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

by

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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 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.

Key words: analytic hierarchy process, nanofluids, thermophysical property, engine cooling

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 [1-3]. Having known the fact that, liquids have poorer thermal properties than solid materials, researchers focused on 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 nanoliquids, single-stage or two-stage methods are used [1]. The nanoparticles, which are frequently used to prepare nanofluids, have been reported in the literature:

- metallic particles (Cu, Al, Fe, Au, and Ag),
- non-amorphous particles (Al₂O₃, CuO, Fe₃O₄, TiO₂, and SiC),
- carbon nanotubes, and
- the nanodroplet [4].

Being a popular research area, nanofluids attract the attention of various scientists. These researches include heat exchangers [5-10], micro-channel heat sink [11, 12], electronics cooling [13], building air conditioning. In addition other sectors, nanofluids have found

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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, aluminum and similar metals with high thermal conductivity. One of the good ways 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. [16] experimentally investigated the characteristics of the steady-state turbulent convective heat transfer for Al₂O₃-water nanofluid in engine cooling. Micali et al. [17] measured the temperatures of the exhaust valve spindle and exhaust valve seat in the cylinder head using CuO based nanofluids. Li et al. [18] 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). Hatami et al. [19] 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, TiO₂, Al₂O₃, and Fe₃O₄) in different shapes with four different Reynolds numbers. It is observed that the ethylene glycol based TiO₂ nanofluid with platelet shape and larger volume fraction of nanoparticles has the best cooling performance for the engine among other modelled nanofluids. Sandhy et al. [20] determined the performance of ethylene glycol and water-based TiO₂ nanofluids as an automobile radiator coolant experimentally. Results demonstrate that increasing the fluid circulation rate can improve the heat transfer performance. Li et al. [21] evaluated microcapsule phase change material slurry as engine coolant. The results show that mass-flow rate and pumping consumption of slurries decrease greatly compared with water. Tijani and Sudirman [22] 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.

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 1970's 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 [23-30] transport systems [31], manufacturing [33, 34], 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. The 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.

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, *etc.* 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 [8] and tab. 1 is formed.

Table 1. Thermophysical properties of different kinds of nanofluids

Nanofluid	Density ρ , [k/m ⁻³]	Specific heat Cp, [Jkg ⁻¹ K ⁻¹]	Kinematic viscosity, $\gamma [m^2 s^{-1}]$	Thermal conductivity, $\lambda [\mathrm{Wm}^{-1}\mathrm{K}^{-1}]$	Thermal expansion coeff. β , $[m^2s^{-1}]$
Cu-water	1316.672	3148.451	0.000008350	0.6684	0.000161244
NiO-water	1230.672	3389.815	0.000008940	0.6640	0.000159157
CuO-water	1218.272	3403.881	0.000009030	0.6621	0.000159664
Water	998.200	4182.000	0.0000009900	0.5970	0.000143012

In this study, the AHP is attributed weights to criteria. Figure 1 shows the hierarchy model for nanofluid type selection and tab. 2 shows the importance scale values and definitions.



Figure 1. Hierarchy model for nanofluid selection

 Table 2. Importance scale values and definitions [37]

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

The AHP was assessed using mathematical equations given below. For the components stated below the diagonal, the eq. (1) was used [38].

$$A = \begin{bmatrix} a_{12} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \qquad a_{ji} = \frac{1}{a_{ji}}$$
(1)

In order to determine the significance levels of the factors, the matrix is calculated by using the normalization method with eq. (2) [39]:

 $B_{i} = \begin{bmatrix} b_{11} \\ b_{21} \\ ... \\ ... \\ b_{n1} \end{bmatrix} bi_{j} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}$ (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:

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

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

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

$$E_i = \frac{d_i}{w_i}$$
 (*i*=1,2,....*n*) (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 eq. (7). Also, CR can be determent by dividing the calculated with eq. (8), the value of CI to random consistency index (RCI) which is tabulated in tab. 3.

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

$$CR = \frac{CI}{RCI} \tag{8}$$

Table 3. The RCI values [40]

n	1	2	3	4	5	6	7	8	9	10
RCI	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 \ge 10% then the achieved data is inconsistent, so the comparison matrix should be revised [41].

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.

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 tab. 4.

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

 Table 4. Comparison matrix of main criteria

Normalization was done according to the eqs. (2) and (3) then the priority vector was obtained as follows, tabs. 5 and 6.

Table 5.	. Weighted	values	of main	criteria
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Table 6. Consistency ratio for thermophysical properties

Importance levels	TT 7 • 1 4				
of main criteria	weight	Nama	Result		
Density	0.0361885	Ivanic			
Specific heat	0.2759000	Maximum eigen value, λ_{max}	5.220000		
Thermal conductivity	0.4488716	Random consistency indicator, RI	1.120000		
Kinematic viscosity	0.1460393	Consistency indicator, CI	0.053780		
Thermal expansion	0.0930005	Consistency ratio, CR	0.048020		

The CR 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.

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 eqs. (2) and (3) then the priority vector was obtained.

Table 7. Comparison matrix forsubcriteria 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

Importance levels of subcriteria density	Weight
Cu-water	0.633345
NiO-water	0.260498
CuO-water	0.106156

Table 9. The CR 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

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

Importance levels of subcriteria specific heat	Weight
Cu-water	0.701437
NiO-water	0.213238
CuO-water	0.085324

Table 12. The CR 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

Table 13. Comparison matrix forsubcriteria 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

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 tabs. 7-9.

The CR 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.

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 tabs. 10-12.

The CR 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.

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 tabs. 13-15.

The CR 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.

Viscosity

Viscosity is another essential factor for applications of heat transfer as the

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pressure drop and the pumping power depends upon it [3]. Comparison of the viscosity of nanofluids was shown in tab. 16-18.

The CR 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.

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 tab. 19-21.

The CR 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 equation then formed for each nanofluid:

Table 14. Weighted values of thermalconductivity

Importance levels of subcriteria thermal conductivity	Weight	
Cu-water	0.7481644	
NiO-water	0.1804021	
CuO-water	0.0714335	

Table 15. The CR for thermal conductivity

Name	Result
Maximum eigen value, λ_{max}	3.029277
Random consistency index, RCI	0.580000
Consistency indicator, CI	0.014639
Consistency ratio, CR	0.025239

Table 16. Comparison matrix for subcriteriakinematic 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 ofkinematic viscosity

Importance levels of subcriteria kinematic viscosity	Weight
Cu-Water	0.737970
NiO-Water	0.167594
CuO-Water	0.094435

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

By using previous equation weighted result was calculated. The obtained equation gives the order of the evaluated nanofluids and the results are Cu-water 0.710.196, CuO-water 0.086, respectively. The Cu-water nanofluid seems the best choice among the three nanofluids, on the other hand, CuO-water nanofluid seems the least preferred choice.

Conclusions

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 thermophysical properties such as

Table 18. The CR 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		

 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

Importance levels of subcriteria thermal expansion coefficient	Weight	
Cu-water	0.623224	
NiO-water	0.239487	
CuO-water	0.137287	

Table 21. The CR for thermalexpansion coefficient

Name	Result		
Maximum eigen value, λ_{max}	3.018337		
Random consistency index, RCI	0.580000		
Consistency indicator, CI	0.009169		
Consistency ratio, CR	0.015808		

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 three 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

Greek symbols	SHW	 weighted specific heat
$\lambda = eigen value$	TCW	- weighted thermal conductivity
	KVW	- weighted kinematic viscosity
Acronyms	TEW	- weighted thermal expansion coefficient
DW – weighted density	W	– weight

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