Experimental and Analytical Study of Aluminum-oxide Nanofluid Implication for Cooling System of an Amphibious Engine

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Abstract: The aim of this manuscript is to study the implication of aluminium-oxide nanofluid for an amphibious vehicle engine (viable on land and under water) cooling system both analytically and experimentally. To achieve this, a one-dimensional model of the engine cooling system (radiator) is considered through a computational fluid code in which the mass flow rate for a range of the coolant temperature is assumed to be constant. By knowing the volumetric flow rate of the air passing over the radiator, the heat transfer rates for different aluminium-oxide nanofluid volume concentrations at different amphibious engine gears are determined. The analytical results indicate that a 7% aluminium-oxide nanofluid increases the engine radiator heat transfer performance by 24.9%, while the experimental results show that the coolant outlet temperature is about 3˚C lower than the case without the nanofluid in the coolant.

Keywords: Amphibious Vehicle, Coolant, Nanofluid, Vehicle Engine Cooling System

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1 INTRODUCTION

In amphibious vehicles, due to complications regarding the design of the cooling system, the cooling agent constituents play an important role to make up for the drawbacks due to complete sealment of the radiators. Since the thermal conductivity of the conventional cooling fluids (e.g. water and ethylene-glycol) is very low, enhancement in the thermal conductivity of the coolant can be considered as one of the methods to improve the efficiency of the cooling process. Through adding nanoparticles of copper- oxide, aluminum-oxide, etc. to the coolant, a significant enhancement of the heat transfer coefficient can be obtained. Among the researches conducted on the nanofluids, one can consider the work of Wen et al., [1]. They investigated the heat transfer phenomena at the entrance of a pipe. Their work demonstrated that the local heat transfer coefficient varies with the volume concentration of the nanoparticles and the Reynolds number.

Jung et al., [2] investigated the amount of enhancement in the convective heat transfer coefficient of water through adding alumina nanoparticles to the fluid in a rectangular base of a micro channel. They realized that when 1.8% alumina nanoparticles were added to the base fluid, an improvement of 32% in the heat transfer coefficient was achievable. Buy et al., [3] numerically studied the impact of utilization of nanofluids in the cooling systems of vehicles. Nanofluids including water-copper, water-alumina, and water-alumina-oxide with a particle concentration of 2% were simulated. The results showed that the copper particles produce a considerable capability in heat transfer enhancement. A. sheikhzade et al., [4] investigated the influence of nanofluid employment on the thermal performance of a vehicle radiator in various environmental conditions. They found that adding nanoparticles to the cooling agent, improves the performance of the radiator.

Torabi et al., [5] investigated the influence of nanofluids on the engine cooling systems through simulation of engine combustion chamber and its cooling system using GT-Suit software. They found that the rate of the heat transfer from the engine which utilized the nanofluid was enhanced and the outlet temperature of the engine experienced a decrease of 9˚C at the target engine speeds. They also concluded that utilization of nanofluids could lead to smaller radiator volumes. Bozorgan et al., [6] studied the effect of shape, size, and the surface of the aluminum-oxide nanoparticles on the heat transfer coefficient of a compound of water and ethylene glycol. Volume percentage of the nanoparticles ranged from 1 to 7% and the investigation was conducted in a double tube heat exchanger with laminar flow. The results revealed that the shape and surface of the nanoparticles influenced the thermal conductivity of the fluid. Furthermore, those particles which were hydrophobic and bar-shaped enhanced the nanofluid's heat transfer coefficient and viscosity which led to improvement of the pumping capability.

Nourazadi et al., [7] investigated the application of nanofluids in vehicle cooling systems. They added nano-particles to the engine oil, hydraulic oil, and water; which resulted in ameliorations in heat transfer coefficient of the respective fluids. Considering the literature on vehicle engine coolings, one can claim that the impact of a mixture of nano- particles with high thermal conductivity and water on the improvement of the coolant heat transfer coefficient has not been investigated for amphibious vehicles.

