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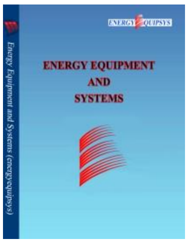

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An overview on the thermal performance of dual-tube heat exchangers in the presence of nanofluids

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ABSTRACT

In this review article, the thermal performance of dual-tube heat exchangers with smooth walls is investigated in the presence of nanofluids. Important challenges in industrial and engineering processes, such as the failure of thermal devices to respond to higher capacities, conservation, saving, and optimization of energy, have been discussed in recent years. Heat exchangers are one of the types of thermal devices that are used in a wide range of engineering and industrial applications. The use of nanofluids is one of the most effective ways to enhance the thermal conductivity of heat exchangers in the industry. In this research, the types of heat exchangers are first introduced. Then, the methods of heat transfer enhancement (active, passive, and combined) are discussed. The introduction and method of preparing nanofluids are discussed, and finally, the studies on dual-tube heat exchangers in the presence of nanofluids are described. This review article examines previous studies on dual-tube heat exchangers and the use of nanofluids in them (216 references and 73 journals). The purpose of this article is to familiarize the readers with the types of heat exchangers and to understand the mechanisms of heat transfer in the context of using nanofluids in smooth dual-tube heat exchangers. It can be concluded that nanofluids are a very good substitute for other fluids because the use of nanofluids in heat exchangers leads to an improvement in their performance, a reduction in their energy consumption and costs, a decrease in their volume, a reduction in environmental effects, etc. Eventually, the challenges in the use of nanofluids in flat dual-tube heat exchangers are discussed. The most important ones include the economic costs of using nanofluids, deposition and accumulation of nanoparticles over time, stability of nanofluids, and lack of standardization among various researches and evaluations.

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1. Introduction

One of the major challenges in the modern era is energy-saving and optimization. Thus, researchers in all fields of engineering and science related to energy are trying to overcome this concern. Significant advances have been made in the cooling and heating of industrial equipment, all of which have resulted in energy savings, heat transfer (HT) improvement, and an increase in the service life of machinery and equipment. One of the ways to save energy and

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improve HT is to use heat exchangers (HEs). The purpose of this article is not only to review the previous studies but to familiarize the readers with the types of heat exchangers and to understand the mechanisms of heat transfer in the context of using nanofluid in smooth dual-tube heat exchangers to save and optimize energy and enhance heat capacity.

2. HEs

A heat exchanger (HE) is a device in which heat is usually exchanged between two fluids (liquid-liquid / gas-gas / liquid-gas) or hot and cold sources. In HEs, two fluids usually exchange heat without contact. The cold fluid receives thermal energy in contact with the hot fluid and its temperature rises. Instead, the hot fluid cools down by losing heat. Heat exchange is based on the basic principles of heat transfer, i.e., convection and conduction can be described. In HEs, regardless of the energy dissipation, the amount of heat lost by the hot fluid and the amount of heat received by the cold fluid are equal. In general, HEs are responsible for heat exchange. HEs are used in a wide range of applications such as power plants [1, 2], petrochemical industries [3, 4], process industries [5, 6], manufacturing industries [7, 8], food and pharmaceutical industries [9-11], heating [12-14], cooling [15-17], air conditioning [18-20], refineries [21, 22], automotive industries [23, 24], etc. Also, they have many applications in equipment such as evaporators [25-27], boilers [28-30], cooling towers [31, 32], steam generators [33, 34], condensers [35], preheaters [36, 37], fan coils [38, 39], furnaces [40, 41], oil coolers and heaters [42-44], radiators [45, 46], etc.

2.1. Classification of HEs

As shown in Fig. 1, HEs are generally divided into two recuperative and regenerative categories, and each of these categories includes different aspects that are categorized as [47-52]:

1. Based on recuperative/regenerative between hot and cold fluids.
2. Based on the HT process (direct and indirect contact between hot and cold fluids).
3. Based on the mechanical structure of the HE.
4. Based on HT mechanisms between cold and hot fluid (single-phase and two-phase flows).
5. Based on the direction of cold and hot fluids.

In the following, each aspect of the classification of HEs is fully explained.

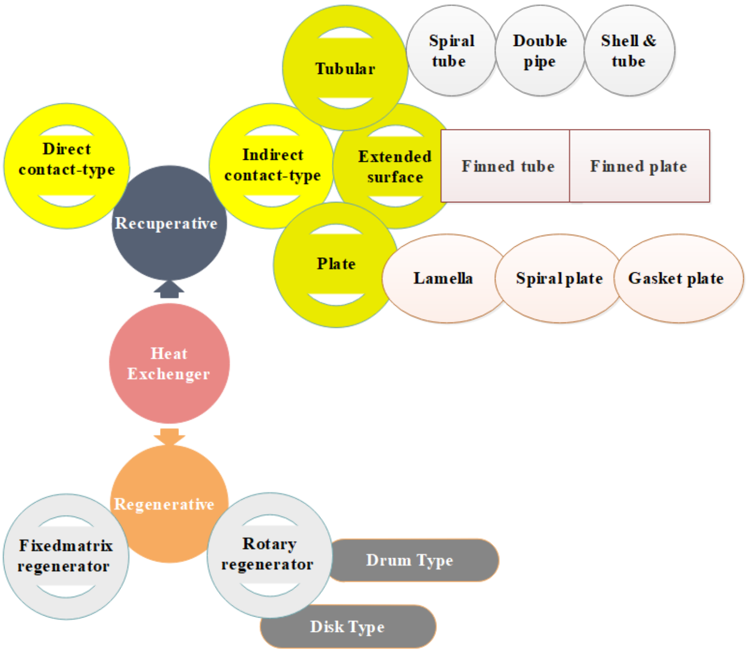


Fig. 1. Classification of HEs.

1) Based on regenerative/recuperative between hot and cold fluid

Regenerative: The first regenerator heat exchanger was invented in 1816 by Rev. Robert Stirling [53]. In this type of HE, shown in Fig. 2 (a), the surface that separates the hot and cold fluid is not fixed so that some parts of the surface are alternately exposed to the hot or cold fluid [54-56]. This type of HE is commonly used in research scales [57, 58].

The regenerator heat exchanger is divided into two categories:

1. Rotary regenerator heat exchangers: Rotary heat exchangers are a type of indirect and compact exchangers in which the flow of hot gas passes through the exchanger and its heat is transferred to the matrix. After a certain time (the hot cycle), the disk is rotated and when the cold current passes through the matrix, the heat stored in it is given to the cold flow. This matrix is located between two hot and cold flows. These tubes are separated by special surfaces that prevent the mixing of hot and cold streams. The flows of hot and cold gases pass through these tubes at the same time and their sensible energy is exchanged with the matrix [59]. The advantages of using rotary heat exchangers are as follows [47, 60, 61]:
    - High and cheap surfaces of heat transfer compared to other types of heat exchangers.
    - The self-cleaning property of matrices using the cross flows of hot and cold gases.
    - Low-pressure drop using the honeycomb structure of matrices.
    - Less consumption than recuperators.

