

Engine Coolant Thermophysical Properties Lab

Arnab Gupta
College of Engineering
Pennsylvania State University
University Park, PA
apg5799@psu.edu

Connor Lloyd
College of Engineering
Pennsylvania State University
University Park, PA
cvl5971@psu.edu

John Nolan O'Connor
College of Engineering
Pennsylvania State University
University Park, PA
jno5123@psu.edu

ABSTRACT

In this paper, the material properties of water and two unknown samples are evaluated by referring to the ASTM standard procedures. The material properties of the unknown samples were compared to water and a prediction of which material can be the best engine coolant was made. Methods followed in this analysis were compared with the ASTM standard. The heat exchanger effectiveness and the overall heat transfer coefficient for each proposed coolant were also calculated.

I. INTRODUCTION

Engine cooling is an integral part of the engine system. Since internal combustion engines rely upon the combustion and expansion of extremely hot gases, unmitigated operating temperatures can cause performance reductions and even complete failure of the engine system [1]. Engine cooling systems combat such reductions in performance by pumping coolant through the engine block to transfer heat from the engine block to the coolant liquid [1]. This heated coolant then continues to the radiator, which uses the flow of air (or other cold fluids) to exchange heat between passing air and the heated coolant [1]. This exchange of heat at the radiator lowers the temperature of the coolant before it goes back into the engine block, thus allowing the heat transfer cycle to continue [1].

An effective heat exchanger has not only efficient geometric design qualities, but also an optimal cooling liquid. Thermophysical properties that describe how optimal of a performance a fluid will return when used as a coolant include thermal conductivity, specific heat capacity, density, and viscosity. The thermal conductivity of a material quantifies how easily heat can be transferred via conductive heat transfer between the material and another medium [2]. Higher values of thermal conductivity indicate a greater ability to transfer heat via conduction (i.e., a more effective heat exchanger) [2]. A material's specific heat capacity refers to how much energy is required to increase the temperature of one gram of the material by 1°C (or 1K) [2]. Higher specific heat capacity values indicate that a material accepts more heat per unit mass before its temperature increases [2]. Thus, higher specific heat capacities are conducive to more effective heat exchangers. Strongly associated with thermal conductivity and specific heat capacity is density. A material's density is the measure of mass

per unit volume [2]. Thus, materials with higher densities have more mass contained in the same volume than a material with a lower density [2]. Coolants with higher densities will allow for the coolant to conduct and absorb more heat per unit volume, as there is simply more material available (which leads to a more effective heat exchanger) [2]. Not related to the heat transfer performance of coolant, but nonetheless important to the overall functionality of engine system is the viscosity of the coolant. Viscosity refers to how much internal resistance fluid elements experience when trying to move past one another [2]. Fluids with higher viscosities will flow more slowly than those with lower viscosity and require greater pressures to achieve a specified flow conditions than a lower viscosity fluid would need [2]. Thus, in the context of an engine coolant system, a lower viscosity fluid is preferred as this allows for a less powerful, more energy-efficient pump to be used to drive the cooling system.

The intent of the experiments covered in this paper is to determine which mixture of propylene glycol and water is the optimal coolant for an engine cooling system that is employed in the Pennsylvania climate. Based on the descriptions of the four thermophysical properties included earlier, it is hypothesized that the optimal coolant chemistry will have the highest thermal conductivity, the highest specific heat capacity, the highest density, the highest viscosity, and the lowest viscosity. Whichever of the three tested samples meets the most of those four criteria is hypothesized to be the optimal coolant. However, exceptions may have to be made should the optimal coolant be insufficient for applications in the Pennsylvania climate (i.e., its freezing point is too high).

In the laboratory, experimental determinations (in compliance with relevant ASTM standards) of the thermal conductivity, specific heat capacity, density, and viscosity of the three tested mixtures were conducted. After data collection was completed, a radiator performance analysis was performed. Heat exchanger effectiveness and overall heat transfer coefficient values associated with each tested mixture were returned by the radiator performance analysis. These values went on to inform the decision of which sample would serve as the optimal coolant in the Pennsylvania climate. More specific information on the methods and materials used to conduct the experimental determinations, the data obtained for the experimental determinations, how the data was analyzed, and the conclusion of the experiment is included in the sections that follow.

