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THERMOPHYSICAL PROPERTIES ANALYSIS FOR AMMONIA-WATER MIXTURE OF AN ORGANIC RANKINE CYCLE

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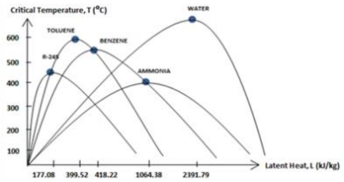
Graphical abstract



Abstract

In an Organic Rankine Cycle (ORC), the thermofluid properties of the organic fluid are key parameters to achieve an optimum energy recovery. Non-azeotropic fluid, such as ammonia-water mixture is suitable for applications in low grade heat source because of the thermodynamic characteristics of this fluid. This paper reports experimental data of thermal conductivity and dynamic viscosity of ammonia-water mixtures that will be used for ORC application. Five ratios of ammonia to water concentration were tested which are; (1) 25:75, (2) 20:80, (3) 15:85, (4) 10:90 and (5) 5:95. These five mixtures are characterized at a temperature range from 25°C to 40°C. The result shows that the thermal conductivity increases as the concentration of the ammonia reduces. The thermal conductivity also increases as the mixture temperature increases. The ammonia-water mixture at the ratio of 5:95 gives the highest thermal conductivity at 40°C which is 30% better than the other concentrations at similar temperature. The dynamic viscosity, and heat capacity, of these mixtures shows a linear relationship to ammonia molar concentration.

Keywords: Organic working fluid, ammonia-water mixture,waste heat recovery

1.0 INTRODUCTION

The ORC system is developed to utilize low-temperature heat source (between 80°C and 600°C) and convert the waste heat into useful energy such as electrical and mechanical power [1]. There are two advantages of ORC as compared to the steam Rankine cycle; (1) higher net power and thermal efficiency, and (2) an organic working fluid has lower vaporization heat than water. Therefore, to recover the low grade waste heat, it is potentially feasible to use organic fluid instead of pure fluid such as water because of the boiling and condensing properties of the pure fluids have a larger temperature difference [2].

The organic fluid must has several criteria to be fulfilled for applying in the ORC. The properties of a good fluid are; (1) a low specific volumes, (2) inexpensive, (3) low Ozone Depletion Potential (ODP) and (4) low Global Warming Potential (GWP) [3]. The fluid must also be (5) thermally stable, (6) non-toxic, (7) non-flammable when exposed to a hot source, (8) non-explosive and (9) safe for equipment operation [4].

Ammonia-water mixture is a highly recommended organic fluid in thermodynamic power cycle. Even though the strong odor of this mixture is an irritation and a nuisance, ammonia does not contribute to global pollution and global warming because it is environmentally friendly and safe enough for engineering application [5–7]. The waste heat recovery (WHR) that uses ammonia has the highest effectiveness with the maximum value of 0.25 compared to R-134a, and Propane [8]. Moreover, the ammonia boiling temperature is substantially lower than the water, so it is practically useful in utilizing the low temperature of waste heat energy. Ammonia-water mixtures exhibits properties such as (1) varying boiling and condensing temperature, (2) the thermo physical properties are highly temperature dependant, (3) it has very low freezing temperatures where the pure ammonia freeze temperature is -78 ^{0}C, while water at 0^{0}C and (4) the properties of the mixture are relative to the mixture concentration ratios [7].

Even though ammonia–water solution is corrosive, this disadvantage can be overcome by selecting an appropriate material for the ORC. At the temperature of 400^{0}C, the ammonia become unstable and leads to nitride corrosion. Thus, using ammonia-water mixture at this temperature is not practical [9]. Hence, nitridation of high temperature component such as superheater and turbine should be of concern as the copper based alloy are subjected to corrosion in the presence of ammonia [10]. However, the working temperature is lower at the condenser, thus carbon steel can be used as condenser tubing [11].

This paper presents the study of ammonia-water mixture properties as a foundation for its application as the working fluid for the ORC. Ammonia-water mixture with different concentrations and temperatures are analysed by using experimental and mathematical model to identify the thermophysical properties. A correlation between thermal conductivity, k, dynamic viscosity, and heat capacity, with ammonia concentrations level were measured and discuss in this paper.

1.1 Ammonia-Water Mixture Analysis

Table 1 shows the properties of some potential fluids that can act as the heat transport medium in the ORC. From the table, water and ammonia has the highest latent heat which are 2391.79 kJ/kg and 1064.38 kJ/kg; comparitively to Benzene, Toluene and R-245, ammonia has the highest solubility percentage in water.

