

Hybrid or mono nanofluids for convective heat transfer applications. A critical review of experimental research

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ABSTRACT

Research on nanofluids has increased markedly in the last two decades. Initial attention has focused on conventional or mono nanofluids, dispersions of one type of solid nano-sized particles in a base fluid. Despite various challenges such as dispersion stability or increased pumping power, nanofluids have become improved working fluids for various energy applications. Among them, convective heat transfer has been the main research topic since the very beginning. Hybrid nanofluids, dispersions of two or more different nanoadditives in mixture or composite form, have received attention more recently. Research on hybrid nanofluids aims to further enhance the individual benefits of each single dispersion through potential synergistic effects between nanomaterials. Multiple experimental studies have been conducted independently analysing the convective heat transfer performance of mono or hybrid nanofluids for single-phase and two-phase convective heat transfer applications. However, there are still no general conclusions about which nanofluids, mono or hybrid, present better prospects. This review summarizes the experimental studies that jointly analyse both hybrid and mono nanofluids for these applications and the results are classified according to the heat transfer device used. Based on this criterion, three large groups of devices were noticed for single-phase convective heat transfer (tubular heat exchangers, plate heat exchangers and minichannel heat exchangers/heat sinks), while one group was identified for two-phase convective heat transfer (heat pipes). The main outcomes of these studies are summarized and critically analysed to draw general conclusions from an application point of view.

1. Introduction

As a society, we are encouraged to comply with the 2 K global warming limit of the Paris Agreement [1] and thereby we should replace conventional primary energy generation methods (for instance burning fossil fuels) with low-emission replacements [2]. Hence, renewable energies and the optimization of energy systems by improving the efficiency of conversion processes affords an environmentally sustainable alternative to carbon-intensive energy. The innovative kind of heat transfer fluids, (mono) nanofluids, showing improved and unique thermal efficacy, is intended to be used in many energy applications requiring high thermal dissipation [3]. Nanofluids are mainly used as working fluids in heat transfer equipment, such as heat exchangers. As pointed out by Kumar et al. [4], any debate about heat transfer and heat exchangers may not be able to draw correct and logical understandings and conclusions without referring to nanofluids, and vice versa.

Heat exchangers can be indexed as indirect contact type and direct

contact type [4]. In an indirect contact heat exchanger, the two media are divided by a wall, whereas in a direct contact heat exchanger, the two media are in direct interaction. However, in a more complete way, these devices can be classified according to different characteristics such as heat transfer mechanism, construction features, flow arrangement, or the already mentioned fluid contact criteria, among others. Fig. 1 shows two of the most employed classifications. According to the involved heat transfer mechanism, single-phase convective heat exchangers and two-phase convective heat exchangers (condensers and evaporators) are the most widespread devices [5]. With regards to construction features, tubular heat exchangers (double pipe, shell and tube, coiled tube) and plate heat exchangers (gasketed, brazed, welded) are the most commonly used [5].

Tubular heat exchangers are efficient process equipment that produce significantly improved heat transfer with high fluid flow rates. Plate heat exchangers are usually arranged of a stack of thin corrugated metal plates, with apertures at the corners to supply channels for two fluid systems, allowing heat transfer between the two fluid media [4].

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List of abbreviations**Abbreviations**

CNF	Carbon nanofibers
CNT	Carbon nanotubes
f-	Functionalized
GNP	Graphene nanoplatelets
GO	Graphene oxide
HA	Hexylamine
MWCNT	Multi-walled carbon nanotubes
OA	Oleic acid
RGO	Reduced graphene oxide
sG	Graphene via the solar exfoliation technique

Symbols

h	Convective heat transfer coefficient [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$]
f	Friction factor [-]
Nu	Nusselt number [-]
Q	Heating power [W]
R	Thermal resistance [$\text{K}\cdot\text{W}^{-1}$]
Re	Reynolds number [-]
ΔP	Pressure drop [kPa]

They are considered for their effectiveness, design flexibility, compactness, and low cost, and are used in many industrial applications [6]. Among other classifications, it is interesting to note that the requirement for smaller sizes and weights in many industrial applications has led to the development of miniature heat exchangers (active and passive micro/minichannel heat exchangers) [5].

Over the years, active or passive methods, depending on whether external power is required or not, provide superior performance of the heat exchangers. An analysis of the literature shows that both passive (for instance, heat transfer enhancing surfaces or nanofluids) and active techniques has been applicable to heat exchangers [6]. It is well recognised that these procedures entail a remarkable potential to improve the heat exchanger thermal-hydraulic performance. Therefore, it is worth investigating the optimization of the efficiency of existing energy systems involving heat exchangers, including those available in renewable energies, from the perspective of fostering the development and practical implementation of nanofluids. In this regard, the interest in the research of hybrid nanofluids has significantly grown in the last years (see Fig. 2a) [7,8] on the assumption or excuse that an enigmatic improvement in relation to mono nanofluids occurs in the heat transfer process [9,10]. Likewise, convection is the main specific research topic in heat transfer of nanofluids from the last two decades. Thus, the number of publications concerning this topic continues to increase year after year, as shown in Fig. 2b. Convective heat transfer is involved in many common heating and cooling processes and applications, as indicated in this figure, through multiple types of heat exchangers, both in the industrial and domestic sectors.

The aforementioned huge demand to achieve thermal performance improvements using hybrid nanofluids is based on the fact that many applications are waiting to be verified. As a simple overview, Table 1 provides some reviews collecting the different potential heat transfer applications of nanofluids and, in particular, of hybrid nanofluids. As can be observed, most of the referred applications involve convective heat transfer related to different types of heat exchangers such as automotive cooling systems or mini/microchannels. In addition, despite the existing studies and reviews on preparation methods, characterizations, challenges like stability and aggregation, thermophysical properties, viscosity increases, and heat transfer processes, there are still a considerable number of conceivable combinations that could be designed from nanoscale materials that could be employed in future works.

In this review, efforts have been made to articulate a revision that may prove to be useful in elucidating whether hybrid or mono nanofluids should be selected for convective heat transfer applications and whether studies that meet the aforementioned challenge are reported. Accordingly, experimental studies dealing with hybrids and the corresponding mono nanofluids in single-phase and two-phase convective heat exchangers have been summarized and critically analysed. Existing papers can be classified according to three large groups of heat exchangers (tubular, plate and minichannel) for single-phase convective heat transfer, while all papers can be included in one group of devices (heat pipes) for two-phase convective heat transfer. The common characteristics and results between studies will contribute to develop conclusions for the scientific debate on whether to select “hybrid or mono nanofluids for convective heat transfer applications”.

2. State-of-art and discussion

2.1. Single-phase convective heat transfer

2.1.1. Tubular heat exchangers

Single-phase convective heat transfer in pipe flow is presented in a wide variety of heating and cooling applications by means of tubular heat exchangers [22,23]. They are broadly employed in chemical engineering processes and heat supply systems [24]. Most studies on single-phase convective heat transfer for nanofluids are carried out through experimental setups whose test section is a pipe or tube [23]. The studied sample generally flows by a closed loop, being electrically heated through the isolated pipe. In addition to the heated test section, the circuit usually contains a cooling unit, a pump, a tank, different instrumentation (thermocouples, flowmeters, pressure drop sensors), and data acquisition and control systems, see Fig. 3. The local or average convective heat transfer coefficients, h , are usually obtained as the quotient of the heat flux applied to the fluid by the difference of the temperature of the wall (tube surface) and the local or average fluid temperature. The pressure drop, ΔP , when measured, is directly obtained from the corresponding differential sensor.

In the literature, two experimental studies [25,26] of single-phase convective heat transfer in pipe flow were found analysing hybrid

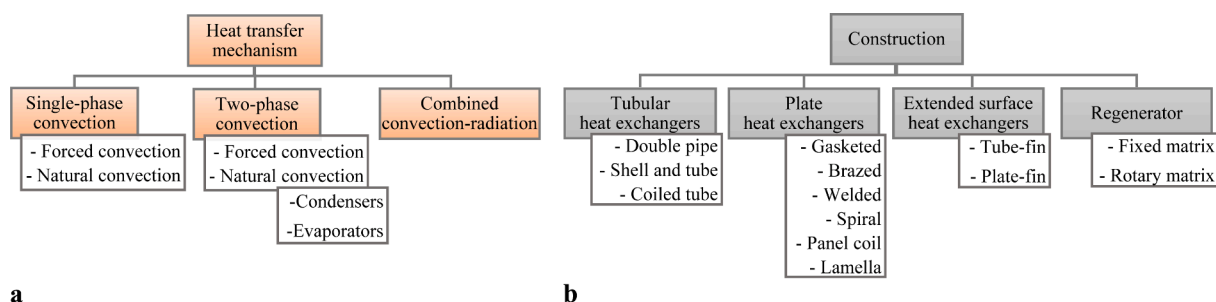


Fig. 1. Classification of heat exchangers according to heat transfer mechanism (a) and construction features (b) [5].

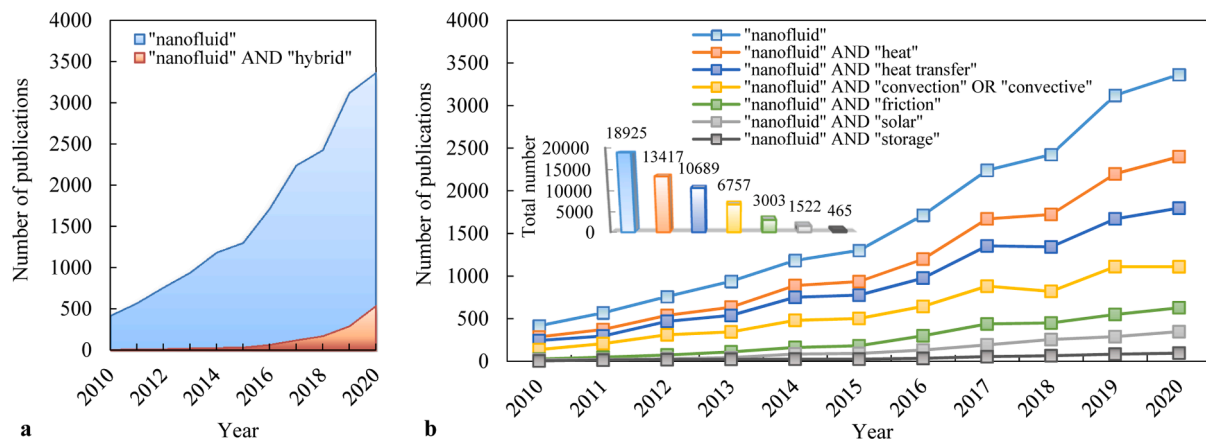


Fig. 2. Number of indexed publications per year that include different terms in the title, abstract or keywords, according to Scopus database [11]. (a) Nanofluids and hybrid nanofluids and (b) applications in the framework of nanofluids.