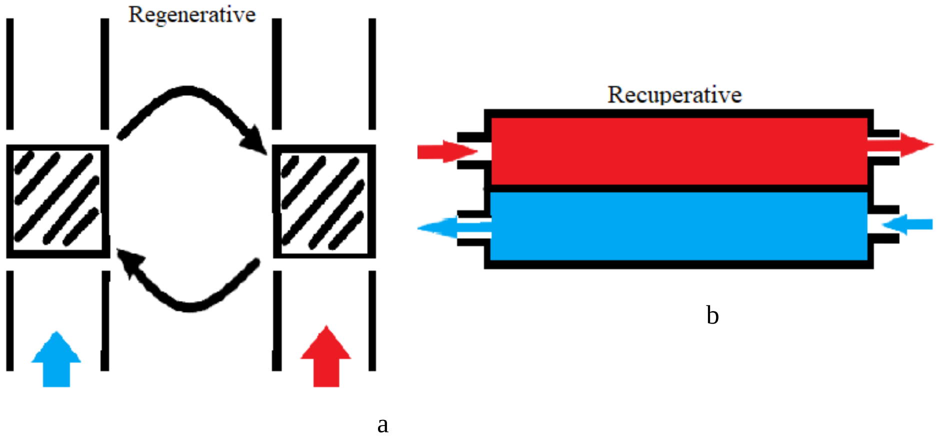


Fig. 2. (a) Regenerative and (b) Recuperative HE.

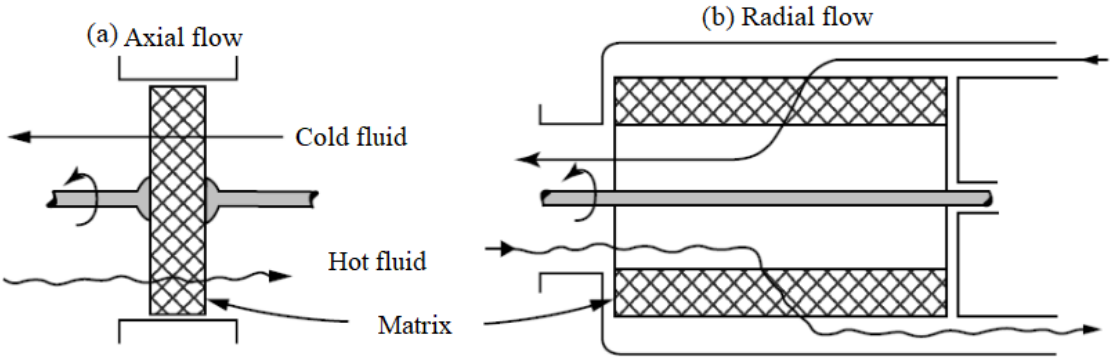


Fig. 3. Rotary HE ((a)Axial flow and (b)Radial flow)[47]

2. fixed-bed regenerator heat exchangers: The fixed-matrix or fixed-bed regenerator is a periodic-flow heat transfer machine with a great thermal valence matrix through which the hot fluid flow and cold fluid flow transmit alternately [62, 63]. Specific parameters characterize regenerators' efficiency, i.e., mechanical and thermal properties of the solid matrix, geometry, working fluid properties as well as discharge and charge time-length periods [64, 65].

As shown in Fig. 4, at first matrix A is heated by hot fluid, and matrix B is cooled by cold fluid. behind a certain course of time, the valves operate so that the hot fluid flows through the formerly cooled matrix B and is cooled by heat transfer to it. The cold fluid similarly transmits through the previously heated matrix A, the cold fluid picks up heat from it to warm it up.

Recuperative: In this type of HE, shown in Fig. 2 (b), hot and cold fluids are separated by a fixed (solid) surface and HT takes place through the solid surface. The solid surface, which is usually made of metal alloys, must have a high heat transfer coefficient (HTC) to increase the thermal efficiency of the HE. The most common heat exchangers are of recuperator type [66-69]. In recuperators, the flow of both fluids is present simultaneously and heat transfer is done continuously. Many HEs used in various industries are of this type [70-72].

As shown in Fig. 1, recuperators can be classified based on the transfer process (direct and indirect contact between hot and cold fluid), which is discussed below.

2) Based on the HT (direct and indirect contact between hot and cold fluid)

As shown in Fig. 5(a), In Direct contact HEs, since there is no surface between hot and cold fluids, the fluids are in direct contact with each other, and HT takes place (Fig. 6). In direct contact HEs, fluid flows, a gas and a liquid, or two liquids are immiscible [73, 74]. These HEs usually have high thermal efficiency. Examples of these HEs are cooling towers, water coolers, and heaters in steam power plants [75, 76].

Indirect HEs are used for indirect heating in the oil and gas industry. As shown in Fig. 5(b), In these exchangers, heat is transferred to the intermediate fluid through fire-fighting tubes. The presence of the intermediate fluid causes uniformity of heat distribution and prevents the formation of points with thermal concentration and high temperature. These HEs have much less risk than other ones. Indirect HEs have a much lower risk than direct HEs due to the indirect HT process and are considered a suitable option for use in a variety of hazardous environments with the possibility of explosion [77-80]. Examples of these HEs are plate HEs [11, 81, 82], tubular HEs [83, 84], spiral HEs [85, 86], and air-cooled HEs [31]. In Table 1, an example of indirect heat exchangers is collected.

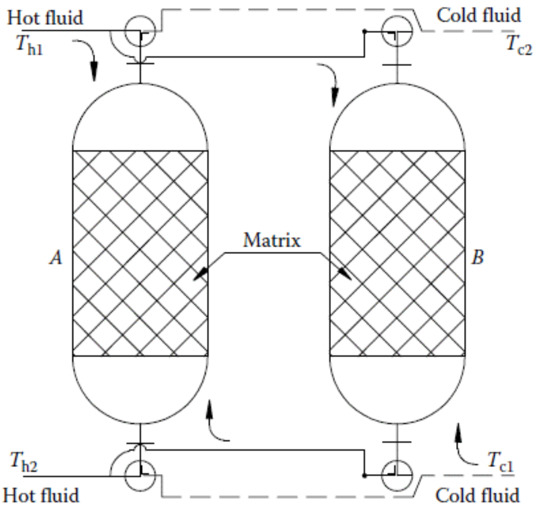
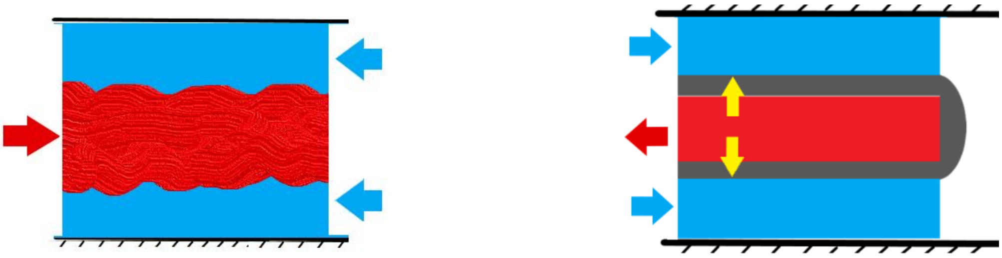


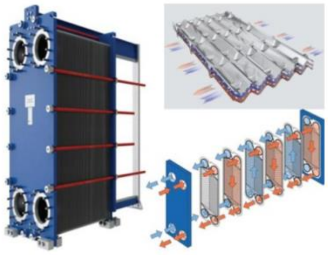
Fig. 4. fixed-bed regenerator HE.



