THE THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE HEAT TRANSFER PROCESS OF AN AUTOMOBILE RADIATOR

Matthew Carl, Dana Guy, Brett Leyendecker, Austin Miller, and Xuejun Fan
mcarl89@gmail.com, dmguy@lamar.edu, bcleyendecker@yahoo.com, ajmiller1@my.lamar.edu
Department of Mechanical Engineering
Lamar University, PO Box 10028
Beaumont, TX 77710

Abstract

This paper analyzes the heat transfer process involved in the operation of an automotive radiator. The paper is written as part of an undergraduate research activity. The analysis of a radiator encompasses nearly all of the fundamentals discussed in a heat transfer class, including the internal and external fluid flow through a heat exchanger and the design and analysis of heat sinks and exchangers. The theoretical heat exchanger investigation begins with analyzing the internal fluid flow through the radiator's noncircular tubes, yielding the convective heat transfer coefficient for water. The external fluid flowing across the radiator tubes and fins is then analyzed to find the convective heat transfer coefficient for the air. The heat sink design of the radiator must then be analyzed using the Effectiveness-NTU method to find the theoretical effectiveness, overall heat transfer rate of the radiator, and outlet temperatures of both air and water. Experimental analysis was conducted on the radiator to compare and confirm the analytical results.

This undergraduate research topic is specifically designed to integrate the numerous areas from the subject of heat transfer. Through the many challenges and successes met during this project, the goals of this undergraduate research topic have been accomplished and the students' understanding of the numerous concepts in heat transfer evolved into a single, unified, and cohesive entity.

Nomenclature

$H_{radiator}$	Radiator height
$L_{radiator}$	Radiator length
$W_{radiator}$	Radiator width
W_{tube}	Tube width
H_{tube}	Tube height
$T_{water,in}$	Inlet water temperature
$T_{water,out}$	Outlet water temperature
$T_{air,in}$	Inlet air temperature
$T_{air,out}$	Outlet air temperature
W_{fin}	Fin width
L_{fin}	Fin length
H_{fin}	Fin thickness

q	Heat transfer rate	
m_{air}	Total air mass flow rate	
$c_{p,air}$	Air specific heat	
m_{water}	Total water mass flow rate	
$c_{p,water}$	Water specific heat	
$D_{hydraulic}$	Hydraulic diameter	
A_{tube}	Tube cross-sectional area	$A_{tube} = W_{tube}H_{tube}$
P_{tube}	Tube perimeter	$P_{tube} = 2W_{tube} + 2H_{tube}$
v_{water}	Water velocity	
Q_{water}	Total water volumetric flow rate	
N_{tube}	Number of tubes	
Re_{water}	Reynolds number of water	
ρ_{water}	Density of water	
μ_{water}	Dynamic viscosity of water	
h_{water}	Convective heat transfer coefficient of water	
Nu_{water}	Nusselt number of water	
k_{water}	Thermal conductivity of water	
v_{air}	Air velocity	
Q_{air}	Total air volumetric flow rate	
$A_{radiator}$	Total radiator area	$A_{radiator} = H_{radiator}L_{radiator}$
Re_{air}	Reynolds number of air	
ν_{air}	Kinematic viscosity of air	
Nu_{air}	Nusselt number of air	
Pr_{air}	Prandtl number of air	
h_{air}	Convective heat transfer coefficient of air	
k_{air}	Thermal conductivity of air	
η_{fin}	Fin efficiency	
m	Coefficient for calculating efficiency	$m = (\, 2h_{air} / k_{aluminum}H_{fin})^{0.5}$
L_c	Corrected fin length	$L_c = L_{fin} + \frac{H_{fin}}{2}$
η_o	Overall surface efficiency	
N_{fin}	Number of fins per tube, top and bottom	
A_f	Single fin surface area	$A_f = 2W_{fin}L_c$
A_b	Base surface area	$A_b = 2L_{radiator}W_{tube} - H_{fin}W_{fin}N_{fin}$
$A_{fin,base}$	Total fin/base surface area of a single tube	$A_{fin,base} = N_{fin}A_f + A_b$
UA	Overall heat transfer coefficient	

