Letters in High Energy Physics
ISSN: 2632-2714

Volume 2025

The Role of Thermal Modification and Nanofluids in Improving Energy Conversion Efficiency in Heat Exchangers

Alwan Flayyih Hussein

yahussein669@gmail.com

Abstract: Enhancing energy conversion efficiency in heat exchangers is a critical objective in modern thermal engineering. Thermal modification techniques and the incorporation of nanofluids represent promising strategies to overcome conventional limitations such as low thermal conductivity and limited heat transfer rates. Thermal modification involves optimizing the design and material properties of heat exchangers to improve heat transfer coefficients, reduce fouling, and increase operational stability. Meanwhile, nanofluids engineered colloidal suspensions of nanoparticles in base fluids demonstrate significantly improved thermal properties, enabling superior convective heat transfer performance. This paper explores the combined and individual roles of thermal modification and nanofluids in improving heat exchanger efficiency, examining the underlying mechanisms, practical implementation challenges, and potential for integration into advanced energy systems.

Keywords: Thermal modification ,Nanofluids ,Heat exchangers ,Energy conversion efficiency ,Heat transfer enhancement

1.Introduction

Heat exchangers are vital components in a wide range of energy systems, including power generation, refrigeration, air conditioning, and chemical processing. Their performance directly influences the overall energy conversion efficiency of these systems. Traditional heat exchangers often suffer from inherent limitations, such as restricted thermal conductivity of working fluids and design constraints that impede effective heat transfer.

In recent years, two promising strategies have emerged to address these challenges: thermal modification of heat exchanger surfaces and the use of nanofluids. Thermal modification encompasses methods such as surface roughening, extended surfaces (fins), coating technologies, and advanced manufacturing techniques like additive manufacturing. These approaches aim to increase surface area, enhance turbulence, and improve heat transfer coefficients while minimizing fouling and maintaining mechanical integrity.[1]

Simultaneously, nanofluids—liquids containing dispersed nanoparticles such as metals, metal oxides, or carbon-based materials—offer enhanced thermophysical properties, including higher thermal conductivity and improved convective heat transfer behavior. The synergy between advanced materials and optimized geometries can lead to substantial improvements in heat exchanger performance.

This paper investigates the role of thermal modification and nanofluids, both individually and in combination, in enhancing energy conversion efficiency. It aims to provide a comprehensive understanding of the fundamental principles, technological developments, and practical considerations for deploying these innovations in real-world energy systems.

2.Materials and Methods

The only way to judge the energy performance of nanofluids is to compare the convective heat transfer coefficients of water and nanofluids at constant pump power , However, it may be interesting to first focus on comparing the convective heat transfer coefficient at constant mean flow rate. This can be useful when a device is designed to operate at a constant or limited flow rate to avoid cavitation effects, for example. Many characteristics are common to the comparison at constant pump power; therefore, it will not be developed in detail.[2]

2_1.At Constant Mean Flow Rate

Figures 1 and 2 represent the evolution of the convective heat transfer coefficient as a function of the mean flow rate for the two nanofluids at different concentrations. In all flow regimes, the convective heat transfer coefficient increases with fluid velocity In laminar flow (Figs. 1b and 2b), the convective exchange coefficients of all fluids are almost equal. A very slight decrease can be observed with increasing mass concentration for the Al_2O_3-water nanofluid. The same is true for the TiO_2-water nanofluid in turbulent flow. All the exchange coefficients are very close, but a degradation of h, which is all the more significant as it increases, is noted at high average flow velocity. On the other hand, the laminar-turbulent transition, characterized by a change in slope in the evolution of the convective exchange coefficient, begins at a lower velocity for water than for the Al_2O_3-water nanofluid. The transition is delayed all the more as the concentration is high. Indeed, since it is triggered at a constant Reynolds number, as shown in section 4.1, the less viscous fluid, in this case water, will have a lower velocity. As a result, it is possible to achieve much higher exchange coefficients for water than for any other concentration of the Al_2O_3-water nanofluid at constant speed. The performance of this nanofluid even decreases very rapidly as the mass concentration increases. From a thermal point of view, this nanofluid is therefore of no interest in the turbulent regime since it[3] degrades heat transfer. This phenomenon is much less visible for the second nanofluid due to its lower viscosity.

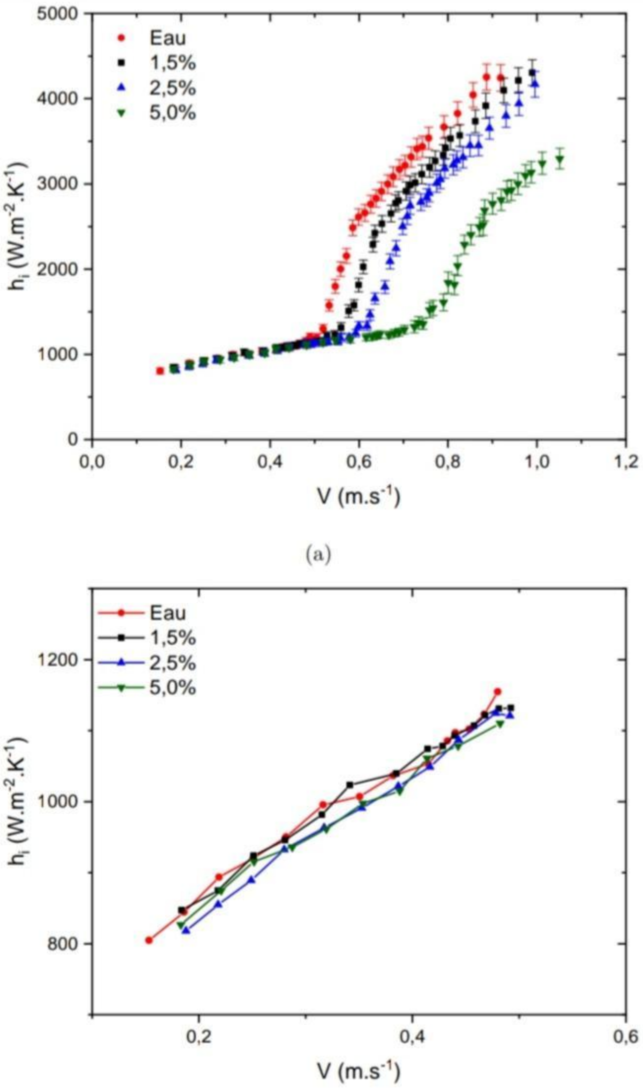
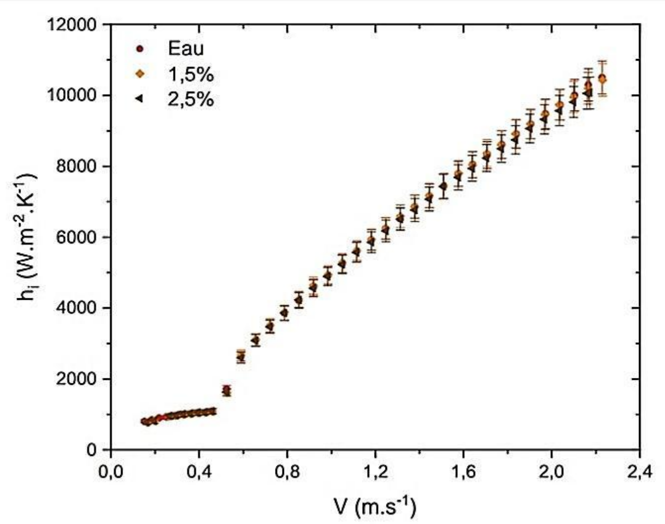