(a) (b)

Fig. 5. (a)Direct contact and (b)Indirect contact HE.

Table 1. An example of indirect heat exchanger

<table>
<tr><th colspan="3">plate HEs</th></tr>
<tr><td>
Lamella</td><td>
Spiral</td><td>
Gasket</td></tr>
<tr><th colspan="3">tubular HEs</th></tr>
<tr><td>
Spiral pipe</td><td>
Double pipe</td><td>
Shell & tube</td></tr>
<tr><th colspan="3">Extended surface HEs</th></tr>
<tr><td colspan="2">
Fin plate</td><td>
Fin tube</td></tr>
<tr><th colspan="3">Air-cooled HEs</th></tr>
<tr><td colspan="3"></td></tr>
</table>

3) Based on the mechanical structure of the HE

- Tubes: As shown in Fig. 6(a), These HEs are made of tubes with a circular cross-section. One fluid flows inside the tubes and the other outside the tubes, and HT takes place through the tube wall. The diameter, number, length, pitch, and arrangement of tubes can vary. Therefore, there is considerable flexibility in their design[19, 87-93].
- Plates: As shown in Fig. 6(b), A plate HE consists of a set of parallel and corrugated plates that are placed side by side to form channels. Plates, usually made of stainless steel, are sealed by special rubber gaskets. The corrugation of the plates leads to flow turbulence even at very low velocities. As a result, the HTC relative to the smooth channel as well as the tube is increased significantly[73-76, 94-108].
- Extended surfaces: As shown in Fig. 6(c), Extended surfaces with fins are surfaces that are widely used in heat transfer. When we want to transfer heat from a hot surface to a cold one, a larger cross-section can be used for the contact between the hot and cold surfaces by adding the fins [109-114].

4) Based on HT mechanisms between cold and hot fluid (single-phase and two-phase)

As shown in Fig. 7, heat exchangers are classified into the following categories based on the mechanisms of heat transfer between cold and hot fluids:

- Convection of one phase on both sides
- Convection of one phase on one side, Convection of two phases on the other side
- Convection of two phases on both sides

In HEs such as air heaters in boilers, heaters used for room heating, car radiators, economizers (HEs in which the fluid moves from supersaturated to saturated liquid conditions), generators, inter-coolers in multi-stage compressors, oil coolers, etc., HT occurs through single-phase convection on hot and cold fluid sides. Boilers, condensers, and steam generators in pressurized water reactors in nuclear power plants, as well as evaporators and radiators used in air conditioning and heating, have condensing and evaporating mechanisms at one of the surfaces of HEs. Two-phase HT can also occur on both sides of the HE, for instance, when condensation occurs on one side and evaporation happens on the other side. However, a form of two-phase HT can take place without phase change. For example, fluidized substrates, gas mixtures, and solid particles transfer heat to or from the surface[115-121].

5) Based on the direction of cold and hot fluid flow

HEs can be classified into the following categories based on the flow direction:

- Parallel flow HEs

As shown in Figure 8, In this type of HE, hot and cold flow are parallel to each other and the direction of hot and cold fluid flow is the same. Two fluids enter the HE on one side end, flow in one direction, and exit on the other side. The temperature of the cold fluid output from the HE never reaches the temperature of the hot output fluid. The close value of the two mentioned temperatures requires the use of a very large effective HT surface [122-126].

According to Fig. 8, hot fluid flows inside the tube and cold fluid flows in the shell. In this HE, hot and cold flows are parallel, i.e. both flows enter from part A and exit from part B. The cold fluid inside the shell is heated by a hot fluid. The above figure also shows the decrease in hot fluid temperature and the increase in cold fluid temperature. Inside the HE with the parallel flow, the temperature of the cold fluid is always lower than the temperature of the hot fluid in each section of the HE. There is the maximum temperature difference and consequently the highest HTat the input. There is also the minimum temperature difference and the minimum HT at the output [122-126].

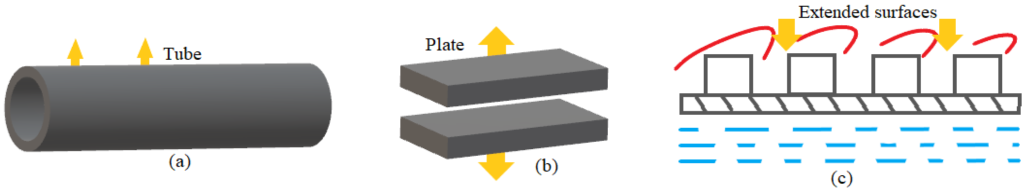


Fig. 6. Classification of HEs based on their mechanical structure ((a)Tubes,(b) Plates, and (c)Extended surfaces).

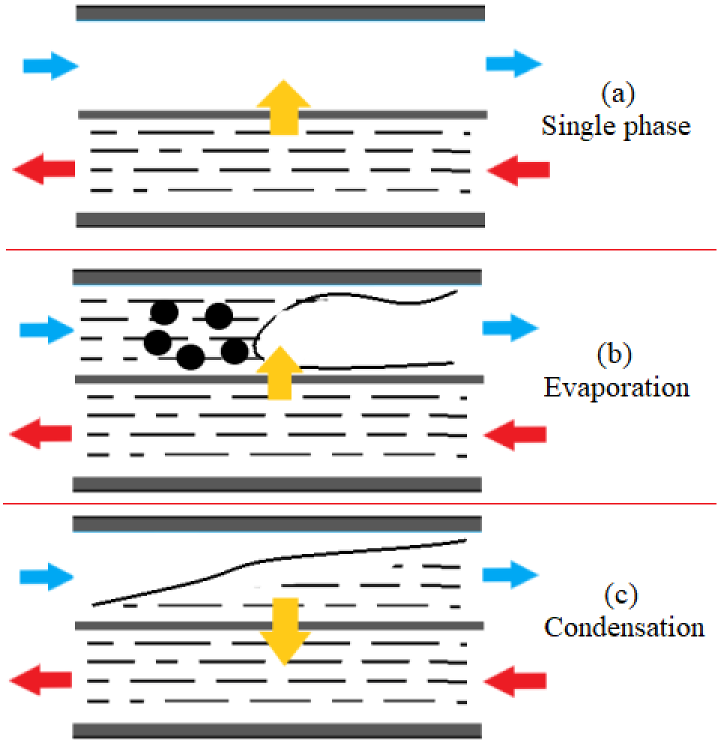


Fig. 7. Classification of HEs based on HTmechanisms between hot and cold fluid ((a) single phase,(b) Evaporation, and (c) Condensation).