$A_{external}$	Total external surface area	$A_{external} = A_{fin,base}N_{tube}$
$A_{internal}$	Total internal surface area	$A_{internal} = (2W_{tube} + 2H_{tube})L_{radiator}N_{tube}$
NTU	Number of transfer units	
C_{min}	Minimum heat capacity	$C_{min} = \min(C_{water,}C_{air})$
C_{max}	Maximum heat capacity	$C_{max} = \max(C_{water,}C_{air})$
ε	Effectiveness	
C_r	Heat capacity ratio	$C_r = C_{min}/C_{max}$
q_{max}	Maximum heat transfer rate	
$q_{predicted}$	Predicted heat transfer rate	
C_{air}	Total air heat capacity	$C_{air} = m_{air}c_{p,air}$
C_{water}	Total water heat capacity	$C_{water} = m_{water}c_{p,water}$
$k_{aluminum}$	Thermal conductivity of aluminum	
$q_{experimental}$	Experimental heat transfer rate	

Introduction

Heat transfer is a core subject of undergraduate mechanical engineering curriculum. It is the movement of heat across a temperature gradient between different objects or substances. This paper seeks to investigate the correlation between the theoretical and experimental solutions to heat transfer problems found in the real world.

There are many new inventions that are icons of modern life. Advances like the computer, the automobile, and the harnessing of electricity are integrally linked by the need of a heat sink for the ability to function. Heat sink technology is applied in various ways for these different inventions, but it takes the form of a radiator in automobiles. Radiators are more technically known as heat exchangers, but the basic principles are very similar. To keep engines cool enough to function properly, water is pumped through the internal combustion engine and heated by the combustion process. The water then flows into the radiator and through numerous smaller tubes, which are connected to the many fins. The rows of fins greatly increase the surface area to enhance the cooling capacity of the air flowing through the radiator. The motion of the car, along with the fan, forces air through the fins and around the tubes of the radiator. The flowing air removes heat from the water flowing through the pipes to dissipate it to the atmosphere.

The objective of this paper is to discuss the heat transfer process of a universal aluminum car radiator and to compare the outlet temperatures found using the theoretical calculations and the experimental data. The methods of theoretically solving this problem and achieving this objective involve analyzing the internal and external fluid flow of the radiator and then comparing these results to the experimental data.

System Configuration

In Fig. 1, the basic universal aluminum radiator and fan analyzed for the problem are shown. A simple schematic with dimensions is seen in Fig. 2. The coolant fluid (water) that passes through the engine block enters on the high side of the radiator as the hot fluid. From here, this hot fluid fills the tube banks of the radiator and makes a single pass across the radiator.

Figure 1: Universal aluminum radiator (left) and 3000 cfm fan (right)

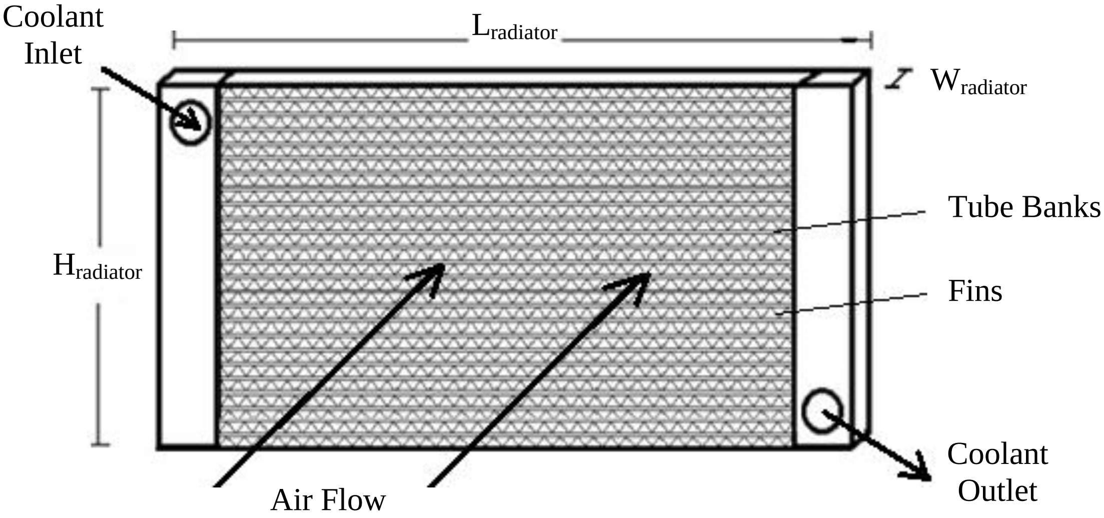

Figure 2: Schematic of radiator

Cool air is then forced across the radiator’s core, by a fan and by using air produced by the motion of the vehicle, to absorb and remove the heat from the coolant. During the entire process two main forms of heat transfer occur: 1) convection due to the internal flow of fluid passing through non-circular tubes and 2) convection due to the external flow of air across the tube bank. Fig. 3 shows the single tube geometry and the internal fluid flow direction through the tubes.