Table 1

List of some review articles related to hybrid nanofluids and heat transfer applications mentioned.

Reference	Year	Described applications
Sureshkumar et al. [12]	2013	Heat pipes.
Sarkar et al. [13]	2015	Electronic cooling; engine cooling/vehicle thermal management; generator cooling; coolant in machining; welding; nuclear system cooling; lubrication; thermal storage; solar heating; cooling and heating in buildings; transformer cooling; biomedical; drug reduction; heat pipe; refrigeration; space; defence and ships.
Sidik et al. [14]	2016	Heat exchanger; transformer; domestic refrigerator; solar water heating; application in grinding; vehicle brake fluids.
Sundar et al. [15]	2017	Heat sink; boiling; micro power generation; solar energy.
Ranga Babu et al. [9]	2017	Heat exchanger; heat sink; solar collectors; boiling; micro power generation.
Sidik et al. [10]	2017	Heat exchanger; electronic cooling; heat pipes; car radiators; coolant in welding and machining; nuclear plant; solar heating.
Huminic et al. [16]	2018	Heat transfer.
Saqib et al. [17]	2019	Refrigerators; solar; microchips; automobiles; cooling and heat of buildings; agriculture; aerospace; drug delivery.
Zhang et al. [6]	2019	Two-phase heat transfer in plate heat exchangers.
Gakare et al. [18]	2019	Heat exchanger; coolant; diesel-electric combustion; thermal absorption systems; fuel cell; cutting fluids.
Shah et al. [19]	2019	Solar energy.
Bumataria et al. [20]	2019	Thermal systems: computer processor; car radiator; heat sinks; minichannel; microprocessor; Brayton cycle; circular concentric pipes; channel; solar collector.
Hussien et al. [21]	2019	Heat exchangers, heat pipes; cooling electronic devices; automotive cooling system.
Pordanjani et al. [7]	2019	Heat exchangers: plate, helical, shell and tube and double-tube.
Almurtaji et al. [8]	2020	Heat exchangers; air purification systems; quenching media; liquid fuels enhancement; medical treatment; magnetic sealing; nano-lubricants.

nanofluids and all the corresponding mono nanofluid (Table 2).

Gupta et al. [25] investigated a hybrid nanoadditive consisting of a mixture of Ag and multi-walled carbon nanotubes (MWCNT) at 3:1 ratio, Ag:MWCNT hybrid nanoadditive, and the corresponding Ag and MWCNT mono nanoadditives. Dispersions of the aforementioned nanoadditives in water at 0.02, 0.05, 0.1, 0.2, and 0.5 wt% total concentrations allowed to design the corresponding hybrid and mono nanofluids by the two-step method. The samples were tested over a

copper tube heated by a tape heater, flowing at various fixed Reynolds numbers, Re , from 1275 to 2200 (mostly in laminar regime). The highest h enhancements were found at the highest analysed concentration, 0.5 wt%, and $Re = 2200$. MWCNT/water mono nanofluid achieved the highest h increase, 67.5%, followed by the hybrid sample and the Ag/water mono nanofluid. No information is provided on ΔP increases.

Naddaf et al. [26] studied dispersions in diesel oil of MWCNT:graphene nanoplatelet (GNP) hybrid nanoadditive (mixture of components) non-covalent functionalized with oleic acid (OA), 1:1 ratio, at 0.05, 0.1, 0.2, and 0.5 wt% total concentrations. Appropriately, they also considered dispersions of MWCNT and GNP mono nanoadditives non-covalent functionalized with oleic acid (OA) and covalent functionalized with hexylamine (HA) at the same concentrations. All nanofluids were designed by the two-step method. The heat transfer performance of the samples was evaluated over an electrical heated straight pipe, flowing at four flow rates in laminar regime. The authors pointed out that the h enhancement for covalently functionalized nanoadditives is higher than for non-covalent. According to the reported data, the non-covalent functionalized OA-MWCNT:GNP/diesel oil hybrid nanofluid usually exhibits lower h than the corresponding mono options (only some higher values appears for the highest concentration). The 0.50 wt% OA-GNP/water mono nanofluid usually exhibits the highest h increase. The authors reported that the ΔP increases are not too high, with a maximum 9.9% rise for the 0.5 wt% OA-MWCNT/diesel oil nanofluid. The 0.50 wt% OA-GNP/water mono nanofluid also presents the lowest ΔP between the OA-functionalized nanofluids, with a maximum 8.4% increase.

Furthermore, fourteen experimental studies [27–40] of single-phase convective heat transfer in pipe flow were found examining hybrid nanofluids but instead only one of the corresponding mono nanofluid options (Table 3). Ten of these fourteen studies [27–36] describe the behaviour of nanofluids with the same total nanoadditive concentration, while four studies [37–40] include analyses at different loaded hybrid and mono nanofluids. We will pay attention to the first group [27–36] for an appropriate and proportional comparison between hybrid and mono nanofluids.

Suresh et al. [27,31] designed a Al_2O_3 :Cu hybrid nanoadditive (composite) by a thermochemical synthesis that involves hydrogen reduction. Afterwards, they prepared 0.1 vol% Al_2O_3 :Cu/water hybrid nanofluid and 0.1 vol% Al_2O_3 /water mono nanofluid by the two-step method. The employed test section for the heat transfer experiments consisted of a straight copper tube that is wound with ceramic beads coated by an electrical heating wire. Analyses in laminar (Re from 700 to 2300) [27] and turbulent (Re from 2300 to 13000) [31] flow regime were carried out. In both conditions, Al_2O_3 :Cu/water hybrid nanofluid showed higher average Nusselt number, Nu , increases than Al_2O_3 /water mono nanofluid (10.9% versus 6.1% in laminar flow conditions, 8.0%

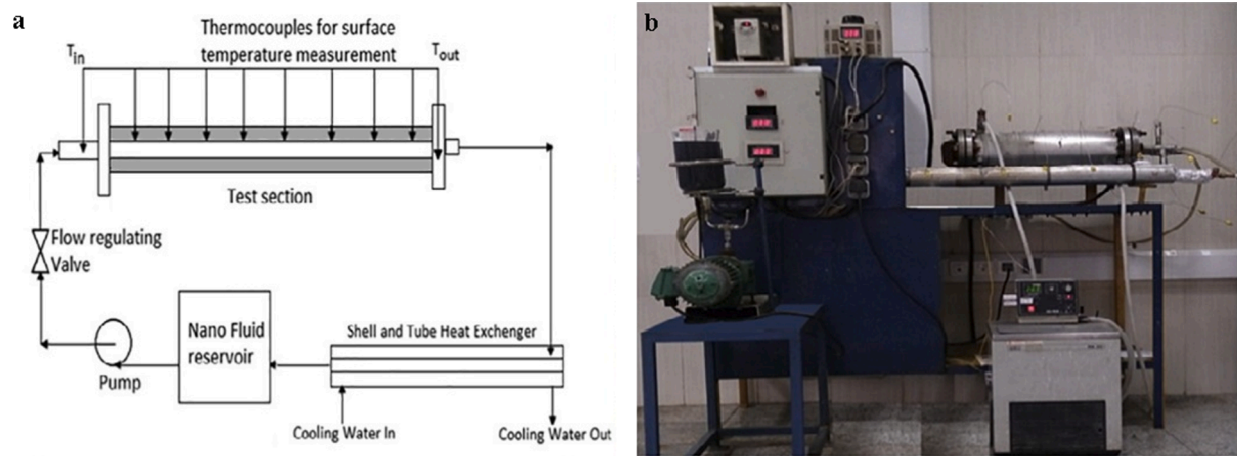


Fig. 3. Experimental setup with a pipe as main element: schematic diagram (a) and photograph (b) [34].

Table 2

Summary of experimental studies [25,26,42,43,49–54] of single-phase convective heat transfer applications analysing hybrid nanofluids and all the corresponding mono nanofluid options.

Reference	Year	Hybrid and mono nanofluids	Nanoadditive concentrations	Test section	Flow regime (Inlet temperature)	Findings
Gupta et al. [25]	2020	Ag:MWCNT (mixture)/water Ag/water	0.02, 0.05, 0.1, 0.2 and 0.5 wt%	tube	laminar (~30 °C)	MWCNT/water mono nanofluid shows the highest h increase, 67.5%, at 0.5 wt% concentration. No $\Delta P/f$ information is provided.
Naddaf et al. [26]	2019	MWCNT/water OA-MWCNT:GNP (mixture)/diesel oil OA-MWCNT/diesel oil HA-MWCNT/diesel oil OA-GNP/diesel oil HA-GNP/diesel oil	0.05, 0.1, 0.2 and 0.5 wt%	tube	laminar (-)	OA-GNP/water mono nanofluid usually shows the highest h increase. 0.5 wt% OA-MWCNT/diesel oil mono nanofluid reaches the maximum ΔP increment, 9.9%.
Bhattad et al. [42]	2019	Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water	0.01 vol%	plate heat exchanger	laminar (10 to 25 °C)	MWCNT/water mono nanofluid exhibits the largest h increment, 15.2%. Negligible ΔP increases with the nanoadditive addition.
Bhattad et al. [43]	2020	Al ₂ O ₃ :TiO ₂ (mixture)/water Al ₂ O ₃ /water	0.1 vol%	plate heat exchanger	laminar (10 to 25 °C)	Al ₂ O ₃ /water mono nanofluid shows the major h increase, 16.9%. TiO ₂ /water mono nanofluid shows the highest ΔP rise, 0.013%.
Ahammed et al. [49]	2016	Al ₂ O ₃ :graphene (mixture)/water Al ₂ O ₃ /water graphene/water	0.1 vol%	multiport minichannel heat exchanger	laminar (-)	Graphene/water mono nanofluid achieves the greatest h enhancement, 88.6%. Al ₂ O ₃ /water obtains the largest ΔP rise, 33.1%.
Hashemzadeh and Hormozi [50]	2019	γ -Al ₂ O ₃ :SiO ₂ (mixture)/water γ -Al ₂ O ₃ /water SiO ₂ /water	0.05, 0.1, and 0.2 vol %	minichannel heat sink	laminar and transition (27 °C)	γ -Al ₂ O ₃ :SiO ₂ /water hybrid nanofluid (75:25 ratio) provides the highest Nu enhancement, 46% at 0.5 wt% concentration. 0.5 wt% γ -Al ₂ O ₃ :SiO ₂ /water hybrid nanofluid (75:25 ratio) also exhibits the largest f rise, 65.2%.
Kumar and Sarkar [51]	2019	Al ₂ O ₃ :TiO ₂ (mixture)/water Al ₂ O ₃ /water TiO ₂ /water	0.1 vol%	minichannel heat sink	laminar (20 to 40 °C)	Al ₂ O ₃ /water mono nanofluid achieves the maximum h , 12.8%, and Nu , 11.8%, enhancements. Similar ΔP increases for all samples are detected.
Kumar and Sarkar [52,53]	2020	Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water MWCNT/water	0.01 vol%	minichannel heat sink	laminar (20 to 40 °C)	MWCNT/water mono nanofluid reaches the maximum improvement of h , 44.0%, and Nu , 41.0%. MWCNT/water mono nanofluid reaches a maximum ΔP increases over 50%.
Ataei et al. [54]	2020	Al ₂ O ₃ :TiO ₂ (mixture)/water Al ₂ O ₃ /water TiO ₂ /water	0.5 vol%	minichannel heat sink	laminar (-)	Al ₂ O ₃ /water mono nanofluid shows higher Nu increases in most conditions. TiO ₂ /water mono nanofluid evidences the higher ΔP rises, up to 29.5%.

versus 5.2% in turbulent flow conditions). Nevertheless, the hybrid sample also reached the higher friction factor, f , increase (17% versus 6% in laminar flow, 10.5% versus 5% in turbulent flow). Hameed et al.

