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The effect of employing nanofluid on reducing the bore length of a vertical ground-source heat pump

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ABSTRACT

In our era ground-source heat pumps are known as energy-efficient air conditioning systems. However, their high initial costs are a major obstacle to the widespread use of such systems. In this study, the effects of using Al_2O_3/water nanofluid as heat transfer fluid on reducing the bore length of a ground heat exchanger in a vertical ground-source heat pump are examined. For this purpose, the effective thermal conductivity and the effective viscosity of the nanofluid, which play prominent roles in the convective heat transfer, are optimized via using multi-objective Flower Pollination Algorithm. In this algorithm, the logic of the second version of non-dominated sorting is utilized to deal with the two objectives of this optimization. Then some of the best possible combinations of the thermal conductivity and the viscosity of the nanofluid, extracted from the obtained Pareto front, were used to compute the required bore length. The results were compared with the required bore length calculated using pure water as the heat transfer fluid in the ground heat exchanger. The comparison demonstrated that employing Al_2O_3/water nanofluid instead of water as heat transfer liquid reduced less than 1.3% of the bore length. Furthermore, investigating the reason of this low reduction in the bore length revealed that grout has the most potential to reduce the bore length among the heat transfer fluid, tubes, and grout.

1. Introduction

The necessity for reducing the emission of greenhouse gases, future worries on energy shortage, and recent moves towards environment sustainability have led to numerous efforts to lower energy consumption in buildings, which contribute to approximately 40% of the total energy demand in US [1] and Europe [2] and 36% of the total greenhouse gases emission in Europe [2]. In buildings the majority of the energy demand is assigned to air conditioning systems [3]. Hence, an energy-efficient air condition system can decrease energy consumption dramatically. Based on ground energy sources, ground-source heat pumps (GSHPs) have been considered as energy-efficient air conditioning systems which benefit from the earth's relatively constant temperature to provide heating, and/or cooling, and/or hot water [4]. The U.S. Environment Protection Agency (EPA) has claimed that GSHPs are the most energy-efficient and environmentally friendly air conditioning technology [5]. Vertical borehole ground heat exchangers (GHEs) are the most applied systems in GSHPs [6]. High initial and installation costs of vertical GHEs, however, are a formidable obstacle to the widespread application of GSHPs. A reason for the high costs of vertical GHEs is the required deep borehole, which may be ascribed to the inherently poor thermal conductivity of conventional heat transfer fluids (HTFs) (water or antifreeze/water mixture).

Using nanofluids, suspension of nanosized particles in fluids, is considered as a promising way to overcome the low thermal conductivity of conventional HTFs. The addition of nanoparticles changes the thermo-physical properties of the base fluid, such as thermal conductivity and viscosity. Since the first report of anomalous thermal conductivity enhancement of nanofluids [7], numerous experimental and analytical researches [8–11] have been conducted on thermal conductivity of nanofluids. Experimental results have demonstrated that many factors, e.g. nanoparticle volume fraction and size, affect the thermal conductivity of nanofluids [12]. Most of the experimental researches have shown that the thermal conductivity of nanofluids increases with the increment of particle volume fraction [8,9] and decrement of nanoparticle size [10,11]. Lee et al. [13] compiled the results of a large number of works in the thermal conductivity of nanofluids in an exhaustive review. Viscosity is another thermo-physical property that plays a prominent part in heat transfer systems due to its effect on convective heat transfer coefficient and the pumping power [14]. In spite of its importance, few researches have been conducted on

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Nomenclature

c_p	specific heat, J/(kg K)
d	diameter, m
ELT	entering liquid temperature, K
F_{sc}	short-circuit loss fraction
f	Darcy friction factor
h_{conv}	convective heat transfer coefficient, W/(m^2 K)
k	thermal conductivity, W/(m K)
k_B	Boltzmann's constant, m^2 kg/(s^2 K)
LLT	leaving liquid temperature, K
L_c	required borehole length for cooling mode, m
L_h	required borehole length for heating mode, m
$L(\lambda)$	levy function
PLF_m	part-load factor during the design month
Nu	Nusselt number
Pr	Prandtl number
p_a	switch probability
q_a	net annual average heat transfer rate to the ground, W
q_{cond}	heat pump condenser heat rate to the ground, W
q_{evap}	heat pump evaporator heat rate from the ground, W
R	thermal resistance, (m K)/W
Re	Reynolds number
r	radius, m
s	levy step size
T	temperature, K
t	nanolayer thickness, m
U, V	normal distributions
φ_p	particle volume fraction
ρ	density, kg/m^3
μ	viscosity, kg/(m s)
$\Gamma(\lambda)$	gamma function
λ	levy exponent