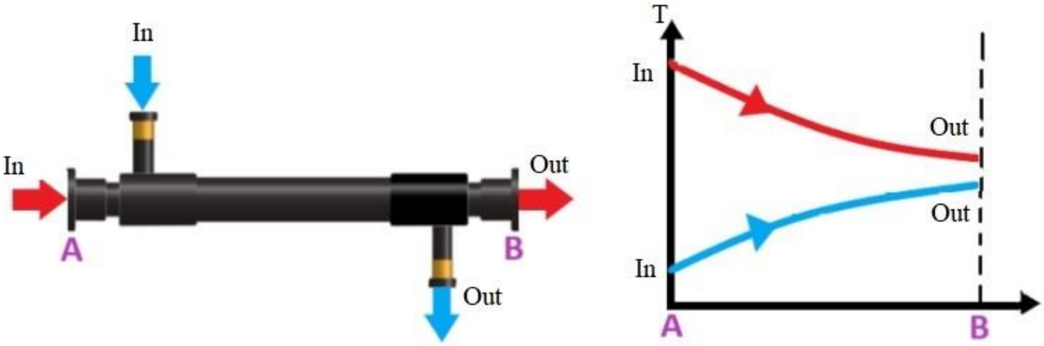


Fig. 8. Parallel flow HE.

- Counterflow HEs

As shown in Fig. 9, When the flow of hot and cold fluids is parallel to each other and in opposite directions, the HE is called counterflow. It should be noted that in this type of HE, it is possible to enhance the output temperature of the cold fluid compared to that of the hot fluid. Under the same conditions, these HEs have a lower HT surface than their parallel flow ones[127-130].

According to Fig. 9, hot fluid flows inside the tube and cold fluid flows in the shell. In this, HE, hot and cold flows are countered. The cold fluid inside the shell is heated by a hot fluid. The above figure also shows the decrease in hot fluid temperature and the increase of cold fluid temperature. Inside the HE with the counter flow, the temperature of the cold fluid is always lower than the temperature of the hot fluid in each section of the HE. In counter-flow HEs, the temperature difference between hot and cold fluids is the same in almost every section. Therefore, the HT rate is almost the same in all parts of the HE [127-130].

- Crossflow HEs

As shown in Fig. 10, In this type of HE, the

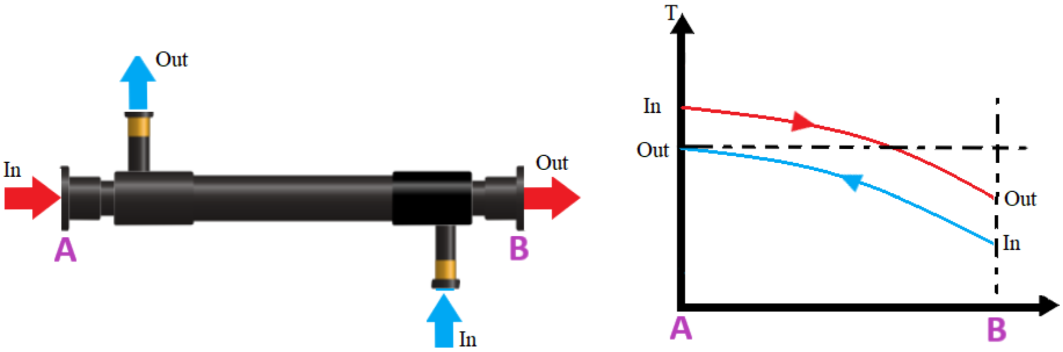


Fig. 9. Counterflow HE.

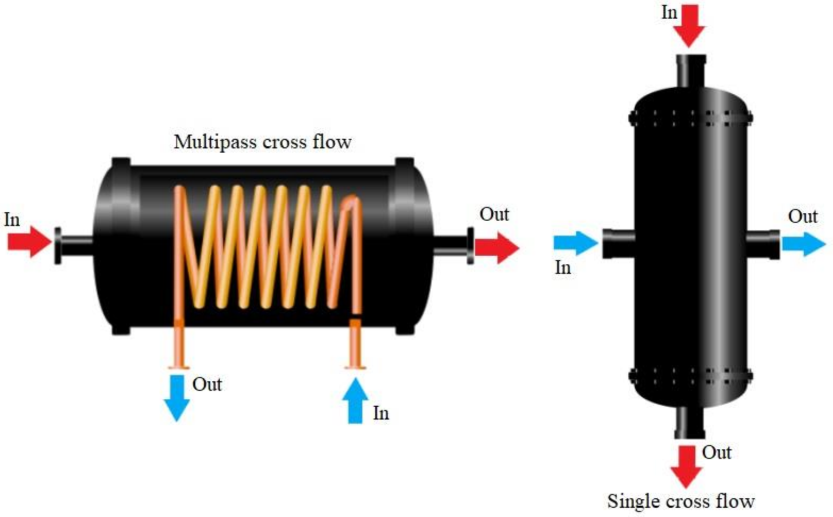


Fig. 10. Crossflow HEs.

directions of cold and hot flows are perpendicular to each other. The most common example is a car radiator. In a cross-flow arrangement, there is mixed or unmixed flow, depending on the design. The fluid inside the tubes is not mixed because it will not be allowed to move in the cross direction of the tube. The external fluid is mixed for finless tubes because the fluid can flow or mix transversely, and it is unmixed for finned tubes because the presence of the fins prevents it from flowing in a direction perpendicular to the main flow direction[127, 128].

As shown in Fig. 1, one of the most widely used types of HEs in the industry is the dual-tube heat exchanger (DTHE), which is discussed in the following [48-50].

2.2.1. DTHE

As shown in Fig. 11, The DTHE consists of two concentric and coaxial tubes with different diameters. One of the fluids flows inside the inner tube and the other fluid flows in the annular space between the two tubes along the tube length. The surface of the inner tube is responsible for heat exchange between the two fluids. The surface of HT in the DTHE can be increased using different techniques[131, 132].

One of the most important factors in the design of dual-tube heat exchangers (DTHEs) is the type of flow pattern in the HE. As shown in Fig. 12, DTHEs can be designed as parallel and counterflow. It is noteworthy that the counter-flow pattern has the highest thermal efficiency and the highest HTC in the design of HEs[48, 133, 134].

Fig. 11. DTHE.