Therefore, enhancing the heat transfer coefficient of the coolant can be considered as an approach in situations where restrictions on radiator size or on fan capacity in amphibious vehicles impose difficulties. Thus, the influence of nanofluid employment in cooling systems of these vehicles seems quite necessary.

In this paper, the impact of aluminum-oxide nanofluid on the diesel engine of an amphibious vehicle is investigated. In order to achieve this, a thermofluid computational software is used to design a radiator for the cooling system of an amphibious diesel vehicle. This vehicle is supposed to move and be viable on land as well as under water. The appropriate governing equations for nanofluids and the calculating methods are developed, and the impact of the shape and size of aluminum-oxide nanoparticles with different concentrations (i.e. 1, 3, 5, and 7%) are studied experimentally for the amphibious vehicle for different gears and the results are tabulated.

2 COOLING SYSTEM MODELING

The following assumptions are made to model the cooling cycle of the diesel engine.

1) A coolant volumetric flow rate of 0.005 m^3/s for the cooling cycle is assumed.

2) The heat generation in the engine (according to the manufacturer) which is considered as the thermal load to the radiator, is taken to be 116 KW.

3) The coolant entrance temperature is considered to be a constant value of 368 K.

4) Taking into account the fan characteristics curve used in the amphibious vehicle, three engine speeds of 1500, 1800, and 2000 rpm are considered.

3 GOVERNING EQUATIONS FOR HEAT TRANSFER BY NANOFLUID COOLING SYSTEM OF THE VEHICLE

To investigate the thermo-physical characteristics of the aluminum-oxide nanofluid with ethylene glycol as the base fluid, Table 1 and equations 1-4 are considered to determine the density, specific heat capacity, viscosity and prandtl number for the nanofluid used.

$$\rho_{nf} = (1-\emptyset)\rho_{\mathrm{bf}} + \emptyset\rho_p \tag{1}$$

$$C_{\mathrm{P,nf}} = \frac{(1-\emptyset)\rho_{\mathrm{bf}}C_{\mathrm{P,bf}}+\emptyset\rho_{\mathrm{p}}C_{\mathrm{p,p}}}{\rho_{\mathrm{nf}}} \tag{2}$$

$$\mu_{\mathrm{nf}} = \mu_{\mathrm{bf}}(1+a\emptyset) \tag{3}$$

$$Pr_{nf} = \frac{C_{P,nf}\cdot\mu_{nf}}{K_{nf}} \tag{4}$$

In order to determine the conductive heat transfer coefficient in the nanofluid, the following equation is utilized [6]:

$$K_{\mathrm{nf}} = K_{\mathrm{bf}}[\frac{K_{\mathrm{p}}+2K_{\mathrm{bf}}-\frac{a}{1.25}\emptyset(K_{\mathrm{bf}}-K_{\mathrm{p}})}{K_{\mathrm{p}}+2K_{\mathrm{bf}}+\frac{a}{2.5}\emptyset(K_{\mathrm{bf}}-K_{\mathrm{p}})}] \tag{5}$$

In the above equations, nf denotes nanofluid and bf denotes base fluid. P refers to nanoparticles and ρ stands for volume concentration of the nanofluid. Here, μ and Pr refer to the viscosity and prandtl number. Also, C_p and k refer to the specific heat capacity and heat transfer coefficient of the nanofluid and φ refers to volume concentration of the nanoparticle.