FIGURE 1 Convective heat exchange coefficient as a function of the average flow velocity for the Al_2O_3-water nanofluid



(a)

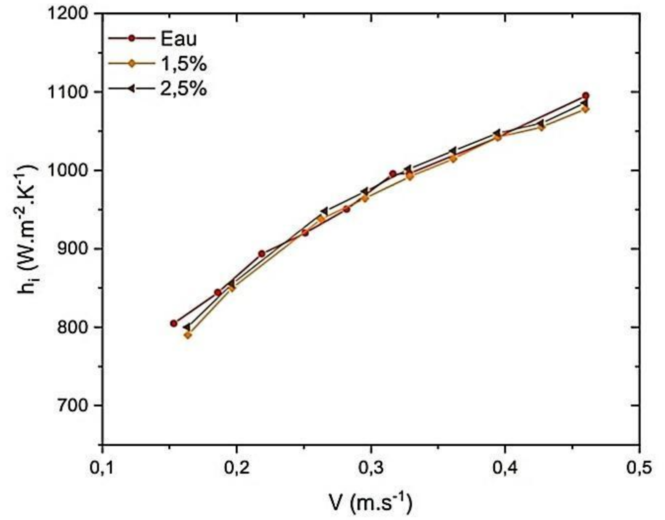


FIGURE 2 Convective heat exchange coefficient as a function of the average flow velocity for the nanofluid TiO_2

It is therefore interesting to highlight the impact of the basis of comparison on the conclusions that can be drawn. In the previous section, the comparison of convective heat transfer coefficients at constant Reynolds number showed an improvement in heat transfer with increasing mass concentration in laminar flow.

Here, at constant mean flow velocity, there is no effect. Worse, when the velocity increases, the alumina nanoparticles degrade the water's ability to transfer heat. Furthermore, this basis of comparison does not take into account the pump power penalty due to the increase in pressure drops with the particles.[4]

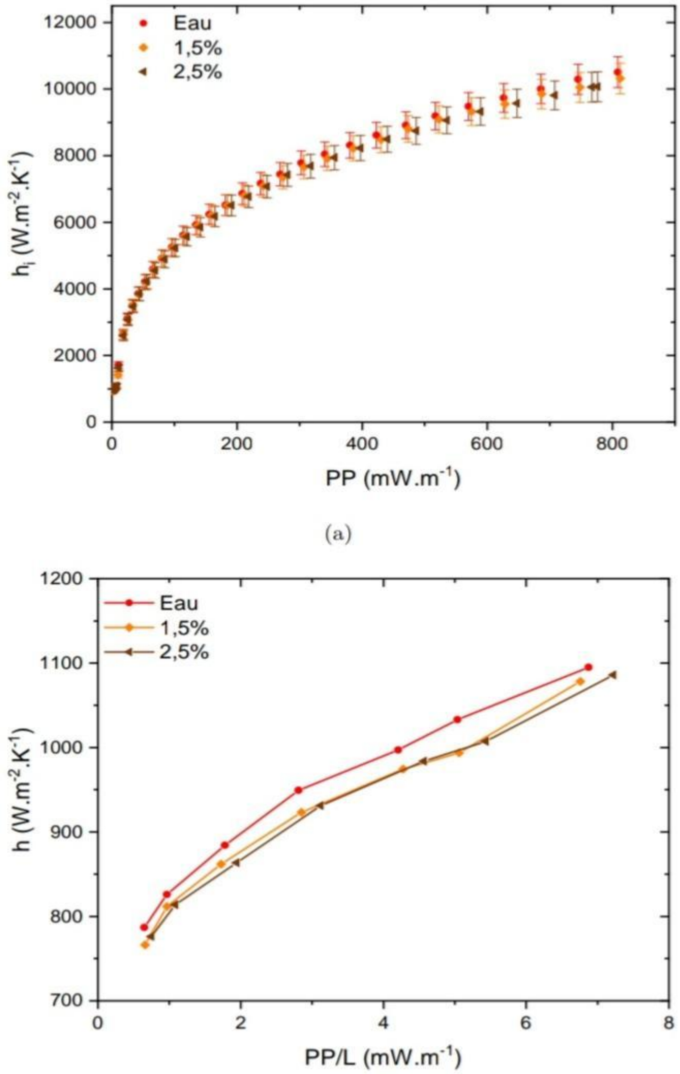
2_2.At constant pump power

As a reminder, the pump power corresponds to the product of the volume flow rate and the pressure drops:[5]

$PP = Q_v \Delta P$ (1)