II. METHODS AND MATERIALS

A. Specific Heat Capacity

For measuring specific heat capacity, the ASTM E1269-11 standard was followed. During this experiment, a differential scanning calorimeter (DSC) manufactured by TA Instruments was used in the ME Knowledge Lab in Reber, 101 University Park, PA 16802. Other materials used for this experiment included a precision scale manufactured by Ohaus, Eppendorf, precision pipettes (with pipette tips) supplied by the ME Knowledge Lab, Tzero pans and hermetic lids sourced from TA Instruments, a cold weld crimper manufactured by TA Instruments, and tweezers supplied by the ME Knowledge Lab. During experimentation, the ambient air temperature of the laboratory was routinely sampled to monitor environmental conditions. Environmental management responsibilities were passed on to the DSC when the filled pan was inserted into the machine.

To briefly describe the experiment, 30 μL of one of the coolant samples was carefully inserted into a pan and lid combination. Pan and lid combinations were carefully determined such that their combined mass within $\pm 0.01\text{mg}$ of the empty reference pan's mass. The filled pan was then crimped and sealed before being inserted into the DSC test chamber. In accordance with ASTM standard E1269-11, the sample was heated at a constant rate whilst its thermal properties were monitored [3]. The DSC's proprietary software, TA TRIOS, output the tested sample's heat flow graph with three measurements: the empty pan reference, the sapphire reference and the sample itself. Using data from the heat flow graph and Equations 2 and 3 from the ASTM E1269-11 standard, the sample's specific heat capacity was calculated [3]. This process was completed once for all three coolant samples.

B. Kinematic Viscosity

To measure kinematic viscosity, the ASTM D445-19a standard was followed. For this experiment, Ubbelohde glass viscometers manufactured by SI Analytics was used in the ME Knowledge Lab in Reber, 101 University Park, PA 16802. More information on the selection and use of viscometers can be found in ASTM D446-12 standard [5]. Additional materials used for this experiment included a ring stand, v-clamp, viscometer holder, funnel, filter paper, pressurized hand pump, an ASTM standard mercury thermometer, and a timer, all of which were supplied by the ME Knowledge Lab. Eppendorf precision pipettes with pipette tips were also used. Ambient air temperature readings were taken prior to each kinematic viscosity measurement to account for any environmental changes that occurred between measurements.

Per the ASTM D445-12 standard procedure, kinematic viscosity was measured using an Ubbelohde viscometer for each of the 3 samples [4]. In summary of the procedure, each sample was passed through a filter before entering the viscometer. The viscometer was filled until the fluid level was between the two markings located on Bulb A [5]. Next, Tube M should be sealed and tubing for the hand pump was connected to Tube N [5]. Then, the viscometer was pressurized such that the loaded fluid would exceed the elevation of Line E

[5]. To measure the flow time of the sample, the pressure was released, and a digital timer was started once the bottom of the meniscus of the sample fluid reached Line E [5]. The timer stopped once the bottom of the meniscus of the sample fluid reached Line F [5]. Using the measured flow time, the kinematic viscosity of the sample was calculated using Equation 2 from the ASTM D445-18 standard procedure [4]. Each sample went through the above process twice, generating 2 kinematic viscosity measurements per sample. The average of these 2 measurements was used in later analyses.

C. Thermal Conductivity

For measuring thermal conductivity, the ASTM D7896-19 standard procedure was followed. During this experiment, the THW-L2 unit, a transient hot wire liquid thermal conductivity measurement system manufactured by Thermtest, was used in the ME Knowledge Lab in Reber, 101 University Park, PA 16802. Other materials used for this experiment included a solid aluminum top block assembly, an aluminum sample holder, two interlocking aluminum parts, and a ring stand with a clamp, which were all supplied by the ME Knowledge Lab. Eppendorf precision pipettes with pipette tips were also used. Environmental controls, including sample fluid temperatures, were all controlled by the THW-L2 unit.

