applied sciences

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Review

Nanotechnology Applications in Ground Heat Exchanger Pipes: A Review

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Abstract: The use of Ground Source Heat Pumps (GSHPs) has grown exponentially around the world over recent decades. The GSHP represents an alternative device to electric heating systems and oil boilers. Additionally, it requires a lower power consumption and less maintenance than combustion-based heating systems. Moreover, the CO_2 emissions produced by a GSHP are lower than other systems based on burning oil, gas, or biomass. However, the main obstacle for the widespread use of GSHPs is the high cost of Ground Heat Exchanger (GHE) installation, a technology that exhibits low thermodynamic efficiencies. Over the past decade, some studies have been conducted to improve heat transfer in GHE pipes using traditional working fluids, creating new pipe materials or designing new heat exchanger configurations. The main contribution of this paper is a summarization of the outcomes of theoretical, numerical and experimental studies to improve heat transfer in GHEs using nanotechnology. Additionally, the development of new fluids (nanofluids) and new materials (nanoparticles and nanocomposites) applied to heat exchanger pipes and the designs and configurations of GHEs are highlighted. As a result, the present review provides a perspective for future research regarding the use of nanotechnology to reduce the costs involved in GHE for GSHP improvement.

Keywords: nanomaterials; nanofluids; Ground Heat Exchanger (GHE); Ground Source Heat Pump (GSHP); heat transfer; thermal conductivity

Citation: Rivas-Cruz, F.; Hernandez-Martinez, E.G.; Portillo-Velez, R.d.J.; Rejón-García, L. Nanotechnology Applications in Ground Heat Exchanger Pipes: A Review. *Appl. Sci.* **2022**, *12*, 3794. https://doi.org/10.3390/app12083794

Academic Editor: Kambiz Vafai

Received: 4 March 2022
Accepted: 3 April 2022
Published: 9 April 2022

1. Introduction

GSHPs are considered to be the best available technology for the air conditioning of residential or commercial spaces [1]. A GSHP is defined as a heating and/or cooling system designed to transfer heat to or from the ground, groundwater, or a surface water as a heat source or sink. A GSHP uses these different energy sources all the time, without any intermittent availability, as a heat source (in the winter) or a heat sink (in the summer). The principal advantages of this technology are the high electrical efficiency, low maintenance, reduction in fossil resources and low-carbon emissions. Attempts have also been undertaken to use water in such a way to minimize the pipe network length [2,3].

The GSHP has three main components. The first component is the GHE, which uses the subsoil as an energy source. The GHE moves fluid using a pump to transfer heat to the space to be conditioned as a source (heating in winter) or a heat sink (cooling in summer) through a pipe network buried under the subsoil (horizontal or vertical). Second, the heat pump (HP) raises the heat collected to a useful temperature, and transfers it to the space to be conditioned. Finally, the third component is a distribution system composed of a duct-work as an air-forced duct system.

Typically, a GHE uses a pipe network with different configurations to capture and/or dissipate heat from the ground, pond or lake (see Figure 1). This paper reviews the main developments in using GSHP pipes as a GHE and the new fluids used to improve the heat exchange.

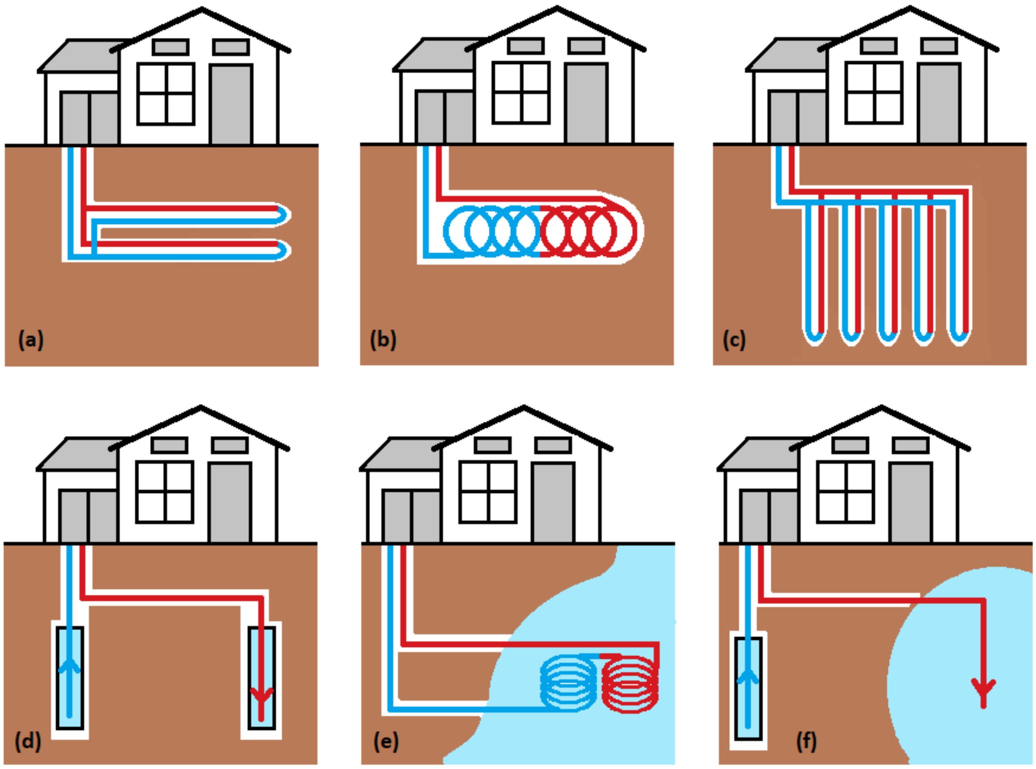

Figure 1. Different configurations of Ground Heat Exchanger: (**a**) closed horizontal loop, (**b**) closed slinky loop, (**c**) closed vertical loop, (**d**) open wells loop, (**e**) closed water loop and (**f**) open-circuit well and surface body.

The most used and available material for pipes in the GHE is high-density polyethylene (HDPE). HDPE has a low thermal conductivity, affecting the heat transfer between the ground and the space to be conditioned. This implies an increased GHE installation cost. Therefore, the installation of GSHPs becomes expensive due to the high costs of the GHE and its pipes, as mentioned by [4]. The vertical GHEs installed in boreholes are more expensive than horizontal installations in trenches. The first alternative was the use of thermally enhanced grout to improve thermal conductivity. For example, in [5], a thermally enhanced grout is used that reduces borehole thermal resistance. It minimizes the length and the number of boreholes for the GHE, reducing the installation costs.

Recently, researchers have striven to develop technologies to improve heat transfer in GSHP systems. This can be achieved by (1) increasing the thermal conductivity of the soil, improving the properties of the pipe material; (2) using different fluids; and/or (3) modifying a geometrical GHE's configurations pipes. A new research area to solve these problems is the use of nanotechnology for different purposes.

Nanotechnology is defined as an applied science, capable of manipulating matter on an atomic and molecular scale to solve different problems [6]. It has been used in many fields such as engineering, computing, and medicine. Nowadays, nanotechnology is deployed in distinct energy applications such as fuel cell, hydrogen, nuclear, photovoltaic, tidal, wind and geothermic technologies. An exhaustive review of these applications (including theoretical and experimental works) of nanotechnology in renewable energy systems can be found in [7].

In nanotechnology, a particle is defined as a small object that behaves as a whole unit with respect to its transport and properties. Nanoparticles are particles between 1 and 100 nanometers (nm) in size with a surrounding interfacial layer. The interfacial layer is an integral part of nanoscale matter, affecting all of its properties. The interfacial layer typically consists of ions and inorganic and organic molecules. This paper will discuss two important aspects of nanotechnology in the sector of geothermic technologies for GSHP: nanomaterials and nanofluids.

On the one hand, scientists have not unanimously settled on a precise definition of nanomaterials, but agree that nanomaterials are identified by their very small size, around a few nanometers. These nanosized particles differ from coarser particles in their tendency to form agglomerates which are macroscopically perceived as one particle [6]. On the other hand, a nanofluid is a nanotechnology-based colloidal dispersion prepared to disperse some nanoparticles in conventional liquids. These advanced fluids have the capacity to enhance the performance of the conventional heat transfer fluids according to [8].

The design of new heat exchanger configurations is an important aspect to improve energy capture. This presents a multivariate problem, requiring the use of computer tools to simulate the heat exchanger before it is manufactured. Additionally, the simulation analyzes the behavior of certain mixtures of fluids and materials in order to develop an optimized design.

Some similar reviews analyzing the nanotechnology in GHSP have been biased, in that they have only focused on specific aspects. For example, the work of [9] presents a review only covering nanofluids. The authors of [10] reported a review about the improvements in the thermal properties of a fluid, with the soil and the material individually affecting the heat exchanger in the geothermal energy pipes. The research work of [11] presents some experimental studies in the laboratory using nanofluids. Finally, in [7], all the possible applications of nanotechnology to any renewable sources addressing the GSHP as a subclass are reported. All these works are relevant. However, they are focused on some particular research focus. A global vision involving all the main aspects of the GSHP technology for the researchers is omitted. A more integral and complete review that summarizes the principal nanomaterials and nanofluids approaches in a single article could therefore be useful.