Table 1 The physical characteristics of different aluminum-oxide nanoparticles [6]

Aluminum-oxide	AK	AR	AF
Shape	Spherical	Spherical	Bar-shaped
Surface	hydrophobic	hydrophilic	hydrophilic
Size (mm)	43	27-43	7
Suspension (%)	4.9407	3.5573	15.4150
Specific Heat (kj/kg.k)	20	20	20
Density (Kg/m^3)	3970	3970	3970
Thermal Conductivity (w/m.k)	36	36	36

In equations (3) and (5), the coefficient "a" stands for the suspension values of nanoparticles [6] which include aluminum-oxide nanoparticles types of AR (spherical hydrophilic shape), AK (spherical hydrophobic shape), and AF (bar-shaped hydrophilic). The value of "a" for AR, AK, and AF are 3.5573, 4.9407, and 15.4150 respectively. The characteristics of the mentioned nanoparticles are tabulated in Table 1. With the physical characteristics of the base fluid in hand, the characteristics of the nanofluid can be calculated for different volume concentrations of the aluminum-oxide nanofluid. These properties can also be used to determine the absorbed heat flux in the radiator.

4 CRITERIA FOR HEAT TRANSFER EFFICIENCY EVALUATION

In order to generally evaluate and compare the thermal performance of the heat exchangers which employ nanofluids, it is essential to define a criterion. To obtain this, it is assumed that the fluid properties and the heat flux from the heat exchanger’s wall, (or the temperature difference between the wall and fluid) are constant. Equations presented in references [9] and [10] are used to achieve the criteria.

5 INVESTIGATION OF THE IMPACT OF NANOFLUID UTILIZATION IN AN AMPHIBIOUS VEHICLE

Initially, a one-dimensional model for working conditions of the vehicle’s radiator is created in a commercially used software. The utilized model includes a mixture of the working fluid, ethylene glycol and water solution, and the external fluid (i.e. air). In order to study the effect of the working fluid properties on the heat transfer rate of the heat exchanger; the coolant volumetric flow rate and the temperature of the fluid are assumed to be 0.005 m^3/s and 368 k, respectively.

For the outside fluid, it is assumed that the air is sucked in from the air source and passes over the radiator and has a pressure drop. Next, the air enters the centrifugal fan and is finally exhausted to the atmosphere.

For the model, it is assumed that both the flow rate and the temperature of the coolant are constant. Also, it is assumed that the air flow rate passing over the radiator is determined based on the amphibious vehicle’s fan characteristic curve. It is noted that, the effect of the aluminum-oxide nanofluid is determined based on the radiator’s heat released for different nanofluid concentrations.

6 AMPHIBIOUS VEHICLE COOLING SYSTEM TEST

In order to evaluate the impact of the aluminum-oxide nanofluid on the amphibious vehicle cooling system, this system is examined at two similar test conditions. In the first test case, ethylene glycol-water mixture (50% each on volume bases) is used as the cooling fluid in the cooling system. The test is carried out with the vehicle moving at different gears. For the second test case, considering the fact that in the previously conducted analysis, the optimum nanofluid was detected to be 7%, the same amount of aluminum-oxide nanoparticles (with 15 nm diameter) is added to the fluid in the amphibious vehicle cooling system. The tests are repeated with the same vehicle and conditions. In both cases, the temperature of the cooling fluid is measured via calibrated instruments.

7 RESULTS AND DISCUSSIONS

The impact of nanofluid concentrations on the heat released from the radiator at different fan speeds is investigated. To do so; initially, the amount of heat released from the radiator, and the inlet and outlet fluid temperatures for the inner and outer fluids are calculated for the ethylene-glycol-water mixture. The obtained data are presented in Table 2.

Table 2 The Heat transfer calculation results for pure ethylene glycol and water mixture

Fan speed (rpm)	1500	1800	2000
Released heat (kw)	84.836	96.57	103.712
Fluid pressure drop (kpa)	20.495	20.437	20.402
Inlet temperature (K)	368	368	368
Outlet temperature (K)	363.382	362.723	362.333
Difference between inlet and outlet temperatures (K)	4.618	5.277	5.667

The results for employment of type AR aluminum-oxide nanoparticles for different volume concentrations of 1, 3, 5, and 7% are summarized in Table 3. As the fan speed increases, the effect of the cooling enhances. If higher volume concentrations of the nanoparticles are utilized, the chances of increasing the deposits accumulation will increase which leads to a pipe blockage and impairs the efficiency of the heat exchanger (radiator).

