Heat transfer rate (W)	866 600	
Convection heat transfer coefficient (W/m^{2}K)	12 353	6884
Overall heat transfer coefficient (W/m^{2}K)	4421	
Friction Factor	0.015	-
Velocity (m/s)	3.41	-
Pressure drop (Pa)	66 751	-
Pumping power (W)	382	-
Operating hours (h/year)	8640	
Pumping cost ($/year)	230.88	-
Pumping cost per surface area ($/m^{2}year)	60.03	-

5.2 Economic analysis

5.2.1 Economic impact of nanofluid use:

Table 4 presents the variations of mass flow rate of the coolant as well as the results obtained from the economic analysis for CS1 and CS2. Note that for CS1B, we show the mass flow rate and pumping power before and after destabilization of the nanofluid.

Table 4 – Results of the economic analysis

Parameters	**CS0**	**CS1A**	**CS1B**[a]	**CS1C**	**CS2**
Nanoparticle	-	MWCNT	MWCNT	MWCNT	CuO
Nanofluid mass flow rate (kg/s)	4.24	3.44	3.44 / 4.24*	3.44	4.66
Pumping power (W)	382	226	226 / 382*	226	441
Pumping cost (\$/m^{2}year)	**60.03**	**35.67**	**47.85**	**35.67**	**128.68**
Pumping cost change	**-**	**-41%**	**-20%**	**-41%**	**+114%**
Cost of Nanofluid (\$/m^{2}year)	-	22.46	22.46	22.46	320.83
Income (\$/m^{2}year)	-	24.36	12.18	24.36	-68.66
Total cash flow (\$/m^{2}year)	**-**	**-20.57**	**-10.28**	**1.90**	**-3919.58**
Payback time (years)	**-**	-	-	< 1	**-**

[a]The two values shown in CS1B represent the flow rate and pumping power in the first 180 days (nanofluid behaviour) and the subsequent 180 days (water only)

5.2.2 Pumping cost

Using a MWCNT-water nanofluid (CS1A) leads to a 41% decrease in pumping costs despite a significant increase in viscosity (38%). The enhancement in thermal conductivity and specific heat capacity (25% and 50% respectively) was sufficiently important to reduce the coolant demand of the system and thus compensate for the expected negative effect of the viscosity. This particular trade-off between viscosity and thermal properties must be considered carefully when looking at the suitability of a nanofluid for a thermal application. This is validated in CS2 where an increase of 5% and 21% in thermal conductivity and viscosity, respectively, and an 8% decrease in specific heat led to a high pumping cost: \$128.68. In other words, the increased thermal conductivity could not offset the negative impact of viscosity, resulting in a 114% increase in pumping costs. The pumping cost in CS1B highlights the importance of nanofluid stability. The decision to not renew the nanofluid beyond its stability period reduced the possible savings on the pumping cost by 21%. As the nanofluid completely loses its thermal properties enhancements when it destabilizes after 180 days of operation, it behaves exactly like fresh water in the base case. This leads to an increase in the required coolant mass flow rate and the pumping power thus explaining the increase in pumping cost.

5.2.3 Impact on Cost-effectiveness

Table 4 demonstrates that, even if pumping costs can be decreased in some cases with a nanofluid, an annual financial loss will occur regardless of the case selected. This cost impact is explained by 2 major reasons: the price of the nanofluid and its stability over time.

If we look at CS1A, an annual income of \$24.36/m^2 is generated due to a lower pumping cost. However, the price of the nanofluid, which represents both the initial cost of implementing the nanofluid and the operating costs because it needs to be periodically replaced, is \$22.46/m^2 due to the unit cost of the MWCNT nanoparticles (\$382/kg, see TABLE 1) and the surfactant, gum arabic, (\$140/kg [77]). This leads to a deficit of \$20.57/m^2. The situation is similar for CS1B, where the use of nanofluid allows an income of only \$12.18/m^2 from decreased pumping costs, leading to a deficit of \$10.28/m^2. The situation is even more critical in CS2, where, in addition to not generating any income, the cost of the nanofluid reaches a high value of \$320.83/m^2 since the price of CuO nanoparticles is \$328/kg. The high cost of nanoparticles clearly undermines the profit potential of nanofluids as coolants.