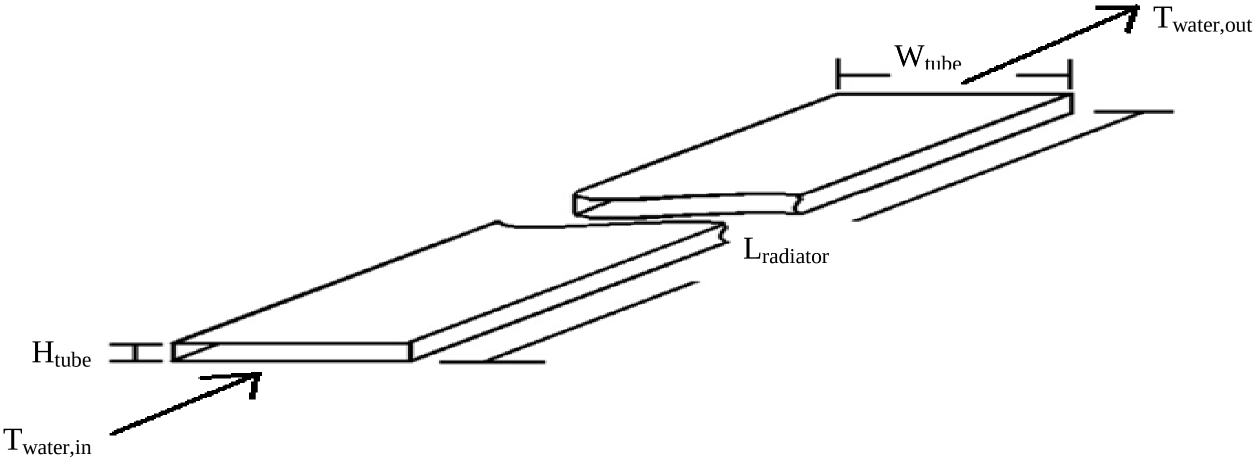

Figure 3: Schematic of single tube

The air from the fan travels perpendicular across the tubes and through the fins. Fig. 4 illustrates how the air enters the radiator at the inlet temperature, exits at the outlet temperature, and flows across the tube banks. There are two rows of fins in this particular radiator.