Table 3 The Heat transfer calculation results of aluminum-oxide nanoparticle AR in base fluid

Fan speed (rpm)	1500	1800	2000
Volume concentration (%)	Released heat (kw)		
1	85.3112	97.7894	105.137
3	87.1121	100.178	107.941
5	88.8483	102.492	110.672
7	90.5203	104.763	113.331
Volume concentration (%)	Pressure drop (kpa)		
1	21.078	21.017	20.980
3	22.243	22.176	22.135
5	23.409	23.335	23.291
7	24.572	24.491	24.433
Volume concentration (%)	Outlet coolant temperature (K)		
1	363.346	362.676	363.276
3	363.276	362.582	362.164
5	363.225	362.489	362.055
7	363.167	362.401	361.948
Volume Concentration (%)	Difference between inlet and outlet temperature (K)		
1	4.654	5.324	5.724
3	4.714	5.418	5.836
5	4.775	5.511	5.945
7	4.833	5.559	6.52

The obtained results for the heat released from the radiator at different fan speeds for various nanofluid volume concentrations are compared in Figure 1. It is observable that, as the volume concentration of the nanoparticles increases, the rate of heat transfer also increases. Therefore, more heat is absorbed from the cooling fluid and is transferred to the environment.

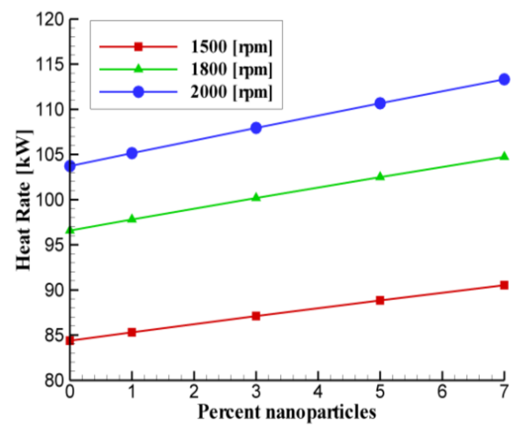

Fig. 1 The Heat transfer rate for different volumetric densities of aluminum-oxide nanoparticle in base fluid at different fan speeds

The pressure drops for the cooling fluid in the heat exchanger is depicted in Figure 2. It is noticed that, at a constant volumetric flow rate, with increasing the volume concentration of the nanoparticles, the coolant pressure drop augments. The main reason for this trend is due to the viscous losses in the radiator, thus, an increase of the pumping power will be required.

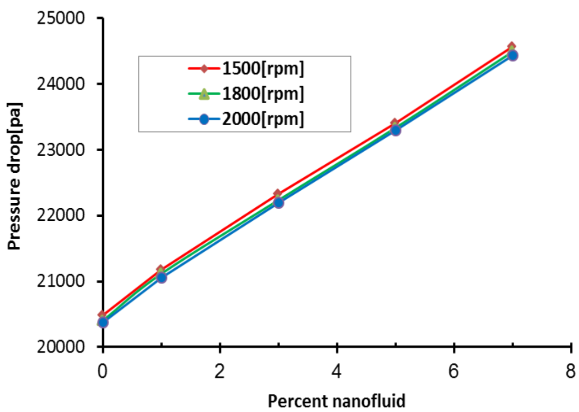

Fig. 2 The coolant pressure drop inside the radiator for different volumetric densities of aluminum-oxide

The radiator heat transfer efficiency for different nanoparticle percentages is calculated and the results are shown in Table 4. From Table 4, it is observed that for all the fan speeds, the heat transfer performance is increased. The highest performance, however, belongs to the volume concentration of 7% for the fan speed of 2000 rpm.

