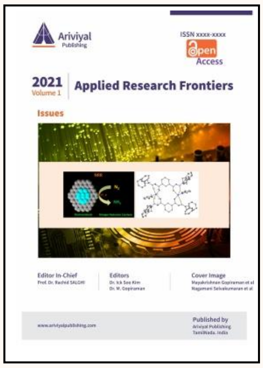
Applied Research Frontiers

Research Article

DOI: 10.36686/Ariviyal.ARF.2021.02.03.008

Appl. Res. Front., 2021, 2(3), 1-5.



Investigation of Heat Transfer Properties of Water-ethylene Glycol Mixture and some Commercial Coolants

Richard Alexis Ukpe[*a] and Augustine A. Chokor[a]

[a]*Federal University Otuoke, Bayelsa State, Nigeria.*

***Corresponding author E-mail address**: ukpera@fuotuoke.edu.ng (Richard Alexis Ukpe)

ISSN: XXXX-XXXX

Abstract: Heat transfer properties of water, ethylene glycol and two commercial coolants in Nigerian markets (Abro and Holt) were studied by observing the effect of various aqueous mixtures of the respective fluid on boiling point, elevation of boiling point and relative density. The results obtained from the study indicated that ethylene glycol has the best heat transfer capacity due to its molecular properties and high ebuloscopic constant (15.38). The performance of ethylene glycol and the commercial coolants was found to increase with increase concentration. The present study gives insight on the design of better heat transfer fluid and the optimum fluid to water ratio that could ensure best performance.

Keywords: Heat transfer fluid; Effectiveness; Water-ethylene glycol.

Publication details
Received: 07th August 2021
Revised: 26th August 2021
Accepted: 29th August 2021
Published: 31st August 2021

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1. Introduction

Water-ethylene glycol: The best known heat transfer fluid is water. Water has a density of approximately 1 g/dm^3, boiling point of 373 K at 1 atmospheric pressure and a freezing point of 273 K. It is said to be a universal solvent because almost all substances is soluble in it. From point of view of heat transfer, water has been successfully used in numerous domestic, commercial and industrial machines and systems.[1-12]

The general mechanism of cooling through the use of heat transfer fluid involves circulating water (by the pumping machine) through the heat generating component (usually the engine block) of the machine. The water takes away the heat generated and returns it to the radiator (which may have an attached cooling fan) before the generated heat is finally transferred to the surrounding. The cooling continues as the water is recycled to continuously transfer heat away from the machine to the surrounding. One major advantage of water is that it has little adverse effect on the environment. However, as most machines continue to run for hours, the heat generated may be too high for water to tolerate, hence the need to regulate the heat transfer mechanisms through the use of heat transfer fluids. The major consequence of uncontrolled generation of heat by engines is overheating. Overheating can be much pronounced and significant in old engines, especially in temperate zones. In order to overcome the effect of excessive heat generation and overheating, some special engineering fluids, called 'heat transfer fluid' (called coolant) have been designed and they have been found to be more effective than using 100 % water (Sandhya et al., 2016).[11]

A coolant is a heat transfer fluid which flows through or around a device and prevents the device from overheating. It transfers the heat produced by the device to other devices that either use or dissipate it (Madhesh and Kalalselvam, 2014).[6] An ideal coolant should have high thermal capacity and low viscosity. It should be less expensive, non-toxic, non-corrosive and chemically-inert (Rashmiet al., 2014).[9] Some applications also require the coolant to be an electrical insulator (Wikipedia, 2016).[12] Major properties that are required for heat transfer fluid includes, the following (Miassoedovet al., 2014).[7]

i. Coefficient of expansion: This defines the fractional change in length (or sometimes in volume, when specified) of a material for a unit change in temperature

ii. Viscosity: resistance of a liquid to sheer forces (and hence to flow)

iii. Thermal capacity: the ability of matter to store heat

iv. Freezing point: the temperature below which a liquid turns into a solid

v. Boiling point: the temperature at which a liquid boils

vi. Flash point: the lowest temperature at which the vapor above a liquid can be ignited in air