Thus, the main contributions of this work are summarized in the following points:

- This paper presents an analysis of theoretical, numerical, and experimental studies, conducted in recent years, addressing the use of nanotechnology to improve heat transfer in a GSHP.
- To the best of our knowledge, a similar integral review has not been published in the literature.
- This work breaks down research on nanofluids and nanomaterials in the composition, designs, and configurations of heat pipes, including the software used to simulate these systems with the objective to enhance the heat transfer efficiency and reduce the installation cost of GHE.
- This review presents some tables to visualize the main contributions of the reviewed works. The methods or models found in the literature are highlighted in these tables.
- A summary of all these works is presented, including a reflection and discussion of the future trends of nanotechnology applied to GHE pipes for GSHP systems.
- Finally, this review clarity to several areas, and can not only be beneficial to those working in nanotechnology, but rather to members of the general public who may be interested in these issues.

2. Literature Review

This review searched and analyzed the available literature on the development of new nanofluids, composed of a fluid (commonly oil or water) and nanoparticles, and new materials (nanoparticles and nanocomposites) which enhance the heat transfer efficiency of heat pipes.

The next sections summarize the most important points as determined by the researchers. Most of the works aimed to improve the heat transfer applied in the GHE. The works are classified into two principal groups: (1) those using nanofluids as a heat-carrying fluid and (2) those modifying the HDPE with nanomaterials. Each group includes research based on theoretical and numerical simulations, as well as experimental works.

2.1. Nanofluids

2.1.1. Theoretical and Numerical Simulations

Several theoretical models based on differential equations have been reported in the literature to simulate the thermodynamic behaviour of GSHPs [12]. The main goal of these mathematical models is to determine the heat temperature carried by the fluid along the pipe from the borehole under certain operating conditions. For example, based on the transient heat conduction in the borehole, the temperature distribution of the ground might be obtained by solving the following partial differential equation:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{\alpha}\frac{\partial T}{\partial r} \quad r_b < r < \infty$$

$$-2\pi r_b \lambda \frac{\partial T}{\partial r} = q \quad r = r_b \quad t > 0$$

$$T - T_0 = 0 \quad r > r_b \quad t > 0$$

where T stands for the ground temperature distribution at a distance r, r_b represents the borehole radius, q is the heating rate per length of the source, t is the time, T_0 is the initial temperature of the ground, and λ and α are the thermal conductivity and diffusivity of the ground. Some numerical methods are commonly used to solve the previous equations. However, additional models are required to improve the approximations of the heat temperature carried by the fluid along the pipe, as in [12]. Moreover, such models must consider the GSHP fluid properties to obtain accurate results to optimize the GHSP performance.

Therefore, nanofluids are attractive in the effort to achieve higher efficiencies and reduce the system size. The volumetric concentrations of nanofluids in the range from 0.1% to 1% can result in a reduction in the borehole thermal resistance. Additionally, they can reduce the borehole length depending on the kind of nanofluid.

For example, with a 1% concentration of Cu, graphite, Ag, and CuO, the reductions in the length of boreholes were 2.3, 0.52, 0.33 and 0.14, respectively [13]. The authors who found this discussed and compared different papers focused on nanofluids used in geothermal systems to improve heat transfer. They concluded that a heat transfer enhancement is dependent on several factors, including the type of nanofluid, concentration, and system specification. Thus, the reduction in the heat exchanger sizes and the borehole sizes used in the geothermal-based system affect the efficiency of the system.

The application of nanofluids in heat pipes, due to their superior thermophysical properties, was addressed in [14]. This work summarizes and provides the outcomes of experimental and theoretical studies of some nanofluids as working fluids in heat pipes, such as metals (Cu, Ag, and Gold, etc.) and metal-oxides (Al_2O_3, CuO, MgO, ZnO, TiO_2, Fe_2O_3, and SiO_2, etc.) to obtain an enhanced thermal performance. The results include the calculations of thermal efficiency, thermal resistance, the effective thermal conductivity, surface temperature gradient and the convective heat transfer coefficient in the evaporator and condenser section. Different configurations of heat pipes were reported according to different sizes and shapes related to the application requirements, integrating summaries and tables. In conclusion, the heat transfer mechanisms depend on the type of heat pipe, the characteristics of the nanofluids, the design and operating parameters of the heat pipes, etc.

An important drawback in the vertical GHE is the existence of possible nanoparticle sedimentation when the system remains static. To solve this, the paper [15] carried out numerical simulations with nanoparticles of Al_2O_3-water and Fe_3O_4-water at constant temperature (26 °C) to visualize the sedimentation inside the exchanger. When the fluid is static, the nanoparticles accumulate after many hours of sedimentation. This can be averted by a high-speed flow, a pulsed flow, or by optimizing the geometry of the bottom borehole. This work simulates important data, such as the effects of soil temperature, the Reynolds number, the effect of the size, type, the concentration of the nanoparticles, the suspension stability of composites, gravity, the effects of a pulsed flow, the borehole geometry and the turbulent eddy diffusivity.

The recent report in [16] shows that the heat transfer characteristics of current fluids are greatly improved by suspending nanosized solid particles with diameters of less than 100 nm. Recent research of nanofluids has analyzed the convective heat transfer rate, thermal achievement rate, viscosity, surface tension, friction factor, environmental impact, thermo-physical properties, the effect of fluid temperature, inlet velocity, the use of a surfactant to achieve a better stability of nanofluids, particle size, and the volume concentration effects, for instance, [17–19]. Several types of nanoparticles have been widely studied by researchers. Thus, the suspension of small amounts of nanoparticles of oxides (Al_2O_3, CuO, TiO_2, Fe_2O_3, SiO_2, etc.), metals (Cu and Ag), and carbon nanotubes (CNTs) in traditional base fluids (water, ethylene glycol, propylene glycol, engine oil, etc.) have increased thermal conductivity [16].

On the other hand, some works study the relevance of the physical properties of a nanofluid. The work [20] presents an approach using nanofluids in geothermal energy applications as working fluids to extract more energy from reservoirs and for space heating/cooling and industrial applications. In this research, a sensitivity analysis was performed to demonstrate the importance of the fluid viscosity and the heat capacity in geothermal energy production. The potential to apply nanofluids as working fluids in abandoned oil wells converted into double-pipe heat exchangers is studied, taking advantage of the significant improvement in the heat transfer of nanofluids. This research remarks on the importance of the thermophysical properties of nanofluids; for example, the viscosity and specific heat capacity and the fluid circulation rate improve the performance and the cost-efficient production of geothermal energy.

A study of the effects of the Al_2O_3-water nanofluid, as the heat transfer fluid, to reduce the length of a vertical GHE in a GSHP is presented in [21]. The authors used an innovative nanofluid which was engineered by dispersing solid nanoparticles in conventional heat transfer fluids. They evaluated the impact of the optimized thermophysical properties of nanofluids, such as the thermal conductivity and viscosity, which play prominent roles in convection heat transfer, both of which are optimized by using the Multi-Objective Flower Pollination Algorithm (MOFPA). The bore length computation with an Al_2O_3-water mix reduced the borehole length by 1.3% more than when just using water. Another important result revealed that the use of tubes and grout reduces the bore length due to their thermal resistances.

Some applications of nanorefrigerants and nanolubricants, mainly in air conditioning and heat pumps, were realized in [22]. The physical-thermal properties of suspended nanoparticles in refrigerants and lubricating oils of refrigeration systems were reviewed, classifying them into six topics: studies related to the Al_2O_3, CuO, TiO_2, CNT, and Cu nanoparticles and studies related to other nanoparticles ($R134a$/polyester mixtures with SiO_2, CuO, POE and other $R410a$ mixtures with $NiFe_2O_4$). The solubility of the mineral-based nanorefrigeration oil (MNRO) in different fluids, $R134a$, $R407C$, $R410a$, and $R425a$ was experimentally investigated. The conclusion of this work is that nanorefrigerants have a much higher and stronger temperature dependence on thermal conductivity at very low particle concentrations than conventional refrigerants. Additionally, the effect of carbon nanotubes (CNTs) enhances heat transfer.

In [7] is presented an exhaustive review of theoretical and experimental works related to the use of nanotechnology in renewable energy systems (solar, hydrogen, wind, biomass, geothermal and tidal energies). This review includes works for all renewable energies, with the use of nanofluids, nanomaterials, and nanoparticles. In the case of geothermal energy, different applications with nanotechnology were addressed, with two of them being highlighted. The first to be addressed was the use of nanofluids to cool fluids inside pipes exposed to high temperatures, using nanofluids to cool sensors and electronic devices in drilling machines and GHE depending on temperature (low, medium or high), and district heating applications using networks piped hot water to heat many buildings in entire communities. Second, the authors noted that nanofluids can be used as a working fluid to extract energy from the ground and process it in a power plant system or produce large amounts of working energy.