Table 4 The Radiator's heat transfer ratio for different percentages of aluminum-oxide nanoparticle AR for different fan speeds

	Nanofluid volume concentration (%)				
Fan speed (rpm)	0	1	3	5	7
1500	1	1.0018	1.0048	1.0075	1.010
1800	1	1.0032	1.0095	1.015	1.0211
2000	1	1.0043	1.013	1.021	1.0289

According to Table 5, if AF type aluminum-oxide particle is used, at a fan speed of 2000 rpm, the heat transfer efficiency improves by 24.9% for 7% nanofluid concentration. This is considered as a significant heat transfer rate improvement compared to conventional coolant.

Table 5 The Radiator's heat transfer performance for different speeds of fan for 7% aluminum-oxide nanofluid

Fan speed	Particle type		
(rpm)	AR	AK	AF
1500	1.010	1.030	1.177
1800	1.0211	1.0435	1.218
2000	1.0289	1.0527	1.249

The heat transfer results for appropriate pressure drops, for different types of aluminum-oxide for 7% nanofluid concentration are tabulated in Table 6.

Table 6 The Radiator's heat transfer rate results at 368k inlet temperature for different fan speeds for 7% AF and AK aluminum-oxide nanofluid types

Particle type	Fan speed(rpm)	Released heat(kw)	Pressure drop(kpa)	Temperature difference (K)
AF	1500	105.849	24.815	5.654
AK	1500	91.487	23.883	4.885
AF	1800	125.963	25.090	6.733
AK	1800	106.039	23.815	5.666
AF	2000	139.16	25.271	7.441
AK	2000	114.882	23.771	6.139

Table 7 shows the results for cooling conducted for two test cases of the ethylene-glycol with and without nanofluid for similar conditions and the same amphibious vehicle.

Table 7 The Amphibious engine cooling system test results at 35℃ air temprature with and without 7% aluminum-oxide nanofluid

Gear	Engine and fan Speed (rpm)	Velocity (km/h)	Distance (km)	Engine Temperature (℃)	
				Plain fluid	with nanofluid
1	1900	15	1	95-96	93-94
2	1900	28	1.5	96-97	93-94
3	1900	42	2	97-98	94-96
4	1900	55	2	98-101	96-97
5	1900	68	3	101-104	97-99
6	1900	75	3	104	99-101

8 CONCLUSION

The following conclusions can be achieved from this research project:

1) As the nanofluid volume increases (up to 7%), so does the radiator heat transfer rate. This increase shows to be linear with respect to the nanofluid percent increase. The maximum heat transfer rate augmentation is about 24.9% at 7% nanofluid volume compared to the conventional coolant, which is a very significant heat transfer rate.
2) The highest heat transfer performance was achieved at 7% aluminum-oxide nanofluid at a fan speed of 2000 rpm.
3) The coolant fluid pressure drop, at a constant mass flow rate, increases linearly as the nanofluid volume concentration ascends.
4) A nanofluid volume concentration greater than 7% would increase the chances of sedimentation of nanoparticles, which results in the radiator piping system blockage and also a heat exchanger effectiveness reduction.
5) The addition of 7% aluminum-oxide nanofluid by volume, results a reduction of the engine coolant temperature by 2 to 3 ℃.

9 NOMENCLATURES

a	Suspension coefficient
C_p	Specific Heat (kj/kg.k)
$C_{P,bf}$	Base fluid Specific Heat (kj/kg.k)
$C_{P,nf}$	Nanofluid Specific Heat (kj/kg.k)
K	Thermal Conductivity (w/m.k)
k_{bf}	Base fluid thermal Conductivity (w/m.k)
k_{nf}	Nanofluid thermal Conductivity (w/m.k)
P	Nanoparticle
Pr	Prandtl number
bf	Base fluid
nf	Nanofluid
φ	Nanofluid volume concentration
μ_{bf}	Base fluid dynamic viscosity(N.s/m^2)
μ_{nf}	Nanofluid dynamic viscosity(N.s/m^2)
ρ_{bf}	Base fluid density (Kg/m^3)
ρ_{nf}	Nanofluid density (Kg/m^3)

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