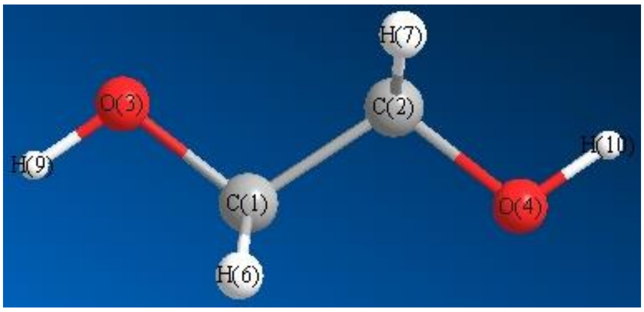

Fig. 1. Optimised structure of ethylene glycol

Several works have been reported on the use of ethylene glycol as heat transfer fluid (Mutuku, 2016).[8] However, study on the right proportion of ethylene glycol to water combination has not been reported. Therefore, the present study is designed to investigate the effect of elevation of boiling point, density and molecular structure on the heat transfer performance of various mixture of water-etylene glycol and some commercial coolants in the Nigerian market. The optimized structure of ethylene glycol is given in Fig.1.

2. Materials and methods

Materials used for the study were distilled water, analar grade ethylene glycol, 150°C graduated scale thermometer, density bottle, weighing balance, measuring cylinder and commercial coolants (Abro and Holt).

All temperature measurements were carried out by inserting the thermometer into the liquid or liquid mixture and the temperature was read out directly from the thermometer. In between measurements, the thermometer was properly rinsed in distilled water and allows to stabilize before re-use. The difference between the boiling point of the mixture and that of water was recorded as elevation of boiling point. That is,

$$\Delta T = T_{b(liquid\ mixture)} - T_{b(water)} \qquad (1)$$

where ΔT is the elevation of boiling point, $T_{b(water)}$ is the boiling point of water, $T_{b(liquid\ mixture)}$ is the boiling point of the liquid mixture.

The relative density was measured using density bottle. It was calculated using the following expression,

$$Relative\ density = \frac{Mass\ of\ the\ liquid\ (orliquid\ mixture)}{Mass\ of\ equal\ volume\ of\ water} \qquad (2)$$

3. Results and Discussions

3.1. Effect of temperature

Table 1 presents the boiling point of various mixtures of water and ethylene glycol. Tables 2 and 4 present similar data for water and Holt (a commercial coolant) and for Abro (another commercial coolant). It can be seen from the results presented in Table 1 to 3 that ethylene glycol has the capacity to increase the elevation of boiling point from 100 to 118°C. Thus the range of value for elevation of boiling point is 2 to 18°C while Holt and Abro (commercial engine coolants) have elevation of boiling point ranging from 2 to 4. These results reveal that ethylene glycol has the better capacity to elevate the boiling point of water. This can be attributed to better heat transfer capacity of ethylene glycol compared to that of Holt and Abro. Interestingly, the elevation of boiling point of water by ethylene glycol seems to increase with increase in concentration of ethylene glycol.

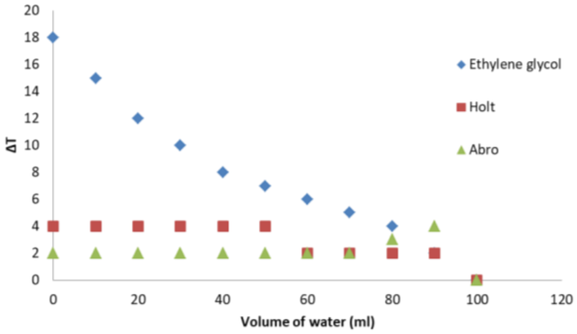

Fig. 2. Variation of elevation of boiling point with volume of water for water-ethylene glycol, water-Holt and water-Abro systems

Fig. 2. shows the variation of elevation of boiling point of water with volume of water in the mixture. From the plot, it is evident that ethylene glycol has outstanding ability to raise the boiling point of water than any of the commercially available coolant (Holt and Abro). This suggests that some of the coolant in the market may not sufficiently meet the challenges of bringing down the temperature of running stationary engines, especially in temperate zones where the atmospheric temperature may be excessively high. For example, in Nigeria, zones like Lokoja, Maiduguri and Kebbi usually have very high temperature during dry season, in the range of 35 to 45°C.

