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Numerical study on thermal performance of an air-cooled heat exchanger: Effects of hybrid nanofluid, pipe arrangement and cross section

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ABSTRACT

This study is a numerical investigation of a heat exchanger under external flow. Temperature variable properties are used to solve the governing equations. Air is selected as an external fluid and water and MgO-MWCNTs/EG hybrid nanofluid are selected as radiator fluid. In this paper, the efficiency of the horizontal and vertical radiator are studied using experimental data for thermo-physical properties of MgO-MWCNTs/EG Nanofluid. Then, tubes with circular and elliptic sections are investigated for different flows, inlet temperatures and concentrations. The pressure drop and Nusselt number for each simulation are analyzed. Results are presented in terms of temperature distribution, pressure drop, Nusselt number and their sensitivity analysis for different states. The results indicate that radiators with vertical tubes have better efficiency up to 10% than radiators with horizontal tubes. In addition, heat exchangers with circular pipes have 25% lower pressure drop and those with elliptical tubes had 10% higher Nusselt number. The finding shows that an increase in the Nano-fluid concentration improves the Nusselt number and increases the pressure drop.

1. Introduction

With the rise of the earth's temperature and increase in the fossil fuels prices, in the twentieth century, the issue of reducing energy consumption became important. Therefore, researchers paid more attention to energy management. Heat exchangers are among the cases in which energy efficiency is essential. The heat exchanger is a device used to transfer optimal heat from one environment to another. Heat exchangers transmit heat between two or more fluid streams flowing into it. Heat exchangers are widely used in industries, such as process, power plant, air conditioning, refrigeration, heat recovery and manufacturing industries. Different types of boilers, heater condensers, regenerators and cooling towers are already in use. In process industries, two-phase flow converters are applied for evaporating, distilling and freezing the crystals; and used also as a fluidized bed with catalytic reactions. Air conditioning and refrigeration systems require both condenser and evaporator. Therefore, it is very important to reduce the energy consumption of heat exchangers. In energy management of heat exchangers, the issues of pressure drop and heat transfer efficiency are highly important. An appropriate type of exchanger, cooling fluid as well as the working conditions of the exchanger can have a positive impact on energy management to reduce the energy consumption and save the costs.

One of the most important types of heat exchangers is the air-cooled heat exchanger. They are widely used in the electronics industry, air conditioning, refrigeration, machinery and process industries where the fluid should be cooled at a temperature above 60 °C. Proper design of the cooling system can increase the efficiency and reduce costs, resulting in a significant effect on the profitability of the system. Since the mid-1950s, efforts made to modify the structure of air-cooled heat exchangers with different fins, embedding different tubes or rough surfaces. In addition, there is research conducted either in the electricity or magnetic and vibration fields. Due to the low coefficient of air displacement in these exchangers, bladed pipes are used. Therefore, one of the ways to optimize these exchangers is to change the alignment of blades. Another way to increase the efficiency of air-cooled heat exchangers is to change the pipes and also to change the cooling fluid [1–7].

1.1. Nanoparticles and its properties

Due to the low thermal conductivity of cooling fluids in the heat exchanger, application of Nano-fluid in heat exchangers can improve the efficiency, leading to a reduction in fuel consumption. By suspending either metal or non-metallic particles (> 100 nm) in the base fluid. The Nano-fluid production process is a key factor in the improvement the fluid's thermal conductivity. There are single-stage and two-stage methods for Nano-fluid production [7].

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Nomenclature

c_p	specific heat, J kg^{-1} K^{-1}
k	thermal conductivity, $Wm^{-1}K^{-1}$
Nu	Nusselt number (hl/k)
p	fluid pressure, Pa
D_h	hydraulic diameter
T^*	non-dimensional temperature
Pr	Prandtl number ($Pr = \frac{\nu_f}{\alpha_f}$)
Re	Reynold number ($Re = \frac{\rho_f u_c H}{\mu_f}$)
T	temperature, K
u,v	velocity components in x, y directions, m/s
f	friction factor
x, y, z	cartesian coordinates, m

Greek symbols

μ	dynamic viscosity $kgs^{-1}m^{-1}$
ϑ	kinematic viscosity, (μ/ρ) m^2S^{-1}
ρ	density, kg/m^2

Subscripts

c	cold
c, o	air outlet
c, i	air inlet
f	fluid (pure water)
h	hot
h, o	radiator fluid outlet
h, i	radiator fluid inlet
nf	nanofluid
out	outlet
p	nanoparticle
in	inlet

Nano particles have an important influence on the characteristics of Nano-fluid heat transfer [8]. Currently, different types of nanoparticles, such as metal and ceramic ones, are used in the production of Nano-fluids.