[29] extended the previous analysis in laminar conditions (Re from 700 to 2300) to Al₂O₃:CNT(composite)/water nanofluids and the analysed concentrations to 0.3 vol%. The 0.3 vol% Al₂O₃:CNT/water hybrid

Table 3

Summary of experimental studies [27–40,44–46,55,56] of single-phase convective heat transfer applications analysing hybrid nanofluids and one of the corresponding mono nanofluid options.

Reference	Year	Hybrid and mono nanofluids	Nanoadditive concentrations	Test section	Flow regime (Inlet temperature)	Findings
Suresh et al. [27]	2012	Al ₂ O ₃ :Cu (composite)/water Al ₂ O ₃ /water	0.1 vol%	tube	laminar (-)	Al ₂ O ₃ :Cu/water hybrid nanofluid shows the maximum <i>Nu</i> increase, 13.6% (10.9% as average). The average <i>Nu</i> enhancement of Al ₂ O ₃ /water is 6.1%. Al ₂ O ₃ :Cu/water hybrid nanofluid also causes the highest <i>f</i> penalty, 17.0%.
Megatiff et al. [28]	2016	TiO ₂ :CNT (composite)/water CNT/water	0.1 wt%	tube	laminar (25 to 38 °C)	0.1 wt% CNT/water mono nanofluid exhibits <i>h</i> about 5% higher than for 0.1 wt% TiO ₂ :CNT/water hybrid nanofluid. No $\Delta P/f$ information is provided.
Hameed et al. [29]	2019	Al ₂ O ₃ :Cu (composite)/water Al ₂ O ₃ :CNT (composite)/water Al ₂ O ₃ /water	0.1 and 0.3 vol%	tube	laminar (-)	0.3% Al ₂ O ₃ :CNT/water hybrid nanofluid shows a maximum <i>Nu</i> improvement of 30.6%, followed by 20.5% for 0.3% Al ₂ O ₃ :Cu/water, and 9.5% for 0.3% Al ₂ O ₃ /water. Average <i>f</i> increases of 38.4% 30.8% and 15.4% are found, respectively.
Allahyar et al. [30]	2016	Al ₂ O ₃ :Ag (composite)/water Al ₂ O ₃ /water	0.4 vol%	helical coil	laminar (-)	Al ₂ O ₃ :Ag/water hybrid nanofluid exhibits <i>Nu</i> enhancements (maximum 31.6%) higher than for Al ₂ O ₃ /water mono nanofluid (maximum 28.4%). Similar ΔP increases for mono and hybrid nanofluids are detected.
Suresh et al. [31]	2014	Al ₂ O ₃ :Cu (composite)/water Al ₂ O ₃ /water	0.1 vol%	tube	turbulent (-)	Al ₂ O ₃ :Cu/water hybrid nanofluid shows the maximum average <i>Nu</i> increase, 8.0%. The average <i>Nu</i> improvement of Al ₂ O ₃ /water is 5.2%. Al ₂ O ₃ :Cu/water hybrid nanofluid also shows superior <i>f</i> increase, 10.5%.
Aravind and Ramaprabhu [32]	2013	sG:f-MWCNT (composite)/water sG:f-MWCNT (composite)/ethylene glycol f-sG/water f-sG/ethylene glycol	0.01 and 0.02 vol%	tube	turbulent (-)	sG:f-MWCNT(c) hybrid nanofluids achieves <i>h</i> improvements higher than for f-sG mono nanofluids. Enhancements of 193% and 283% are reported for the 0.02 vol% water and ethylene glycol based nanofluids, respectively. No $\Delta P/f$ information is provided.
Zubir et al. [33]	2015	RG0:carbon nanofiber(mixture)/water RG0:MWCNT (mixture)/water RG0:GNP (mixture)/water RG0/water	0.05 wt%	tube	turbulent (-)	RG0/water mono nanofluid reaches local <i>h</i> and <i>Nu</i> enhancements (from 63 to 144%) higher than for hybrid samples. Minimal increments of ΔP and <i>f</i> are reported for all nanofluids. No $\Delta P/f$ information is provided.
Askari et al. [34]	2017	Fe ₃ O ₄ :graphene (composite)/water Fe ₃ O ₄ /water	0.1 wt%	tube	turbulent (-)	Fe ₃ O ₄ :graphene/water hybrid nanofluid exhibits a higher <i>h</i> enhancement (14.5%) than Fe ₃ O ₄ /water mono nanofluid (8.5%). No $\Delta P/f$ information is provided.
Sundar et al. [35,36,41]	2018, 2014	Nanodiamond:Ni (composite)/water Ni/water	0.1 and 0.3 vol%	tube	turbulent (-)	Nanodiamond:Ni/water hybrid nanofluid shows <i>Nu</i> enhancements of 24.7% and 35.4% at 0.1 vol% and 0.3 vol%, respectively. Ni/water mono nanofluid exhibits 7.2% and 9.4% lower <i>Nu</i> as compared to hybrid 0.1 vol% and 0.3 vol% samples, respectively. <i>f</i> increases reaches 7% and 12 % for 0.1 vol% and 0.3 vol% hybrid nanofluids, respectively. These penalties are lower than those of the mono samples.
Shahsavari et al. [37] ^a	2016	Fe ₃ O ₄ :CNT (mixture)/water Fe ₃ O ₄ /water	0.5 to 0.9 vol% Fe ₃ O ₄ + 0.25 to 1.35 vol% CNT	tube	laminar (-)	(0.9 vol% Fe ₃ O ₄ + 1.35 vol% CNT)/water hybrid nanofluid reaches the highest ^a local <i>Nu</i> enhancements in the absence and presence of a magnetic field, 62.7% and 20.5%, respectively. No $\Delta P/f$ information is provided.
Hussien et al. [38] ^a	2017	MWCNT:GNP (mixture)/water MWCNT/water	0.075, 0.125 and 0.25 wt% MWCNT + 0.035 wt% GNP	tube (minitube)	laminar (27 °C)	(0.25 wt% MWCNT + 0.035 wt% GNP)/water hybrid nanofluid shows the highest ^a <i>h</i> increase, 43.4%, and the highest ^a ΔP rise, 11%.
Arunachalam and Edwin [39] ^a	2018	Al ₂ O ₃ :Cu(mixture)/water Al ₂ O ₃ /water	0.4 vol% Al ₂ O ₃ + 0.01 vol% Cu	tube (with and without V-cut twisted tape insert)	laminar (-)	(0.4 vol% Al ₂ O ₃ + 0.01 vol% Cu)/water hybrid nanofluid shows the highest ^a <i>h</i> increases without and with tape insert, 25.8% and 42%, respectively. ΔP increases 0.89 times without tape insert and 15–16 times with tape insert for the hybrid sample.
Hussien et al. [40] ^a	2019	MWCNT:GNP (mixture)/water MWCNT/water	0.075 and 0.125 wt% MWCNT + 0.035 wt% GNP	tube (microtube)	laminar (27 °C)	(0.125 wt% MWCNT + 0.035 wt% GNP)/water hybrid nanofluid exhibits the highest ^a <i>h</i> increase, 58%, and the highest ^a ΔP rise, 12.4%.
	2019		0.1 vol%			

(continued on next page)

Table 3 (continued)

Reference	Year	Hybrid and mono nanofluids	Nanoadditive concentrations	Test section	Flow regime (Inlet temperature)	Findings
Bhattad et al. [44]		Al ₂ O ₃ :SiC(mixture)/water Al ₂ O ₃ :AlN (mixture)/water Al ₂ O ₃ :MgO (mixture)/water Al ₂ O ₃ :CuO (mixture)/water Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water		plate heat exchanger	laminar (10 to 25 °C)	Al ₂ O ₃ :MWCNT/water hybrid nanofluid shows the maximum <i>h</i> enhancement, 31.2%, with a negligible ΔP increase, 0.08%.
Bhattad et al. [45]	2020	Al ₂ O ₃ :graphene (mixture)/water Al ₂ O ₃ /water	0.01 vol%	plate heat exchanger	laminar (10 to 25 °C)	Al ₂ O ₃ :graphene/water hybrid nanofluid achieves the maximum <i>h</i> enhancement, 25.4%, with a reduced ΔP increase, 0.35%.
Huang et al. [46] ^a	2016	Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water	1.89% Al ₂ O ₃ /water + 0.0111% MWCNT/water (1:2.5 volume ratio)	plate heat exchanger	- (28 °C)	Al ₂ O ₃ :MWCNT/water hybrid nanofluid exhibits slightly larger ^a <i>h</i> than Al ₂ O ₃ /water nanofluid and lower ^a ΔP .
Kumar and Sarkar [55]	2020	Al ₂ O ₃ :MgO (mixture)/water Al ₂ O ₃ :SiC(mixture)/water Al ₂ O ₃ :AlN (mixture)/water Al ₂ O ₃ :Cu(mixture)/water Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water	0.01 vol%	minichannel heat sink	laminar (20 to 40 °C)	Al ₂ O ₃ :MWCNT/water hybrid nanofluid exhibits the highest <i>h</i> improvement, 42.2%. This sample also reaches the highest ΔP rise, 22%.
Kumar and Sarkar [56]	2020	Al ₂ O ₃ :AlN (mixture)/water Al ₂ O ₃ :Cu(mixture)/water Al ₂ O ₃ :MWCNT (mixture)/water Al ₂ O ₃ /water	0.01 and 0.1 vol%	minichannel heat sink	laminar (20 to 40 °C)	Al ₂ O ₃ :MWCNT/water hybrid nanofluid exhibits the highest <i>h</i> improvement. This sample also reaches the highest ΔP rise. The 0.1 vol% nanofluids showed slightly higher <i>h</i> and ΔP rises than the 0.01 vol% nanofluids.