Per the ASTM D7896-19 standard, the thermal conductivity for each sample fluid was measured using the THW-L2 unit. To briefly describe the process, the aluminum parts were assembled to form a small chamber as instructed in the ASTM D7896-19 standard. The cavity created by the aluminum assembly was then filled with sample fluid using precision pipettes. Once the sample was filled, the sensor with the hotwire was inserted into the channel, and the aluminum top block assembly was attached [6]. The Thermtest THW software was then instructed to run 10 trials of thermal conductivity measurements. After the trials were completed, the Thermtest THW software output the ten precise readings of thermal conductivity for each sample. The average of these ten trials was taken for use in future analyses. Thermal diffusivity and volumetric heat capacity calculations were also performed using Equation 1 and Equation 2 from the ASTM D7896-19 standard [6].

D. Density

To measure density, a self-constructed procedure was developed. To execute the procedure, a Navigator Precision Scale manufactured by Ohaus and three 10mL graduated cylinders were used in the ME Knowledge Lab in Reber, 101 University Park, PA 16802. Additional materials used for this experiment include paper towels, a source of running water, and Eppendorf precision pipettes with pipette tips. The room temperature was measured between each reading and was found to be constant for the duration of this experiment.

Briefly summarized, to measure density, an unused 10mL graduated cylinder was placed on the scale. Once the mass reading reached steady-state, the scale was tared. Next, the cylinder was filled using a precision pipette with a fresh tip until 3mL of the sample fluid was contained by the 10mL graduated cylinder. At this point, the mass reading from the scale and the

volume reading from the graduated cylinder were recorded. The density of the sample fluid was then calculated using the formula listed below in Equation 1.

$$\rho = \frac{M}{V} \quad (1)$$

The above process was conducted three times for each sample fluid, generating nine density calculation total. The average of each sample's 3 density calculations was used in later analyses.

III. RESULTS

A. Specific Heat Capacity

As referenced earlier in Section 2, the ASTM E1269-11 standard (with a release year of 2018 and a download date of 6/15/2021) was used to obtain the specific heat capacities of the three engine coolant test specimens. Testing was completed on February 1st, 2024, in Mechanical Engineering Knowledge Lab on the Pennsylvania State University's University Park, PA campus. Due to the unknown contents of the test specimens, no manufacturer's code was made available. The instruction team of Penn State's ME 435 course provided all test specimens. The three test specimens are mixtures of water and propylene glycol with unknown compositions. Test specimens were stored and processed during the experiment at room temperature (23 °C). Test specimens were sealed under standard atmospheric pressure (1 ATM).

A differential scanning calorimeter (DSC) was used to perform the specific heat determination. A Discovery DSC25 (model number 2-02019, manufactured by TA Instruments, located at Station B in the Mechanical Engineering Knowledge Lab) was used. Its accompanying software, TA TRIOS, was used for data acquisition and calculations related to specific heat capacity. Specimen holders provided by the instruction team of Penn State's ME 435 course were used to hold the test specimens and reference materials during testing. These include lightweight, aluminum Tzero alodined pans and Tzero alodined hermetic lids, with both the pans being produced by TA Instruments (model numbers 901683.901 and 901684.901, respectively). Each pan has a liquid volume capacity of 40 microliters.

The Discovery DSC2-02019's heat flow calibration was performed once before experimentation with the test specimens began. Synthetic sapphire was used as the standard material for heat flow calibration. A four-minute isothermal equilibrium time was used for each test specimen. For the specific heat capacity dataset used in later analyses of each sample's thermal properties, no change in mass exceeding 0.3% was noted for any of the test specimens. The mass of the specimen holders were 53.39 mg, 53.44 mg, and 53.43 mg for samples A, B, and C, respectively. Other test settings, such as the scan rate and purge gas atmosphere's flow rate, purity, and composition, were configured by the instructional team of Penn State's ME 435 course and not disclosed. The specific heat capacities obtained from the TA TRIOS software for the three test specimens are specified in Table 1. The reported values are

single measurements taken at one temperature, 67°C, for each sample.