Similarly, the paper [23] summarizes works with the use of suspended nanoparticles to enhance the heat transfer characteristics into the heat pipes. The researchers found new opportunities with the use of nanofluids, e.g., to improve the thermal efficiency and reduce the thermal resistance of the heat pipe. This work summaries experimental and theoretical studies of some of the preparation methods, processes and heat transfer characteristics of nanofluids. The thermal performance of the nanofluid heat pipe was superior to that of the conventional working fluid, usually water.

A preliminary evaluation of the potential of nanofluids that guarantee the vertical temperature of the heat carrier in the borehole was performed in [24], using the mathematical model in [25]. Some assumptions were imposed on the model, for example, the variations of temperature with depth, the heat conduction in the vertical direction within the pipe wall, the grout, the borehole thermal resistance between the pipe and the borehole wall, and the ground. The objective was to know which nanoparticle leads to the best performance in the borehole heat exchanger, showing the properties and comparative cost of various nanoparticles. The best thermal performance was found with Cu, followed by graphite, SiO_2, and Ag. On the other hand, Al_2O_3 and CuO were the worst choices. The mixes tested using CuO, Al_2O_3, Ag, SiO_2, Al, graphite and Cu with a volumetric concentration of 1% allowed reductions in the borehole length to 0.14, 0.19, 0.33, 0.36, 0.36, 0.52 and 2.33%, respectively. Therefore, the cost of GHE increases using nanofluids depending on the shape and size of the particles, plus the energy consumption of the circulation pump due to the increased pressure drop. However, this cost is marginal compared to the costs of nanoparticles due to the low value of the mass flow rate.

The results of numerical simulations for the application of the CuO-water and Al_2O_3-water nanofluids, as the working fluids of a geothermal GHE, were reported in [26]. The simulations were compared with literature data. The Reynolds Averaged Navier–Stokes (RANS) equations with the shear stress transport (SST) k-ω turbulence model were numerically solved to represent the flow and the physical properties of the nanofluids using the available correlations. Fluent software and the SIMPLEC algorithms were used for the coupling between pressure and velocity, and the finite volume method on collocated cells was applied to discretize the RANS equations. In the same research, some studies of the influences of natural factors in the analytical method, such as groundwater flow on heat pump design, was presented to obtain the temperature distribution along the heat exchanger. Additionally, the modeling and optimization of a novel combined cooling, heating, and power (CCHP) cycle driven by geothermal and solar energies using the CuO-water nanofluid are presented. The results show that the CuO-water nanofluid allows a higher heat extraction than the alumina-water nanofluid, but at the cost of higher pressure losses and pumping powers.

A numerical solution to optimize MgO-water nanofluids to reduce the cost and increase the heat transfer coefficient is analyzed in [27]. The optimization was performed by the non-dominated sorting genetic algorithm (NSGA-II), which has a significant capability to achieve an optimal response. For this purpose, the solid volume fraction (φ), Reynolds number (Re) and the diameter of nanoparticles (Dp) were selected as the optimization variables. Thus, to reach the heat transfer coefficient of 280 W/m^2K, the cost is equal to USD 355 per liter in the first generation and USD 218 per liter in the last generation (total population of 50 members and repetition of 15 times) according to the Pareto diagram. This result proves that theoretically the optimization has been able to reduce the cost by up to 38%.

The work of [28] presents some numerical and theoretical studies of heat transfer applied to rotating machines that convert electrical energy into mechanical energy or vice versa, using the CuO-*EG* (ethylene glycol) nanofluid under different conditions inside the heat pipe. The properties of nanofluids were implemented in a wide range of numerical models, using experimental data to study the effects of the mass of the fluid to be inserted in the pipe, the speed of rotation of the machine, and the size and concentration of nanoparticles to evaluate the performance of heat transfer. A new methodology based on Particle Swarm Optimization (PSO) in MATLAB© was presented to solve the equations (flow of nanofluids inside the heat pipe) and the heat transfer equation. The authors give the thermo-physical properties of pure CuO and pure *EG* at the reference temperature and the thermophysical properties of the CuO-*EG* nanofluid. The heat transfer through the heat pipe depends on various factors such as the input nanofluid mass, the rotation speed of the heat pipe, nanoparticle size and nanoparticle concentration.

Recent studies found, by using numerical simulations, several novel phenomena such as a radiative effect for an electrically conductive Williamson nanofluid [29]; a radiative effect for a Casson nanofluid with solar thermal radiation [30]; variability in the viscosity and conductivity of hybrid nanofluids [31]; and heat transfer in a magneto two-phase nanofluid enclosed in an adiabatic rotating cylinder [32]. All of these have potential applications in GSHPs.

A summary of the results reported by the previous researchers using theoretical and numerical simulations, classified by the type of applied nanofluid and its application, is shown in Tables 1 and 2.

Table 1. Summary of theoretical and numerical studies on heat exchanger pipes using nanofluids.

Authors	Nanofluids	Applications	Results and Remarks	Model or Method
Ahmadi et al. [13]	Ag, Cu, Al, graphite, Al_2O_3, CuO, SiO_2, Al_2O_3/water, and CuO/water	Review of geothermal systems using nanofluids	Increasing the temperature and concentration of nanoparticles leads to a higher thermal conductivity of nanofluids at higher flow rates	Taguchi algorithm, thermal resistance model, group method of data handling (GMDH), and artificial neural networks
Diglio et al. [24]	Ag, Cu, Al, graphite, Al_2O_3, CuO, and SiO_2	A numerical study of nanofluids used to replace conventional ethylene glycol/water mixture as heat carrier in a BHE	Copper-based nanofluid has the highest borehole thermal resistance reduction, reaching 3.8% compared to base fluid. The best thermal performance is obtained using Cu, graphite, SiO_2, and Ag. The worst case using Al_2O_3 and CuO	Geometry used for 1D mathematical model and thermal resistance model
Gupta et al. [14]	Ag, Cu, gold, Al_2O_3, CuO, TiO_2, ZnO, Fe_2 O_3, MgO, and SiO_2	A review of the applications and exploration of the dependence of all parameters on each other of nanofluids used in heat pipes	Outcomes of experimental and theoretical studies of nanofluids as a working fluid in heat pipes, like metals (Cu, Ag and Gold), metal oxides (Al_2O_3, CuO, MgO, ZnO, TiO_2, Fe_2O_3 and SiO_2). The authors state that the parameters have their own individual and combined effect on the thermal performance of a heat pipe	Thermal resistance network of heat pipe
Sun et al. [15]	Al_2O_3 and Fe_3O_4	Numerical simulation of the nanoparticle stability in a vertical GHE	Nanoparticles appear at the hole bottom after many static hours, but they can be removed using fluid flow at high velocity or optimizing the borehole geometry	Non-linear complex fluid and particle flux
Ganvir et al. [16]	Ag, Cu, Al_2O_3, CuO, TiO_2, Fe_2 O_3, SiO_2, and CNTs	Nanofluid applications: automotive radiators, electronic cooling, space and defence, heat pipes, biomedical industry, etc.	The review of nanofluid studies for convective heat transfer performance, thermo-physical properties, effect of fluid temperature, inlet velocity, among others	Theoretical predictions of two-component mixtures suggested by Hamilton and Crosser's analysis. Static and dynamic model of thermal conductivity and finite volume method

Table 2. Summary of theoretical and numerical studies on heat exchanger pipes using nanofluids (Continuation).