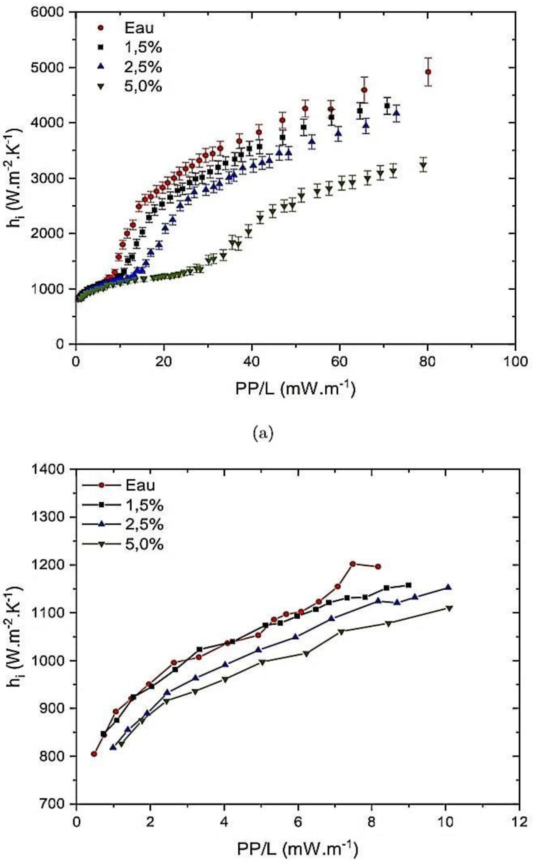
Here, only linear pressure drops between the inlet and outlet of the test zone are considered. Figures 3 and 4 show the evolution of the convective heat exchange coefficients as a function of linear pump power for the Al_2O_3-water and TiO_2-water nanofluids, respectively, and compare them to those of water. Several observations are worth highlighting. First, the heat exchange coefficient increases with pump power for all the fluids studied, which is explained by the increase in the average flow velocity. Second, for the Al_2O_3-water nanofluid, the laminar-turbulent transition can be clearly identified for each of the concentrations and is characterized by a change in slope in the evolution of hi As with the comparison at constant average flow velocity, it is triggered later and later as the mass concentration increases, to 9 mW-m for water and to 30 mW-m^1 for the highest concentration. In addition, the transition also lasts longer with increasing viscosity. For example, for water 7 mW-m^1 is sufficient to go from laminar to turbulent regime compared to 12 mW-m at a mass concentration of 2.5 wt% and 20 mW-m^1 at 5.0 wt%. Therefore, it is possible to achieve much higher convective exchange coefficients with water than with any concentration studied as soon as the laminar-turbulent transition is triggered for water. At a pump power of 30 mW-m^2, where the turbulent regime is reached for water but the 5 wt% Al_2O_3-water nanofluid is still in laminar regime, the decrease in the convective exchange coefficient reaches 60%. Although this effect is less marked for the [6]

FIGURE 3 Energy performance of the Al_2O_3-water nanofluid



(a)

FIGURE 4 Energy performance of the TiO_2-water nanofluid



(a)

At two lower concentrations, energy performance still decreases with increasing concentration once the laminar-turbulent transition is initiated for water. For the TiO_2-water nanofluid, the laminar-turbulent transition is more difficult to demonstrate due to the wide range of pump power covered. It occurs at very similar pump powers for all the fluids studied, since the increase in viscosity is moderate compared to the Al_2O_3-water nanofluid. Once the turbulent regime is established,[7]the performance of the three fluids begins to be equal, and then, quite quickly, it appears that water remains slightly better than the nanofluid at removing heat. The deterioration in heat transfer only reaches about 2% This slight decrease in the heat transfer capacity compared to the average flow velocity comparison (Fig. 2) is explained by the increase in pressure losses with concentration. At low pump power, i.e. in laminar flow, the energy performance of all fluids is relatively close (Figs. 3b and 4b). Water and the mass concentration of 1.5% of **Al2O3** allow the same convective exchange coefficients to be achieved at constant pump power up to 7mW-m-^{1}. On the other hand, h, decreases with increasing concentration for both nanofluids. The deterioration in heat transfer represents approximately 6.4% for Al_2O_3-water and 3.8% for TiO_2-water at the highest concentration. From this study, it is clear that in turbulent flow, neither nanofluid improves heat transfer at constant pump power. The Al_2O_3-water nanofluid even deteriorates it very significantly. In laminar flow, the results presented also do not tend towards an improvement in convective exchanges.

However, since the flow is not thermally established, it is necessary to ensure this throughout the thermal development.[8]

3.Result

In laminar flow that is not thermally established, the energy performance of nanofluids will depend on the state of the thermal boundary layer and therefore on the axial position.

As a reminder, the pump power 2is defined as:

$PP = Q_v \Delta P$ (1) For a fluid whose pressure drop coefficient evolution follows Poiseuille's law as is the case for all the concentrations studied here, the losses of charge are written :[9]

$AP = 128\mu L_p / \pi d^4_i \, Qv$

with:

$Q_v = \pi d^2_i / 4$ (2)

Finally, the pump power required to circulate the fluid per unit of length can be expressed:

$PP/L_p = 8\pi\mu\nu^2$, (3)

$V = (pp / 8\pi\mu L_p)^{1/2}$ (4)

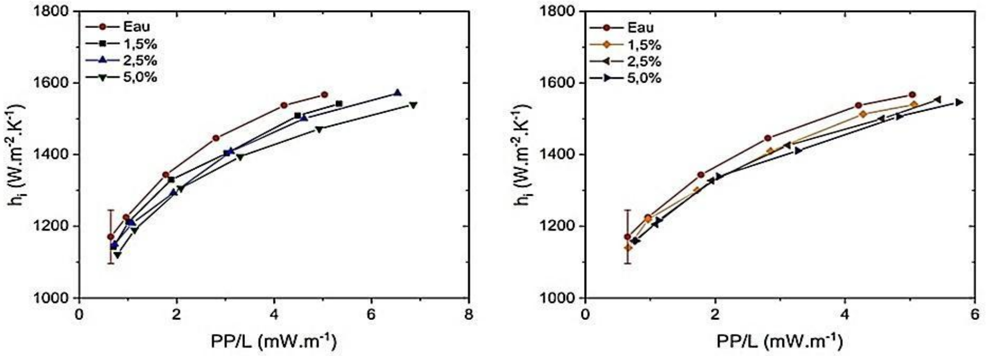
Furthermore, the ratio of the inverse of the Graetz number of a nanofluid and its base fluid at constant pump power and axial coordinate is written according to the definition of the Graetz number and equation :

$Gz^{-1}_{nf} < Gz^{-1}_{bf} < 1$ (7)