Table 1 – Specific Heat Capacity (Cp(s)) at 67°C

Sample ID	Cp(s) from TRIOS Software	Unit
A	3.200	J/(g·K)
B	4.184	J/(g·K)
C	4.282	J/(g·K)

B. Kinematic Viscosity

As stated in Section 2, the ASTM D445-19a standard was used to obtain the kinematic viscosities of the three engine coolant test specimens. The ATSM D446-12 standard was also used for reference on proper operation of the Ubbelohde viscometers used during testing. Testing was completed on February 8th, 2024, in Mechanical Engineering Knowledge Lab on the Pennsylvania State University's University Park, PA campus (Reber, 101, University Park, PA 16802). A noteworthy departure in the methods of this experiment from the ASTM D445-19a standard was the absence of a constant-temperature liquid bath used to hold the fluid inside the viscometer at a constant temperature. Since no constant temperature liquid bath was used, a digital contact thermometer (DCT) was also omitted from the test apparatus. Due to the unknown contents of the test specimens, no manufacturer's code was made available. The instruction team of Penn State's ME 435 course provided all test specimens. The three test specimens are mixtures of water and propylene glycol with unknown compositions. The obtained kinematic viscosities and the temperatures at which testing was conducted are included below in Table 2.

Table 2 – Viscometer Experiment Data

Sample	Test Temperature (C)	Kinematic Viscosity 1 (mm ² /s)	Kinematic Viscosity 2 (mm ² /s)	Average Kinematic Viscosity (mm ² /s)
A	23.33	2.786	2.764	2.775
B	23.33	5.283	5.297	5.290
C	23.33	0.993	0.986	0.989

C. Thermal Conductivity

As stated earlier in Section 2, the ASTM D7896-19 standard was used to obtain the thermal conductivities of the three engine coolant test specimens. Testing was completed on February 15th, 2024, in the Mechanical Engineering Knowledge Lab on the Pennsylvania State University's University Park, PA campus. Included below in Table 3 are the measured thermal conductivities for each of the engine coolant test specimens, along with the temperature at which the thermal conductivity measurement was made, and the average thermal conductivity and measurement temperature for each engine coolant test specimen.

Table 3 – Thermal Conductivity Data

	Sample A		Sample B		Sample C	
Trial	K (W/m·K)	Temp. (°C)	K (W/m·K)	Temp. (°C)	K (W/m·K)	Temp. (°C)
1	0.4490	24.00	0.3670	24.50	0.5980	26.40
2	0.4490	23.90	0.3680	24.50	0.5980	26.20
3	0.4490	23.90	0.3670	24.40	0.5970	26.10
4	0.4490	23.80	0.3680	24.40	0.5970	26.00
5	0.4490	23.80	0.3670	24.30	0.5970	25.90
6	0.4490	23.70	0.3670	24.30	0.5970	25.80
7	0.4490	23.70	0.3670	24.20	0.5960	25.60
8	0.4490	23.60	0.3670	24.20	0.5960	25.50
9	0.4480	23.60	0.3680	24.10	0.5960	25.40
10	0.4490	23.50	0.3670	24.10	0.5960	25.30
Mean	0.4489	23.75	0.3673	24.30	0.5968	25.30

Included below in Table 4, Table 5, and Table 6 are the remaining report requirements as specified in Section 9 of the ASTM D7896-19 standard [6].