^a It should be noted that hybrid nanofluids have higher total mass nanoadditive concentrations than mono nanofluids.

nanofluid exhibited the maximum *Nu* enhancement, followed by the 0.3 vol% Al₂O₃:Cu/water hybrid nanofluid and the 0.3 vol% Al₂O₃/water mono nanofluid, 30.6%, 20.5% and 9.5%, respectively. The magnitude of *f* increases followed the same order, 38.4%, 30.8% and 15.4%, respectively.

Megatif et al. [28] synthesized TiO₂:carbon nanotube (CNT) hybrid nanocomposites by a modified hydrolysis method and then designed TiO₂:CNT/water nanofluids at different concentrations from 0.1 to 0.2 wt% by the two-step method, employing SDBS as surfactant. The authors also studied 0.1 wt% CNT/water nanofluid for comparison. The convective heat transfer tests were developed over a straight copper tube laminar, at various *Re* from 1940 to 4900 and average temperatures from 25 to 38 °C. The highest *h* improvement was reported for the 0.2 wt % hybrid nanofluid, 38%, but no comparison with the 0.2 wt% mono option was assessed. At the same concentration, the 0.1 wt% CNT/water mono nanofluid showed about 5% higher average *h* than 0.1 wt% TiO₂:CNT/water hybrid nanofluid, its thermal conductivity being 3% higher. No information is provided on ΔP or *f*.

Allahyar et al. [30] compared a 0.4 vol% dispersion in water of Al₂O₃:Ag hybrid nanocomposite prepared by a sol-gel method with a 0.4 vol% Al₂O₃/water mono nanofluid designed by the one-step method. The test section was a helical copper coil immersed in a water tank heated by an electric heater, with the tested fluids flowing mainly in laminar regime. The 0.4 vol% hybrid nanofluid obtained the maximum *Nu* enhancement, 31.6%, while a 28.4% improvement was reached for the one-step 0.4 vol% mono nanofluid. Both nanofluids showed similar increases in ΔP , with the hybrid sample showing slightly higher values.

Aravind and Ramaprabhu [32] designed graphene via the solar exfoliation technique (sG) from graphene oxide (GO) and then

functionalized the resulting nanopowder (f-sG) to prepare stable dispersions in water and ethylene glycol and creating the corresponding mono nanofluids at 0.01 and 0.02 vol% concentrations. MWCNT nanopowder was also designed by the authors by using a catalytic chemical vapour deposition and then functionalized. The sG:f-MWCNT hybrid nanoadditive (composite) was created from GO and f-MWCNT by reflux in nitric acid and solar exfoliation, and then dispersed in the same base fluids generating the corresponding 0.01 and 0.02 vol% hybrid nanofluids. The heat transfer study was carried out over a horizontal tube at *Re* of 2000, 5000 and 10000 (mostly in turbulent regime). The analysed sG:f-MWCNT hybrid nanofluids achieved *h* improvements higher than those for the analysed f-sG mono nanofluids for both base fluids, according with higher experimental thermal conductivity values. The *h* improvements reach 193% and 283% for the 0.02 vol% hybrid nanofluids based on water and ethylene glycol, respectively, at *Re* of 2000. No data is provided on the ΔP or *f*.

Zubir et al. [33] compared a 0.05 wt% reduced graphene oxide (RGO) aqueous mono nanofluid with other 0.05 wt% hybrid aqueous nanofluids. The hybrid nanoadditives were mixtures of RGO with other carbon-based nanomaterials: GNP, carbon nanofibers (CNF) and MWCNT. The mixing ratios were decided according the solubility of the included carbon nanomaterial in the RGO aqueous dispersion (1:1, 2:1 and 3:1 for RGO:GNP, RGO:CNF and RGO:MWCNT, respectively). The tested fluids flowed across a straight seamless stainless steel tube at various velocities under turbulent regime. RGO/water mono nanofluid reached higher local *h* and *Nu* enhancements (from 63 to 144%) than hybrid samples. Slight increments of ΔP and *f* were reported for all nanofluids. No data is reported concerning ΔP or *f*.

Askari et al. [34] synthesized Fe₃O₄:graphene hybrid nanoadditive

(composite) from ferrous chloride, ferric chloride and GO. Afterwards, they prepared Fe_3O_4 :graphene/water hybrid nanofluid and 0.1 wt% Fe_3O_4 /water mono nanofluid through the two-step method. These nanofluids were tested over a horizontal copper tube in turbulent regime, Re ranging from 2000 to 5000. They observed h enhancements of 14.5 and 8.5% for Fe_3O_4 : graphene and Fe_3O_4 aqueous nanofluids, respectively. The authors pointed out that thermal conductivity enhancements were also higher for the hybrid than for the mono option. Data on ΔP or f are not reported on the study.

Sundar et al. [35,36] synthesized Nanodiamond:Ni hybrid nano-additive (composite) using in-situ and chemical co-precipitation method. They studied the convective heat transfer and pressure drop for Nanodiamond:Ni/water hybrid nanofluids at 0.1 and 0.3 vol% concentration by a copper test tube. The obtained results were compared with a previous study over the same test section for Ni/water mono nanofluids at the same concentrations [41]. They pointed out that 0.1 vol% and 0.3 vol% Nanodiamond:Ni hybrid aqueous nanofluids showed Nu increases of 24.7% and 35.4%, respectively. The corresponding f increases with respect to water are 7% and 12 %. However, Ni/water mono nanofluids showed 7.2% and 9.4% lower Nu as compared to 0.1 vol% and 0.3 vol% hybrid samples, respectively, with a higher f penalty.

2.1.2. Plate heat exchangers

Plate heat exchangers are broadly used in food processing industry, chemical and power plants or central air conditioning, among other applications [4]. Some studies on single-phase convective heat transfer for nanofluids have been developed by means of experimental setups whose test section is a plate heat exchanger [4,7]. The tested fluid flows through one of the sides of the exchanger, being directly heated or cooled by another reference fluid. Heating/cooling units, pumps, tanks, different instrumentation (thermocouples, flowmeters, pressure drop sensors), as well as data acquisition systems are common elements in such setups, see Fig. 4. The convective heat transfer coefficients, h , are obtained by the thermal resistance method. The pressure drop, ΔP , when measured, is directly obtained from the corresponding differential sensor.

Up to our knowledge, two experimental studies [42,43] analyse hybrid nanofluids and all the corresponding mono nanofluid options for single-phase convective heat transfer in plate heat exchangers (Table 2).

Bhattad et al. [42] used Al_2O_3 :MWCNT hybrid nanoadditives, mixtures at 4:1, 3:2, 2:3, and 1:4 volume ratios. The corresponding aqueous hybrid nanofluids at 0.01 vol% concentration were prepared by the two-step method. The 0.01 vol% Al_2O_3 /water and 0.01 vol% MWCNT/water mono nanofluids were also included in the analysis. The heat transfer

performance was examined over a plate heat exchanger at fixed flow rates ranging from 2.0 to 4.0 l/min (laminar regime) and inlet temperatures ranging from 10 to 25 °C. The authors pointed out that no optimum mixing ratio of nanoadditives was observed, the increasing amount of MWCNT being beneficial. The MWCNT/water mono nanofluid reached the highest h improvement, 15.2%, with a negligible rise of the pumping power, 0.017%. The pumping power increases negligibly with the addition of nanoparticles in base fluid and the Al_2O_3 mono nanofluid shows the maximum pump work. The authors conclude that Al_2O_3 :MWCNT hybrid aqueous nanofluid exhibited superior performance than Al_2O_3 mono aqueous nanofluid due to the comparatively higher thermal conductivity of MWCNT than Al_2O_3 .

Bhattad et al. [43] also employed Al_2O_3 : TiO_2 hybrid nanoadditives, mixtures at 4:1, 3:2, 2:3, and 1:4 volume ratios. The corresponding 0.1 vol% hybrid nanofluids based on water were designed by the two-step method. The 0.1 vol% Al_2O_3 /water and 0.1 vol% TiO_2 /water mono nanofluids were also scrutinized in the study. The evaluation of the heat transfer through a plate heat exchanger was carried out under the same conditions of the previous study: flow rates from 2.0 to 4.0 l/min (laminar regime) and inlet temperatures from 10 to 25 °C. The maximum enhancements of convective heat transfer coefficient were detected for the Al_2O_3 /water mono nanofluid, 16.9%, and the lowest for the TiO_2 /water mono nanofluid. The authors noticed that the performance variation is nearly linear, which means that there is no optimal concentration. The authors conclude that the heat transfer coefficient decreases with the increase of TiO_2 particles in the proportion, since the thermal conductivity of TiO_2 is lower than that of Al_2O_3 . On the other hand, the highest pumping power increase were noticed for the TiO_2 /water mono nanofluid, a negligible 0.013%, and the lowest for the Al_2O_3 /water mono nanofluid.

Furthermore, three studies [44–46] of single-phase convective heat transfer in plate heat exchangers have examined hybrid nanofluids but only one of the corresponding mono nanofluid options (Table 3). Among those studies, only the two by Bhattad et al. [44,45] have included equally loaded hybrid and mono nanofluids.