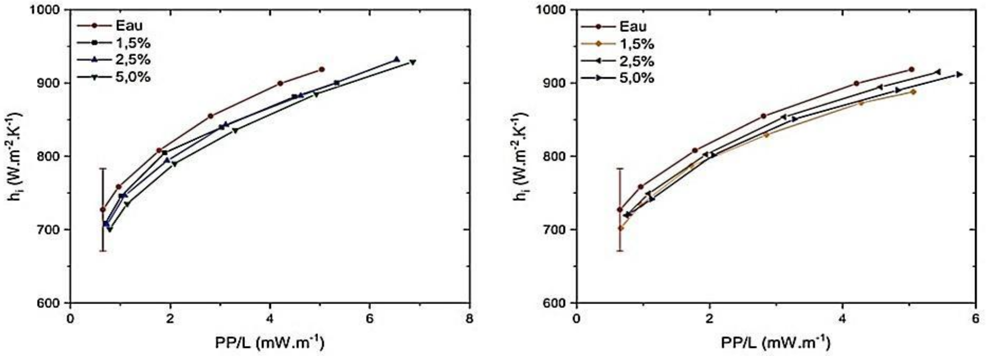
$\Leftrightarrow (K\sqrt{\mu} / pC_P)_{nf} < (K\sqrt{\mu} / pC_P)_{bf}$ (8)

The PC ratio is almost constant at all concentrations studied with a maximum decrease of 0.5% at a mass concentration of 5% for both nanofluids Since both viscosity and thermal conductivity increase with concentration, this implies that the inverse of the Graetz number will be greater for a nanofluid than for water at constant pump power. Therefore, the development of the thermal boundary layer will be accelerated by the addition of nanoparticles. The thermal establishment length will be shorter as the viscosity, and therefore the mass concentration, is high. This effect is the exact opposite of what was observed at constant Reynolds number (Fig.8). [10]

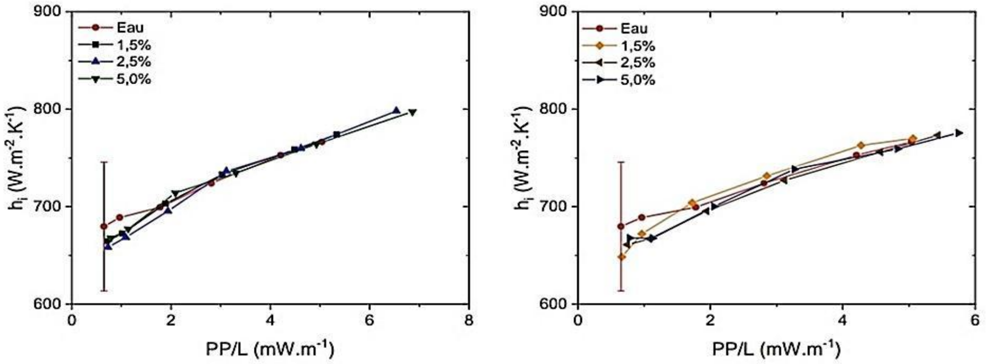
This phenomenon will therefore always result in a higher Nusselt number (or equal in the case of thermally established flow) for water. The improvement or deterioration of heat transfer with increasing mass concentration in the thermal establishment zone will therefore depend on three factors: the acceleration of the development of the thermal boundary layer, the increase in thermal conductivity with the addition of particles and the axial coordinate. In detail, a strong acceleration of thermal development with the addition of nanoparticles will significantly reduce the Nusselt number and, with it, the convective exchange coefficient at constant pump power. On the other hand, this effect may be significantly reduced at large axial distances where the thermal boundary layer hardly changes and the steady state is almost reached. In this region, the advance over the Thermal development will have little impact. Moreover, it is entirely possible to obtain a higher convective exchange coefficient with nanofluids even if the Nusselt number is lower, provided that the increase in thermal conductivity is sufficient. This also implies that in thermally established laminar flow, where the Nusselt number no longer changes, nanofluids will theoretically make it possible to achieve higher convective exchange coefficients than water thanks to the increase in thermal conductivity. Unfortunately, achieving this flow regime is not possible for all fluids with the current device.[11] Figure 5 represents the convective exchange coefficient as a function of the pump power required to circulate the fluid over 1 m at different axial positions At the tube inlet (Figs. 5a and 5d), the energy performance of water is better than any concentration of the two nanofluids at all pump powers studied. In addition, the heat exchange coefficient decreases with increasing concentration. For the Al_2O_3-water nanofluid, the energy performance degradation reaches about 2% at 1.5wt% and 5% at 5wt%. For the second nanofluid, the same mass concentrations decrease the convective heat exchange coefficient by about 2% and 4% respectively. At this level, we are in the case where the thermal boundary layer develops very rapidly and consequently, the advance of the nanofluids over water in the thermal development results in a strong decrease in the Nusselt number and therefore in the convective heat exchange coefficient which cannot be counterbalanced by the increase in thermal conductivity. As r increases, the energy performance of nanofluids approaches that of water. At 269 cm (Figs. 5c and 5f), all Al_2O_3-water concentrations achieve the same convective heat transfer coefficient as water at pump powers above 2 $w.m^{-2}$. Here, the advance in thermal development is reduced by the fact that the flow tends to be thermally established. Therefore, the decrease in the Nusselt number with the addition of particles is moderate and can be compensated by the increase in thermal conductivity. Surprisingly, water remains a better heat transfer fluid at lower pump powers, whereas the flow should be closer to established and therefore the advance in thermal development of nanofluids should be negligible. It should be noted, however, that the difference in the exchange coefficients does not exceed 20 w.m^{-2}.K^{-1}, while the uncertainties reach approximately 65 w.m^{-2}.K for these measurement points.[12]Regarding the mass concentrations of 2.5% and 5.0% of theTiO$_2$-water nanofluid, the convective exchange coefficient is almost constant for the first two measurement points, a sign that the thermally established regime is almost reached.



(a) Al_2O_3-eau, $x = 9\,\mathrm{cm}$ (d) TiO_2-eau, $x = 9\,\mathrm{cm}$



(b) Al_2O_3-eau, $x = 39\,\mathrm{cm}$ (e) TiO_2-eau, $x = 39\,\mathrm{cm}$



(c) Al_2O_3-eau, $x = 69\,\mathrm{cm}$ (f) TiO_2-eau, $x = 69\,\mathrm{cm}$

FIGURE 5 Evolution of the convective heat exchange coefficient as a function of pump power at different axial coordinates

When the pump power increases, the thermal settling length lengthens and the heat exchange coefficient changes again. As with the Al_2O_3-water nanofluid, all fluids tend to have the same energy performance beyond 2 w.m^{-1}.