Table 4 – Test Date and Time of Measurements

	Sample A		Sample B		Sample C	
Trial	Date	Time	Date	Time	Date	Time
1	2/15/2024	11:33:58	2/15/2024	12:25:58	2/15/2024	13:03:47
2	2/15/2024	11:35:14	2/15/2024	12:27:12	2/15/2024	13:05:01
3	2/15/2024	11:36:40	2/15/2024	12:28:38	2/15/2024	13:06:27
4	2/15/2024	11:37:54	2/15/2024	12:29:52	2/15/2024	13:07:41
5	2/15/2024	11:40:08	2/15/2024	12:31:06	2/15/2024	13:08:55
6	2/15/2024	11:41:34	2/15/2024	12:32:32	2/15/2024	13:10:21
7	2/15/2024	11:42:48	2/15/2024	12:33:46	2/15/2024	13:11:35
8	2/15/2024	11:44:02	2/15/2024	12:35:00	2/15/2024	13:12:49
9	2/15/2024	11:46:28	2/15/2024	12:36:26	2/15/2024	13:14:15
10	2/15/2024	11:47:48	2/15/2024	12:37:40	2/15/2024	13:15:29

Table 5 – Thermal Diffusivity Data

	Sample A		Sample B		Sample C	
Trial	α ($10^6 \times \text{m}^2/\text{s}$)	Temp. (°C)	α ($10^6 \times \text{m}^2/\text{s}$)	Temp. (°C)	α ($10^6 \times \text{m}^2/\text{s}$)	Temp. (°C)
1	0.1391	24.00	0.0851	24.50	0.1444	26.40
2	0.1391	23.90	0.0853	24.50	0.1444	26.20
3	0.1391	23.90	0.0851	24.40	0.1442	26.10
4	0.1391	23.80	0.0853	24.40	0.1442	26.00
5	0.1391	23.80	0.0851	24.30	0.1442	25.90
6	0.1391	23.70	0.0851	24.30	0.1442	25.80
7	0.1391	23.70	0.0851	24.20	0.1440	25.60
8	0.1391	23.60	0.0851	24.20	0.1440	25.50
9	0.1389	23.60	0.0853	24.10	0.1440	25.40
10	0.1391	23.50	0.0851	24.10	0.1440	25.30

Table 6 – Volumetric Heat Capacity Data

	Sample A		Sample B		Sample C	
Trial	VHC (kJ/m ³ ·K)	Temp. (°C)	VHC (kJ/m ³ ·K)	Temp. (°C)	VHC (kJ/m ³ ·K)	Temp. (°C)
1	3228	24.00	4314	24.50	4139	26.40
2	3228	23.90	4314	24.50	4139	26.20
3	3228	23.90	4314	24.40	4139	26.10
4	3228	23.80	4314	24.40	4139	26.00
5	3228	23.80	4314	24.30	4139	25.90
6	3228	23.70	4314	24.30	4139	25.80
7	3228	23.70	4314	24.20	4139	25.60
8	3228	23.60	4314	24.20	4139	25.50
9	3228	23.60	4314	24.10	4139	25.40
10	3228	23.50	4314	24.10	4139	25.30

In accordance with Sections 9.1.4, 9.1.6, and 9.1.8 of the ASTM D7896-19 standard, the average thermal properties (thermal conductivity, thermal diffusivity, and volumetric heat capacity) for each of the three evaluated samples were calculated and are reported below in Table 7.

Table 7 – Average Thermal Properties

Sample	K (W/m·K)	α ($10^6 \times \text{m}^2/\text{s}$)	VHC (kJ/m ³ ·K)
A	0.4489	0.1391	3228
B	0.3673	0.0851	4314
C	0.5968	0.1442	4139

D. Density

Density testing was completed on February 15th, 2024, in the Mechanical Engineering Knowledge Lab on the Pennsylvania State University's University Park, PA campus. Results reported below in Table 8 were obtained using a self-developed procedure that was covered earlier in Section 2.