Consequently, when the atmospheric temperature is very high, running engines build up heat (Especially when the engine is running with extra load such as air condition) that needs to be dissipated away from the engine. Hence there is need for engagement of efficient heat transfer fluid. The finding of the study reveals that ethylene glycol has excellent heat transfer ability and most of its molecular properties are available in literature. Therefore, it is necessary to model the thermodynamic behaviour of various mixtures of ethylene glycol and water.

A liquid such as water turns to vapour at its boiling point. The boiling point of a liquid is constant at atmospheric pressure. However, in the presence of solute particles, the boiling point will be increased. Given a pure solvent (i.e water) A, addition of solute particles, B (ethylene glycol) to a solvent will increase the chemical potential of the water from $\mu^0_{A(l)}$ to $\mu^0_{A(l)} + RTlnX_A$. The equation relating the increase in boiling point of a liquid with composition can be derived by considering the heterogeneous equilibrium that exist between the liquid and it vapour(to equation 3) (Atkin, 2010)[1]:

$$\mu^0_{A(g)} = \mu^0_{A(l)} + RTlnX_A \qquad (3)$$

where X_A is the mole fraction of the solvent which is related to that of the solute (X_B) according to the equation, $X_A + X_B = 1$

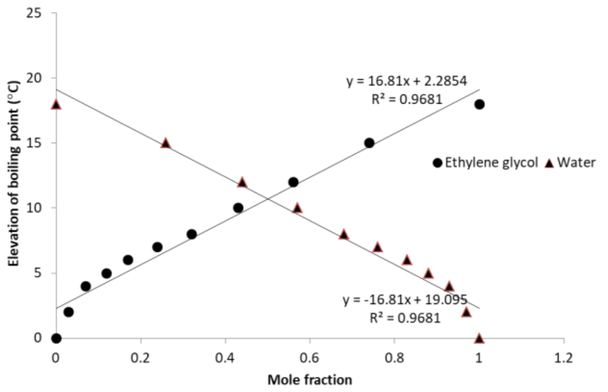

Fig. 3. Variation of elevation of boiling point of various mixtures of water and ethylene glycol with mole fraction of the components

Table 1. Boiling point and elevation of boiling point for various mixtures of water and ethylene glycol

Volume of water (ml	Volume of ethylene glycol (ml)	Boiling point (°C)	Elevation of boiling point (ΔT)(°C)
100	0	100	0
90	10	102	2
80	20	104	4
70	30	105	5
60	40	106	6
50	50	107	7
40	60	108	8
30	70	110	10
20	80	112	12
10	90	115	15
00	100	118	18

Table 2. Boiling point and elevation of boiling point for various mixtures of water and Holt coolant

Volume of water (ml	Volume of Holt (ml)	Boiling point (°C)	Elevation of boiling point (ΔT) (°C)
100	0	100	0
90	10	102	2
80	20	102	2
70	30	102	2
60	40	102	2
50	50	104	4
40	60	104	4
30	70	104	4
20	80	104	4
10	90	104	4
00	100	104	4

Table 3. Boiling point and elevation of boiling point for various mixtures of water and Abro coolant

Volume of water (ml	Volume of Abro (ml)	Boiling point (°C)	Elevation of boiling point (ΔT) (°C)
100	0	100	0
90	10	104	4
80	20	103	3
70	30	102	2
60	40	102	2
50	50	102	2
40	60	102	2
30	70	102	2
20	80	102	2
10	90	102	2
00	100	102	2

hence = $1 - X_B = X_A$ Therefore, equation 3 can be written as, $\mu^0_{A(g)}$ = $\mu^0_{A(l)} + RTln(1 - X_B)$ and upon rearrangement, equation 4 is obtained:

$$ln(1 - X_B) = \frac{\mu^0_{A(g)} - \mu^0_{A(l)}}{RT} = \frac{\Delta G_{vap}}{RT} \tag{4}$$