To quantitatively assess the performance of each fluid, and to reduce the significance of measurement anomalies that may appear at certain measurement points, an average heat exchange coefficient h can be determined by calculating the area under the curve representing the convective heat exchange coefficient as a function of axial distance at constant pump power (Figs. 6 and 7):[13]

$h_i = 1/x_s - x_1 \int_{x_1}^{x_s} h_i(x)dx$, (5)

where z_1 and zs denote the first and last measurements at 9 cm and 79 cm respectively. The integral is calculated numerically using OriginPro 2018 software from the data points. Although it does not allow the exact amount of heat removed by each fluid in the test zone to be determined, this parameter still allows the nanofluids to be compared to water overall over most of the thermal development.

Tables 4.1a and 4.1b list the average convective heat transfer coefficients for all fluids studied at three different pump powers. The missing data for the 2.5% mass concentration of the two nanofluids is explained by the fact that no measurement point was close enough to the indicated pump power. It is clear that regardless of the type of nanoparticles and concentrations studied, these two nanofluids degrade heat transfer in the thermal establishment region Generally, the average heat transfer coefficient decreases with increasing concentration, except for the TiO_2-water nanofluid at a pump power of 1.95 $w.m^{-1}$. However, the data for the 2.5wt% and 5.0wt% concentrations are from pump powers that are about 10% higher than those used for water. The degradation of heat transfer is therefore slightly offset by the increase in pump power. Despite this, the average convective heat transfer coefficient is lower than that of water.[14]

Regarding the effect of pump power on heat transfer degradation, its contribution appears moderate for several concentrations. The decrease in the heat transfer coefficient is roughly constant for the 1.5% and 5% mass concentrations of the TiO_2-water nanofluid and 5% of the Al_2O_2-water nanofluid, with the exception of the data points from higher pump power. For all other concentrations, and particularly the 1.5wt% Al_2O_2-water nanofluid, the average heat transfer coefficient approaches that of water as the pump power increases.[15]

TABLE 1- Comparison of average heat transfer coefficie ($w.m^{-2}.K^{-1}$)at constant pump power. The deterioration in heat transfer compared to water is indicated (%).

(a) Al_2O_3–water

PP/L ($mW \cdot m^{-1}$)	Water	1.5 wt%	2.5 wt%	5.0 wt%
1.05 ± 0.10	809	787 (–2.7 %)	783 (–3.2 %)	781 (–3.5 %)
1.95 ± 0.12	853	846 (–0.8 %)	834 (–2.2 %)	838† (–1.8 %)
5.10 ± 0.20	969	953 (–1.7 %)	–	934 (–3.6 %)

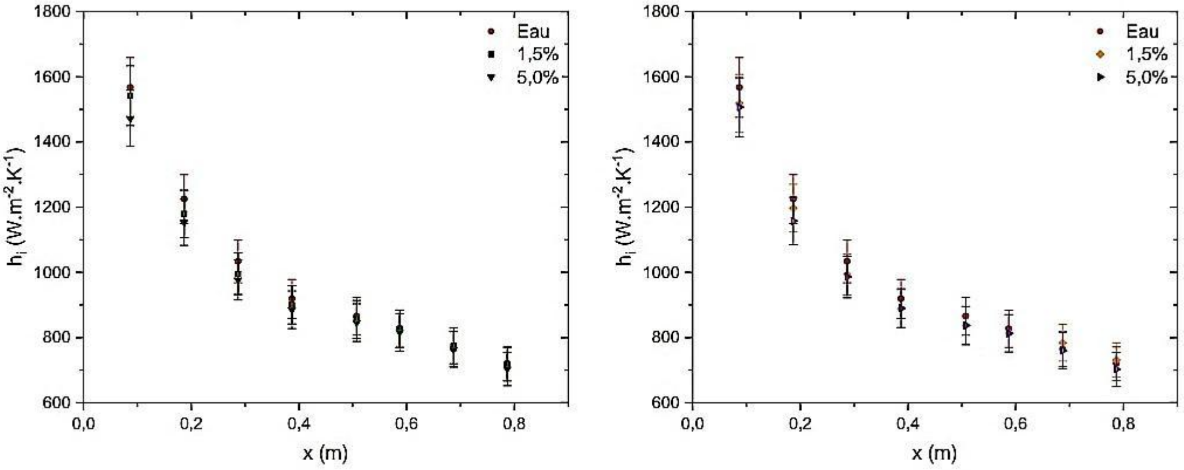
(b) TiO_2–water

PP/L ($mW \cdot m^{-1}$)	Water	1.5 wt%	2.5 wt%	5.0 wt%
1.05 ± 0.10	809	792 (–2.1 %)	788 (–2.6 %)	786 (–2.8 %)
1.95 ± 0.12	853	836 (–1.9 %)	834† (–1.5 %)	838† (–1.2 %)
5.10 ± 0.20	969	949 (–2.1 %)	–	936 (–3.4 %)

† These data come from a pump power about 10 % higher than indicated.

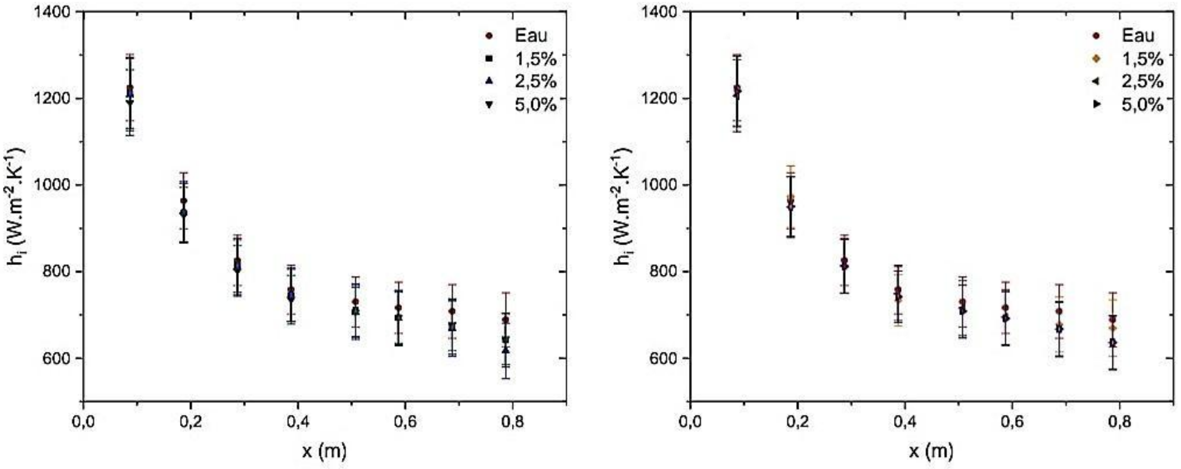
Finally, it can be noted that the TiO_2-water nanofluid degrades heat transfer less severely in laminar flow.