Table 8 – Density Data

Sample	Trial	Mass (g)	Volume (mL)	Density (g/mL)	Average Density (g/mL)
A	1	3.010	3.000	1.003	1.009
	2	3.030	3.000	1.010	
	3	3.040	3.000	1.013	
B	1	3.080	3.000	1.027	1.031
	2	3.100	3.000	1.033	
	3	3.100	3.000	1.033	
C	1	2.880	3.000	0.960	0.966
	2	2.900	3.000	0.967	
	3	2.910	3.000	0.970	

E. Experimental Results Summary

Using a Discovery DSC, specific heat capacities of 3.200 J/(g·K), 4.184 J/(g·K), and 4.282 J/(g·K) were obtained for samples A, B, and C, respectively. Using Ubbelohde glass viscometers, average kinematic viscosities of 2.775 mm²/s, 5.290 mm²/s, and 0.989 mm²/s were obtained for samples A, B, and C, respectively. Using the THW-L2 unit, average thermal conductivities of 0.4489 W/m·K, 0.3673 W/m·K, and 0.5968 W/m·K were obtained for samples A, B, and C, respectively. Average thermal diffusivities and volumetric heat capacities were also obtained in compliance with the ASTM D7896-19's standard's report requirements, but since these values are not necessary for future analyses, they will not be covered any further. Lastly, using a self-developed data collection procedure, average densities of 1.009 g/mL, 1.031 g/mL, and 0.966 g/mL were obtained for samples A, B, and C, respectively. These experimentally determined thermophysical properties will form the basis of analyses that are described in the following section.

IV. DISCUSSION

A. Comparison with ASTM Standard Procedure

For the specific heat capacity experiment, only one discrepancy is noted between the ASTM E1269-11 procedure and the one followed in this experiment. The ASTM E1269-11 standard procedure followed the 3-run method. More specifically, this means that the specific heat capacity determination using the DSC is repeated 3 times: first with an empty pan and lid combination, next with sapphire standard and only then with the sample. The experimental procedure used to generate the specific heat capacity data reported in this paper did not follow the 3-run method; the instruction team of Penn State's ME 435 course performed the empty pan and sapphire standard measurements earlier. The authors of this report only performed measurements on the unknown samples. Otherwise, the conducted experimental procedure was congruent with the ASTM E1269-11 standard procedure.

Regarding the kinematic viscosity measurements, the primary difference between ASTM D445-19a standard procedure and the procedure followed in this experiment was that no constant-temperature water bath (or digital contact thermometer) was used to hold the fluid inside the viscometer at a constant temperature. Differing temperatures within the fluid will change the properties of the fluid at those points. Such a variance could be a source of error during data collection (for example, lower temperatures than what is measured will cause a bias toward higher viscosity measurements). Another key step from the ASTM D445-19a standard procedure that was omitted from the streamlined experiment performed was the validation of each viscometer's calibration constant. It is recommended in ASTM D445-19a standard that the calibration constant of the accelerometer be checked to ensure it is still valid (less than 0.1% difference when measuring the acceleration due to gravity). Other than these discrepancies, the conducted experimental procedure was congruent with the ASTM D445-19a standard procedure.

When measuring thermal conductivity there were no major discrepancies between the ASTM D7896 standard procedure and the procedure used to collect the data reported earlier in Section 3. Aside from minor details such as a precise measurement of 40mL of the sample being inserted into the sampling chamber, everything else was identically followed according to ASTM D7896-19.

Just to clarify, this section does not mention the density experiment as no ASTM standard procedure was provided to measure density. The authors of this report solely designed the implemented experimental procedure.

B. Radiator Analysis

To compare the heat exchanger effectiveness and the overall heat transfer coefficients of the sample coolants, the geometry of the radiator must be first understood. In this experiment, a radiator with overall dimensions of 702 mm (H) x 420 mm (L) x 21 mm (W) with a crossflow configuration was used. Incoming air flowed across the width of the radiator and acted as the cold fluid. Coolant flowed across the length of the radiator and functioned as the hot fluid in the heat exchanger.