By extension, nanofluid stability plays a role in the loss of profitability via a recurring annual investment. In CS1A, the nanofluid, as it is only stable for 180 days, must be replaced twice a year in order to maintain its thermal properties, resulting in a total annual operating cost of \$44.92/m^2. In CS2, where nanofluid stability is lower (30 days), the deficit reaches a high value of \$3919.58/m^2 (12 replacements over the year). It is interesting to note here that, according to CS1B, it would be more beneficial to invest only once in the nanofluid annually and operate the heat transfer system with fouling after the nanofluid has destabilized, rather than pay for more frequent replenishment (though CS1B remains economically unviable). However, the larger agglomerated particles generated by the destabilization of the nanofluid would likely increase the risk of erosion and clogging of the pipes and in the pump, which would likely impact equipment costs, on top of affecting pumping power due to decreased efficiency.[4, 78] In CS1C, an investment for the purchase of the nanofluid is needed only every 5 years because of its high stability, allowing a positive cash flow of \$1.90/m^2 in the first year of its implementation and \$24.36/m^2 the following 4 years. The annual savings on pumping cost in this case is higher than the investment needed for the purchase of nanofluid, resulting in a payback time of less than a year. As 5 years represents an extreme case, this result shows that increasing the stability of the nanofluid by only 6 months would be enough to generate an annual profit and make its use economically viable.

The results from the analysis clearly demonstrate that obtaining nanofluids at a reduced cost, which may be possible by finding less expensive methods of nanoparticles synthesis and ensuring a greater stability over time are key solutions to allow nanofluid use in industrial applications.[47, 57, 79]

5.3 Economic operating window

While the previous section described specific scenarios of nanofluid economic performance in a simplified Hex geometry, this can be generalized by formulating an operating window for the studied heat transfer system, (FIGURE 2). This tool, while specific to the Hex geometry selected, helps illustrate trends for nanofluid economics (assuming long-term stability) as a function of its properties. The pumping cost (red spheres) depends on the increase of viscosity and thermal conductivity of the fluid (as compared to water), according to its specific heat. A pumping cost threshold is set at \$60.03/m^2, corresponding to the base case of water – thus, any viscosity-conductivity scenario located below this threshold, assuming long-term fluid stability, will lead to a positive economic outcome. For instance, a nanofluid with a 20% increase in thermal conductivity and an 80% increase in viscosity can immediately be dismissed as its pumping cost would be way over the threshold. Similarly, a quick evaluation of the nanofluid used in CS1, represented by the blue triangle in FIGURE 2B, confirms that investigating its economical potential was relevant. It is interesting to mention here that the number of potential candidates increases as heat capacity increases.