This is obviously explained by the fact that the increase in its viscosity is more moderate than that of the Al_2O_3-water nanofluid. Consequently, the development of the thermal boundary layer is less accelerated and therefore approaches that of water. In return, the improvement in thermal conductivity is also weaker, which does not allow it to be a better heat transfer fluid than water.



(a) Al_2O_3-eau (b) TiO_2-eau

FIGURE 6



(a) Al_2O_3-eau (b) TiO_2-eau

FIGURE 7 Evolution of the convective exchange coefficient as a function of the axial coordinate at PP/L=5.10±0.20 mW-m^{-1}. The average convective exchange coefficient (Tab.1) is calculated from the area under each of the curves (Eq.7)

4. Discussion

Based on the results presented, the use of nanofluids as heat transfer fluids may seem compromised. The question of the general benefit of adding nanoparticles, whatever they may be, to increase heat transfer may then arise. To attempt to answer this question, the reasoning begun in the previous section can be generalized. For the addition of nanoparticles to be advantageous, the convective heat exchange coefficient must be improved at constant pump power. For this to happen, it is sufficient for the Nusselt number of the nanofluid to be greater than that of its base fluid, since thermal conductivity always improves with increasing mass concentration In turbulent flow, this type of performance criterion already exists, such as the Mouromtseff number which links the convective exchange coefficient to the thermophysical properties of a nanofluid and its base fluid.[16]

However, it is based on empirical correlations of the Nusselt number. In laminar flow, the local Nusselt number follows the theoretical law of Kays and Crawford [88]. In non-thermally developed flow, it decreases with increasing Gz^1 as has already been shown. Thus, to achieve a better Nusselt number, it is necessary and sufficient that the inverse of the Graetz number is as small as possible. In other words:

$(PP/L_p = 1\ mWm^{-1})$. $\varepsilon = h_{nf} / h_{bf} - 1$

$Gz^{-1}_{nf} < Gz^{-1}_{bf} \Leftrightarrow Nu_{nf} > Nu_{bf} \Leftrightarrow h_{nf} > h_{bf}$ (6)

It is very important to note that the last part of the previous relationship is an implication and not an equivalence. Indeed, the fact that the Nusselt number of the nanofluid is greater than that of its base fluid is a sufficient but not necessary condition for enhanced heat transfer. Based on Equation 4.6, which relates the ratio of the inverse Graetz number of a nanofluid to that of its base fluid and their thermophysical properties at constant pump power, the previous condition can be rewritten:

$Gz^{-1}_{nf} < Gz^{-1}_{bf} < 1$ (7)

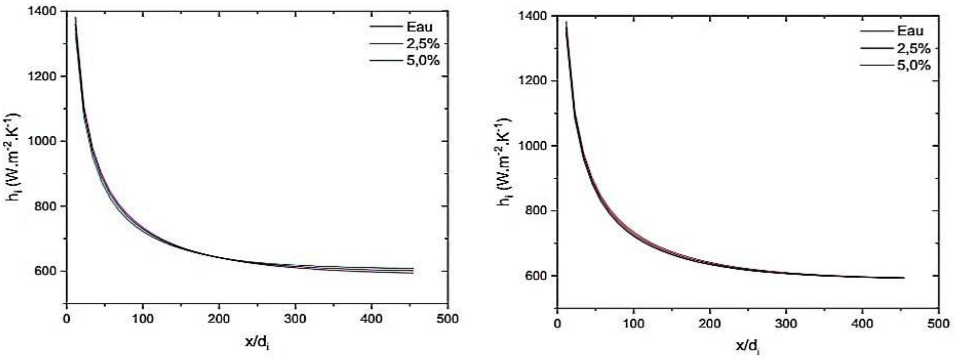
$\Leftrightarrow (K\sqrt{\mu} / pC_P)_{nf} < (K\sqrt{\mu} / pC_P)_{bf}$ (8)

It is then interesting to note that this condition depends only on the thermophysical properties of the base fluid and the nanofluid. Since thermal conductivity and viscosity always increase with the addition of nanoparticles, it may seem difficult to meet this criterion. Indeed, although the density of the [17] nanofluids is higher than that of their base fluid, their specific heat capacity is generally lower, at least for water-based nanofluids

TABLE 2Specific heat capacity of different materials commonly used in nanofluids at 20°C

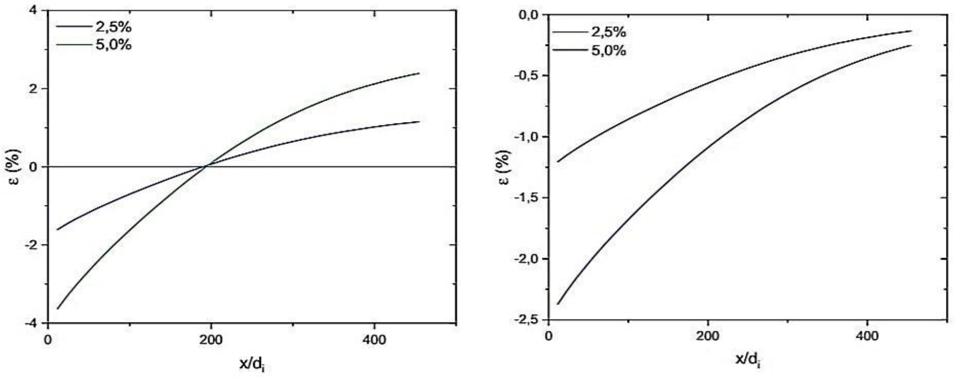
State	Material	ρCp [$MJ \cdot m^{-3} \cdot K^{-1}$]
Liquids	Water	4.2
	Ethylene glycol	2.7
	Engine oil	1.7
Metallic solids	Copper	3.4
	Silver	2.5
	Gold	2.5
	Aluminium	2.4
Non-metallic solids	Al_2O_3	2.8
	TiO_2	2.8
	ZnO	2.8
	SiO_2	1.7