The radiator featured fins with dimensions 12 mm (fH) x 15 mm (fL) x 21 mm (fW). The coolant tubes of the radiator had dimensions of 2 mm (tH) x 420 mm (tL) x 21 mm (tW). In the heat exchanger analysis performed in this experiment, it is assumed that the fins feature no curvature. Knowing these geometrical parameters, the radiator's fin quantity could be calculated by using the formula specified below in Equation 2 [2].

$$N_{fins} = \left(\left(\frac{L}{fD} \right) + 1 \right) \cdot \left(\frac{H - t_H}{(fH + t_H)} \right) \quad (2)$$

Plugging in the appropriate values, it was calculated that the radiator used in this analysis featured 1450 fins. With the number of fins calculated, the heat transfers surface areas of a single fin, the gas-side of the radiator, and the coolant-side of the radiator could be calculated using the formulae specified in Equation 3, Equation 4, Equation 5, and Equation 6 [2].

$$A_{fins} = 2f_h f_w + t f_h \quad (3)$$

$$A_{base} = 2(Lf_w) \quad (4)$$

$$A_{gas-side} = N_{fins} A_f + N_{layers} A_b \quad (5)$$

$$A_{coolant-side} = N_{layers} (2 \cdot tW \cdot rL + 2 \cdot tH \cdot rL) \quad (6)$$

Plugging in the appropriate dimensions to each formula, the following areas are obtained.

$$\begin{aligned} A_{fins} &= 504.24 \frac{\text{mm}^2}{\text{fin}}; A_b = 17640 \frac{\text{mm}^2}{\text{layer}}; \\ A_{gas-side} &= 1,613,148 \text{ mm}^2; \\ A_{coolant-side} &= 966000 \text{ mm}^2 \end{aligned}$$

To continue the analysis, the operating conditions of the radiator must also be understood. For this analysis, a coolant volumetric flow rate of 0.0015 m³/s and an air volumetric flow rate of 1.15 m³/s. Other properties of air needed for further analysis of the heat exchanger effectiveness analysis include the thermal conductivity (0.0266 W/(m·K)), specific heat capacity (1004.16 J/(kg·K)), and density (1.13731 kg/m³). The inlet and outlet temperatures (373K and 353K) of the coolant and the inlet temperature of the air (263K) also need to be known. Using the volumetric flow rates and the densities of air and each of the 3 coolant samples (which were experimentally determined), the mass flow rate of each fluid could be calculated using the formula below in Equation 7 [2].

$$\dot{m}_{fluid} = \rho_{fluid} \cdot \dot{V}_{fluid} \quad (7)$$

Using these calculated mass flow rates, 3 heat capacity rates, C_{max} , C_{min} , and C_r , could be determined for each of the coolant samples using the formulae included below in Equation 8, Equation 9, and Equation 10 [2]. Note that the specific heat capacities of the coolant samples ($C_{p,coolant}$) were experimentally determined.

$$C_{min} = \dot{m}_{air} \cdot C_{p,air} \quad (8)$$

$$C_{max} = \dot{m}_{coolant} \cdot C_{p,coolant} \quad (9)$$

$$C_r = \frac{C_{min}}{C_{max}} \quad (10)$$

Using these calculated heat capacity rates, the maximum heat transfer rate, q_{max} , and the actual heat transfer rate for each of the coolant samples, q_{sample} , could be calculated using the formulae below in Equation 11 and Equation 12 [2].

$$q_{max} = C_{min}(T_{hi} - T_{ci}) \quad (11)$$

$$q = C_{max}(T_{hi} - T_{ho}) \quad (12)$$

Using the, the maximum heat transfer rate, q_{max} , and the actual heat transfer rate for each of the coolant samples, q_{sample} , the heat exchanger effectiveness of each coolant could be calculated using the formula below in Equation 13 [2].

$$\epsilon = \frac{q}{q_{max}} \quad (13)$$

Plugging in the appropriate values related to each of the coolant samples into the above formula, the following heat exchanger effectiveness values are obtained.

$$\epsilon_{Sample A} = 0.868; \epsilon_{Sample B} = 0.878; \epsilon_{Sample C} = 0.899;$$

