USING ANALYTIC HIERARCHY PROCESS FOR EVALUATING DIFFERENT TYPES OF NANOFLUIDS FOR ENGINE COOLING SYSTEMS

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The radiator is an important heat exchanger for cooling the engine. Usually, water and ethylene glycol are used in vehicles as cooling fluids. However, these fluids have lower thermal conductivity. In the automotive industry, coolants with better characteristics are being searched to develop more efficient engines. In recent years, nanofluids have become more attractive to car manufacturers, with higher thermal conductivity to increase heat transfer. In this study, the Analytic Hierarchy Process (AHP) is used to structure the decision problem and to attribute weights to criteria. Three types of nanofluid (Cu-water, NiO-water and CuO-water) were evaluated. Among the thermophysical properties of nanofluid, the most important one is calculated as the thermal conductivity and also the Cu-water is determined as the most suitable coolant in terms of thermophysical properties among the evaluated nanofluid.

Keywords*: Analytic Hierarchy Process, Nanofluids, Thermophysical Property, Engine Cooling*

1. Introduction

Cooling is a vital subject in many engineering fields such as power generation, electronic applications, air conditioning, heating/cooling, and nuclear systems. Nowadays, water, oil and traditional fluids used as coolants [1,2,3]. Having known the fact that, liquids have poorer thermal properties than solid materials, researchers focused on to increase thermophysical properties of the cooling fluid. With these investigations, new fluids have been created in the last decade with the addition of nanomaterials, named as nanofluids. A nanofluid can be produced by dissolving metallic or non-metallic nanoparticles, which has a typical size less than 100 nm in the base liquid. In the production of nano-liquids, single-stage or two-stage methods are used [1]. The nanoparticles, which are frequently used to prepare nanofluids, have been reported in the literature as follows:

(1) metallic particles (Cu, Al, Fe, Au and Ag);

(2) non-amorphous particles (Al_2O_3, CuO, Fe_3O_4, TiO_2 and SiC);

(3) carbon nanotubes; and

(4) the nanodroplet [4]

Being a popular research area, nanofluids attract the attention of various scientists. These researches include heat exchangers [5-10], microchannel heat sink [11,12], electronics cooling [13], building air conditioning. In addition to other sectors, nanofluids have found a working area as a coolant in car engines and cooling equipment. The radiator is one of the important parts of the vehicle engine which is usually used as the cooling system of the engine which transfers heat with water [14]. Cooling of an engine is one of the most important factors in maintaining normal operation. Increasing the cooling performance is possible with some methods. These methods include using the microstructures to improve the effective area of the radiator, to increase the cooling flow rate, to use high thermal conductivity materials in the production of the radiator, and to use the cooling fluid with high heat transfer performance. Radiators are usually made of copper, aluminium and similar metals with high thermal conductivity. One of the good ways to improve cooling performance of the working fluid is using nanomaterials. Nanomaterials used to improve the thermal conductivity of the working fluid and the heat transfer performance of conventional working fluids yields good results [15].

There are several studies on engine cooling enhancement with nanofluids in literature. Moghaieb et al experimentally investigated the characteristics of the steady state turbulent convective heat transfer for Al_2O_3/water nanofluid in engine cooling [16]. Micali et al measured the temperatures of the exhaust valve spindle and exhaust valve seat in the cylinder head using CuO based nanofluids [17]. Li et al reported that the thermal conductivity of silicon carbide (SiC) nanofluids when used in the engine as coolant increased with the volume fraction and temperature (10–50°C) [18]. Hatami et al modelled a flat tube of an engine radiator numerically for improving the cooling process or heat recovery of the engine using nanofluids by using two kinds of fluids, water and ethylene glycol, as base fluid and four nanoparticles (CuO, TiO_2, Al_2O_3 and Fe_3O_4) in different shapes with four different Reynolds numbers. It is observed that the ethylene glycol based TiO_2 nanofluid with platelet shape and larger volume fraction of nanoparticles has the best cooling performance for the engine among other modelled nanofluids [19]. Sandhy et al determined the performance of ethylene glycol and water-based TiO_2 nanofluids as an automobile radiator coolant experimentally. Results demonstrate that increasing the fluid circulation rate can improve the heat transfer performance [20]. Li et al evaluated microcapsule phase change material (MPCM) slurry as engine coolant. The results show that mass flow rate and pumping consumption of slurries decrease greatly compared with water [21]. Tijani and Sudirman evaluated the performance of the heat transfer characteristics of water/anti-freezing based nanofluid as a coolant for car radiator. It was found that the nanofluid that exhibited the highest heat transfer performance was the CuO nanofluid [22].