Abbreviations and acronyms

FPA	Flower Pollination Algorithm
GSHP	ground-source heat pump
GCHP	ground-coupled heat pump
GHE	ground heat exchanger
HTF	heat transfer fluid

Subscripts

b	bore
cp	complex particle
f	fluid
g	ground
grt	grout
i	inside
nf	nanofluid
nl	nanolayer
o	outside
p	particle

the viscosity of nanofluids. Experimental studies revealed that viscosity of nanofluids also depends on many factors such as nanoparticle volume fraction and size. The viscosity of nanofluids augments with the increment of nanoparticle volume fraction [15,16]. Furthermore, most of the studies have disclosed that the viscosity of nanofluids increases with the decrement of nanoparticles size [17,18]. Well-synthesized and well-prepared nanofluid could be efficiently utilized in heat exchangers. Allahyar et al. [19] investigated experimentally thermal performance of hybrid nanofluid, consisted of 97.5% alumina and 2.5% Ag in distilled water, in a coiled heat exchanger at laminar regime and constant wall temperature. They observed the maximum rate of heat transfer using nanofluid was 31.58% higher than distilled water. In another study, Peyghambarzadeh et al. [20] accessed the heat transfer performance of a nanofluid in a car radiator experimentally. They employed a various range of nanofluid with different base fluids (water, ethylene glycol and water–ethylene glycol mixtures) and Al_2O_3 particle concentrations. They reported the Nusselt number in the nanofluid cases augmented up to 40% with both Reynolds number and particle volume concentrations.

The ultimate aim for using nanofluids is enhancing the total efficiency of the heat transfer systems. Since the dispersion of nanoparticle in the base fluid results in viscosity increment as well as thermal conductivity increase, both of these properties should be studied simultaneously and meticulously, because the increase of viscosity may offset the increase of thermal conductivity, and thus, the total efficiency of the heat transfer system decreases. Metaheuristics optimization algorithms could be a useful tool to find optimal points by making a trade-off between conflicting objectives of an optimization problem. Recently evolutionary based optimization has become the mainstay of a plethora of researches in both engineering and industrial areas. For instance, Tahani et al. [21] optimized a hybrid PV/Wind/Battery system for a three store building by using a newly developed hybrid Flower Pollination Algorithm/Simulated Annealing (FPA/SA) algorithm. Duan et al. [22] applied multi-objective particle swarm optimization (MOPSO) algorithm for the thermodynamic design of Stirling engine. Ahmadi et al. [23] performed a thermo-economic optimization on a Stirling heat pump using the second version of non-dominated sorting genetic algorithm (NSGA II). In another study Ahmadi et al. [24] too optimized an irreversible Stirling cryogenic refrigerator cycle. Sayyaadi et al. [25] performed a thermodynamical single objective optimization on a vertical Ground-coupled heat pump (GCHP), in addition to a thermo-economic single objective and multi-objective optimization.

In this study, the potential for reduction of the borehole length under the impact of using nanofluid as the HTF in a vertical GHE was investigated. For this purpose, a building with complete information available in [26] was selected. At first, an optimization of thermo-physical properties of nanofluid was performed. The objectives of this optimization were maximizing thermal conductivity increase as well as minimizing viscosity increment, due to dispersing nanoparticles in HTF, by varying nanoparticles volume fraction and size. Then, some of the best possible combinations of thermal conductivity and viscosity, known as the Pareto front, was used to assess the borehole depth of the GHE. Finally, the results of nanofluid thermo-physical properties optimization and assessment of potential borehole reduction were mentioned and a thorough discussion about these results was presented.

2. Ground-source heat pump

A GSHP is a system in which a heat pump uses the ground as a heat sink in cooling mode and a heat source in heating mode operation. In heating mode, heat is absorbed from the ground and is used to heat a building whereas in the cooling mode, a GSHP absorbs heat from the conditioned space and reject it to the ground [27]. The GSHPs with vertical BHEs are far more preferred, especially in industrial and institutional buildings, because of the less required ground areas. The performance of a vertical GSHP relies on the borehole behavior that is very dynamic. Various analytical