Bhattad et al. [44] investigated 0.1 vol% aqueous dispersions of Al_2O_3 :SiC, Al_2O_3 :AlN, Al_2O_3 :MgO, Al_2O_3 :CuO, and Al_2O_3 :MWCNT hybrid nanoadditives, mixtures of components at 4:1 volume ratio, and Al_2O_3 mono nanoadditive. The study was developed over a plate heat exchanger, the flow rates ranging from 2.0 to 4.0 l/min (laminar regime), and the operating temperatures ranging from 10 to 25 °C. The maximum h enhancement was detected for the Al_2O_3 :MWCNT/water hybrid nanofluid, 31.2%, with a slight ΔP increase, 0.08%, which is also the highest among the analysed samples. The authors remark that

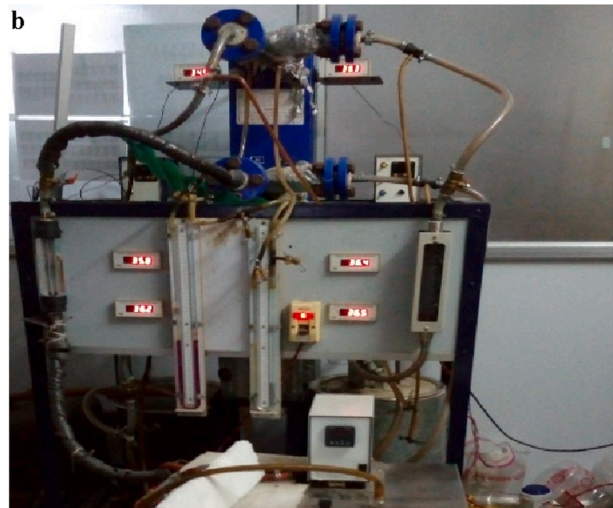
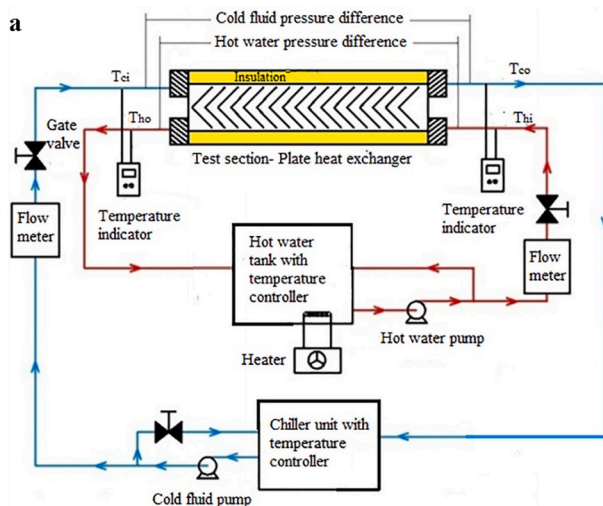


Fig. 4. Experimental setup with a plate heat exchanger as main element: schematic diagram (a) and photograph (b) [42].

MWCNT has much higher thermal conductivity. Contrarily, the Al_2O_3 :CuO/water hybrid nanofluid showed the lowest h values. The convective heat transfer coefficient by using the analysed nanoadditives follows the sequence $h_{\text{Al}_2\text{O}_3:\text{CuO}} < h_{\text{Al}_2\text{O}_3} < h_{\text{Al}_2\text{O}_3:\text{MgO}} < h_{\text{Al}_2\text{O}_3:\text{AlN}} < h_{\text{Al}_2\text{O}_3:\text{SiC}} < h_{\text{Al}_2\text{O}_3:\text{MWCNT}}$. It should be highlighted that it is the same order as that established between the thermal conductivity enhancements.

Bhattad et al. [45] analysed Al_2O_3 :graphene hybrid nanoadditive (mixture, 4:1 nanoparticle ratio) and Al_2O_3 mono nanoadditive with 0.01 vol% concentration in water. The study was developed over a plate heat exchanger in the same conditions of their previous works, flow rates from 2.0 to 4.0 l/min (laminar regime) and inlet temperatures from 10 to 25 °C. The hybrid nanofluid reached the higher h enhancement, 25.4%, and the higher ΔP increase, 0.35%.

2.1.3. Minichannel heat exchangers/heat sinks

Minichannel heat exchangers can be used in heating, ventilation, and air conditioning systems or fuel cell systems, among other fields [47]. The main application for minichannel heat sinks is to absorb and dissipate heat from electronic devices, maintaining the recommended temperature [47]. Different studies on single-phase convective heat transfer for nanofluids have been carried out by experimental setups whose test section is a minichannel heat exchanger or heat sink, as summarized by Kumar et al. [48]. The tested fluid flows through the minichannel, exchanging heat with the assistance of electric heaters or coolers. Heating/cooling units, pumps, tanks, instrumentation (thermocouples, flowmeters, pressure drop sensors), and data acquisition systems are also usually present in these setups, see Fig. 5. The convective heat transfer coefficients, h , are generally obtained as the quotient of the exchanged heat (product of the mass flow rate, the specific heat capacity, and the difference between the inlet and outlet temperatures of tested fluid) by the product of the available heat transfer surface in the minichannel and the difference of the bulk fluid temperature and the average wall temperature. The pressure drop, ΔP , is generally measured directly by a differential sensor.

Six experimental studies [49–54] of single-phase convective heat transfer in minichannel heat exchangers/heat sinks were found investigating hybrid nanofluids and all the corresponding mono nanofluid options (Table 2).

Ahmed et al. [49] designed Al_2O_3 :graphene hybrid nanoadditive, mixture at 1:1 ratio, and prepared Al_2O_3 :graphene/water hybrid nanofluid and Al_2O_3 /water and graphene/water mono nanofluids at 0.1 vol% concentration by the two-step method. The heat transfer analysis was developed through a two pass multipoint minichannel heat exchanger, cooled by a thermoelectric cooler, at Re from 200 to 1000 (laminar regime). Graphene, Al_2O_3 :graphene and alumina nanofluids reached h increments of 88.6%, 63.1% and 31.9%, respectively. It should be noted that the order in thermal conductivity increases for graphene, Al_2O_3 :

graphene and alumina nanofluids followed the same trend, 26.9%, 13.8%, and 8.2%, respectively. Contrarily, the order in ΔP rises correspond to 11.2%, 20.4% and 33.1%, respectively. Therefore, the authors concluded that graphene/water mono nanofluid showed the best heat transfer characteristics.

Hashemzadeh and Hormozi [50] synthesized $\gamma\text{-Al}_2\text{O}_3$: SiO_2 hybrid nanoadditives, mixtures at 3:1, 1:1 and 1:3 volume ratios, and prepared $\gamma\text{-Al}_2\text{O}_3$: SiO_2 /water hybrid nanofluids and $\gamma\text{-Al}_2\text{O}_3$ /water and SiO_2 /water mono nanofluids by the two-step method at 0.05, 0.1 and 0.2 vol% concentrations. The analyses were carried out through a minichannel heat sink, with Re in the range 490–3100 (laminar and transition regimes). The authors reported that the 0.2 vol% $\gamma\text{-Al}_2\text{O}_3$: SiO_2 /water hybrid nanofluid (3:1 ratio) provided the highest Nu enhancement (46% as an average increment), and the 0.2 vol% $\gamma\text{-Al}_2\text{O}_3$ /water mono nanofluid, the lowest (11% mean increment), according with the order in the experimental thermal conductivity increases. Nevertheless, these increases are not in accordance with the provided values for the bulk materials of the nanoparticles. Likewise, the highest f also corresponds to the 0.2 vol% $\gamma\text{-Al}_2\text{O}_3$: SiO_2 /water hybrid nanofluid (3:1 ratio), maximum increases up to 65.2%, which agrees with the experimental dynamic viscosity rises.

Kumar and Sarkar [51] synthesized Al_2O_3 : TiO_2 hybrid nanoadditives, mixtures at 4:1, 3:2, 2:3 and 1:4 volume ratios, and designed 0.1 vol% Al_2O_3 : TiO_2 /water hybrid nanofluid and 0.1 vol% Al_2O_3 /water and TiO_2 /water mono nanofluids by the two-step method. The analysis was developed over a minichannel heat sink, with Re ranging from 90 to 500 (laminar regime) and inlet temperature ranging from 20 to 40 °C. The authors did not observe an optimum particle mixture ratio and reported maximum h and Nu increases (12.8% and 11.8%, respectively) for the Al_2O_3 /water mono nanofluid. The authors pointed out that as the TiO_2 nanoparticles fraction increases, h decreases. They attributed this phenomenon mainly to the low thermal conductivity of TiO_2 nanoparticles. All the nanofluids showed similar ΔP increments, the maximum being for the TiO_2 /water mono nanofluid (10.9%). They conclude that no synergetic effects appear when mixing different nanoparticles with similar shape and size.

Kumar and Sarkar [52,53] also developed Al_2O_3 :MWCNT mixtures at 4:1, 3:2, 2:3 and 1:4 volume ratios and designed 0.01 vol% Al_2O_3 :MWCNT/water hybrid nanofluids and 0.01 vol% Al_2O_3 /water and MWCNT/water mono nanofluids through the two-step method. Similarly, the study was developed over the same minichannel heat sink, with Re varying from 140 and 460 (laminar regime) and inlet temperature varying from 20 to 40 °C. The mono nanofluid MWCNT/water achieved the highest h and Nu enhancements, 44.0% and 41.0%, respectively. This mono nanofluid also exhibits the higher thermal conductivity increase. Nevertheless, a maximum ΔP rise over 50% is also reached, in accordance with the maximum dynamic viscosity rise. The

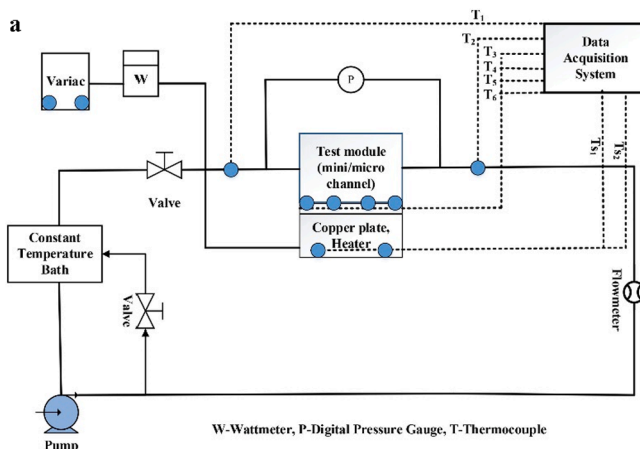


Fig. 5. Experimental setup with a minichannel device as main element: schematic diagram (a) and photograph (b) [51].

authors concluded that the addition of MWCNT increases the pressure drop much more than the addition of Al_2O_3 due to the higher surface area of the former. They also concluded that the mixture of dissimilar nanoparticles of different shapes and sizes will lead to different flow characteristics.

Ataei et al. [54] used Al_2O_3 and TiO_2 nanoparticles of 20 nm size to create a hybrid nanoadditive $\text{Al}_2\text{O}_3\text{:TiO}_2$, mixture at 1:1 ratio. The 0.5 vol% Al_2O_3 /water and TiO_2 /water mono nanofluids and the 0.5 vol% $\text{Al}_2\text{O}_3\text{:TiO}_2$ hybrid nanofluid were designed by the two-step method. The heat transfer study was conducted through an aluminium minichannel heat sink with rectangular cross-sections. A constant heat flow boundary condition was applied by a heater rated at 36 W and different Re from 400 to 1000 were scrutinized. At the most conditions, the Al_2O_3 /water mono nanofluid shows higher Nu than hybrid nanofluid. The thermal conductivity of $\text{Al}_2\text{O}_3\text{:TiO}_2$ hybrid nanofluid is lower than that of the single Al_2O_3 /water nanofluid. The higher ΔP increases are reported for the TiO_2 /water mono nanofluid whereas the lowest for the Al_2O_3 /water mono nanofluid.

Furthermore, two studies [55,56] of single-phase convective heat transfer in minichannel heat exchangers/heat sinks were found examining hybrid nanofluids and only one of the corresponding mono nanofluid options (Table 3).