Authors	Nanofluids	Applications	Results and Remarks	Model or Method
Daneshipour and Rafee [26]	Al_2O_3/water, CuO/water	Applications of the CuO water and Al_2O_3-water nanofluids as the working fluids of a GHE	Numerical simulation using Fluent software, finite volume method, and the SIMPLEC algorithms. The CuO-water nanofluid gives higher extracted heat than the alumina-water nanofluid and it has higher coefficients of convection heat transfer	Reynolds Averaged Navier–Stokes
Esfe et al. [27]	MgO-water	Numerical solution to optimize MgO-water nanofluids to reduce the cost and increase the heat transfer coefficient.	The NSGA-II algorithm has been used to reduce the cost and increase the heat transfer coefficient. The optimization has been able to reduce the costs up to 38%.	Non-dominated sorting genetic algorithm II (NSGA-II)
Sui et al. [20]	Al_2O_3, Al_2O_3-EG	Nanofluids as working fluids to extract more energy from reservoirs and improve the exploitation of geothermal resources.	The viscosity and specific heat capacity of nanofluids in the operation of geothermal wells are very important for geothermal applications, to improve the exploitation of reservoirs.	Heat transfer models
Uddin et al. [28]	CuO-*EG*	Heat transfer in rotating heat pipes.	The heat transfer depends on the nanofluid mass, nanoparticle size and the concentration.	Non-linear differential equations with a new methodology based on particle swarm optimization (PSO).
Narei et al. [21]	Al_2O_3-water	Effects of the nanofluids to reduce the bore length of vertical GSHP.	Using Al_2O_3/water nanofluid instead of water reduced 1.3% the bore length of a vertical GHE. However, the results of the application of nanofluids are not entirely satisfactory, since the grout had the greatest potential to decrease the length of the perforation.	Prediction models
Alawi et al. [22]	Cu, Al_2O_3, CuO, TiO_2, and CNTs	Studies and applications on nanorefrigerants and nanolubricants, mainly for air conditioning and heat pumps	The nanorefrigerants reduced the energy consumption. They have a higher and strongly temperature-dependent thermal conductivity at very low particle concentrations than conventional refrigerants	Heat transfer models through thermal and rheological properties
Hussein [7]	Al_2O_3	Applications of nanotechnology in renewable energy systems	Geothermal energy has various applications, such as district heating networks using piped hot water to heat many buildings in entire communities. More than 72 countries have reported the direct use of geothermal energy	Heat transfer models
Sureshkumar et al. [23]	Ag, Cu, Al, Au, Al_2O_3, CuO, TiO_2, ZnO, Fe_2O_3, SiO_2, Al_2O_3/water, CuO/water, Al_2O_3-*EG*, and ZnO-*EG*	Some experimental methods and theoretical studies in the preparation of nanofluids for thermal conductivity improvements in heat pipes	The thermal performance of the nanofluid heat pipe was superior to that of the conventional working fluid, mainly water.	Heat transfer models
W. Jamshed et al. [31]	TiO_2/water and Cu/water	Applications of the CuO water and Al_2O_3-water	Numerical simulation of the unsteady flow of a non-Newtonian Casson nanofluid to investigate the slip condition and solar thremal transport in terms of convection	Boundary layer equations

2.1.2. Experimental Work

An experimental study was presented in [11] using Al_2O_3/ethylene glycol-water (EG-water) nanofluids applied to a spiral and U-type GHEs. The GSHP system was used to heat a 21 m^2 room located in Sivas Cumhuriyet University Campus, Turkey, where normally the weather is cold. The authors addressed the improvement of thermal conductivity only in Al_2O_3 nanofluids, but these studies do not provide test results related to the use of nanofluids in the specific system of GHEs or GSHPs. Other studies show that nanofluids have better heat transfer properties than base fluids under constant heat flow. Their effects have been investigated in many areas, such as radiators, heat exchangers and electronic devices. Researchers have described the experimental setup, including the heat load calculation, the trench depth and GHE design based on the ASHRAE book, using a 25% EG ratio of the fluid to prevent freezing. The experiments showed that a concentration of 0.1% nanofluid in the U-type heat exchanger increased the performance by 19% compared to glycol-water and by 17.7% compared to the nanofluid with a concentration of 0.2%. The nanofluid with a concentration of 0.1% increased the heat transfer rate by up to 2% in a U-type GHE and 3.2% in a spiral GHE according to the unit pipe length heat exchange rates.

The thermal performances and economic efficiencies of different nanofluids (Ag, MgO, $MWCNT$ and $DWCNT$), comparing the price, the efficiencies and the benefices, to improve the heat transfer are addressed in [33]. The experiments compared the relative thermal conductivity and the relative viscosity of $MWCNT$-water, $DWCNT$-water, Ag-water and MgO-water. The $MWCNT$-water nanofluid showed higher relative thermal conductivity (0.2 vol.%) and relative viscosity than the other nanofluids. Some factors influenced the thermal conductivity of nanofluids, e.g., the method of nanofluid production (single and two stage), the type of surfactant, sonication rate, the device of characteristic measurement, nanoparticle size and shape. The thermal efficiency of carbon nanofluids is slightly better than that of oxide nanofluids, although their price is several times higher. For this reason, the authors state that the use of nanofluids for heat transfer is not profitable and can only be used in high-tech and high-profit industries.

The existence of two different methods (one- and two-step methods) useful for the preparation of nanofluids is explained in [34]. The authors noted that thermal conductivity and viscosity are important parameters to study the potential for heat transfer enhancement. They presented experimental and theoretical studies affecting thermal conductivity, for example, particle type, charge, size, and shape, including environmental parameters such as the base fluid, concentration, temperature, and dwell time. In summary, the material type has a great effect on the thermal conductivity of nanofluids such as graphene, $CNTs$, Au, Ag, etc., which are more conductive than the TiO_2, SiC, and SiO_2 nanofluids. However, it appears that the type of material has little effect on the viscosity of nanofluids. Most of the results reveal that the viscosity and thermal conductivity increase as the particle load increases [34].

Olson [35] patented a nanofluid to increase heat transfer, introducing nanoparticles into the GHE (propylene glycol or a heat transfer oil). The inventor improved the thermal conductivity by 40% or more, achieved with only a 0.10% nanoparticle concentration. These nanofluids are quite different from conventional two-phase flow mixtures because it is recommended to use a new parameter for nanofluids, the so-called Mouromtseff number (Mo), which is a function of the viscosity (μ), the conductivity thermal (κ), density (ρ) and specific heat (Cp). The improved heat transfer reduced the installation cost because the circulation loop can be smaller and the pumping cost is also less expensive.

An experimental study in a closed loop of cold water with a storage tank is presented in [36]. An electrical heater controlled by adjusting the voltage and a cooling coil immersed inside a storage tank using a refrigerant (R11) with a mixture of titanium nanoparticles sized 21 nm were implemented. The aim of this research was to improve the efficiency of the heat transfer inside the pipe. The authors prepared five mixtures of different nanofluid concentrations using an ultrasonic homogenizer. The experiments were conducted with different work conditions and the experimental device was designed in a modular form using various heat fluxes.

A summary of the results reported by the previous researchers with experimental work given in Table 3.

Table 3. Summary of experimental studies on heat exchanger pipes using nanofluids.

Authors	Nanofluids	Applications	Results and Remarks
Kapıcıoğlu and Esen [11]	Al_2O_3-*EG*-water	Using the nanofluid Al_2O_3/ethylene glycol-water (EG-water) in two HGHE systems and one GSHP system	The results showed that with a 0.1% nanofluid concentration in the U-type GHE, the heat exchanger improved the performance by 19% compared to glycol-water and increased performance by 17.7% with a concentration of 0.2%. The setup was based on the ASHRAE book.
Alirezaie et al. [33]	Ag, MgO, *MWCNT*, and *DWCNT*	Experimental data of efficiency of different nanofluids are reviewed and an efficiency-price index is proposed	An economic analysis concluded that nanofluids do not have economic justification except in high-tech devices with critical application
Yang et al. [34]	Graphite, Al_2O_3, CuO, TiO_2, Fe_2O_3, SiO_2, *SiC*, and *CNTs*	Viscosity and thermal conductivity improvement of nanofluids	Graphene, *CNTs*, Au, and Ag are more conductive than the TiO_2, SiC, and SiO_2 nanofluids. Most of the results reveal that the viscosity and thermal conductivity increase as the particle charge increases.
Olson [35]	Al_2O_3, TiO_2, and Fe_2O_3	Patented nanofluid to introduce nanoparticles into the GHE of GSHP	A new parameter called the Mouromtseff (Mo) number is introduced, which is a function of the μ, κ, ρ, and Cp. Heat transfer is improved, GHE size is reduced and pumping cost is reduced; therefore, installation cost is reduced
Naphon et al. [36]	Refrigerant *R*11	Closed circuit of cold water using a storage tank, with the refrigerant (R11) used as base working fluid with a mixture of titanium nanoparticles of 21 nm size	The results indicate that the heat transfer capacity of the pipe depends on the fluid transport properties; that is, the efficiency of the heat pipe tends to increase with increasing heat flow. Increasing the temperature between the evaporator and condenser sections results in a higher rate of heat transfer.

2.2. Nanomaterials

2.2.1. Theoretical and Numerical Simulations

The research in [37] focused on the advantages and disadvantages of fillers, commonly used as thermally conductive polymer composites (metallic, ceramic, carbon nanotube, and graphite) applied to HDPE. The acceptable thermal conductivity used in modeling was found to demonstrate its effect on tubing to reduce the GHE well length in a GSHP system. The best model choice was to use low-temperature in situ expandable graphite filler added to the HDPE polymer (LTEG/HDPE composite). This produces a composite filled with 20 vol % of LTEG with acceptable thermal and rheological properties with a thermal conductivity filled ($Wm^{-1}K^{-1}$), 10 wt% of LTEG. The length of the GHE was reduced to near to 10% of the total borehole pipe. They recommended the use of LTEG as a suitable filler to add to the HDPE polymer. Additionally, additional work on the performance of the mechanical properties of the hydrostatic design basis is proposed.