Since there are many factors affect the thermophysical properties of nanofluids a decision - making method can be offered such as Analytic Hierarchy Process (AHP) for determining the best option among a number of nanoparticles. In the 1970s the AHP was introduced by Saaty. Each element in every level is compared bi-directionally with respect to a target element [23]. A number of criteria were required when selecting the best option from a range of alternatives. Every criterion should be weighted to show their relative importance. The alternatives are then given a performance score based on their performance on the criteria. The total performance score of an alternative is the sum of the scores of the alternative for a particular criterion multiplied by the weight of the relevant criterion. The best alternative is the one with the highest overall performance score [23]. There are several studies used AHP for a decision on different subject areas such as energy [24-31] transport systems [32], manufacturing [33-35], risk analysis [36, 37] etc.

The purpose of this study is to select the most efficient nanofluid among the three different water-based nanofluids for using as a coolant in the engine. AHP is used for selecting the suitable nanofluid which is regarded as a multi-criteria decision-making problem. Literature studies have shown that, although there is a lot of work on nanofluid as engine coolant, there is not any study on evaluation of nanofluid by using decision support systems. So this study will be a pioneer work in this area. The main difference of this study is using AHP to evaluate the thermophysical properties of three different nanofluids.

2. MATERIAL and METHOD

The nanofluids are characterized by thermophysical properties. Some of these properties include; density, specific heat, kinematic viscosity, thermal conductivity, thermal expansion coefficient, the On the other hand, the concentration of nanoparticles, purity level, shape and size of the nanoparticles are some of the prime factors that affect the thermophysical properties [3]. Among the stated thermophysical properties density, specific heat, kinematic viscosity, thermal conductivity and thermal expansion coefficient were chosen as indicating characteristics. Therefore, the objective of this paper is to decide the most efficient nanofluid which meets the criteria according to the importance ratings determined by the experts. Experimental values of three different kinds of nanofluids, which are frequently used, were taken from literature [8] and table 1 is formed.

Table 1. Thermophysical properties of different kinds of nanofluids

Nanofluid	Density ρ (kg/m^3)	Specific heat Cp (J/kgK)	Kinematic Viscosity γ (m^2/s)	Thermal Conductivity λ (W/mK)	Thermal Expansion Coeff. β (m^2/s)
Cu-Water	1316.672	3148.451	0.0000008350	0.6684	0.000161244
NiO-Water	1230.672	3389.815	0.0000008940	0.6640	0.000159157
CuO-Water	1218.272	3403.881	0.0000009030	0.6621	0.000159664
Water	998.200	4182.000	0.0000009900	0.5970	0.000143012

In this study, the Analytic Hierarchy Process (AHP) is attributed weights to criteria. Figure 1 shows the hierarchy model for nanofluid type selection and Table 2 shows the Importance scale values and definitions.

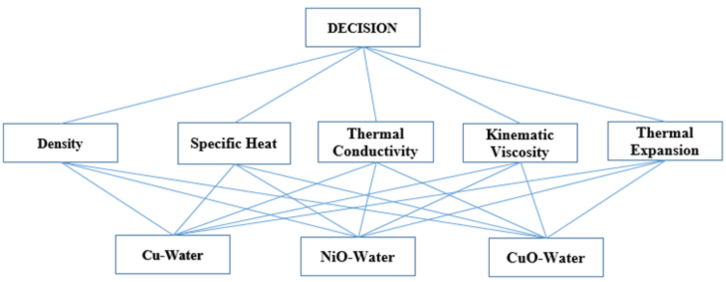

Figure 1. Hierarchy model for nanofluid selection

Table 2. Importance scale values and definitions [38]

Numerical scale	Verbal Scale	Numerical scale	Verbal Scale
1	Equal Importance	7	Very Strong Importance
3	Moderate Importance	9	Extreme Importance
5	Strong Importance	2,4,6 and 8	Intermediate Values

AHP was assessed using mathematical formulas given below. For the components stated below the diagonal, the formula 1 was used [39].

$$A = \begin{bmatrix} a_{12} & a_{12} & . & . & a_{1n} \\ a_{21} & a_{22} & . & . & a_{2n} \\ \dots & . & . & . & . \\ \dots & . & . & . & . \\ a_{n1} & a_{n2} & . & \dots & a_{nn} \end{bmatrix} \qquad a_{ji} = \frac{1}{a_{ji}} \tag{1}$$