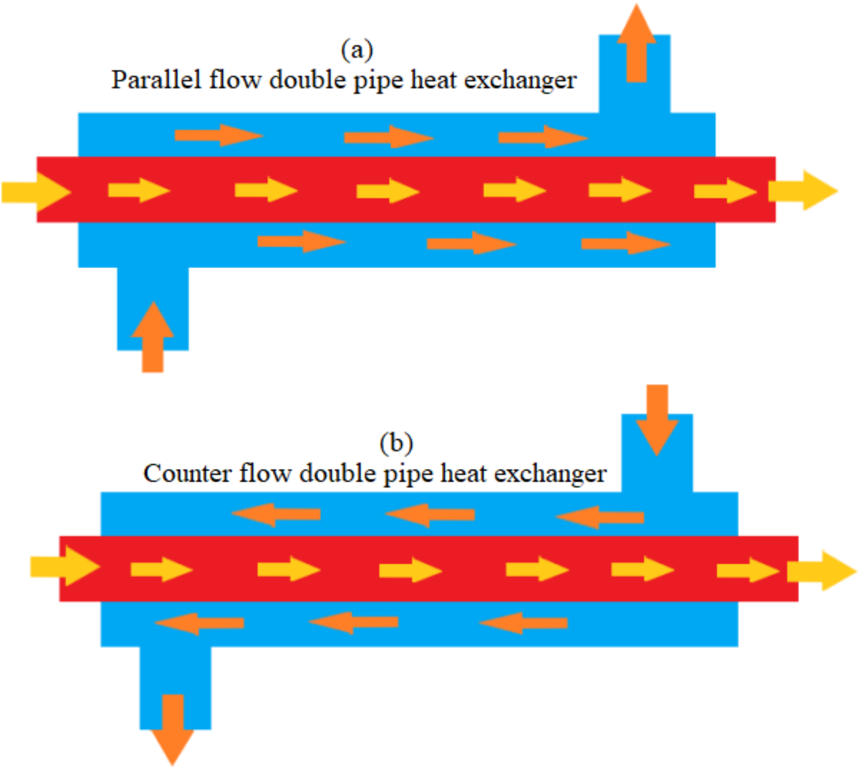


Fig. 12. Flow pattern in a DTHE ((a) Parallel flow double pipe heat exchanger and (b) Counter flow dual-tube heat exchanger).

DTHEs are usually suitable for specific applications[48, 131-134]:

- High-temperature changes are considered.
- The flow rate of fluids is low.
- Sufficient space is available for installation.
- Low HT is required for high flow rates.

The advantages of using a DTHE include:

- Easy calculations and design
- Easy fabrication
- Relatively low cost
- Easy maintenance
- Simple flow control in two directions

It should also be noted that in industry, DTHEs are used for fluids that are usually sedimentary.

3. Methods of enhancing heat transfer

Increasing HT has been an effort of designers to reduce the size of heating equipment and reduce costs. The use of various methods to enhance HT has been studied for many years.

According to the classification of Kakac et al. [135] and Webb et al.[136], there are different methods for improving heat transfer, which is classified into three groups:

- Active methods
- Passive methods
- Combined methods

3.1. Active methods

In the active method, an external force is required to increase heat transfer. Examples of this method are magnetic field, reciprocating pistons, the vibration of flow surface, use of electromagnetic fields (Table 2).

Moghlany et al.[137] examined a DTHE with a rotating inner tube experimentally and evaluated the effect of hot and cold fluids, flow type, and the rotational velocity of the tube on the performance of the HE. The results showed that the HT rate and efficiency increase with the rotational velocity of the inner tube. In another study, Zhang et al. [138] examined the thermal properties of a simple tube connected to a rotor with different geometries. The results showed that the Nusselt number and friction coefficient increase significantly compared to a simple tube, and the performance of the HE is enhanced.

3.2. Passive methods

HT increases by creating turbulence in the flow or changing the flow regime without the need for an external force. This method is always associated with pressure drop.

Geometric changes and multiple interior coatings play a major role in passive methods[139-142]. In recent years, researchers have conducted extensive investigations on passive methods such as twisted tapes[143-145], extended surfaces [133, 146-149], wire loops[150-153], etc (Table 2).

3.3. Combined methods

In this method, both active and passive methods are used simultaneously to improve heat transfer[154]. Simultaneous use of coils and fluid vibration is one of the methods to enhance HT that has been considered by many scientists [155]. Omkar et al. [156] conducted an experimental study on a DTHE with an inner rotating tube when the outer surface of the outer tube contained a helical tube. They used water in the inner tube and glycerol in the ring between the two tubes. The results demonstrated the improvement of heat transfer.

4. Nanofluid in DTHEs

The prefix "nano" means one billionth or 10^{-9}. So one nanometer is one billionth of a meter[157]. It is hard to imagine how tiny it is.

As mentioned in Fig.13, here are some examples of nano comparison with other dimensions:

- A sheet of paper is about 100,000 nanometers thick.
- The width of human hair is approximately 80,000 to 100,000 nm.
- A single strand of human DNA is 2.5 nm in diameter.
- The diameter of a gold atom is about a third of a nanometer.
- There are 25,400,000 nanometers in an inch.
- One nanometer is about as long as a fingernail grows in one second.
- On a comparative scale, if the diameter of a marble was one nanometer, the diameter of the earth would be about one meter.

Table 2. Methods of enhancing heat transfer.

Combined	Passive	Active
Simultaneous use of active and passive methods	Rough surfaces	Injection
	Extended levels	Suction
	Coated surfaces	Fluid vibration
	Rotary flow devices	Mechanical equipment
	Surface tensioning devices	Electrostatic field
	Spiral tubes	
	Add to liquids	Using the jet
	Add to gases	