Table 1 Properties of some refrigerant fluids [12,13]

Fluid	Boiling Point,T [°C]	Freezing Point, T [°C]	Latent heat, L [kJ/kg]	Solubility in water, (%)	ξ (J/kg.K²)	Critical Temperature Tc (°C)	Critical Pressure, Pc (MPa)	Thermal Conductivity, k [W/mK] at 27°C
Water	100	0	2391.79	N/A	-17.78	647.1	22.06	0.609
Ammonia	-33	-77.7	1064.38	31% at 25 °C	-10.48	405.4	11.33	0.507
Benzene	80.1	5.5	418.22	0.018% at 30 °C	-0.7	562.05	4.89	0.141
Toluene	110.62	-94.99	399.52	0.052% at 25 °C	-0.21	591.75	4.13	0.135
R-245	15.3	< -153	177.08	0.071%	0.19	427.2	3.64	0.081

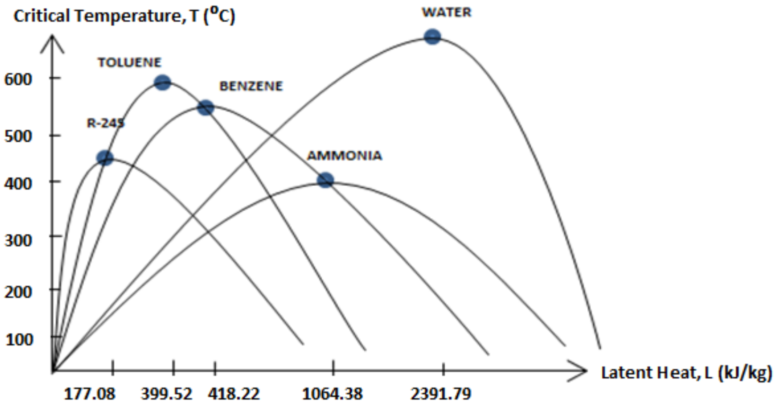


Figure 1 Fluid critical temperature versus latent heat

From Fig. 1, it is shown that the ammonia has the lowest critical temperature. Ammonia exists as vapor at room conditions as the boiling temperature is -33 °C with a critical temperature is 405.4 °C. The boiling temperature of the water is 100 °C due to the hydrogen bonds which tend to hold water molecules together, preventing them from breaking apart and entering the gaseous state and has the highest critical pressure which is 22.06 MPa. However, the main disadvantage of water as a refrigerant is that the boiling temperature is high. As a result, water is unsuitable for low temperature heat recovering system. Mixture of ammonia and water that has thermodynamic benefit in utilizing a low great heat source is a good combination because of the characteristic of this mixture is suitable for the ORC application.

2.0 EXPERIMENTAL ANALYSIS

In order to identify thermophysical properties of the ammonia-water mixture, different concentrations of mixtures were prepared. The volume concentrations are calculated, using Eq. 1. Ammonia-water solutions were diluted into 5 different concentration as followed:

1. (30:70) – original solution volume.
2. (25:75) – containing 25% of ammonia (NH_3) and 75% of distill water.
3. (20:80) – containing 20% of ammonia (NH_3) and 80% of distill water.
4. (15:85) – containing 15% of ammonia (NH_3) and 85% of distill water.
5. (10:90) – containing 10% of ammonia (NH_3) and 90% of distill water.
6. (05:95) – containing 5% of ammonia (NH_3) and 95% of distill water.

$$\Delta \mathrm{V} = (\mathrm{V}_2 - \mathrm{V}_1) = \mathrm{V}_1(\frac{\Phi 1}{\Phi 2} - 1) \qquad (1)$$

where, ΔV : Dilution volume
V_1 : Original solution volume
V_2 : Final solution volume
Φ_1 : 30% volume concentration
Φ_2 : Final volume concentration

Table 2 Mol and concentration of ammonia-water mixture

Ratio of the concentration level	Mol Concentration
(30:70)	0.49
(25:75)	0.4
(20:80)	0.32
(15:85)	0.24
(10:90)	0.16
(5:95)	0.08

The ratio of the concentration level for ammonia-water mixture based on mol concentration is shown in Table 2. The thermal conductivity, k, of these concentration was measured by using KD2* Pro thermal property analyzer as shown in Fig.2.

Figure 2 Thermal conductivity meter (KD2* PRO)

2.1 Heat Transfer Analysis

Other thermophysical properties of the mixture such as dynamic viscosity, μ, and heat capacity, Cp can be determined as following.

$$\mu^{x} = \mu(1 + 2.5\phi) \qquad (2)$$

where, : Dynamic viscosity of the mixture, kg/m.s
: Fluid viscosity, kg/m.s
: A drop of fluid concentration

$$Cp = \frac{(1-\varphi)(\rho Cp)_a + \varphi(\rho Cp)_w}{(1-\varphi)\rho_a + (\varphi\rho)_w} \qquad (3)$$

where, Cp : Heat capacity, J/K.kg
φ : Percentage of fluid concentration
ρ : Density of a fluid, kg/m3

3.0 RESULTS AND DISCUSSION

The result of thermal conductivity of the mixture in Fig. 3 shows that the thermal conductivity of the mixture increases as the ammonia concentration is reduced. However at the temperature of 40^0C, the ammonia-water mixture thermal conductivity reading is affected by the vaporization of the ammonia component, producing a non-linear relationship as the ammonia concentration is increased.