ΔG_{vap} is related to enthalpy and entropy of vapourization according to the Gibb equation. Therefore, $\Delta G_{vap} = \Delta H_{vap} - \Delta S_{vap}$ indicating that upon substitution to equation 3, equation 5 is obtained:

$$ln(1 - X_B) = \frac{\Delta G_{vap}}{RT} = \frac{\Delta H_{vap}}{RT} - \frac{\Delta S_{vap}}{R} \tag{5}$$

When X_B is equal to zero, the boiling point is that of the pure liquid and the temperature becomes T^0. Hence equation 5 becomes,

$$ln(1) = \frac{\Delta G_{vap}}{RT} = \frac{\Delta H_{vap}}{RT^0} - \frac{\Delta S_{vap}}{R} \tag{6}$$

Subtracting equation 4 from equation 6, yields,

$$ln(1 - X_B) = \frac{\Delta H_{vap}}{RT} - \frac{\Delta H_{vap}}{RT^0} = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T} - \frac{1}{T^0}\right) \tag{7}$$

In most cases, the number of mole of B present in the system will often be small compare to that of the solvent. Therefore, $ln(1 - X_B) \approx X_B$ and equation 7 becomes,

$$X_B = = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T^0} - \frac{1}{T}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{T - T^0}{TT^0}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{\Delta T}{T^2}\right) \tag{8}$$

In the above equation, TT^0 is equated to T^2 because $T \approx T^0$. From equation 8, we can make ΔT the subject of the equation and this represent the amount of elevation in temperature due to the addition of n_B mole of solute. Therefore,

$$\Delta T = \left(\frac{RT^2}{\Delta H_{vap}}\right) X_B \tag{9}$$

The bracketed terms constitute a constant called ebuloscopic or boiling point elevation constant (i.e K_B). Therefore, for a given system, ΔT $=K_B X_B$. Also, X_B is proportional to molality (concentration in terms of number of moles of solute per kilogram).

Values of mole fractions of water and ethylene glycol and the corresponding elevation of boiling point are presented in Table 4. Since elevation of boiling point is proportional to mole fraction, plots showing the variation of elevation of boiling point with mole fraction of ethylene glycol and water (Fig. 3) were developed. The two plots are seen to present a high degree of linearity (R^2 = 0.968) and similarity in** slope value (slope =16.86) which indicate the heat transfer ability of various mixtures of ethylene glycol and water obeys the model, hence the ebuloscopic constant of water ethylene mixture is 16.86.

Table 4. Number of moles of various mixtures of water and ethylene glycol, their mole fraction and corresponding elevation of boiling point

n_{H_2O}	$n_{Ethy-Gly}$	X_{H_2O}	$X_{Ethy-Gly}$	ΔT (°C)
5.50	0.00	1.00	0.00	0
4.95	0.18	0.97	0.03	2
4.40	0.35	0.93	0.07	4
3.85	0.53	0.88	0.12	5
3.30	0.70	0.83	0.17	6
2.75	0.88	0.76	0.24	7
2.20	1.05	0.68	0.32	8
1.65	1.23	0.57	0.43	10
1.10	1.40	0.44	0.56	12
0.55	1.58	0.26	0.74	15
0.00	1.75	0.00	1.00	18

$**\mathrm{nH_2o} = \text{number of moles of water},$
$n_{Ethy-Gly} = number\ of\ moles\ of\ ethylene\ glycol,$
$\mathrm{XH_2o} = \text{mole fraction of water}, n_{Ethy-Gly} =$
$mole\ fraction\ of\ ethylene\ glycol$