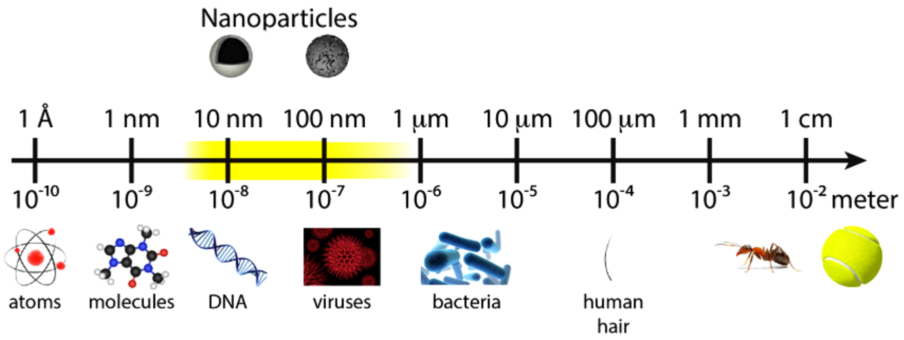
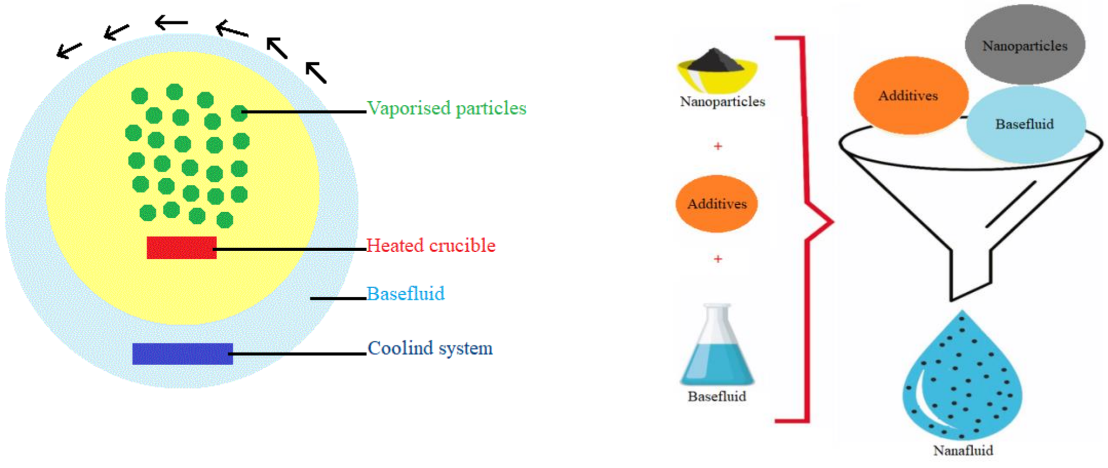


Fig. 13. Comparing nano with other dimensions[158].

One of the most effective factors to enhance thermal efficiency and HTcoefficient is to utilize one or more fluids with suitable thermal properties. Nanofluids have appropriate thermal properties to increase heat transfer. The term nanofluid was first used by Choi [159] in 1995 by a research institute in the United States for a new type of fluid with solid suspended particles of 1 to 100 nm was used, which is compared to other dimensions in Fig. 13.

Nanofluids are better thermal conductors than conventional fluids due to the size of the solid particles suspended in them. The main reason for choosing a nano-scale for the size of these particles compared to other particles is its greater stability, higher HT rate, and lower weight. Hence, the possibility of sedimentation of particles, wear, blockage, and pressure drop in the pipes is prevented due to low particle weight [160].

Nanofluids are produced by one-step and two-step methods (Fig. 14). In the single-step method, evaporation of nanoparticles and dispersion in the base fluid are all done in one step. In this method, the metal source is evaporated under vacuum conditions, and in the next step, nanofluid is produced by condensing the nano powder from the vapor phase in a low-pressure fluid [161-164]. In the two-step method, first, nanoparticles are produced by one of the physical or chemical methods, and then in the next step, they are suspended in the fluid [165, 166]. In many nanofluids produced by the two-phase method, the aggregates of nanoparticles are not completely separated, which leads to the instability of the nanofluid [167]. To solve this problem and stabilize nanofluids, various methods are used, such as adding surface activators, changing the pH value of the suspension, and using ultrasonic vibrators[168, 169].



(a) (b)

Fig. 14. Nanofluid preparation ((a) one-step and,(b) two-step [170] methods).

Nanofluids have certain aspects that distinguish them from two-phase fluid compositions in which particles in millimeters or micrometers are used [170]. Researchers have shown that the most obvious effect of nanofluids is the tremendous increase in thermal conductivity [171-173]. Numerous studies have been performed by various researchers and it was shown that the use of nanofluids can be one of the most interesting techniques to increase HT in HEs [174-186].

In the following, the investigations carried out on DTHEs in which nanofluid is used are introduced.

4.1. Investigations performed on nanofluids in DTHEs with smooth walls

In an experimental study, Darzi et al. [187] investigated the effect of water/Al_2O_3 nanofluid on heat transfer, pressure drop, and thermal performance (TP) of a DTHE. They performed the experiments at 27 to 55 °C, with Res of 5,000 to 20,000, and volume fraction of nanoparticles (φ) less than 1%. The results showed that the TP of the DTHE increases significantly with φ. Besides, the HT rate was intensified at high Res, and the friction coefficient was increased at low Res. Thus, it can be concluded that increasing φ leads to an enhancement in the Re.

Duangthongsuk and Wongwises [188] investigated the forced convection HT of a water/TiO2 nanofluid In a two-tube HE. They measured the HT coefficient and friction coefficient in the turbulent flow regime. The results showed that the HTC of nanofluid increases by about 6 to 11% compared to the base fluid. On the other hand, the HTC increases with the velocity of hot water and nanofluid. Also, decreasing the nanofluid temperature and increasing the hot water temperature does not have a significant effect on the HTC. Finally, they revealed that a significant increase in thermal conductivity and pressure drop occur by adding nanoparticles to the base fluid in a DTHE at different Res, resulting in an improvement in the performance of the HE.

Chun et al. [189] examined the HTC of alumina-oil nanofluid in a DTHE in a laminar flow regime experimentally. They observed that although the thermal conductivity of alumina is not high, it is much higher than the base fluid, and the addition of alumina nanoparticles to the base fluid leads to a significant increase in the HTC. They also attributed the enhancement in HT coefficient is due to the high concentration of nanoparticles in the thermal boundary layer near the wall of the DTHE.

Aghayari et al. [190] evaluated the TP of water/Al_2O_3 nanofluid in a DTHE. In their experiments, they used nanoparticles with a diameter of about 20 nm and $\varphi = 0.1$ to 0.3% in a turbulent flow regime. They examined the effect of temperature, Re, and φ on TP. The results demonstrated that the use of nanofluid enhances the HTcoefficient by at least about 12% compared to the base fluid.

Khedkar et al. [191] assessed the HTC of TiO_2-water nanofluid as a coolant in a DTHE. In this experiment, an internal copper tube with a length of 1000 mm was employed. The results showed that the TP is significantly increased (about 14%) by adding nanoparticles to the base fluid.

Akhtari et al. [192] examined the TP of Al_2O_3/water nanofluid in a DTHE under a laminar flow regime. They investigated the effect of parameters such as nanofluid temperature, φ, as well as hot and cold flow rate on TP. The results demonstrated that TP increases by enhancing the rate of hot and cold flow, φ, and nanofluid temperature. They showed that by adding nanoparticles to the base fluid, the HTC is improved by 13.2%.

Table 3 presents the studies performed on the TP of nanofluids in DTHEs.

Table 3. Studies performed on the TP of nanofluids in DTHEs.