In order to determine the significance levels of the factors, the matrix is calculated by using the normalization method with the formula 2 [40].

$$B_i = \begin{bmatrix} b_{11} \\ b_{21} \\ .. \\ .. \\ b_{n1} \end{bmatrix} bi_j = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \tag{2}$$

Subsequently, the matrix C which is constructed by combining the B column vectors as many as the number of factors in a matrix format. The arithmetic mean of the row components forming the matrix C is taken from the column vector W, which is named as Priority Vector and showing significance values, is obtained (3).

$$C = \begin{bmatrix} c_{11} & c_{12} & .. & .. & c_{1n} \\ c_{21} & c_{22} & .. & .. & c_{2n} \\ .. & .. & .. & .. & .. \\ .. & .. & .. & .. & .. \\ c_{n1} & c_{n2} & .. & .. & c_{nn} \end{bmatrix} W = \begin{bmatrix} w_1 \\ w_2 \\ .. \\ .. \\ w_n \end{bmatrix} \quad w_i = \frac{\sum_{j=1}^{n} c_{ij}}{n} \tag{3}$$

Consistency Ratio (CR) is obtained by comparing the number of factors and a coefficient (λ) called Eigen Value. For the calculation of (λ), firstly A the comparison matrix is compared with the priority vector W to obtain the D column vector.

$$D = \begin{bmatrix} a_{11} & a_{12} & .. & .. & a_{1n} \\ a_{21} & a_{22} & .. & .. & a_{2n} \\ .. & .. & .. & .. & \dots \\ .. & .. & .. & .. & .. \\ a_{n1} & a_{n2} & \dots & .. & a_{nn} \end{bmatrix} \times \begin{bmatrix} w_1 \\ w_2 \\ .. \\ . \\ w_n \end{bmatrix} \tag{4}$$

E is calculated from equation (5) and taking the arithmetic mean value (6) will give the eigenvalue λ. The eigenvalue is used to determine consistency ratio.

$$E_i = \frac{d_i}{w_i} \qquad (i = 1,2,....n) \tag{5}$$

$$\lambda = \frac{\sum_{i=1}^{n} E_i}{n} \tag{6}$$

Once the λ is calculated the Consistency Indicator (CI) can be determined by the formula (7). Also, Consistency Ratio (CR) can be determent by dividing the calculated with the formula (8), the value of CI to Random Consistency Index (RI) which is tabulated in table 3.

$$CI = \frac{\lambda - n}{n - 1} \tag{7}$$

$$CR = \frac{CI}{RI} \quad (8)$$

Table 3. Random Consistency Index Values [41]

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

The consistency test is completed when the CR is numerically calculated. If CR <10 % then the achieved data is consistent. If CR ≥10 % then the achieved data is inconsistent, so the comparison matrix should be revised [42].

3. RESULTS and DISCUSSION

In this section, a binary comparison matrix was prepared with the aim of evaluating the thermophysical properties of nanofluid obtained from different nanoparticle and used water as a base fluid by comparing them with AHP.

3.1 Thermophysical Property Evaluation

It has been determined that the following evaluation points are the most important properties in the thermophysical properties nanofluid; density, specific heat, kinematic viscosity, thermal conductivity, thermal expansion coefficient. In order to form the comparison matrix various specialists were asked to answer the priority chart, then the arithmetic mean value was taken. The comparison matrix is formed as shown in table 4.

Table 4. Comparison matrix of main criteria

Physical Properties	Density	Specific Heat	Thermal Conductivity	Kinematic Viscosity	Thermal Expansion
Density	1	1/7	1/9	1/4	1/4
Specific Heat	7	1	1/2	3	3
Thermal Conductivity	9	2	1	4	5
Kinematic Viscosity	4	1/3	1/4	1	3
Thermal Expansion	4	4	1/5	1/3	1

Normalization was done according to the formulas 2 and 3 then the priority vector was obtained as follows.

Table 5. Weighted values of main criteria

Importance levels of Main Criteria	Weight (W)
Density	0.0361885
Specific Heat	0.2759000
Thermal Conductivity	0.4488716
Kinematic Viscosity	0.1460393
Thermal Expansion	0.0930005

Table 6. Consistency ratio for thermophysical properties

Name	Result
Maximum Eigen Value (λ_{max})	5.220000
Random Consistency Indicator (RI)	1.120000
Consistency Indicator (CI)	0.053780
Consistency Ratio (CR)	0.048020

Consistency Ratio of thermophysical properties equals to 0.04802 which is smaller than 0.1 then the comparison is consistent. The main criteria are ranked in the following order: Thermal conductivity, Specific Heat, Kinematic Viscosity, Thermal Expansion and density, respectively.