Table 5. Number of moles of various mixtures of water and ethylene glycol, their mole fraction and corresponding relative density

n_{H_2O}	$n_{Ethy-Gly}$	X_{H_2O}	$X_{Ethy-Gly}$	p
5.50	0.00	1.00	0.00	0
4.95	0.18	0.97	0.03	0.908
4.40	0.35	0.93	0.07	1.370
3.85	0.53	0.88	0.12	1.421
3.30	0.70	0.83	0.17	1.415
2.75	0.88	0.76	0.24	1.030
2.20	1.05	0.68	0.32	1.415
1.65	1.23	0.57	0.43	1.030
1.10	1.40	0.44	0.56	1.345
0.55	1.58	0.26	0.74	
0.00	1.75	0.00	1.00	0.955

$**\mathrm{nH_2o} = \text{number of moles of water},$
$n_{Ethy-Gly} = number\ of\ moles\ of\ ethylene\ glycol,$
$\mathrm{XH_2o} = \text{mole fraction of water}, n_{Ethy-Gly} =$
$mole\ fraction\ of\ ethylene\ glycol,$
$\Delta T = elevation\ of\ boiling\ point$, p = relative density

3.2. Effect of density

Heat transfer is the exchange of thermal energy between physical systems. The rate of heat transfer is dependent on the temperatures of the systems and the properties of the intervening medium through which the heat is transferred. The three fundamental modes of heat transfer are conduction, convection and radiation. According to Hsu and Smith (1961),[4] density can affect heat transfer properties of a moving fluid by inducing natural convection when it is significantly large. It is worth stating that the density of a heat transfer fluid correlates with the proximity of its molecules, indicating that a material with a higher density has close proximity of molecules than materials of lower density (Cremers, 1971.[2] Therefore, materials of higher density will transfer heat at a faster rate than materials of lower density. Density also influences the boiling point of a fluid because the higher the density, the higher is the expected boiling point.

Table 5 presents data for the variation of the density of the studied heat transfer fluid (mixture of water and ethylene glycol) with mole fraction. It is seen from the results that the density of the fluid fluctuates with fluid composition. This may be due to effect of temperature, which can affect molecular vibrations and properties such as viscosity and density.

3.3. Molecular study

The optimized structure (i.e the structure with the minimum energy) of ethylene glycol was shown in Fig 1. Calculated hydration energy, molecular volume (i.e. cosmo volume), polarizability, logP and molecular surface area for the molecule are -12. 95 kCal/mol, 265.79 Å^3, 5.72 Å3, -0.71 and 224.82 Å^2. The hydration energy of water is -21.53 kCal/mol indicates that ethylene glycol can easily be hydrated by water.

Theoretically, ethylene glycol is miscible in water. Calculated value of log (Henry's constant) from vapor pressure/water solubility ratio reveals that the solubility is 1,000,000, which points toward a high solubility index. On the contrary, the molecular volume of water is 118. 49 Å^3 compare to 265.79 Å^3 (for ethylene glycol). Therefore, ethylene glycol has greater molecular volume than water and thus a higher space for storing or transferring heat compare to water. The surface area of water is 128.32 Å, which are still less than that of ethylene glycol (i.e 224.82 Å^2). Hence, ethylene glycol has unique molecular properties that make it a better heat transfer fluid than water.

4. Conclusions

The aim of the present study was to investigate the heat transfer capacity of some commercial coolant and that of ethylene glycol. The study reveals that the heat transfer capacity of the studied fluids varies with composition and that the heat transfer potential of ethylene glycol is better than that of Holt and Abro radiator coolants. Ethylene glycol possesses unique molecular properties that enable it to resist overheating. This property becomes more effective as the concentration of ethylene glycol in the aqueous mixture increases. Although there was no unique pattern of variation of density with composition for various mixture of ethylene glycol and water, ethylene glycol favourably adjusted the density of the fluid and enhances its heat transfer potential. Molecular study reveals that ethylene glycol has some structural advantages (such as molecular volume, surface area, etc.) in serving as a heat transfer fluid.

Acknowledgements

Authors of this article are grateful to Prof. Nnabuk Okon Eddy for sponsoring the research and consequent publication of this article.

Conflicts of Interest

The authors declare no conflict of interest

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