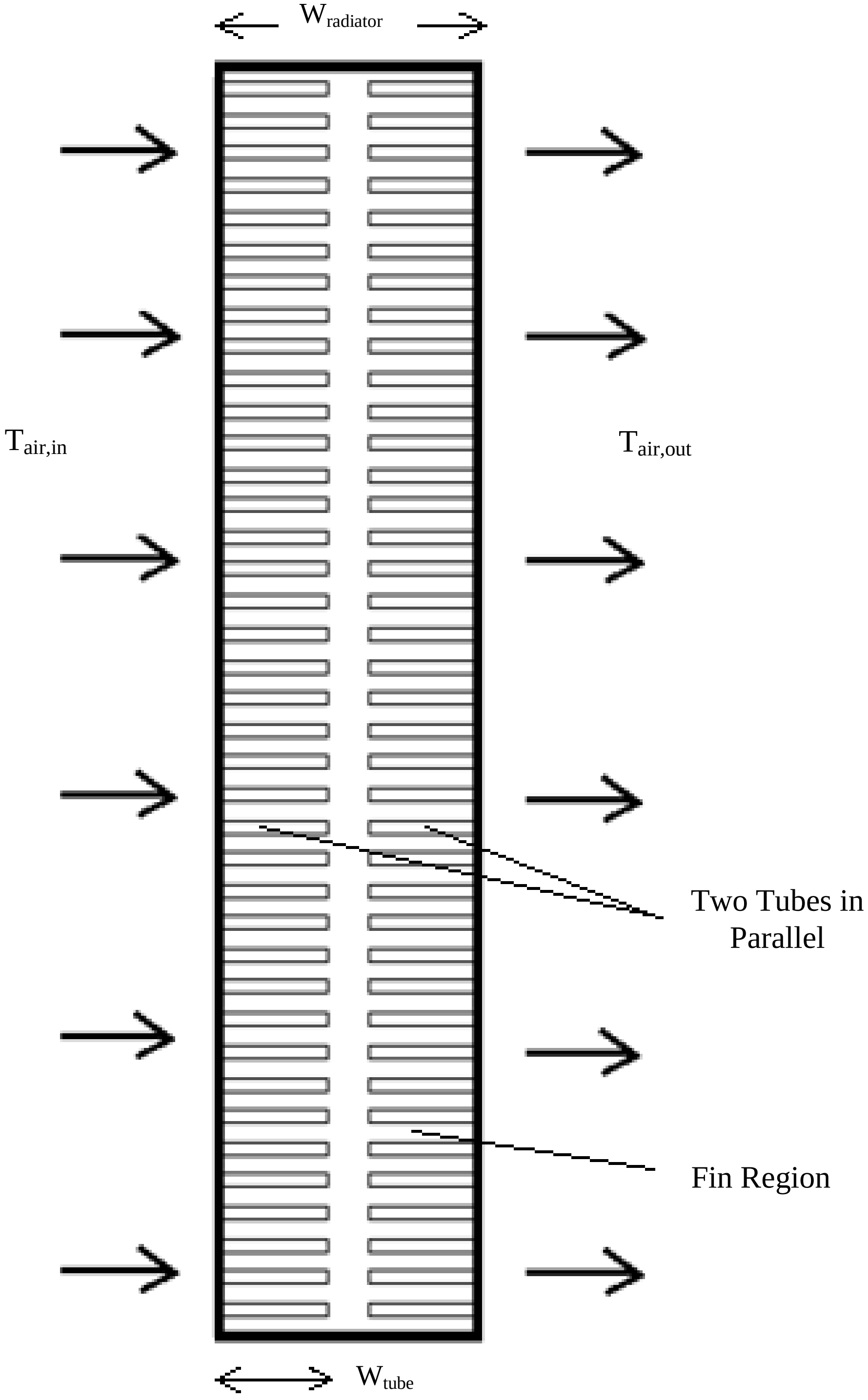

Figure 4: Cross flow of air

In order to properly analyze the external flow, the fins must be considered in the calculations. Fig. 5 shows the actual geometry of the fins in between each row of tubes. Since the fins are actually extremely narrow sinusoidal waves, they can be assumed to be straight, rectangular fins. In addition, the fins are assumed to be half the height in order to assume that the tip is adiabatic. Fig. 6 shows a detailed diagram of a segment of the tubes with both heat transfer processes.