3.2 Evaluation of Different Nanoparticles

Three different nanofluids were taken for evaluation. A matrix was formed for each thermophysical property by using importance scale values. The scale values were given according to the base fluid (water). Normalization was done according to the formulas 2 and 3 then the priority vector was obtained.

3.2.1 Density

Being an important thermophysical property, the density plays a vital role in evaluating the heat transfer performances of nanofluids [3]. Comparison of the density of nanofluids was shown in Table (7-9).

Table 7. Comparison matrix for subcriteria Density

Density	Cu-Water	NiO-Water	CuO-Water
Cu-Water	1	3	5
NiO-Water	1/3	1	3
CuO-Water	1/5	1/3	1

Table 8. Weighted values of Density (DW)

Importance levels of Subcriteria Density	Weight (W)
Cu-Water	0.633345
NiO-Water	0.260498
CuO-Water	0.106156

Table 9. Consistency ratio for Density

Name	Result
Maximum Eigen Value (λ_{max})	3.038715
Random Consistency Indicator (RI)	0.580000
Consistency Indicator (CI)	0.019357
Consistency Ratio (CR)	0.033375

Consistency Ratio of Density equals to 0.033375 which is smaller than 0.1 then the comparison is consistent. The subcriteria of the density of three nanofluids are ranked in the following order: Cu-Water, NiO-Water, CuO-Water, respectively.

3.2.2. Specific Heat

The specific heat plays an important in affecting the heat transfer rate of nanofluids. Specific heat is the amount of heat required to raise the temperature of one gram of nanofluids by one degree centigrade [3]. Comparison of the specific heat of nanofluids was shown in Table (10-12).

Table 10.Comparison matrix for subcriteria Specific Heat

Specific Heat	Cu-Water	NiO-Water	CuO-Water
Cu-Water	1	4	7
NiO-Water	1/4	1	3
CuO-Water	1/7	1/3	1

Table 11. Weighted values of Specific Heat (SHW)

Importance levels of Subcriteria Specific Heat	**Weight (W)**
Cu-Water	0.701437
NiO-Water	0.213238
CuO-Water	0.085324

Table 12. Consistency ratio for Specific Heat

Name	**Result**
Maximum Eigen Value (λ_{max})	3.032576
Random Consistency Indicator (RI)	0.580000
Consistency Indicator (CI)	0.016288
Consistency Ratio (CR)	0.028083

Consistency Ratio of Specific Heat equals to 0.028083 which is smaller than 0.1 then the comparison is consistent. The subcriteria of the specific heat of three nanofluids are ranked in the following order: Cu-Water, NiO-Water, CuO-Water, respectively.

3.2.3 Thermal Conductivity

The addition of nanoparticles in a conventional fluid increases the thermal conductivity. The studies show that the thermal conductivity of nanofluids is higher than the base fluids [3]. Comparison of thermal conductivity of nanofluids was shown in Table (13-15).

Table 13. Comparison matrix for subcriteria Thermal Conductivity

Thermal Conductivity	Cu-Water	NiO-Water	CuO-Water
Cu-Water	1	5	9
NiO-Water	1/5	1	3
CuO-Water	1/9	1/3	1

Table 14. Weighted values of Thermal Conductivity (WTC)

Importance levels of Subcriteria Thermal Conductivity	Weight (W)
Cu-Water	0.7481644
NiO-Water	0.1804021
CuO-Water	0.0714335

Table 15. Consistency ratio for Thermal Conductivity

Name	Result
Maximum Eigen Value (λ_{max})	3.029277
Random Consistency Indicator (RI)	0.580000
Consistency Indicator (CI)	0.014639
Consistency Ratio (CR)	0.025239

Consistency Ratio of Thermal Conductivity coefficient equals to 0.025239 which is smaller than 0.1 then the comparison is consistent. The subcriteria of the thermal conductivity of three nanofluids are ranked in the following order: Cu-Water, NiO-Water, CuO-Water, respectively.

3.2.4 Viscosity

Viscosity is another essential factor for applications of heat transfer as the pressure drop and the pumping power depends upon it [3]. Comparison of the viscosity of nanofluids was shown in Table (16-18).