Kumar and Sarkar [55] synthesized $\text{Al}_2\text{O}_3\text{:MgO}$, $\text{Al}_2\text{O}_3\text{:SiC}$, $\text{Al}_2\text{O}_3\text{:AlN}$, $\text{Al}_2\text{O}_3\text{:Cu}$, and $\text{Al}_2\text{O}_3\text{:MWCNT}$ hybrid nanoadditives, mixtures at 1:1 volume ratio. Subsequently, 0.01 vol% hybrid and mono Al_2O_3 aqueous nanofluids were prepared by the two-step method. The heat transfer analysis was carried out over a minichannel heat sink, with the fluids flowing at Re from 50 to 450 (laminar regime) and with fluid inlet temperatures from 20 to 40 °C. The results showed a maximum h improvement for the $\text{Al}_2\text{O}_3\text{:MWCNT}$ /water hybrid nanofluid, 42.2%. The authors remark that this can be mainly attributed to the higher thermal conductivity of MWCNT comparing to the other nanoparticles. This sample also reaches the maximum ΔP increment, 22%. Contrarily, the Al_2O_3 /water mono nanofluid showed the lowest h improvement. The authors attribute this to the lower thermal conductivity of Al_2O_3 than the other nanoadditives. The convective heat transfer coefficient by using the analysed nanoadditives follows the sequence $h_{\text{Al}_2\text{O}_3\text{:MWCNT}} > h_{\text{Al}_2\text{O}_3\text{:Cu}} > h_{\text{Al}_2\text{O}_3\text{:AlN}} > h_{\text{Al}_2\text{O}_3\text{:SiC}} > h_{\text{Al}_2\text{O}_3\text{:MgO}} > h_{\text{Al}_2\text{O}_3}$. It can be noted that the order is almost the same to that for the thermal conductivity values for the nanoadditives given by the authors.

In other work, Kumar and Sarkar [56] included data for 0.1 vol% aqueous nanofluids with the same $\text{Al}_2\text{O}_3\text{:AlN}$, $\text{Al}_2\text{O}_3\text{:Cu}$ and $\text{Al}_2\text{O}_3\text{:MWCNT}$ hybrid nanoadditives and Al_2O_3 mono nanoadditive. The heat transfer analysis was developed in the same equipment and conditions. Identical comparison could be assessed between h increments. The 0.1 vol% concentration showed slightly higher h and ΔP increments than the 0.01 vol% concentration for all analysed nanofluids.

2.1.4. Overview

The experimental studies that jointly analyse hybrid and mono nanofluids for single-phase convective heat transfer include applications on tubular, plate and minichannel heat exchangers as well as minichannel heat sinks. Among them, those that include hybrid nanofluids and all the corresponding mono nanofluid options [25,26,42,43,49–54] for the same load of nanoadditives, Table 2, showed the following common features:

- The employed base fluid is mostly water.
- The used nanoadditives are carbon-based nanoparticles (carbon nanotubes, graphene), metals and oxides at low concentrations (maximum 0.5 %).
- The hybrid nanoadditives are mixtures between the single nano-materials (not composites synthesized by chemical routes).
- The evaluated flow regime is laminar and the studies analyse a narrow temperature range (20–40 °C) that is not always reported.

- The main results on heat transfer are focused on the variation of the convective heat transfer coefficient and the Nusselt number.
- The main results on pumping power are focused on the variation of the pressure drop and the friction factor.

As it can be observed in Fig. 6, most of these studies concludes that one of the mono nanofluids achieve heat transfer coefficient enhancements or Nusselt number increases higher than those for the hybrid proposals. For the described conditions (aqueous nanofluids, carbon, metal and oxide nanomaterials, hybrid nanoadditives designed as mixtures, low concentrations, and medium temperature), the outcomes of the literature mainly support that there is no synergistic effect for hybrid nanofluids on convective heat transfer in laminar flow [51]. These results would also confirm that one of the components of the mixture exhibit the best qualities for the enhancement of the convection phenomenon (higher thermal conductivity improvement, lower viscosity increase, better dispersability and stability, higher level of chaotic movements, higher Brownian motion or higher specific surface area, among other [51,57]), while the hybrid represents a midpoint between the characteristics of the two individual components for these conditions. Furthermore, as noted in most cases, the highest thermal conductivity improvement is identified as the main cause for the highest h enhancement in laminar flow. This is in agreement with the figures of merit used in the literature that assume that the ratio of h improvement between nanofluid and base fluid is directly related to the ratio between its thermal conductivity values for fully developed laminar flow in a circular tube subjected to constant surface heat flux [58,59]. It should be noted that modifications in dynamic viscosity, density and isobaric heat capacity have shown superior relevance for nanofluids flowing in turbulent regime [60,61].

Some studies analysing hybrid nanofluids and one of the corresponding mono nanofluid options, Table 3, as those of Megatiff et al. [28] and Zubir et al. [33], reinforce our previous stated conclusions. Other authors [27,29–32,34–36,44,45,55,56] pointed out that a hybrid nanofluid showed h or Nu improvements higher than those for the analysed mono option. Nevertheless, the mono nanofluid with better thermal characteristics may not have been included in the analysis, as clearly occurs in the studies of Bhattad et al. [27] and Kumar and Sarkar [55,56], which do not analyse MWCNT/water mono nanofluids. However, these authors later showed the best results by using the cited mono nanofluids in other papers [42,52,53]. The same conclusion could be drawn from Bhattad et al. [45], which does not include the graphene/water mono nanofluid in the comparison. In other cases, the hybrid nanoadditive consist of a composite synthesized by a chemical route. As there are no studies comparing them with both mono nanoadditives, this conclusion cannot be exported to that cases. The synergistic effects when hybrid nanoadditive are used in dispersions under turbulent flow cannot be identified with the existing literature.

In the same way, most of the studies analysing hybrid nanofluids and all the corresponding mono nanofluid options, Table 2, conclude that one of the mono nanofluids achieves increases in pressure drop or friction factor higher than those of the hybrid nanofluids (see Fig. 7). In some cases, the mono nanofluids with higher h or Nu enhancements cause the lowest pumping power increase [26,42,43,49,51,54], the ideal situation. In other cases, both increases are maximum for the same mono nanofluid [52,53]. The variations range from negligible values [42,43], to increments of up to 50% [52,53] which make more difficult the application. According to the reported literature, the higher pressure drop or friction factor penalties correspond to the rises and order in the dynamic viscosity of the nanofluids, when reported.

2.2. Two-phase convective heat transfer

2.2.1. Heat pipes

Two-phase heat exchangers provide higher efficiency than single-phase devices due to the inclusion of the latent heat of vaporization/

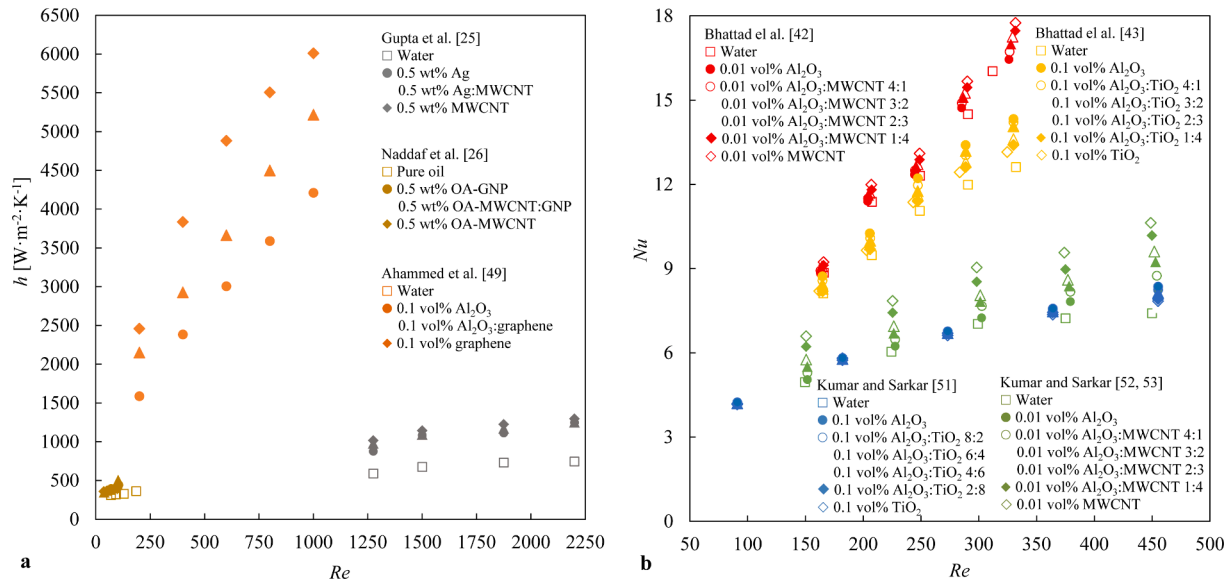


Fig. 6. Convective heat transfer coefficient, h , (a) and Nusselt number, Nu , (b) as a function of Reynolds number, Re , from different experimental studies [25,26,42,43,49,51–53] that analyse hybrid nanofluids and all the corresponding mono nanofluid options for single-phase convective heat transfer applications in laminar flow.