The performances of different GHE configurations (single U-pipe, double U-pipe, and coaxial) are compared in [4]. This work was carried out with standard HDPE pipes and thermally enhanced polymers pipes with inorganic nanomaterial fillers. The main goal was to evaluate the economic benefits of thermally enhanced (TE) pipes by comparing sizing calculations and 10-year hourly simulations for some configurations. The Ground Loop Heat Exchanger Professional (GLHEPro©) was used for calculations using a synthetic heat load profile as input, a medium heat dominated office building located in the US in the Colorado climate zone. This study demonstrates that the use of TE pipes instead of standard HDPE pipes allows a reduction in the borehole thermal resistance of between

22.3 and 24.4%, a reduction in the total GHE length of between 9.0 and 14.8% and a reduction in the construction cost of between 3.3 and 8.6%. GSHP fitted with TE pipes can be a financially feasible and environmentally beneficial solution, even though the current typical commercial cost of TE pipes is almost twice that of conventional HDPE pipes. The authors proposed to work with the development of a tool to quickly and easily carry out size, performance and cost comparison analyses for a wide range of situations to present a more accurate and realistic view of the advantages and disadvantages of using TE pipes in the construction of GHE.

A new idea to improve the thermal conductivity of HDPE pipes, which are resistant to oxidation but have low thermal conductivity and are used in many land source applications, was presented by [38]. The computational analysis presents a new fabrication composed of HDPE with aluminum wires that are distributed circumferentially and equally in the thickness of the pipe. Using a finite volume method and FORTRAN, a model comparing the pure HDPE and the new material was developed. The results shows an enhancement in the equivalent thermal conductivity of the composite by almost 25% for the 2 mm aluminum wires, and 150% for the 3 mm wires depending on the number of wires. Similarly, in [39] is realized research on the effect of adding aluminum powder to an HDPE with different volumetric concentrations. A numerical model shows that the thermal conductivity of the composite was less than 10% by volume, while [40] proposed a model using an aluminum nitride-HDPE mix, increasing the thermal conductivity.

A review is given in [10] on the enhancement of the thermal properties of individual components affecting the heat exchanger between the heat carrier fluid and the ground applied in geothermal energy piles. Some geometrical modifications and the application of nanofluids as a heat carrier fluid are presented. Additionally, modifications of the pipe material (the heat extracted/rejected in the ground using HDPE pipes) and the concrete mixture are carried out to reduce the total pile thermal resistance. This was achieved using a geometrical optimization in different pipe configurations. Thus, reducing the number of pipes and their arrangement improves the thermal behavior of the GHE. The authors mentioned that Versaprofiles (an HDPE pipe manufacturer for geothermal applications) developed an HDPE pipe for borehole heat exchangers, known as the GEOperforms, with a thermal conductivity 75% higher than the conventional HDPE pipe.

In a similar work, several types of heat pipes classified into three groups, sintered, groove and mesh types, were presented, [41]. The authors reviewed various types of heat pipes for different applications such as ground source heat pumps, thermal diodes, rotating heat pipes, etc. They included a review of nanotechnology applications in heat pipes using nanoparticles and introduce a new term, “nanobubbles”. In this case, no research work has been conducted so far on the applications of nanobubbles to improve heat pipes, only theoretical research, as a recent study phenomenon. As a conclusion, they claim that the technology and the science using nanoparticles in heat pipes is still in the initial stages.

In [42], the performances of different configurations of vertical coaxial exchangers are modeled. These configurations are tested using a thermally improved HDPE pipe, applying carbon nanoparticles to the outside. This enhances the thermal conductivity of 0.7 W/m-K, corresponding to a 75% higher than ordinary HDPE. The GLHEPro© and the Earth Energy Design (EED©) programs were used for the simulation. The thermal resistance of the well decreased and the thermal mass of the water contained in the coaxial exchange increased. GHE coaxial configurations helped reduce the total well length by up to 23%.

The review [43] introduced a new interdisciplinary theory: nanothermodynamics. This is an extension of the classic thermodynamics theory to the nanometer scale. It serves as a bridge between macroscopic and nanoscopic systems. The focus and emphasis are placed on the use of nanothermodynamics models to find the size-dependent thermal stability, magnetic properties, photoelectric behaviors, thermoelectric phenomena, mechanical properties, electrical properties, volume expansion coefficient, mass density, and energies of nanomaterials. It is desirable to predict the macroscopic, mesoscopic, and nanoscopic properties of materials. This work presents a complete comparison of different materials evaluating the thermal stability, enthalpies, magnetic and mechanical properties, thermal and electrical conductivity, diffusivity, photoelectric behaviors, relativity permittivity, and other parameters.

The thermal conductivity of *CNTs* and their polymer nanocomposites offers new possibilities to improve TC in several applications, including power electronics, electric motors, and generators, heat exchangers, among others; this is reviewed in [44]. Some papers using CNT-HDPE were reported. The crystallinity of the polymer strongly affects its TC, which roughly varies from 0.2 W/mK, for amorphous polymers such as polymethylmethacrylate (PMMA) or polystyrene (PS), to 0.5 W/mK, for highly crystalline polymers such as HDPE. The use of the different nanoparticles in HDPE filled with 7% expanded graphite of nanometric size has a TC of 1.59 W/mK, double that of the microcomposites which have a size of 0.78 W/mK at the same volumetric content. The conclusion was that the unusually high thermal conductivity makes CNT the most promising candidate material for thermoconductive composites. However, the thermal conductivities of polymer CNT nanocomposites are relatively low compared to expectations for the intrinsic thermal conductivity of CNTs.

Another work that addresses the improvement of thermal properties in piles is found in [45]. This paper found that the values for the heat rejected for U- and double-shaped pipes configurations were 53.81 W/m and 68.71 W/m, respectively, in an energy pile system of air conditioning for buildings such as offices and houses. The main objective was to reduce the cost of GHE. The average COP for heating was quite high, 3.9, and the seasonal primary energy reduction rate compared to a typical air conditioning system reached 23.2%. The authors of [46] used single and double U-tubes for application with *DN*32 HDPE pipes in boreholes and foundation piles. With the same flow rate with an inlet temperature of 35 °C for the heat reject mode and 3 °C for heat extract mode, the heat transfer values of the double U-pipes were about 50% and 45%, respectively, greater than those of a single U-pipe.

The summary of results reported by the previous works in theoretical and numerical simulations of nanomaterials is given in Table 4.

Table 4. Summary of theoretical and numerical studies on heat exchanger pipes using nanomaterials.

Authors	Nanomaterials	Applications	Results and Remarks	Model or Method
Narei et al. [37]	*CNTs*, *LTEG*, Ag, Al, and Cu	Thermal conductive polymer composites applied to HDPE pipes to reduce the pipe length of the borehole GHE	It is recommended to add *LTEG* composite as a suitable filler to the HDPE polymer. With a 10 wt% of *LTEG*, the length of the GHE was reduced to near 10% of the total borehole pipe	Thermal Network Model for U-Tube GHE [47]
Gosselin et al. [4]	TE	Different GHE configurations: single U-pipe, double U-pipe and coaxial, each with standard HDPE pipes and thermally enhanced (TE) pipes	A performance comparison of different GHE configurations. GLHEPro used to calculate different parameters. The use of TE pipes instead of HDPE pipes allowed a reduction in the Bore Thermally Resistance (BTR) of between 22.3 and 24.4%, a reduction in the total GHE length of between 9.0 and 14.8% and a reduction in construction costs of between 3.3 and 8.6%	Synthetic thermal load profile methodology
Bassiouny et al. [38]	HDPE-aluminum wires	HDPE pipes with aluminum wires used for ground source applications	Improvement of thermal conductivity depending on the number of aluminum threads used in HDPE. Increasing the number of wires increases the outer surface temperature, which can save heat exchanger piping length	Finite volume method