One of the applications of the air-cooled heat exchanger is in the automobiles. The combustion of internal combustion engines produces so much of heat that might melt both cylinder and piston. The cooling system is used to prevent heat increase in the engine. This system is used to act against the effective performance at all engine speeds and to control different situations. During combustion when the fuel and the air are mixed in the combustion chamber, the temperature elevates considerably and even reaches to 2000 centigrade. This temperature is higher than the melting point of the material used in the engine, so the engine will be damaged due to high temperature; as a result, the engine's temperature must be maintained within a specific range. In the case of a water-cooling system, this temperature varies from 75 to 95, being rather high for the air-cooling process, where the radiator transfers the engine's cooling fluid heat. To achieve higher efficiency, modern engines work at higher working temperatures, so that efficient cooling radiators are needed to cool them.

In the areas with either very cold or very hot weather, the antifreeze is respectively used to either reduce the freezing temperature or increase the boiling temperature of the fluid used in the radiator. Since water is an appropriate fluid for cooling the radiator, it is typically used as the base fluid, which ethylene glycol is added to. Both concentration percentage and usage amount of pure glycol and water depend on the area's weather conditions. The characteristics of water, air and ethylene glycol with different percentages are presented in Tables 1 and 2.

1.2. Experimental studies

Lots of studies have conducted on the performance of exchangers, especially radiators, a number of them are presented as follows.

As the first-time experimental studies on the performance of a radiator cooling system using Nano-fluid, Tzeng et al. [10] investigated the efficiency of silica, alumina and antifoam as nano particles added to motor oils. In this study, the two-axis throttle power systems of Mazda engine were tested in 400, 800, 1200 and 1600 rpm respectively. Tzeng concluded that compared with all the other tested nanoparticles, silica had the best performance. Hatami [11] studied the addition of four Nanoparticles with different shapes (i.e. CuO, TiO_2, Al_2O_3 and Fe_2O_3) to the cooling system. At last, he concluded that in comparison with other modeled Nano fluids, an EG-TiO_2 having a platelet shape and a larger volume fraction of nanoparticles had the best cooling performance in the engine. In a research, aiming at studying the effect of using Nano-fluid, bulk temperature and flow velocity on the engine's cooling performance, Hussein et al. [12] have made use of water as the base fluid and investigated a 0–2% concentration of Alumina particles as nanoparticles. Results revealed that for a varied heat flux, the highest heat transfer coefficient was 78.67%, achieved at 1% volume concentration of nanoparticles compared with pure water. Naraki et al. [13] have investigated the effect of the volumetric flow of air, volumetric concentration of nano-fluid, inlet temperature and volumetric flow of the cooling fluid flow on the heat transfer coefficient CuO-water nanofluid in a vehicle's radiator. According to their studies, it can be concluded that the heat transfer coefficient of nanofluid is higher than the base fluid. At a volumetric concentration of 0.15% and 0.4%, the overall heat transfer coefficient elevated from 6% to 8%, respectively. Using Taguchi method, they concluded that the studied volumetric air flow (42%), Nano fluid volumetric flow rate (23%), radiator inlet temperature (22%), and Nano fluid volume concentration (13%) had a positive and significant effect on improvement of the heat transfer coefficient. Kannan et al. [14] investigated the nanofluid concentration, the inlet temperature, and the mass flow rate of Al_2O_3-water nanofluid and its effect its effect on the radiator's thermal transfer rate. Their results indicated that addition of alumina increased the radiator heat transfer rate. For example, at a constant flow rate of 0.1 kg/s, a cooling rate of 24% and 49%, were respectively observed at the concentrations of 0.25% and 0.5%. In addition, they concluded that an increase in radiator inlet temperature, mass flow rate and nano-fluid concentration has a positive effect on the performance of the radiator. In another study, Hossein et al. [15] have investigated the effects of volumetric concentration, flow rate and radiator inlet temperature on the forced heat transfer in a radiator with copper pipes. They have concluded that at a slow flow rate, Nusselt numbers increase with increasing the flow rate and inlet temperature. Also, the Nusselt number increased by 11% for TiO_2-water and 22.5% for silica-water. Experimental studies conducted on the radiator of the vehicle's cooling system are presented in

Table 1
Pure Ethylene Glycol, water and air properties [9].

Specification	Water	Ethylene Glycol	Air (at 25 °C)
Density (g/cm^3)	1.0	1.1132	0.001412
Molar mass (g/mol)	18.02	62.07	62.07
Freezing temperature (°C)	0	−12.9	−209.89
Boiling temperature (°C)	100	197.3	−194.35
Viscosity (Ns/m^2)	1.002×10^{-2}	1.61×10^{-2}	01.7894×10^{-5}
Thermal conductivity (W/mK)	0.609	0.258	0.02428