Thus, it is determined that Sample C has the most effective coolant chemistry. This is to be expected, as water has better heat transfer properties than propylene glycol. Thus, the effectiveness will increase as the composition of water is increased, with pure water (Sample C) being the most effective. Using the calculated heat exchanger effectiveness values and NTU values obtained from a cross-flow Effectiveness-NTU graph, the overall heat transfer coefficient, U , could be obtained for each of the coolant samples by using the formula enumerated below in Equation 14 [2].

$$U_{Sample} = NTU_{Sample} \cdot \frac{C_{min}}{A_t} \quad (14)$$

Plugging in the appropriate values related to each of the coolant samples into the above formula, the following overall heat transfer coefficient values are obtained.

$$U_{Sample A} = 1901.13 \frac{W}{m^2 \cdot K}$$

$$U_{Sample B} = 1983.41 \frac{W}{m^2 \cdot K}$$

$$U_{Sample C} = 2164.98 \frac{W}{m^2 \cdot K}$$

As expected, overall heat transfer coefficient, U , increases with increasing heat exchanger effectiveness. Again, this result makes sense, as water has the most conducive heat transfer properties (highest specific heat capacity, highest thermal conductivity) relative to the other two coolant samples.

C. Sample Composition

To determine the composition of each sample, the formula listed below in Equation 15 was used.

$$k_{mix} = \frac{w_{water} * k_{water} + (1 - w_{water}) * k_{glycol}}{(w_{water} + (1 - w_{water}))} \quad (15)$$

Using this formula, Sample A was calculated to have a composition of 61.55% water (38.45% glycol), Sample B was calculated to have a composition of 40.20% water (59.80% glycol) and Sample C was calculated to have a composition of 100% water. The reasoning behind the use of the formula is simple. Since the thermal conductivity of the mixture was experimentally determined and the thermal conductivities of the mixture's components are known via literature reports, the percent composition of each mixture component can be reversed-engineered using a standard percent composition formula. In other words, the weight of each component that would return the experimentally determined value is solved for.

D. Recommendations

Sample C had the highest radiator efficiency, and it has the lowest viscosity, which makes it an optimal engine coolant. However, since Sample C is pure water, it will freeze at temperatures below 0 °C. This is problematic for the Pennsylvania climate, which has temperatures routinely below 0°C for a third of the year. Between Sample A and Sample B, Sample A is preferable, as it achieves 95.85% of Sample B's heat transfer performance with 98.86% of Sample B's efficiency while being only 52.46% as viscous as Sample A. Thus, a far less powerful pump is needed when using Sample A to achieve essentially the same heat transfer performance as Sample B. Further testing on the freezing points of Sample A and Sample B is required to verify that they freeze at temperatures much lower than 0°C to ensure that they are safe for implementation in the Pennsylvania climate year-round.

REFERENCES

- [1] "What is Car Engine Coolant?", UTI Corporate, 7 July 2020, <https://www.uti.edu/blog/automotive/car-coolant>
- [2] T.L. Bergman and A. S. Lavine, Fundamentals of Heat and Mass Transfer, Wiley, Hoboken, NJ, USA, 2019
- [3] Standard Test Method for Determining Specific Heat Capacity by Differential Scanning Calorimetry, ASTM E1269-11, ASTM International, Washington, D.C., USA, 2018
- [4] Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (and Calculation of Dynamic Viscosity), ASTM D445-19a, ASTM International, Washington, D.C., USA, 2017
- [5] Standard Specifications and Operating Instructions for Glass Capillary Kinematic Viscometers, ASTM D446-12, ASTM International, Washington, D.C., USA, 2017
- [6] Standard Test Method for Thermal Conductivity, Thermal Diffusivity, and Volumetric Heat Capacity of Engine Coolants and Related Fluids by Transient Hot Wire Liquid Thermal Conductivity Method, ASTM D7896-19, ASTM International, Washington, D.C., USA, 2019