Table 4. *Cont.*

Authors	Nanomaterials	Applications	Results and Remarks	Model or Method
Narei et al. [37]	*CNTs*, *LTEG*, Ag, Al, and Cu	Thermal conductive polymer composites applied to HDPE pipes to reduce the pipe length of the borehole GHE	It is recommended to add *LTEG* composite as a suitable filler to the HDPE polymer. With a 10 wt% of *LTEG*, the length of the GHE was reduced near to 10% of the total borehole pipe	Thermal Network Model for U-Tube GHE [47].
Gosselin et al. [4]	TE	Different GHE configurations: single U-pipe, double U-pipe and coaxial, each with standard HDPE pipes and thermally enhanced (TE) pipes	A performance comparison of different GHE configurations. GLHEPro used to calculate different parameters. The use of TE pipes instead of HDPE pipes allowed a reduction in the Bore Thermally Resistance (BTR) of between 22.3 and 24.4%, a reduction in the total GHE length of between 9.0 and 14.8% and a reduction in construction costs of between 3.3 and 8.6%	Synthetic thermal load profile methodology
Bassiouny et al. [38]	HDPE-aluminum wires	HDPE pipes with aluminum wires used for ground source applications	Improvement of thermal conductivity depending on the number of aluminum threads used in HDPE. Increasing the number of wires increases the outer surface temperature, which can save heat exchanger piping length	Finite volume method
Faizal et al. [10]	Nanoparticles	Improve the thermal properties of elements in geothermal piles to improve the thermal conductivity of HDPE pipes	Geometrical optimization with the use of different diameters, numbers, and configuration piles. To improve the thermal conductivity of the HDPE material, nanofluids and highly thermally conductive material fillers are used. GEOperform pipe is 75% higher than the conventional HDPE pipe	Geometrical optimization
Chan et al. [41]	Nanobubbles	Distinct types of heat pipes classified into three groups, sintered, groove and mesh, applied in GSHP, thermal diodes, and rotating heat pipes	Introducing the new term "nanobubbles". This is a recent technology with few studies available. The applications using nanoparticles in heat pipes are still in the initial stages and future works may explore hybrid technologies with nanotechnology	Thermal model
Raymond et al. [42]	TE-HDPE	Performance of the coaxial pipe configuration in a vertical GHE	The coaxial GHE configurations decrease the total borehole length from 9% to 23% using TE-HDPE.	Dimensional thermal resistances according to Hellström's method
Yang and Mai [43]	Nanothermo- dynamics	Introduce the concept of nanothermodynamics	This is an extension of the classic thermodynamics theory to the nanometer scale. The developed model predicts macroscopic, mesoscopic, and nanoscopic properties of materials	Nanothermodynamics model
Han and Fina [44]	*CNTs*, *CNT*-metallic, *CNT*-ceramic	*CNTs* and their polymer nanocomposites to replace metal parts in several applications, power electronics, electric motors, generators and heat exchangers	The use of different nanoparticles in HDPE filled with 7 vol.% nanometer-size expanded graphite has a TC of 1.59 W/mK, twice that of microcomposites, which have a TC of 0.78 W/mK at the same volume. The *CNT* becomes the best promising candidate material for thermally conductive composites.	Thermal conductivity model
Hamada et al. [45]	CNTs	To reduce the cost of GHE using U-shaped and double-shaped pipe configurations	The average COP for heating was quite high, 3.9, and the seasonal reduction rate of primary energy compared to a typical air conditioning system reached 23.2%	Building thermal load analysis

2.2.2. Experimental Work

Experimental work is one of the least explored types of research due to the cost of test benches for GSHP. In [48], the mixed fabrication of HDPE and graphite nanopaletes at different filler concentrations is studied, analyzing the thermal, mechanical, and electrical properties of nanocomposites. The addition of Graphene Nanoplatelets (GNPs) has a significant effect on the thermal conductivity of HDPE, as mentioned in [49–52]. These works used fillers, such as graphite and carbon nanotubes, due to their ability to add thermal and electrical properties to HDPE composites by increasing Young's modulus. The best result was at 40 wt% of GNPs with HDPE, the κ of composite increases at 1.32 W/mK and Young's modulus reached 1330 MPa, while the pure HDPE values were 0.36 W/mK with 821 MPa. The GNPs greatly reduced the electrical resistivity of 1.6×10^{14} pure HDPE to 3.0×10^4 for mixed $40GNP$-HDPE.

The work in [53] prepared nanocomposites and hybrid nanocomposites based on high-density polyethylene (HDPE) as a matrix reinforced with an alternate and possible combination of $0D$ nanodiamonds (NDs), $1D$ Multi-Walled Carbon Nanotubes (MWCNTs) and $2D$ GNPs. This work evaluated the nanomechanical behavior of HDPE by the addition of nanofillers. The hybrid filled with ND and GNP exhibited superior surface properties. Exceptional toughness, a high elastic modulus, high fracture toughness, a low coefficient of friction, and excellent thermal conductivity can be achieved using ND. The HDPE/ND/GNP combination would improve the quasi-static and dynamic properties.

Experimental results of the form-stable phase change materials (FSPCM) are presented in [54]. Due to high thermal energy storage capacity and thermal conductivity, the FSPCM was manufactured by adding expanded graphite (EG) to stearyl alcohol (SAL) and HDPE mixtures. In the composites, HDPE was used to prevent SAL leakage and EG was not only a support material like HDPE, but also a promoter of thermal conductivity. The thermal conductivity of FSPCM underwent a 3% EG increase up to 0.6698 $W(mK)^{-1}$, while the thermal conductivity of FSPCM without EG was only 0.1966 $W(mK)^{-1}$. Finally, the thermal properties, chemical stability, and the microstructure of the FSPCM were presented. The addition of EG could provide a considerable thermal energy storage capacity and a high thermal conductivity for latent heat storage. A similar work is found in [55], where the thermal properties of phase change materials (PCMs) using mixes with cetyl alcohol (CtA), HDPE, and carbon fiber (CF) are measured. The experiment was divided into groups of 8 mixtures with temperatures around 5–100 °C. The TC with 5 wt% CF + HDPE + CtA were 0.3220 $W(mK)^{-1}$ and 0.4719 $W(mK)^{-1}$ (liquid and solid states) compared with HDPE, 0.1834 $W(mK)^{-1}$ liquid and 0.2023 $W(mK)^{-1}$ solid state.

In [51], the researchers carry out a series of studies improving the thermal conductivity of the form-stable phase change materials (FSPCM) using palmitic acid (PA) and high-density polyethylene (HDPE) modified by graphene nanoplatelets (GNP). The authors conducted a miscellaneous analysis of the different compositions: FT-IR, XRD, microstructure, thermal energy store properties, thermal reliability, leakage and thermal conductivity. They concluded that the PA is dispersed uniformly into the network structure of the HDPE and the PA-HDPE composite is attached to the broad surface of the GNP. The thermal conductivity of FSPCM increased to 0.8219 $W(mK)^{-1}$, which is almost 2.5 times that of pure FSPCM when the GNP mass fraction is 4%.

As a variant of the previous work, the authors presented an improved the thermal conductivity of FSPCM with two types of nanopowders with a high thermal conductivity [52], using Nano–Al_2O_3 (NAO) and nanographite (NG) as nanoparticles. NG and NAO were added into the FSPCM to improve the thermal conductivity using myristic acid (MA) as a solid–liquid phase change material (PCM) and the HDPE. The FSPCM can be a solution to overcome the defect of storing and releasing latent thermal energy. A field emission scanning electron microscope (FESEM) showed that the mass fraction of the MA in the MA/HDPE composite was less than 70%. The thermal conductivity of the FSPCM can increase from 0.2038 $W(mK)^{-1}$ to 0.3972 $W(mK)^{-1}$ (NAO) and 0.4503 $W(mK)^{-1}$ (NG) at

30 °C when the mass fraction of nanoadditives is 12%. Additionally, at 60 °C the value can increase from 0.1918 W(mK)$^{-1}$ to 0.3471 W(mK)$^{-1}$ (NAO) and 0.3923 W(mK)$^{-1}$ (NG).

An important result was found in [56]. The reinforcement effect depends on the shape and the dimension of the carbon-based nanofillers. They mixed HDPE with graphene nanosheets (GNs), and HDPE with multi-walled carbon nanotubes (MWCNTs) nanocomposites at filler loadings (0.5, 1 and 3 wt%). The material, graphene synthesis, nanocomposites preparators, characterization techniques of material and methods, and the structural, morphological, rheological, mechanical, and thermal properties of the mixtures were reported. In this last property, the result was the HDPE nanocomposite containing 0.5 wt.% GNs shows an increase of 24 °C in 5% (weight loss of 5% for neat HDPE) compared to neat HDPE. The HDPE/MWCNTs exhibits a smaller increase of 3 °C at the same content, concluding that the addition of nanofillers leads to a notable improvement in the thermal stability of HDPE.

In [57] is patented a pipe with enhanced thermal conductivity for geothermal applications (GreenGeopipe). The thermal properties of HDPE material can be enhanced using different types of thermally conductive fillers, for example, metallic oxide, non-oxides, and graphite. The latter is a material that has shown promise in improving the thermal properties of HDPE material. Different studies showed the graphite is a good material applied to HDPE material. For instance, [58] experimentally analyzes the thermal and electrical conductivity, mechanical properties, elongation at break, and stress at break of HDPE/graphite and LDPE/graphite composites. The percolation concentration (defined as the increase in electrical conductivity with a particular filler concentration) exhibits a non-linear increase of 11 vol% for both compounds with increasing graphite content and thermal conductivity comparison of filled HDPE vs. filled LDPE was higher due to the higher degree of crystallinity of HDPE.

In the pioneering study [59], the authors used GEOperforms HDPE pipes to test the thermal performance of the installed wells and the experimental results of the thermal response tests showed that the equivalent thermal resistance of the well was 17% lower. Simulations consider a vertical pipe thermal conductivity of 0.41 W/m/°C (conventional HDPE) and 0.71 W/m/°C (GEOperform) and the results showed a reduction in borehole lengths of around 10% with respect to a conventional HDPE pipe. In addition, the heat dissipated by the GEOperforms test with a single well was 25% higher (2300 W) compared to the HDPE pipe.