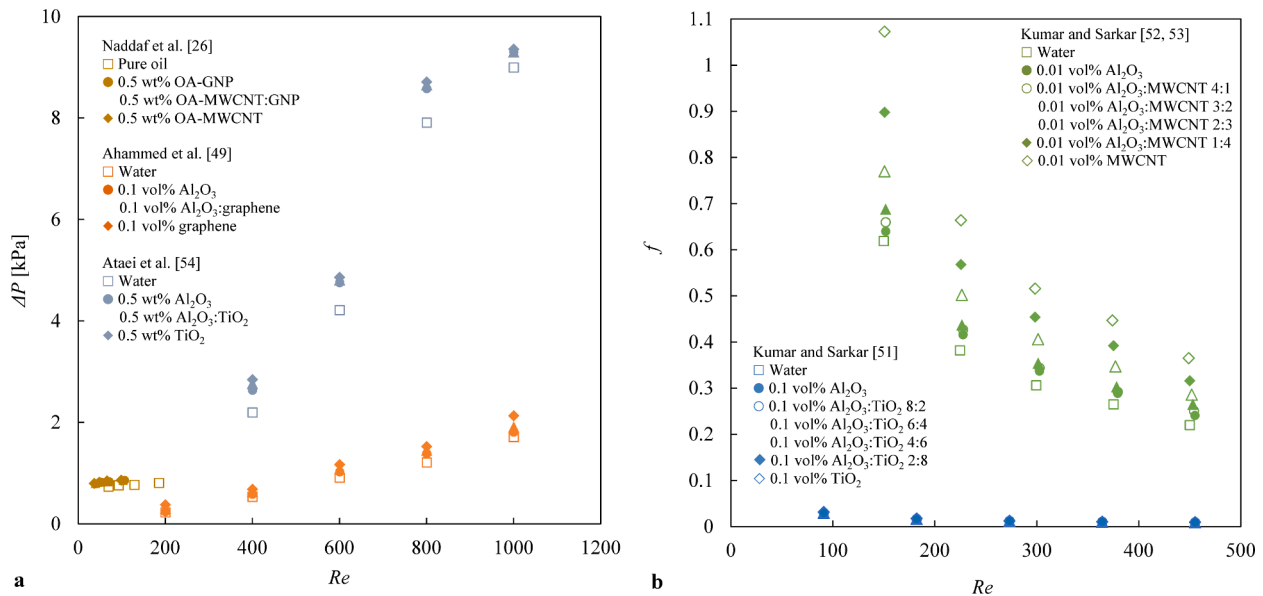


Fig. 7. Pressure drop, ΔP , (a) and friction factor, f , (b) as a function of Reynolds number, Re , from different experimental studies [26,49,51–54] that analyse hybrid nanofluids and all the corresponding mono nanofluid options for single-phase convective heat transfer applications in laminar flow.

condensation in the thermal energy transfer process, improving the transport capability [62,63]. Recognized applications are found in primary production sector, power generation, air conditioning or electronic refrigeration [62]. The hazard of the appearance of critical heat flux and boiling crisis is a key issue for conventional heat transfer fluids [63]. The addition of solid nanoparticles adds more challenges, such as the variable effective thermophysical properties (thermal conductivity, viscosity, heat capacity, density, and surface tension), surface effects due to the deposition of nanoparticles on the heating surface (wettability, capillary wick and surface roughness), or durability of the working fluid [64,65]. Nanofluids have shown increases, decreases, or no effect on pool boiling, while their boiling heat transfer coefficients and critical heat fluxes presented unpredictable data [66].

The vast majority of studies on two-phase convective heat transfer of nanofluids have been conducted in experimental facilities whose test

section is a heat pipe. A heat pipe is a passive device that transfers thermal energy from a heat source to a heat sink with low temperature gradient using the latent heat of vaporization and condensation of the working fluid [20,67]. Heat pipes are constituted by three sections known as evaporator, adiabatic and condenser (see Fig. 8). A very important parameter in this type of devices is the amount of working fluid that is filled and sealed inside after performing the required vacuum. Multiple configurations such as cylindrical, flat, pulsating, oscillating, or rotating heat pipes can be found in the literature [20]. Thermosyphon is one of the most widely used to test nanofluids and consists of a wickless heat pipe that is assisted by gravity to return the condensate [67].

The usual structure of the used experimental setups to test nanofluids consists of an electric heater (wire, coil, jacket) over the evaporator section and a refrigeration unit (cold water circuit or chamber, constant

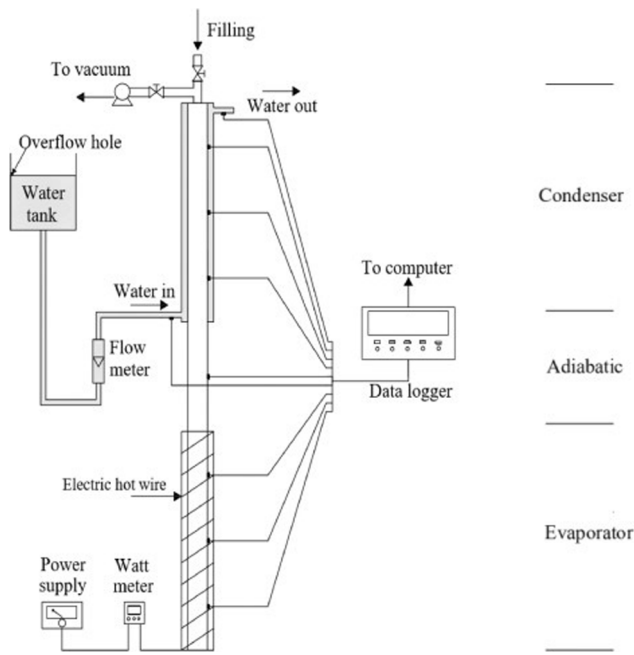


Fig. 8. Schematic diagram of an experimental setup with a heat pipe as main element [69].

temperature water bath or other) over the condenser section. Another usual parts are also a working fluid injection system and a vacuum pump. Thermocouples, a flowmeter in the refrigeration unit, and a data acquisition system are other common elements in these setups (see Fig. 8). The heat absorbed in the evaporator section or input power is usually calculated from the current and voltage provided by the electric power supply. The heat transferred in the condenser section is commonly calculated as the product of the mass flow rate, the specific heat capacity, and the difference between the inlet and outlet temperatures of the cooling fluid (water). The thermal resistance for a heat pipe is defined as the quotient of the difference between the average

temperatures in the evaporator and condenser sections to the input power.

Regarding the literature on two-phase convective heat transfer in heat pipes, three experimental studies [68–70] were found analysing hybrid nanofluids and all the corresponding mono options (Table 4). No works were found examining hybrid nanofluids and one of the corresponding mono options.

Han and Rhi [68] designed Ag/water and Al_2O_3 /water mono nanofluids at 0.005, 0.05, and 0.1 vol% and the following mixtures among them: 0.005 vol% Ag/water + 0.005 vol% Al_2O_3 /water, 0.05 vol% Ag/water + 0.05 vol% Al_2O_3 /water, 0.1 vol% Ag/water + 0.1 vol% Al_2O_3 /water, 0.1 vol% Ag/water + 0.005 vol% Al_2O_3 /water, and 0.005 vol% Ag/water + 0.1 vol% Al_2O_3 /water. Therefore, Ag: Al_2O_3 hybrid nanofluids were analysed at 0.01, 0.1, and 0.2 vol% total concentrations, 1:1 volume ratio, and at 0.105 vol% total concentration, 20:1 and 1:20 volume ratios. The two-phase heat transfer analysis was carried out over a grooved heat pipe charged with 32% of the total inner volume, varying different parameters as the inclination of the pipe (5° , 45° and 90°), the heat transfer rate (50, 100, 150, 200, 250, and 300 W), the cooling water temperature (1, 10 and 20°C), or the depositions in the inner surface. The authors noted that overall thermal resistance increases with increasing concentration of nanoadditives for both mono and hybrid samples, causing system performance to deteriorate. Thermal resistances were found around 40–50% higher for nanofluids than for pure water. The authors attributed this worsening to the settling and agglomeration of the nanoparticles and/or the surface depositions during the boiling experiments. The depositions were visually verified by cutting the pipe after the experiments and obtaining scanning electron microscopy images of the walls, observing different forms (flat, spherical) for the different working positions (evaporator, adiabatic, condenser). If the thermal resistance, R , of the total coinciding concentration between hybrids and mono nanofluids is compared, 0.1 vol %, the sequence $R_{\text{Ag}} < R_{\text{Ag:Al}_2\text{O}_3} < R_{\text{Al}_2\text{O}_3}$ is observed. As can be seen, the hybrid sample obtains an intermediate result between the mono options. The authors also concluded that for the lower inclination angle, 5° , the grooved heat pipe demonstrates a superior performance than for the vertical position, 90° , and that the increasing cooling water temperature in the condenser section leads to lower the overall thermal resistance.

Table 4

Summary of experimental studies [68–70] of two-phase convective heat transfer applications analysing hybrid nanofluids and all the corresponding mono nanofluid options.

Reference	Year	Hybrid and mono nanofluids	Nanoadditive concentrations	Test section	Parameters	Findings
Han and Rhi [68]	2011	Ag: Al_2O_3 (mixture)/water Ag/water Al_2O_3 /water	0.1 vol% ^a 0.005 to 0.1 vol% Ag/water + 0.005 to 0.1 vol% Al_2O_3 /water ^b	grooved heat pipe	filling ratio: 32% inclination: 5° , 45° , and 90° heating power: 200, 250, 300, 350, and 400 W cooling water temperature: 1, 10, and 20°C depositions in the surface	R increases (worsens) with increasing concentration of nanoadditives for both mono and hybrid samples. 1:3 Al_2O_3 : TiO_2 /water samples shows the best heat transfer performance
Xu et al. [69]	2020	TiO_2 : Al_2O_3 (mixture)/water TiO_2 /water Al_2O_3 /water	0.2 vol%	two-phase closed thermosyphon	filling ratio: 30, 50, and 70% heating power: 50, 100, 150, 200, 250, and 300 W cooling water flow rate: 0.4, 0.48, and 0.56 l/min	R decreases (improves) for mono and hybrid samples. Al_2O_3 : TiO_2 (1:3)/water hybrid nanofluid shows the highest R reduction, 26.8%, followed by the TiO_2 (1:3)/water hybrid nanofluid, 22.8%
Bumataria et al. [70]	2020	CuO: ZnO (mixture)/water CuO/water ZnO /water	1.0 wt%	straight tube-shaped heat pipe	filling ratio: 60% inclination: 0° , 15° , 30° , 45° , 60° , 75° , and 90° heating power: 60, 80, 100, 120, 140, and 160 W	R increases (worsens) for mono and hybrid samples. 75:25 CuO: ZnO /water hybrid nanofluid shows the best performance.

^a Coincident total nanoadditive concentration.

^b All nanoadditive concentrations analysed.

Xu et al. [69] studied Al_2O_3 and TiO_2 as mono nanoadditives and mixtures among them at 3:1, 1:1 and 1:3 ratios as hybrid nanoadditives. Thus, 0.2 vol% Al_2O_3 /water and TiO_2 /water mono nanofluids, and three different Al_2O_3 : TiO_2 /water hybrid nanofluids were designed through the two-step method. The two-phase heat transfer analysis was performed on a closed thermosyphon at three filling ratios (30, 50 and 70%), five heating powers (200, 250, 300, 350, and 400 W), with and three cooling water flow rates (0.4, 0.48 and 0.56 l/min). According to a preliminary orthogonal experimental design, the TiO_2 /water and Al_2O_3 : TiO_2 (1:3)/water samples showed the best heat transfer performance between the mono and hybrid nanofluids, respectively. Therefore, a deeper analysis was developed for these samples. The authors concluded that the order of importance for the involved parameters in the thermal performance is heating power > filling ratio > cooling water flow. From the experimental data, they concluded that the optimum conditions are 400 W heating power, 50% filling ratio and 0.4 l/min cooling water flow rate. For these conditions, the thermal resistance achieves a 26.8% decrease for the Al_2O_3 : TiO_2 (1:3)/water hybrid nanofluid and a 22.8 % for the TiO_2 /water mono nanofluid.