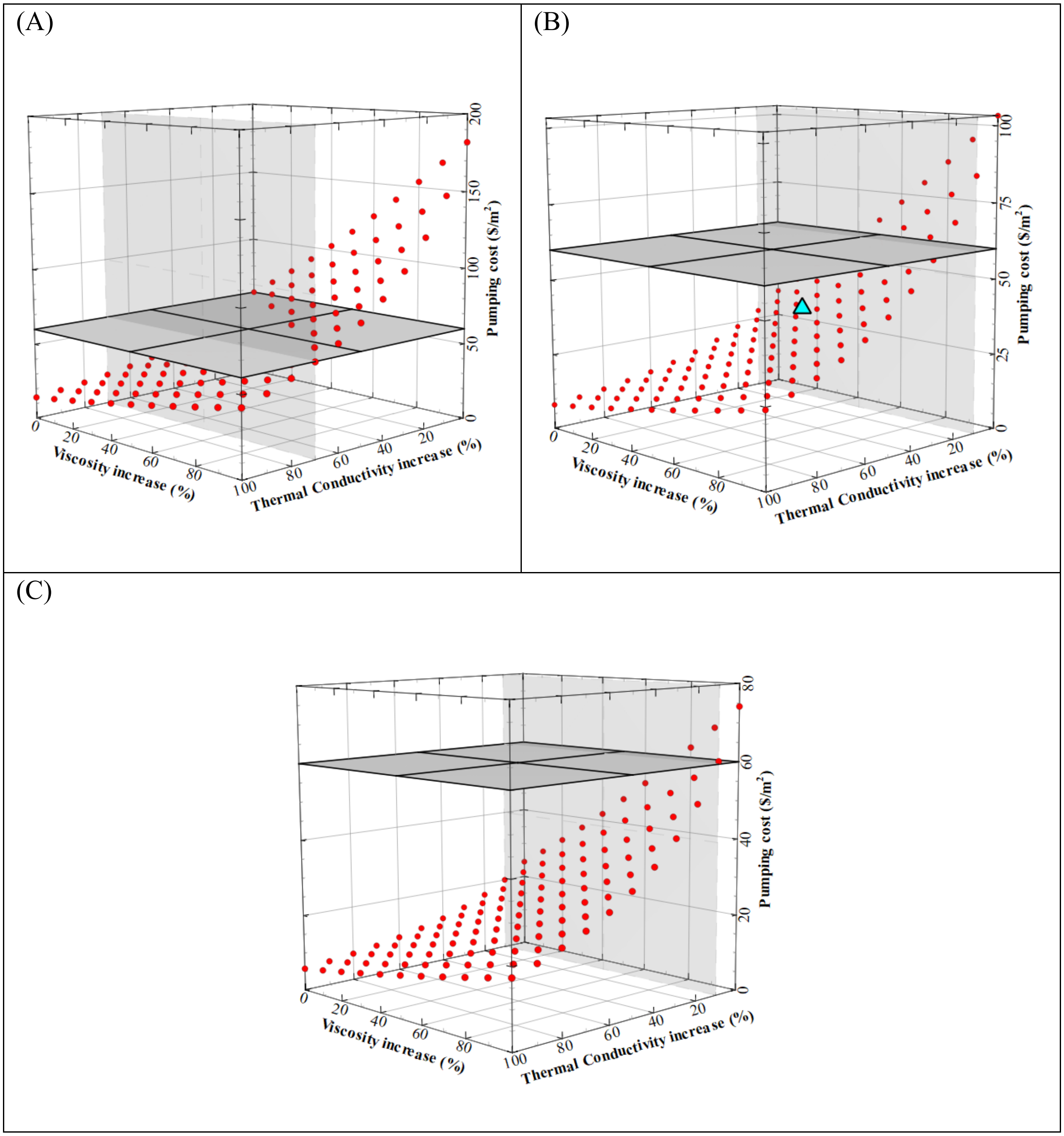

FIGURE 2 Operation window and selection tool of our heat transfer application at an enhanced heat capacity of coolant: A) 0% enhancement in C_p, B) 50% enhancement in C_p (blue triangle is CS1), C) 90% enhancement in C_p. The gray planes indicate the pumping cost threshold.

6 CONCLUSIONS

In this work, an economic analysis on four different scenarios has been performed on a heat transfer system using MWCNT/water and CuO/water as nanofluid test cases to better understand why industrial uptake of such fluids remains limited. The analysis revealed that three of the four scenarios were not economically sustainable as they would generate an annual deficit due to the nanofluid's low stability (requiring an annual investment for its renewal). Economies of scale can be possible at large scale for few selected nanofluids, but it has been demonstrated that their purchase cost of and their stability, which plays as big a role, if not more, than their price of acquisition itself, are the major hurdles preventing the large-scale use of nanofluid as they can negatively impact the cost-efficiency of the system. An operating tool was finally developed to quickly evaluate, as a first step, the economic potential of a nanofluid on a thermal application as a function of its physical properties (thermal conductivity, viscosity, and heat capacity) in order to help orient further nanofluid research for industrial applications. As future work, conducting life cycle assessments to deepen the analysis and evaluate the environmental impact of the chosen nanofluid would acknowledge this highly pertinent concern.

NOMENCLATURE

Symbols

Q	Heat flux (W)
$\dot{m}$	Mass flow rate (kg/s)
C_p	Specific heat (J/kgK)
h	Heat transfer coefficients
U	Overall heat transfer coefficient (W/m^2K)
C_e	Electrical cost ($/kWh)
EX	Expenses ($)
C_{nf}	Total Cost of nanofluid ($)
CF	Total cashflow ($/year)
K	Thermal Conductivity (W/mK)
V	Velocity (m/s)
D	Diameter of pipes (m)
Δp	Pressure drop (Pa)
f	Friction factor
L	Tube length of heat exchanger (m)
IC	Income ($)
P_c	Pumping cost
P_p	Pumping power

Greek letters

ρ	Density (kg/m^3)
μ	Viscosity (Pa.s)
η	Pump efficiency (W)
τ	Operating hours

Subscripts

i	Inner tube
o	annulus

Dimensionless numbers

Re	Reynolds number
Pr	Prandtl number
Nu	Nusselt number

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