In [60], through differential scanning calorimetry (DSC) and thermomechanical analyzer (TMA) tests, the authors investigated the thermal and mechanical properties of the HDPE-$CaCO_3$ nanocomposite mixture to improve the poor thermal properties of HDPE polymer and polypropylene (PP). The principal composition, 10% $CaCO_3$ nanocomposite, was added to HDPE. The results of the tests showed that the addition of nanosized calcium carbonate to HDPE increased the heat capacity, sensible heat and crystallinity index. The dimensional stability of HDPE increases as the nanometer size of calcium carbonate leads to a lower thermal expansion and compressibility coefficient than plain HDPE.

In the work [61], an experimental technique using carbon nanotubes (CNTs) reinforced with the specific volumetric fraction of CNT to improve mechanical and tribological properties, especially to improve the stiffness, wear resistance and rigidity of the HDPE composite material using injection molding, is reported. The results showed that the melting point and oxidation temperature of the composites are not affected by the addition of CNTs. However, its crystallinity seems to increase. By increasing the volume fraction of CNTs, the properties of the material improve considerably.

In the work [62], the researchers reported that some mechanical properties of HDPE, like all polymers, are very sensitive to the service temperature. In general, all polymers at temperatures significantly below their glass transition temperatures (Tg) undergo brittle fracture. Thus, an increase in mechanical properties results in variations in the material properties. These are tested using different materials such as HDPE, nanodiamonds, multi-walled carbon nanotubes and graphite nanoplatelets. A quasi-static nanoindentation test was used to evaluate the mechanical properties of hardness, plasticity, the tensile modulus of the pure HDPE and different HDPEs with nanocomposites. The authors conclude that the filled hybrid of nanodiamonds and Graphite Nanoplatelets had higher surface properties. For this reason, HDPE, nanodiamonds and graphite nanoplatelets could improve the quasi-static and dynamic properties of materials.

In [63], two different configurations of graphite were used. One had a different distribution of particle sizes and the other had a different specific surface to improve the diffusivity and thermal and electrical conductivity of HDPE. The authors reported the graphite characterization, thermal conductivity and diffusivity, Young's modulus of elasticity, elongation, the stress at break, and the electrical conductivity of HDPE/graphite composites. The latter showed that the different types of graphite have a different influence on the percolation concentration of the composites.

A summary of the previous results of experimental works related to nanomaterials is given in Table 5.

Table 5. Summary of experimental studies on heat exchanger pipes using nanomaterials.

Authors	Nanomaterials	Applications	Results and Remarks
Chaudhry et al. [48]	GNPs and EG	Analysis of the thermal, mechanical, and electrical properties of nanocomposites	The best result was gained with 40 wt% of GNPs with HDPE; the κ of the composite increases at 1.32 W/mK while pure HDPE was 0.36 W/mK
Sahu et al. [53]	CNTs, NDs, MWCNTs, and GNPs	The nanomechanical properties of HDPE-based composites and hybrids using quasi-static and dynamic nanoindentation	The local surface properties were evaluated using quasi-static and dynamic nanoindentation. Properties such as hardness, Young's modulus, plasticity index and dynamic modulus were reported
Tang et al. [54]	EG-SAL-HDPE	Experiments with FSPCM by adding expanded graphite (EG) to stearyl alcohol (SAL) and high-density polyethylene (HDPE) mixtures	Effects of EG on the thermal conductivity and leakage rate in the $SAL - HDPE - EG$ composites. The thermal conductivity of FSPCM with 3% EG increase up to 0.6698 $W(mK)^{-1}$, while the thermal conductivity of FSPCM without EG was only 0.1966 $W(mK)^{-1}$.
Tang et al. [51]	GNPs and PA-HDPE	Enhancement of FSPCM and PAHDPE	FSPCM with 4wt% of the GNP has high thermal enthalpy and thermal conductivity. Promising application in solar energy and building heating systems
Tang et al. [52]	MA-HDPE, NG, and nano-Al_2O_3	Enhancement of FSPCM and MAHDPE	In the modified FSPCM, the MA was used as a solid–liquid PCM. The HDPE acted as a supporting material to prevent the leakage of the melted MA, and the NAO and NG were additives for the thermal conductivity enhancement
El Achaby and Qaiss [56]	MWCNTs and GNs	Two mixtures: HDPE/GNs and HDPE/MWCNTs. The nanocomposites had 0.5%, 1% and 3% nanofiller	Discussion of morphological, rheological, thermal and tensile properties of GN and MWCNT nanocomposites. The HDPE/GN nanocomposites show better thermal properties than HDPE/MWCNTs nanocomposites with identical filler content
Dorrian and Mumm [57]	GNs	A patented pipe with enhanced thermal conductivity for geothermal applications (GreenGeopipe)	The thermal properties of HDPE material enhanced using thermally conductive fillers such as graphite, which enhances the thermal properties of HDPE material.
Pasquier et al. [59]	Nanoparticles	GEOperforms HDPE pipe used to test the thermal performance of boreholes	A vertical pipe TC of 0.41 W/m/°C (HDPE) vs. 0.71 W/m/°C (GEOperform). Reduction in borehole lengths (10% less). The heat dissipated by GEOperforms pipe with a single well was 25% higher (2300 W). The borehole thermal resistance of the well was 17% lower
Sahebian et al. [60]	$CaCO_3$	Thermodynamic parameters of HDPE	Thermal and mechanical properties by adding 10% of $CaCO_3$ nanocomposite to polymer HDPE and polypropylene (PP)

Table 5. *Cont.*

Authors	Nanomaterials	Applications	Results and Remarks
Kanagaraj et al. [61]	*CNTs*	Using *CNTs* to improve mechanical and tribological properties such as the stiffness, wear resistance, and rigidity of HDPE material	By increasing the volume fraction of *CNT*, the properties of the *CNT*-HDPE improve considerably (mechanical and reinforcement properties). The melting point and oxidation temperature are not affected by the addition of *CNT* but the crystallinity of composites increases
Merah et al. [62]	*CNTs*, *NDs*, *MWCNTs*, *GNPs*	Increase the mechanical properties using *ND*, *MWCNTs* and *GNPs* into HDPE	Higher surface properties were seen by the *NDs* and *GNPs* filled hybrid. For this reason, *HDPE*, *ND*, and *GNPs* could improve the quasi-static and dynamic properties of materials such as service temperature
Krupa et al. [58]	HDPE-graphite and LDPE-graphite	Thermal and electrical conductivity, mechanical properties, elongation at break, and stress at the break between HDPE and LDPE composites with graphite	The increasing nonlinear electrical conductivity was 11 vol% for both composites. The thermal conductivity of filled HDPE was greater than filled LDPE due to the higher degree of HDPE crystallinity
Krupa and Chodak [63]	HDPE-graphite, graphite-Ks, and graphite-EG	Two different graphite configurations were used to improve the diffusivity as well as thermal and electrical conductivity of HDPE/graphite composite	Better surface properties were obtained from the nanodiamonds and Graphite Nanoplatelets filled hybrid. HDPE, nanodiamonds, and Graphite Nanoplatelets could improve quasi-static and dynamic properties of materials in service temperature

3. Discussion

Nanotechnology is a technological innovation whose use has grown in recent years in different energy sectors (solar, fuel cells, hydrogen, nuclear, photovoltaic, and wind). This technology is currently applied in various areas of geothermal energy. One of these technologies, Geothermal Heat Pumps (GSHP), is known as the best available technology for energy-efficient air conditioning systems to condition residential or commercial spaces to provide space heating and cooling. Currently, GSHPs are used in 54 countries, making up 59% of total energy use in the world, with China, the US, Sweden, Germany and Finland leading with 84% of total use [64].

Although GSHPs are highly efficient, their installation costs are very high, mainly due to the Ground Heat Exchanger (GHE), which is the most expensive component of all the systems, which is the main obstacle to the widespread use of GSHPs. The horizontal system configuration is generally easier and less expensive to install than a vertical setup, because vertical hole drilling is more expensive than horizontal loop trenching. However, horizontal loops require a large floor space due to the longer length of pipes.

New research using nanotechnology in GSHPs points to the use of new nanomaterials as alternatives to traditional fluids to increase heat in the GHE. Some of these traditional fluids and materials (water pipes and HDPE) are mentioned in [65–69]. It is clear that improvements in the heat exchanger are relevant using nanotechnology. Therefore, the analysis of recent advances in nanotechnology for GHSP becomes of paramount importance.

The objective of this review was to show different methods, types, applications, results and conclusions that have been made with the use of nanotechnology applied to GHE to improve the absorption/rejection of heat from the ground and from the space to be conditioned. Theoretical, numerical and experimental developments in the use of nanofluids and nanomaterials applied to GHE pipes to improve heat transfer efficiency were presented. Reviews indicate that early studies of nanotechnology applications to GSHP have been critical in optimizing and improving sink energy capture by splitting it into two main approaches; the first is the use of nanofluids moving through HDPE pipes, and the second one is developing new pipes with nanomaterials.