Bumataria et al. [70] selected CuO:ZnO hybrid nanoadditives, mixtures at 25:75, 50:50 and 75:25 mass ratio, and CuO and ZnO mono nanoadditives to design by the two-step method the corresponding 1.0 wt% aqueous nanofluids. The two-phase heat transfer analysis was conducted on a straight tube-shaped heat pipe of copper, considering a 60% of the evaporation section volume for filling the working medium. The inclination was varied from 0° to 90° (15° step) and the heat input from 60 W to 160 W (20 W step). The authors reported thermal resistance increases for all nanofluids, both mono and hybrid samples. The CuO:ZnO(75:25)/water hybrid nanofluid showed the lowest thermal resistance increase with respect to water. The authors attributed the better behaviour of the hybrid to the possible synergic effect of individual nanostructures in the base media. The best performance for all nanofluids was detected with 60° inclination angle and 160 W heat input.

2.2.2. Overview

The experimental studies that jointly analyse hybrid and mono nanofluids for two-phase convective heat transfer were developed over heat pipes. The published studies evaluate hybrid nanofluids and all the corresponding mono nanofluid options [68–70], Table 4, and showed the following common features:

- The employed base fluid is water.
- The used nanoadditives are metals and oxides at a maximum concentration of 1 wt%.
- The hybrid nanoadditives are mixtures between the single nano-materials (not composites synthesized by chemical routes).
- The common study variable is the heating power applied in the condenser. Other characteristics as the cooling water circuit conditions (temperature, flow rate) or the inclination angle are employed. The common observed result is the variation of the overall thermal resistance of the heat pipe.

Nevertheless, in these type of studies there are many variables that make comparisons more difficult as the percentage of working fluid inside the pipe. A filling ratio higher than the optimum value means that the liquid does not completely evaporate in the evaporator. Thus, the condenser blocks and then its temperature increases, reducing the evaporator temperature, increasing the temperature difference between them, and consequently increasing the overall thermal resistance. On the other hand, a filling ratio below the optimum value means that the vapour does not completely condense in the condenser. Thus, the reflux fluid flowing to the evaporator decreases, making the amount of working fluid insufficient. Since the heat is supplied continuously in the evaporator, it may eventually dry out [69]. Bumataria et al. [20] concluded that a filling ratio of 50% with respect of the evaporator

section volume is the optimal according with the majority of literature on mono nanofluids in heat pipes. The study of Xu et al. [69] affirmed the same for hybrid nanofluids, obtaining that the best filling ratio among 30, 50 and 70% is 50%, but more studies are required to endorse this hypothesis. Other important variables that are not always taken into account and difficult comparisons are the orientation of the pipe, the working pressure inside and the modification of the internal surface after several evaporation-condensation cycles. Moreover, the selected materials (metals, oxides) and nanoadditive concentrations (from 0.005 vol% to 1 wt%) are very different between the literature. In this framework, the results of the existing studies (see Fig. 9) show divergent conclusions on the improvement or deterioration of nanofluids with respect to the base fluid and on the type of nanofluid which better performs (mono or hybrid). Therefore, no remarkable conclusions can be drawn for the discernment between mono and hybrid nanofluids for two-phase convective heat transfer applications, not even for specific characteristics. More comprehensive experimental studies are required to characterize these processes, which opens an interesting field for future research.

3. Challenges and suggestions for future work

According to the previous results (summarized in Table 5), the selection between mono and hybrid nanofluids for convective heat transfer is only clear in favour of the mono option with better thermal properties and lowest viscosity increase for single-phase heat exchangers and specific characteristics (laminar flow regime, hybrid nanoadditives as mixtures among mono nanoadditives (no clear for composites), near ambient temperature). There is still scope on the following features for future research works on hybrid nanofluids:

- Comprehensive analyses studying hybrid nanofluids (mixture) and both mono nanofluid options through single-phase heat exchangers in turbulent regime at different temperatures or in laminar regime at high and low temperatures.
- Studies scrutinizing hybrid nanofluids (composite) and both mono nanofluid options through single-phase heat exchangers in laminar or turbulent regime and all temperatures.
- Analyses of hybrid nanofluids (mixture, composite) and both mono nanofluid options through two-phase heat exchangers.

These studies should include rigorous investigations concerning the

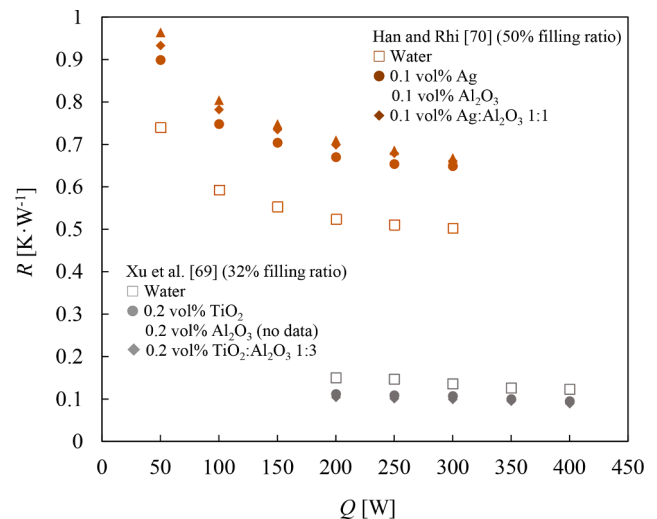


Fig. 9. Thermal resistance, R , as a function of heating power, Q , from different experimental studies [69,70] that analyse hybrid nanofluids and all the corresponding mono nanofluid options through heat pipes for two-phase convective heat transfer applications.

Table 5

Common characteristics and findings of the experimental works that jointly study hybrid nanofluids and all the corresponding mono nanofluids [25,26,42,43,49–54,68–70] classified according to the heat transfer device.

Heat transfer device	Base fluid	Nanoadditives	Concentration	Flow regime	Findings heat transfer	Findings pumping power
Tubular heat exchangers	Water and oil	Carbon-based and metal Hybrid: mixture of components (not composite)	0.02 to 0.5 wt%	laminar	One of the mono nanofluids achieves higher h enhancements than the hybrid nanofluid. Maximum 67.5 % h increase.	One of the mono nanofluids obtains higher ΔP increases than the hybrid nanofluid, when analysed. Maximum 9.9% ΔP increase.
Plate heat exchangers	Water	Carbon-based and metal oxides Hybrid: mixture of components (not composite)	0.01 to 0.1 vol %	laminar	One of the mono nanofluids achieves higher h enhancements than the hybrid nanofluid. Maximum 16.9 % h increase.	One of the mono nanofluids obtains higher ΔP increases than the hybrid nanofluid, when analysed. Maximum 0.013% ΔP increase.
Minichannel heat exchangers/heat sinks	Water	Carbon-based and metal oxides Hybrid: mixture of components (not composite)	0.05 to 0.5 vol %	laminar	One of the mono nanofluids usually achieves higher h or Nu enhancements than the hybrid nanofluid (in one case does not). Maximum 44 % h increase.	One of the mono nanofluids usually gets higher ΔP or f increases than the hybrid nanofluid (in one case does not). Maximum 50% ΔP increase.
Heat pipes	Water	Metal oxides Hybrid: mixture of components (not composite)	Up to 1.0 wt%	–	Divergent conclusions: R increases (worsens) or increases (improves) with nanoadditive addition. Multiple parameters involved.	–

stability of the analysed nanofluids and the thermophysical and rheological properties used in the calculations, since in some cases there are not clearly defined. Furthermore, the construction and geometrical parameters of the heat exchanger should be clearly stated. In addition, temperatures and pressures of the heat transfer analyses should be also provided for appropriate comparisons.

4. Conclusions

This review is focused on experimental studies dealing with hybrid nanofluids and the corresponding mono nanofluids for single-phase and two-phase heat convective transfer applications. The following conclusions can be drawn:

1. The existing literature develops experimental analyses in three types of devices for single-phase convective heat transfer (tubular heat exchangers, plate heat exchangers and minichannel heat exchangers/heat sinks), an in one type for two-phase convective heat transfer (heat pipes).
2. The studies of single-phase convective heat transfer that include hybrid nanofluids and all the corresponding mono options are developed in laminar flow regime and at near ambient temperature. These studies mostly use water as base fluid. Low concentrations of carbon allotropes, metals and oxides are selected as mono nanoadditives and mixtures among them (no composites) are used as hybrid nanoadditives. In these studies, one of the mono nanofluids usually achieves superior improvements of the heat transfer coefficient or Nusselt number than the hybrid nanofluids comparing equally loaded samples. In the same way, these studies conclude that one of the mono nanofluids achieves increases in pressure drop or friction factor higher than those of the hybrid nanofluids.
3. Some studies of single-phase convective heat transfer that include hybrid nanofluids and one of the corresponding mono nanofluid options emphasize the previous conclusion. Other studies concluded that a hybrid nanofluid showed higher improvements of heat transfer coefficient or Nusselt number, but the mono nanofluid with better thermal characteristics may not be included in the analysis, as clearly occurs in various studies that not examine the corresponding MWCNT/water mono nanofluids or graphene/water mono nanofluids.
4. According to the previous statements, the outcomes of the literature mainly support that there is no synergistic effect for hybrid nanofluids in laminar single-phase convective heat transfer. The highest

thermal conductivity improvement is identified as the main cause for the highest convective heat transfer coefficient enhancement in laminar flow. Likewise, the highest dynamic viscosity increment is identified as the main cause for the highest pumping power augmentation.

5. With the existing literature, the three previous conclusions cannot be extended to hybrid nanofluids with nanoadditives consisting on composites synthesized by chemical routes, neither to turbulent flow conditions.
6. The studies of two-phase convective heat transfer that include hybrid nanofluids and all the corresponding mono options use water as base fluid. Metals and oxides are selected as mono nanoadditives and mixtures among them are used as hybrid nanoadditives. These studies include multiple variables in the analyses (heating power, cooling water circuit conditions, orientation of the pipe, filling ratio) and the few existing studies with divergent conclusions do not allow to draw any concluding remarks.
7. Research on hybrid (mixture) and mono nanofluids in single-phase heat exchangers for laminar regime is the most approached in the literature. There is still scope for this research on turbulent regime and for hybrid (composite) nanofluids in all regimes. Furthermore, joint studies on hybrid (mixture, composite) and mono nanofluids are still required on two-phase heat exchangers in multiple working conditions.

CRediT authorship contribution statement

Javier P. Vallejo: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jose I. Prado:** Data curation, Formal analysis, Writing – review & editing. **Luis Lugo:** Conceptualization, Formal analysis, Investigation, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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