Table 16. Comparison matrix for subcriteria Kinematic Viscosity

Kinematic Viscosity	Cu-Water	NiO-Water	CuO-Water
Cu-Water	1	5	7
NiO-Water	1/5	1	2
CuO-Water	1/7	1/2	1

Table 17. Weighted values of Kinematic Viscosity (KV)

Importance levels of Subcriteria Kinematic Viscosity	Weight (W)
Cu-Water	0.737970
NiO-Water	0.167594
CuO-Water	0.094435

Table 18. Consistency ratio of Kinematic Viscosity

Name	Result
Maximum Eigen Value (λ_{max})	3.014201
Random Consistency Indicator (RI)	0.580000
Consistency Indicator (CI)	0.007100
Consistency Ratio (CR)	0.012242

Consistency Ratio of Kinematic Viscosity equals to 0.012242 which is smaller than 0.1 then the comparison is consistent. The subcriteria of the kinematic viscosity of three nanofluids are ranked in the following order: Cu-Water, NiO-Water, CuO-Water, respectively.

3.2.5. Thermal Expansion Coefficient

The characteristic thermal expansion of a fluid also affects its heat transfer performances. Comparison of thermal expansion coefficient of nanofluids was shown in Table (19-21).

Table 19. Comparison matrix for subcriteria Thermal Expansion Coefficient

Thermal Expansion	Cu-Water	NiO-Water	CuO-Water
Cu-Water	1	3	4
NiO-Water	1/3	1	2
CuO-Water	1/4	1/2	1

Table 20. Weighted values of Thermal Expansion Coefficient (TE)

Importance levels of Subcriteria Thermal Expansion Coefficient	**Weight (W)**
Cu-Water	0.623224
NiO-Water	0.239487
CuO-Water	0.137287

Table 21. Consistency ratio for Thermal Expansion Coefficient

Name	**Result**
Maximum Eigen Value (λ_{max})	3.018337
Random Consistency Indicator (RI)	0.580000
Consistency Indicator (CI)	0.009169
Consistency Ratio (CR)	0.015808

Consistency Ratio of Thermal Expansion Coefficient equals to 0.015808 which is smaller than 0.1 then the comparison is consistent. The subcriteria of the thermal expansion of three nanofluids are ranked in the following order: Cu-Water, NiO-Water, CuO-Water, respectively.

Once the calculations were done for each thermophysical property. The weighted formula then formed for each nanofluid as follows:

$$Weighted\ Nanofluid = W_{1,1} * DW_{1,1} + W_{1,2} * SHW_{1,1} + W_{1,3} * TCW_{1,1} + W_{1,4} * KVW_{1,1} + W_{1,5} * TEW_{1,1} \qquad (9)$$

By using the above formula weighted result was calculated. The obtained formula gives the order of the evaluated nanofluids and the results are as follows: Cu-Water 0.718, NiO-Water 0.196, CuO-Water 0.086, respectively. Cu-Water nanofluid seems the best choice among the three nanofluids, on the other hand, CuO-Water nanofluid seems the least preferred choice.

4. CONCLUSION

A wide variety of features are required for the coolants to be used in automotive applications. A nanofluid which will be used in an engine must have various thermo-physical properties such as have high thermal conductivity, specific heat capacity and boiling point, as well as low viscosity and freezing point. It must also be eco-friendly by being non-toxic and chemically inert also it should not be corrosive in order not to cause corrosion in the cooling system. It would be appropriate to increase the heat transfer performance of the cooling systems and to use cooling fluids with higher thermal conductivity. The use of nanofluids for this purpose has a very crucial severity.

In this study, the thermophysical properties of three different nanofluids (Cu-water, NiO-water, CuO-water) were evaluated by using Analytical Hierarchy Process. During this evaluation, five different thermophysical properties (density, specific heat, kinematic viscosity, thermal conductivity, thermal expansion coefficient) and 3 different nanofluids were compared. As a result, the importance of fuel properties is listed as thermal conductivity, specific heat, kinematic viscosity, thermal expansion coefficient and density, respectively.

The evaluation showed that Cu-water nanofluid seems the best choice among the three nanofluids, on the other hand, CuO-water nanofluid seems the least preferred choice. To verify the result of this study, an evaluation of the nanofluids Cu-water, NiO-water, and CuO-water as a coolant in the vehicle radiator could be done experimentally.

Nomenclature

λ	Eigenvalue
DW	Weighted Density
SHW	Weighted Specific Heat
TCW	Weighted Thermal Conductivity
KVW	Weighted Kinematic Viscosity
TEW	Weighted Thermal Expansion Coefficient

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