TABLE 2 shows the volumetric heat capacity (PC) of the most commonly used materials in nanofluids. It is clear that the volumetric heat capacity of all the solids presented is lower than that of water. Adding these particles to water will decrease the volumetric heat capacity in addition to increasing thermal conductivity and viscosity. Therefore, the previously mentioned condition can never be met for water-based nanofluids. However, this statement must be put into perspective. As previously stated,[18] The condition presented is sufficient to prove that a nanofluid is better than its base fluid, but it is not necessary. Indeed, it is always possible for a fluid to have a higher convective heat exchange coefficient while having a lower Nusselt number, provided that the thermal conductivity is sufficiently high. On the other hand, increasing thermal conductivity also increases Gz and therefore paradoxically decreases the local Nusselt number in undeveloped flow. This can be explained by the fact that for a highly thermally conductive fluid flow, the fluid temperature will quickly approach that of the tube wall, which characterizes the thickening of the thermal boundary layer. From a general point of view, the use of aqueous nanofluids in undeveloped laminar flow is therefore strongly discouraged. When the flow is thermally established, the Nusselt number of the nanofluids must be equal to that of their base fluid. Their higher thermal conductivity must then allow them to achieve a higher local heat exchange coefficient. However, achieving this flow regime can require very long pipe lengths, on the order of several meters, which is not compatible with current industrial installations. Figure 8 illustrates this phenomenon. Based on the previously measured thermophysical properties of water and nanofluids and on the Kays and Crawford law it is possible to extrapolate the experimental data of the convective heat exchange coefficient over the entire thermal establishment length It is clearly visible that for low z/d_1, water allows to achieve better heat exchange coefficients, as shown experimentally in the previous section. [19] As for the Al2O3-water nanofluid, it becomes a better heat transfer fluid than water when /d exceeds about 200, or 90 cm in our experimental setup. However, the degradation of the energy performance at the tube inlet means that the total amount of heat that can be removed remains lower for the nanofluid than for water. For the second nanofluid, the increase in thermal conductivity is so small that it only allows it to reach the same ha as water at z/d > 400. At higher pump power, the thermal settling length will be even greater and the phenomena illustrated here will be amplified. It is therefore clear that the use of these two nanofluids is not recommended for heat transfer applications, even when the settling length is reached. Generally speaking, water-based nanofluids do not seem to be suitable for replacing their base fluid, which has very interesting thermophysical properties from a thermal point of view: the highest thermal conductivity among common fluids, low viscosity and high specific heat capacity. However, exchangers operating with water are limited in their operating temperature. Oils, for high temperatures or a water-ethylene glycol mixture, below 0°C may be preferred.[20] Returning to TABLE 2, it can be seen that these two fluids have volumetric heat capacities much lower than water and may even be lower than certain solid materials such as copper. The increase in thermal conductivity and viscosity could then, in part, be offset by the improvement in specific heat capacity. Thus, condition 4.10 could possibly be met. It would therefore be interesting to experimentally study the energy performance of this type of nanofluid with a view to replacing their base fluid, which is a poor thermal conductor.



(a) h_i, Al_2O_3-eau

(c) h_i, TiO_2-eau



(b) ε, Al_2O_3-eau

(d) ε, TiO_2-eau

FIGURE 8 Theoretical evolutions of the convective exchange coefficients at constant pump power ($PP/L_p = 1$ mWm^{-1}). $\varepsilon = h_{nf} / h_{bf} - 1$

5.Conclusion

Firstly, the study of nanofluids in flow has made it possible to highlight that they can be assimilated to single-phase fluids, both from a dynamic and thermal point of view. Indeed, in laminar flow, the theoretical relations of Poiseuille and Kays and Crawford are perfectly found. This results in an increase in the convective exchange coefficient at constant Reynolds number which can be explained by a delay in the thermal development of the nanofluids. Regarding the turbulent regime, the usual empirical correlations also make it possible to predict the evolution of our measurements in a satisfactory way. The Nusselt number is then unchanged at constant Reynolds number whatever the concentration studied. A small increase in the convective exchange coefficient can then be observed, due to the increase in thermal conductivity with the addition of nanoparticles. At the same time, the pressure losses increase sharply because of the increase in viscosity with the concentration. Between the two regimes, the laminar-turbulent transition is not disrupted by particles and occurs for all fluids, including water, at R_{ep} 2300. Changing the basis of comparison yields completely different conclusions. At constant pump power, and to a lesser extent at constant mean flow velocity, the convective heat transfer coefficient decreases with increasing concentration.

In both cases, the laminar-turbulent transition occurs earlier for water than for the two nanofluids, allowing higher heat transfer coefficients to be achieved more quickly with water. Consequently, these two nanofluids are of no interest for heat transfer in turbulent flow and in the concentration ranges studied. Although our experimental results are difficult to compare quantitatively with those reported in the literature because of the large number of different parameters (size of nanoparticles, concentrations studied, stabilization techniques, etc.), they are nevertheless in agreement on the fact that increasing the mass concentration decreases the energy performance. In non-thermally established laminar flow, the energy performance of fluids depends on multiple factors, the most important of which is the development of the thermal boundary layer.

At constant pump power, thermal development is, this time, accelerated by the addition of particles. The consequence of this phenomenon is the faster thickening of the thermal boundary layer of the nanofluids and with it, the reduction of the convective exchange coefficient. At significant axial distance, when the flow tends to establish itself thermally, the energy performance of all fluids converges and, theoretically, nanofluids should make it possible to achieve greater convective exchange coefficients in this regime. Nevertheless, during the vast majority of the thermal development studied here, water remains a better heat transfer fluid. Moreover, from an industrial point of view, the thermal establishment lengths are too long for these two nanofluids to be of interest From a general point of view, many of the phenomena highlighted in this chapter, such as the deterioration of heat transfer at constant pump power, the delayed and advanced thermal development of nanofluids at constant Reynolds number and pump power, respectively, and the delayed onset of the laminar-turbulent transition at constant pump power, are much more moderate for the TiO_2-water nanofluid than for Al_2O_3-water. Its viscosity, closer to that of water, obviously plays a key role in this behavior. This behavior could then be related to the way it was stabilized. On the other hand, the too low thermal conductivity of titanium oxide particles does not allow for a significant improvement in heat transfer. The option of nanofluids based on more conductive particles such as silver, whose stabilization would be achieved by modifying the pH to avoid the use of surfactants, most of which are viscous liquids, is therefore to be favored.