Fig. 4 shows that the thermal conductivity of pure ammonia is the lowest and the mixing with water greatly has improved its thermal conductivity. The thermal conductivity of the mixture increases as the temperature increases. However, at the temperature of 40 ^{0}C, the reading of the thermal conductivity, k, for (25:75), (20:80), (15:85) and (10:90) is more stable than (5:95). This is because the low concentration ammonia is sensitive to temperature increase and it starts to vaporize. Thermal conductivity of pure water also increases as the temperature increases. However, at the temperature of 30^{0}C, the thermal conductivity of pure water is lower than ammonia-water mixture at the ratios of (5:95), (10:90) and (15:85).

The dynamic viscosity, and heat capacity, Cp of the ammonia-water mixture are shown in Fig.5 and Fig.6. The results show that the internal resistance flow and heat capacity of the mixtures are sensitive to the ammonia concentration levels in the mixture and they are increased as the concentration of the ammonia is increased.

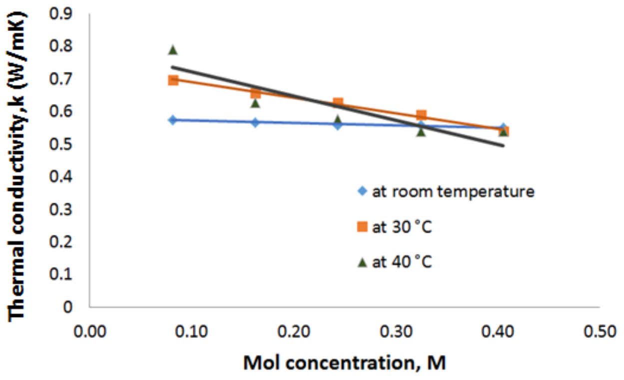


Figure 3 Thermal conductivity vs mol concentration of ammonia-water mixture

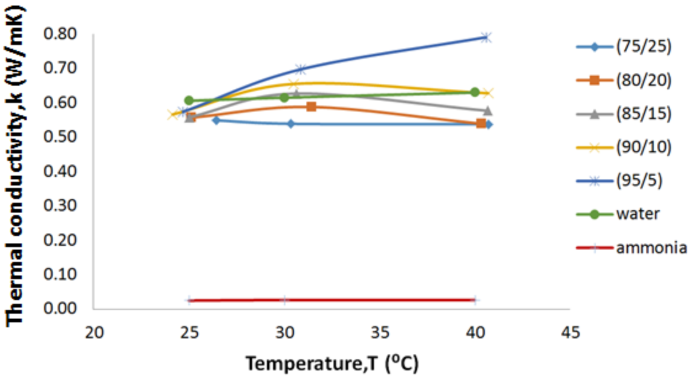


Figure 4 Thermal conductivity vs temperature of ammonia-mixture

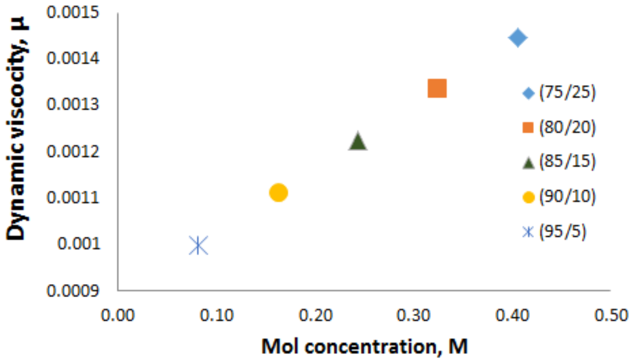


Figure 5 Dynamic viscosity versus mol concentration

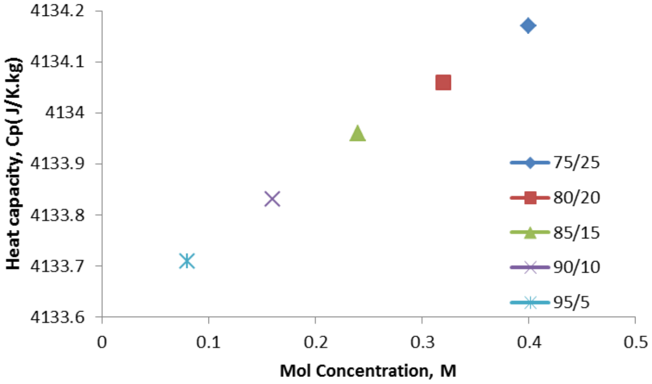


Figure 6 Heat capacity versus mol concentration

4.0 CONCLUSION

The analysis deduces that the thermal conductivity, dynamic viscosity and heat capacity of ammonia-water mixture are affected by the concentration level of the ammonia and water. Apart from that organic working fluid such as ammonia-water mixture has potential to be used as working fluid for the ORC application. This is because, the thermophysical properties of this mixture shows the positive result as the thermal conductivity of this mixture can achieve higher than the water at the certain temperature and concentration. The ammonia here is to act as a catalyst to accelerate the boiling temperature of the mixture. The analysis of thermophysical properties of ammonia-water mixture can be used in investigating the heat transfer process in the compact heat exchanger.

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