Ref.	Nanofluid	Characteristics	Results
Bahmani et al. [193] 2018	Al_2O_3 – water	• DTHE with counterflow • Nanofluid, internal fluid (hot fluid with a temperature of 350 K) • Water, external fluid (cold fluid with a temperature of 285 K) • Turbulent flow regime	By increasing φ or by increasing the Re, the Nusselt number enhances by 32.7%, and the convection HTC is improved by 30%.
Bahireie et al. [194] 2017	Ag-Eg/water (50/50)	• DTHE with counterflow • Nanofluid, internal fluid (cold fluid, 298 K) • Water, external fluid (hot fluid, 360-308 K) • $\varphi = 0.1$ to 1% • Laminar flow regime (500-2000)	As φ and the Re increase, the overall HTcoefficient and HT rate enhance. Also, the pumping power increases with the Re and decreases with φ. On the other hand, the HTto pressure drop ratio is enhanced with φ. Therefore, the nanofluid exhibits a higher TP at values of φ.
Zamzamian et al. [195] 2011	Al_2O_3-Eg Cu-Eg	• DTHE • Al2O3 volume fraction: 0.1, 0.5 and 1% • Cu volume fraction: 0.1, 0.3, 0.5, 0.7 and 1% • Turbulent flow	As the temperature and φ increase, the convection HTC increases significantly compared to the base fluid.
Jassim et al. [196] 2020	Al_2O_3-water Cu- water	• DTHE • Re: 7000-15000 • φ : 0.26 to 0.83%	The presence of nanoparticles in the base fluid offers a high potential for heat transfer. As φ increases, the Nusselt number increases at a constant Re. As the Re increases, the Nusselt number enhances, and ultimately the TP improves.
Kumar [197] 2017	Fe_3O_4-water	• DTHE • Turbulent flow regime (15000-30000) • φ : 0.005, 0.01, 0.03 and 0.06%	By adding nanoparticles to the base fluid, the overall performance of the HE is enhanced dramatically. The maximum Nusselt number of 14.7 is obtained for $\varphi = 0.06\%$ and Re of 30,000.
Shakiba et al. [198] 2016	Fe_3o_4-water (4%)	• DTHE with counterflow • Uniform transverse magnetic field • Laminar flow regime • Nanofluid, inner fluid (hot) • Air, external fluid (cold)	Applying a uniform transverse magnetic field creates a Kelvin force in the direction perpendicular to the ferrofluid flow. This penetrates the cold boundary layer into the hot ferrofluid and ultimately leads to an increase in the Nusselt number and improves the HT of the ferrofluid (the application of a magnetic field increases the Nusselt number by about 45%).
Sarafraz and Hormozi [199] 2015	Ag/ Eg-water (50/50)	• DTHE • Laminar-transient-turbulent flow regime • φ : 0.1, 0.5 and 1%	The addition of nanoparticles to the base fluid leads to the HTcoefficient increasing dramatically so that for $\varphi = 1\%$, the HTcoefficient increases by about 67%.
Sonawane et al. [200] 2013	Al_2O_3 – water	• DTHE • Laminar-transient-turbulent flow regime • φ : 2 and 3%	The average HT rate for the nanofluid as a coolant is higher than the base fluid so the HT rate increases as φ increases.
Hassan et al. [201] 2014	Al_2O_3 – water TiO_2 - water	• DTHE • Laminar flow regime • φ : 0.05 to 0.3% • Flow rate: 0.5 to 2 lit/min • Hot water, inner tube • Nanofluid, outer tube (cold)	The addition of nanoparticles to the base fluid leads to an increase in the overall HTcoefficient so that the HTcoefficient increases by 18.25% with the addition of Al_2O_3 nanoparticles and by 15.5% with the addition of TiO_2 nanoparticles.
El-Maghlany et al. [202] 2016	Cu - water	• DTHE • Turbulent flow regime • φ : 1 to 3%	The addition of nanoparticles to the water leads to a significant increase in thermal conductivity and pressure drop and improves the performance of the HE.
Bahiraei and Hangi [203] 2013	Zn-Mn/water	• DTHE with counterflow • Euler-Lagrange two-phase method • Presence of magnetic field • Nanofluid as a coolant, inner tube • Hot water, outer tube	Increasing φ, particle size and magnetic field size leads to an enhancement in pressure drop and improvement in heat transfer. At higher Res, the effect of magnetic force decreases.
Chavda et al. [204]	Al_2O_3 – water	• DTHE with counterflow • φ : 0.001 to 0.01%	Compared to the base fluid, the overall HTcoefficient increases and then decreases with

2014			φ to 0.008%.
Azeez et al. [205] 2020	Al_2O_3 – water	• DTHE • Turbulent flow regime (5000-30000) • φ : 1 to 4%	The addition of nanoparticles can increase the thermal properties of the fluid by up to 20% and increase the overall HT rate.
Raei [206] 2019	Al_2O_3 – water	• DTHE • Turbulent flow regime (18000-40000) • φ : 0.05 to 0.15% • Nanofluid inlet temperature: 45 to 65 ° C	The addition of nanoparticles to the base fluid increases the HT in the best conditions by up to 16%. The TP coefficient of the nanofluid can reach 1.11%. This value is obtained for φ = 0.15% and Re of 18000.
Arya et al. [207] 2019	MgO-Eg	• DTHE with counterflow • Laminar-transient-turbulent flow regime • φ: 0.1, 0.2, 0.3%	The HTC of the HE increases by 27% for φ = 0.3% compared to the base fluid. The presence of nanoparticles enhances the pressure drop by 0.35% for φ = 0.3%.
Arani and Amani [208] 2012	TiO_2-water	• DTHE with counterflow • Turbulent flow regime (8000-51000) • Φ: 0.002 to 0.02%	As the Re and φ enhance, the Nusselt number increases. For all values of φ, the Nusselt number is greater than the Nusselt number of the base fluid. To compensate for the pressure drop at high Res, more power is needed, so the use of nanofluids at high Res has fewer advantages and applications compared to nanofluids at low Res.
Reddy [209] 2014	TiO_2-Eg/water	• DTHE • Turbulent flow regime (4000-15000) • Φ: 0.0004 to 0.02%	HTC and coefficient of friction increased by 10.2% and 8.73% in φ by 0.02%, respectively, compared to the base fluid.
Madhesh et al. [210] 2014	Cu/TiO_2-water	• DTHE with counterflow • Turbulent flow regime • φ : 0.1 to 2%	The HTC, Nusselt number, and total HTcoefficient are increased by 52%, 49%, and 68%, respectively, for φ up to 1%. On the other hand, for φ = 1% to 2%, the HTC and Nusselt number are increased significantly. In general, for all values of φ, the total HTC is increased.
Han et al. [211] 2017	Al_2O_3 – water	• DTHE with counterflow • Turbulent flow regime (20000-60000) • φ : 0.25 and 0.5%	HT enhances dramatically with the temperature and φ. Also, by increasing the inlet temperature, HT and Nusselt number are increased.
Aghayari [212] 2014	Al_2O_3 – water	• DTHE with counterflow • Turbulent flow regime • φ : 0.1 to 0.3%	HTC and Nusselt number are enhanced significantly up to 19% and 24%, respectively. Also, increasing temperature and φ have an important effect on the HTC.
Arani and Amani [213] 2013	TiO_2-water	• DTHE with counterflow • Turbulent flow regime • φ : 0.01 to 0.02% • Nanoparticles with diameters of 10, 20, 30, 50 nanometers	The Nusselt number increases for all dimensions and volumetric fractions relative to the base fluid. On the other hand, by reducing the diameter of nanoparticles, the Nusselt number does not increase in general. For φ and Re range of the study, nanofluids with a nanoparticle diameter of 20 nm have the highest coefficient of TP.
Kassim et al. [214] 2019	SiO_2-water	• DTHE with counterflow • Turbulent flow regime (3019.43-4824.22) • φ : 0.1, 1 and 3%	The HTC increases with φ and Re. The percentage increase of Nusselt number is 15.72%, the friction coefficient is 11.51% and the TP is 11.57% when φ is 3% and the flow rate is 1.6 lit/min.
Shahsavar et al. [215] 2017	Fe_3O_4/ Cnt-water	• DTHE with counterflow • Laminar flow regime • Under the influence of magnetic field	With increasing Re and φ of Fe_3O_4 and Cnt nanoparticles, the overall HTcoefficient enhances. To achieve maximum heat transfer, a high φ should be used along with low values of Re.
Bezaatpour and Goharkkhah [216] 2020	Fe_3O_4-water	• DTHE with counterflow • Laminar flow regime • Under the influence of magnetic field	The use of an external magnetic field increases HT by up to 320% (with a slight increase in pressure drop). The best conditions for the HE operation are low Re, high magnetic field strength, and high φ.