Finally, the establishment of a criterion for comparing the energy performance of any two fluids in non-thermally established flow allowed us to generalize the results obtained here. In particular, it was possible to demonstrate that adding any type of particle, metallic or not, to water will most certainly decrease the convective heat exchange coefficient at constant pump power.

Indeed, compared to other fluids, the thermophysical properties of water make it an ideal heat transfer fluid. It is therefore recommended to consider oil- or ethylene glycol-based nanofluids in cases where water cannot be used, particularly when the operating temperature is incompatible with its liquid phase. In such cases, the gain provided by nanoparticles could be more significant. In addition to increasing thermal conductivity, the volumetric heat capacity could also be improved. The use of copper particles is therefore recommended since its two properties are among the highest of common materials.

Reference

K. S. Hwang, S. P. Jang, and S. U. S. Choi. Flow and convective heat transfer characteristics of water-based Al2O3 nanofluids in a fully developed laminar flow regime. International Journal of Heat and Mass Transfer, 52(1–2):193–199, 2022

1. J. L. Routbort, D. Singh, E. V. Timofeeva, W. Yu, and D. M. France. Pumping power of nanofluids in a flowing system. J. Nanoparticle Res., 13(3):931–937, 2021
2. M. A. Hachey, C. T. Nguyen, N. Galanis, and C. V. Popa. Experimental investigation of Al2O3 nanofluids thermal properties and rheology - Effects of transient and steady-state heat exposure. International Journal of Thermal Sciences, 76:155–167, 2024
3. A. K. Sharma, A. K. Tiwari, and A. R. Dixit. Rheological behavior of nanofluids: A review. Renew. Sustain. Energy Rev., 53:779–791, 2019
4. G. Paul, M. Chopkar, I. Manna, and P. K. Das. Techniques for measuring the thermal conductivity of nanofluids: A review. Renew. Sustain. Energy Rev., 14(7):1913–1924, 2020.
5. K. D. Antoniadis, G. J. Tertsinidou, M. J. Assael, and W. A. Wakeham. Necessary Conditions for Accurate, Transient Hot-Wire Measurements of the Apparent Thermal Conductivity of Nanofluids Are Seldom Satisfied. Int. J. Thermophys., 37:78, 2019.
6. [78] Y. Yang, A. Oztekin, S. Neti, and S. Mohapatra. Characterization and Convective Heat Transfer with Nanofluids. ASME/JSME 2011 8th Thermal Engineering Joint Conference, AJTEC 2011, pages 1-6, 2021
7. V. Rudyak, A. V. Minakov, D. V. Guzey, V. A. Zhigarev, and M. I. Pryazhnikov. On laminar-turbulent transition in nanofluid flows. Thermophysics and Aeromechanics, 23(5):773–776, 2020.
8. M. K. Meybodi, A. Daryasafar, M. M. Koochi, J. Moghadasi, R. B. Meybodi, and A. K. Ghahfarokhi. A novel correlation approach for viscosity prediction of water-based nanofluids of AlO, TiO, SiO, and CuO. J. Taiwan Inst. Chem. Eng., 58:19–27, 2019
9. M. Raja, R. Vijayan, P. Dineshkumar, and M. Venkatesan. Review on nanofluids characterization, heat transfer characteristics, and applications. Renewable and Sustainable Energy Reviews, 64:163–173, 2019.
10. W. J. Tseng and K. Lin. Rheology and colloidal structure of aqueous TiO2 nanoparticle suspensions. Mater. Sci. Eng. A, 355:186–192, 2020.
11. K. B. Anoop, S. Kabelac, T. Sundararajan, and S. K. Das. Rheological and flow characteristics of nanofluids: Influence of electroviscous effects and particle agglomeration. J. Appl. Phys., 106:034909, 2021
12. M. H. Kayhani, H. Soltanzadeh, M. M. Heyhat, M. Nazari, and F. Kowsary. Experimental study of convective heat transfer and pressure drop of TiO 2/water nanofluid. Int. Commun. Heat Mass Transf., 39(3):456–462, 2022.
13. D. Zhong, H. Zhong, and T. Wen. Investigation on the thermal properties, heat transfer, and flow performance of a highly self-dispersion TiO 2 nanofluid in a multiport mini channel. Int. Commun. Heat Mass Transf., 117(July), 2020
14.] R. Martínez-Cuenca, R. Mondragón, L. Hernández, C. Segarra, J. Jarque, T. Hi-biki, and J. Juliá. Forced-convective heat-transfer coefficient and pressure drop of water-based nanofluids in a horizontal pipe. Applied Thermal Engineering, 98:841–849, 2019.
15. [103] S. Ferrouillat, A. Bontemps, J. Ribeiro, J. Gruss, and O. Soriano. Hydraulic and heat transfer study of SiO2/water nanofluids in horizontal tubes with imposed wall temperature boundary conditions. Int. J. Heat Fluid Flow, 32(2):424–439, 2021
16. W. Yu, D. M. France, E. V. Timofeeva, D. Singh, and J. L. Routbort. Comparative review of turbulent heat transfer of nanofluids. International Journal of Heat and Mass Transfer, 55:5380–5396, 2022.

17. J. P. Meyer, T. J. McKrell, and K. Grote. The influence of multi-walled carbon nanotubes on single-phase heat transfer and pressure drop characteristics in the transitional flow regime of smooth tubes. Int. J. Heat Mass Transf., 58:597–609, 2021
18. A. Nikulin, A. S. Moita, A. L. N. Moreira, S. M. S. Murshed, A. Huminic, Y. Grosu, A. Faik, J. Nieto-maestre, and O. Khliyeva. International Journal of Heat and Mass Transfer Effect of Al2O3 Nanoparticles on Laminar, Transient, and Turbulent Flow of Isopropyl Alcohol. Int. J. Heat Mass Transf., 130:1032-1044, 2019.
19. A. A. Minea. Comparative study of turbulent heat transfer of nanofluids. Journal of Thermal Analysis and Calorimetry, 124(1):407-416, 2020.