The use of nanofluids in the circulation circuit or the development of new nanomaterials has the objective of increasing heat transfer, reducing the installation cost and reducing the operating cost of GSHPs.

The improved heat transfer is expected to lower the installation cost because the circulation loop can be smaller and the pumping cost will also be lower. This work is the first that collects and compares these aspects as central points to review everything that has been undertaken in recent years. In this way, it gives clarity to various areas, not only nanotechnology but also areas of interest to the general public, who can look into these issues. Table 6 shows a summary of the research works. Table 6 displays a summary discussed in the research papers. The first column presents the main parameters and characteristics of the nanofluids or nanomaterials used to improve the ground heat exchanger pipe, and the second column shows the references found in the literature.

Table 6. Summary of parameters and analysis in heat exchangers.

Parameters Analysis	References
Reduction length of the heat exchanger	[4,7,10,13,21,24,35,45,54,57]
Comparative cost of materials	[9,24,33,57,59]
Comparative cost of heat exchangers	[4,24,59]
Comparative cost of construction	[4]
Comparative cost of GSHP	[4,24,59]
(κ)—Thermal conductivity (W/mK)	[13,14,16,20–24,26,51,52,54,56,57,59–63]
(μ)—Viscosity	[4,11,14,16,20–24,33,35–37,43,56,60]
(σ)—Surface tension	[14,16,43,51,56]
(R)—Thermal resistance (K/W)	[4,10,11,14,23,24,33–35,37,38,43–45,51,52,56,61]
(T)—Temperature (°C)	[4,10,11,14,22,24,26,34,43–45,54,56,57,59,60,62]
(ρ)—Density (kg/m^3)	[11,14,20,22,23,26,35,43,51,52,57,60]
(Cp)—Specific heat (J/kg K)	[11,14,20,21,23,26,28,33,35,37,43]
(h)—Heat transfer coefficient (W/m^{2}K)	[14,24,43]
(s)—Volumetric heat capacity (J/Km^3)	[14,24,43,44,60]
(ε)—Young's modulus	[53,56,61–63]
(γ)—Particle size and shape (nm)	[14,28,33,34,37,43,44,51,52]
Particle type	[34,37,43,51,52]
Morphology, dispersion, structure, alignment	[44]

This review identifies some works that improved the thermal conductivity of pipes, reducing costs in some cases, such as [9]. In this work, the thermal conductivity of the exchanger is increased and the cost of the product is reduced by using magnesium oxide, while in other works such as [10] nanomaterials are used. They mention the development of an improvement in HDPE pipes, increasing thermal conductivity by 75% and reducing the use of conventional pipes by 10%.

The work in [4] is one of the most complete numerical simulations working with nanomaterials. Some benefits are mentioned such as the reduction in the length of the heat exchanger, comparative costs of different configurations and their construction, including the simulation costs of the GSHP system. Furthermore, the authors of [24] based their numerical simulations with nanofluids that reported the heat exchanger length reductions and comparative costs of GSHPs. The research in [59] is the only experimental work with nanomaterials, which reduces the size of the exchanger, compares the costs and benefits of the materials, as well as compares the costs of the GSHP. From different studies considering different particles, Table 7 shows a classification considering theoretical and numerical works and experimental results separately.

Table 7. Summary of parameters and analysis of heat exchangers.

Particle Material	Theoretical and Numerical	Experimental
Ag	[13,14,16,23,24,37]	[33]
Cu	[13,14,16,22–24,37]	-
Al	[13,23,24,37]	-
Graphite	[13]	[34]
Al_2O_3	[7,13–16,20,22–24]	[35,52]
CuO	[13,16,22–24]	[34]
Al_2O_3-water	[13,21,23,26]	-
CuO-water	[13,23,26]	-
MgO-water	[27]	-
SiO_2	[13,14,16,23,24]	[34]
Au	[14,23]	-
TiO_2	[14,16,22,23]	[34,35]
ZnO	[14,23]	-
$Fe_2 O_3$	[14,16,23]	[34,35]
Fe_3O_4	[15]	-
MgO	[14]	[33]
Al_2O_3-EG	[20]	
CuO-EG	[28]	-
CNTs	[22,37,44,45]	[34,53,61,62]
Al_2O_3-EG	[23]	[11]
ZnO-EG	[23]	-
MWCNT	-	[33,53,56,62]
DWCNT	-	[33]
SiC	-	[34]
Titanium	-	[36]
LTEG	[37]	-
HDPE-TE	[4,42]	-
HDPE-Al wires	[38]	-
HDPE-EG-SAL	-	[54]
HDPE-PA	-	[51]
HDPE-MA	-	[52]
HDPE-graphite	-	[58,63]
CNT-metallic	[44]	-
CNT-ceramic	[44]	-
GNPs	-	[48,51,53]
EG	-	[48]
GN	-	[56,57,59,62]
$CaCO_3$	-	[60]
graphite-Ks	-	[63]
graphite-EG	-	[63]

4. Conclusions

Each paper reviewed in this article benefits the field through simulations or experiments, using nanofluids or nanomaterials. However, the results are usually reported through percentage estimates, without mentioning the actual costs. For future work, contributing to this field of knowledge may be of great value in solving current heat pump technology challenges outlined in this review paper. This will allow the widespread use of the systems on a larger scale and could lead to accessible applications of GSHPs in countries that are developing technology in this area.

Therefore, further works should focus on finding the effect of the particle shape (temperature, size, aspect ratio, and weight concentration) on thermal conductivity of nanomaterials. Additionally, tests of different concentrations or various types of nanoparticles should be conducted. In addition, investigations of different shape configurations, such as U-shaped or double-shaped tubes and slinky configurations, among others, should be conducted.

The structures of nanoparticles need to be investigated further. Models and correlations that consider all effective factors are required to mathematically evaluate the effects of key parameters on the thermal conductivity of pipes. More cost comparisons of real systems considering every aspect involving nanofluids or nanomaterials need to be carried out to make the field of heat pump usage more attractive for real engineering implementations.

Finally, the trends of the GSHP according to the current revision are summarized in the following points:

- The most common theoretical GHE models consider the general Navier–Stokes equations. However, when considering more system components, such as GSHPs, researchers need to propose novel dynamic models based on thermal resistances to simplify the simulation of GHE systems. In this context, more research is needed to integrate control systems in numerical simulations with the aim of improving GHE efficiency and minimizing operating costs.
- While most successful applications of nanoparticles are those involving CuO, Al_2O_3, SiO_2, and Ag [4,7,13,24], additional experiments are encouraged to compare their performances. Concerning nanomaterials, HDPE-TE seems to be the most successful for GHE applications.
- Until now, most research studies have involved laboratory tests, while long-term experiments for everyday applications are required to validate the real benefits of new nanomaterials and nanoparticles in GHE applications. Likewise, the study of the durability of the new nanomaterials will help to validate the cost-efficiency ratio.
- The optimization of GHEs through nanotechnology is part of the efficiency improvements of a GHSP. Therefore, a comprehensive analysis of the complete optimization of the system is necessary, considering the improvement in heat transfer together with the optimal control strategies applied to the electric pump to save energy. This multidisciplinary approach is required in future research instead of the disciplinary approach of nanotechnology areas.
- Nanomaterials and nanofluids in GHE have allowed the creation of new technologies for GHSPs in the proof-of-concept stage through laboratory tests. However, for the next product deployment in the GHSP industry, it is important to analyze the processes and costs for mass production. Thus, the availability of supplies, production times, and environmental impact, among others, will allow these new technologies to be put into use.

Author Contributions: Conceptualization, R.d.J.P.-V. and F.R.-C.; methodology, F.R.-C.; investigation, F.R.-C. and E.G.H.-M.; resources, F.R.-C. and E.G.H.-M.; original draft preparation, F.R.-C., E.G.H.-M. and R.d.J.P.-V.; review and editing, F.R.-C., E.G.H.-M., R.d.J.P.-V. and L.R.-G.; supervision, E.G.H.-M.; project administration, F.R.-C. and E.G.H.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Second author acknowledges support form Universidad Iberoamericana through project DINVP-0051.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Acronyms	
CNT	carbon nano tube composite
FSPCM	form–stable phase change materials
GNP	graphene nanoplatelets
GHE	ground heat exchanger

GSHP	ground source heat pump
HDPE	high density polyethylene
LTEG	low-temperature in situ expandable graphite
NG	nano–graphite
NSGA	non-dominated sorting genetic algorithm
PA	palmitic acid
PCM	phase change material
TE	thermally enhanced
Symbols	
Ag	silver
Al_2O_3	aluminum oxide
Au	gold
Cu	copper
EG	ethylene glycol
EO	engine oil
Fe_2O_3	iron oxide
MgO	magnesium oxide
SiO_2	silicon dioxide
TiC	titanium carbide
TiO_2	titanium dioxide
ZnO	zinc oxide
DWCNT	double-walled carbon nanotube
MWCNT	multi-walled carbon nanotubes
BHE	borehole heat exchanger

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