According to the investigations carried out on nanofluids in DTHEs with smooth walls, it can be concluded that:

- The use of dual-tube smooth HEs with the counter flow is more appropriate at high Res.
- Surface properties of nanoparticles, φ, and the shape of nanoparticles are the most important parameters for increasing HT in a DTHE.
- The thickness of the thermal boundary layer and the thermal conductivity of the nanofluid has a significant effect on the HTC.
- As φ and Re increase, the HT rate and overall HTcoefficient are enhanced dramatically.
- By adding tape inside the tube, the HTC of the nanofluid increases dramatically.
- The use of coil inserts inside smooth DTHEs is useful for improving HT and at the same time causing a pressure drop.
- Nanofluid has no limitations in terms of pumping power and can be suitable for practical applications.
- The use of nanofluids can improve the TP and efficiency of HEs.
- By applying a non-uniform magnetic field, the ferrofluid flow can be controlled and the HT process is improved.
- By increasing the amount of heat transferred to the cold fluid, the performance of the DTHE is improved.
- The use of nanofluids can change the rate of transition of the flow regime from laminar to transient and transient to turbulent.
- As φ and Re are enhanced, the average Nusselt number increases.
- The HT rate of nanofluids is higher than that of the base fluid and this rate enhances with φ.

Review literature demonstrates that studies on DTHEs depend on the type of nanofluid used and as a result, the results obtained cannot be generalized to all nanofluids.

According to Fig. 15, it can be observed that in addition to the impact of the type of nanofluid used in the HE performance, experimental conditions, including laminar or turbulent, φ, the size of nanoparticles have a very significant effect on the performance of the HE. It is also shown in Fig. 15 that silver nanoparticles have the greatest effect on TP.

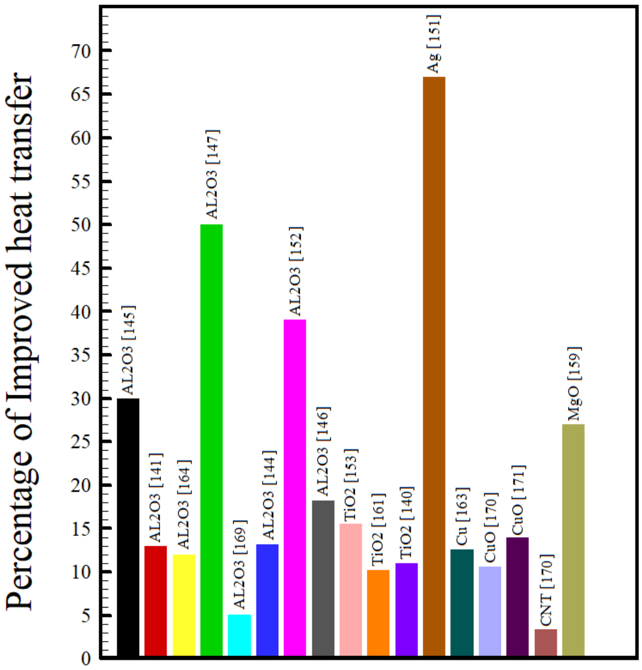


Fig. 15. Comparison of TP of some nanofluids used in DTHEs.

6. Conclusions

The present review evaluates the TP of DTHEs in the presence of nanofluids. Since DTHEs are widely used in industrial and engineering processes, and on the other hand, due to the appropriate and desirable properties of nanofluids (an extraordinary increase in thermal conductivity) compared to other fluids, many investigations have been done considering the use of nanofluids in HEs. Most studies have shown that the use of nanofluids in DTHEs significantly improves the HT rate compared to other fluids. By enhancing φ and Re, the Nusselt number increases, leading to an improvement in HT and the performance of DTHEs. The following research challenges can be expressed from this review:

- The advantages of using nanofluids in HEs with different thermophysical properties depend on the working conditions, the type, and the geometric shape of other heat exchange equipment. Nanofluids can have different results in different conditions.
- Since nanofluids sediment if they lose their stability, the TP of the HE is affected significantly. A few researches have been done in this field and therefore more research are required to develop appropriate design strategies.
- The development and presentation of accurate correlations that can predict the pressure drop and HTC of nanofluids in HEs is very effective. Therefore, due to the increase in economic considerations in designing and presenting new methods in mathematical computing, it is necessary to provide appropriate analytical correlations.
- According to the studies conducted in this review article, it is observed that there is a major problem to use nanofluids in HEs, which is the lack of standardization among various studies and evaluations. It can be seen that it is difficult to compare different published articles due to extensive changes in data analysis and interpretation and the lack of standard approaches. As a recommendation, the existence of extensive communication between researchers can help the rapid growth of this technology.
- Synthesis and stability of nanoparticles and nanofluids are among the factors influencing the experiments. Therefore, in addition to considering the performance of nanofluids, the costs required to prepare nanofluids must also be considered.
- Future studies on nanofluids and the performance of HEs containing nanofluids should be more comprehensive. Because the results demonstrate that factors such as morphological shape, preparation techniques, type of nanoparticles, and surfactants have a significant impact on the measurement of variables. Therefore, if these factors are ignored, their effect is significant in the results and the correct results are not obtained. Hence, it is recommended to avoid simplifying assumptions as much as possible and to carefully examine and measure all factors.

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