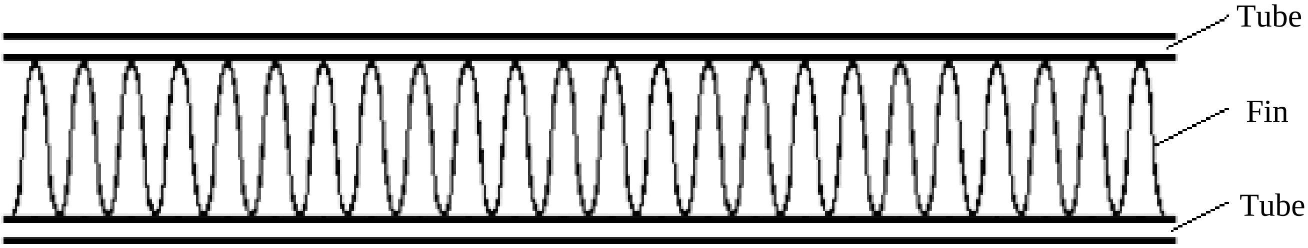

Figure 5: Actual fin geometry

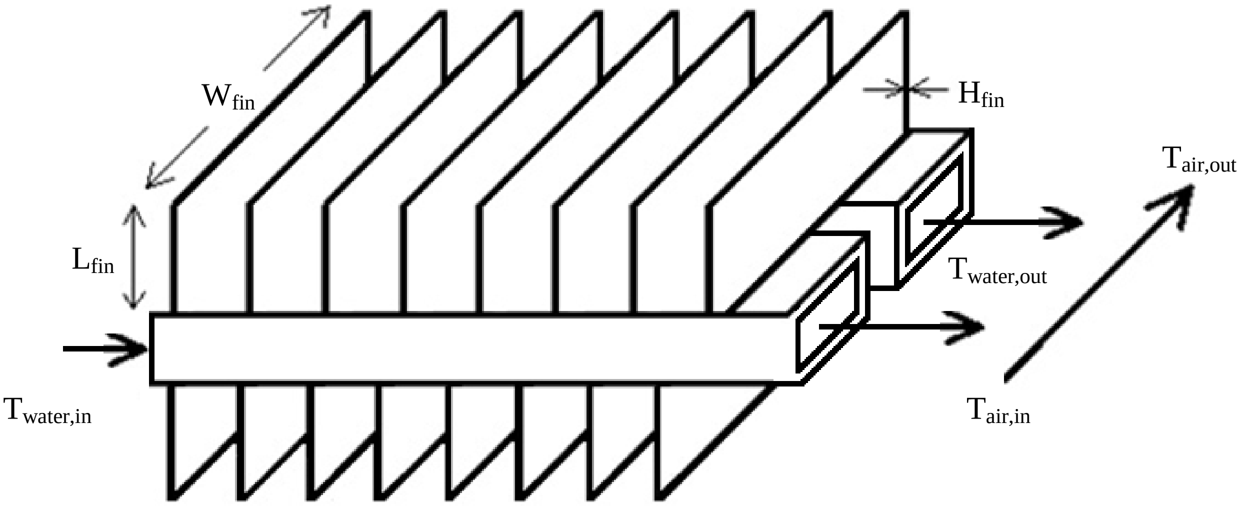

Figure 6: Assumed fin geometry

Mathematical Models

The goal of the project is to use the analytical heat transfer process to determine outlet coolant and air temperatures and to compare this data with experimental results. To begin the theoretical process, it is important to distinguish the given, known information from the unknown information. All dimensions for both the fan and radiator are known from precise measurements. The mass flow rates of both the air and water are known based on the given specifications of the fan and radiator. The inlet temperature for air can be assumed to be nearly equal to the ambient temperature. The inlet temperature of water is equal to the temperature of the engine. The entire theoretical process begins with Equation 1 below for the heat transfer rate of the radiator. From this equation, it is clear that the only two unknowns for the system are the outlet temperatures for air and water. These two unknowns are initially assumed. The equations and calculations following are simply used to solve for both outlet temperatures. The initially assumed outlet temperatures and calculated outlet temperatures are then iterated to solve for the actual values for the outlet temperatures for air and water.

$$q = m_{air} c_{p,air} \left(T_{air,out} - T_{air,in}\right) = m_{water} c_{p,water} \left(T_{water,in} - T_{water,out}\right) \qquad (1)$$

Internal Flow of Water

The hot water from the engine travels through the tubes of the radiator.

Area of Tubes

$$D_{hydraulic} = \frac{4A_{tube}}{P_{tube}} \tag{2}$$

The hydraulic diameter must be used because it is a non-circular cross section. The hydraulic diameter can then be used to estimate the Reynolds number. The equation for the hydraulic diameter calls for the wetted perimeter of the tubes. However, the difference in the outer and inner tube dimensions is so negligible that the outer perimeter is used for convenience.

Mean Temperature of Water

The average temperature of water must be calculated to find the fluid's material properties. The properties will be interpolated at this temperature. The properties that are needed are density, Prandtl number, thermal conductivity, dynamic viscosity, and specific heat. [1]

Velocity

$$v_{water} = \frac{Q_{water}}{N_{tube}A_{tube}} \tag{3}$$

The velocity of the water through each tube must be found to calculate the Reynolds number. The number of tubes is given by the chosen radiator.

Reynolds Number

$$Re_{water} = \frac{\rho_{water}v_{water}D_{hydraulic}}{\mu_{water}} \tag{4}$$

Nusselt Number

The Nusselt number was found as a constant for a rectangular cross section from Table 8.1 for fully developed laminar flow. The ratio of width over height of the tube is used in this table to determine the Nusselt number. This leads to a Nusselt number of 3.96. [1]

Convective Heat Transfer Coefficient for Water Flow

$$h_{water} = \frac{Nu_{water}k_{water}}{D_{hydraulic}} \tag{5}$$

Finally, the convective heat transfer coefficient for the internal flow can be found using the equation from the same table, Table 8.1.

External Flow of Air

The air flows from the fan across the radiator tubes and through the fins utilizing convective heat transfer. In reality, the flow of air over the tubes will be slightly different due to the fluid flowing around the first tube before reaching the second tube, so calculating the heat transfer coefficient would be very difficult. To simplify the calculations, the flow is assumed to be the same over both tubes. Also, because the height to width ratio of the tubes is so small, the air will be assumed to be flowing on both sides of a flat plate.

Mean Temperature of Air

The average temperature of air must be calculated to find the correct material properties for later use. These properties are specific heat, thermal conductivity, kinematic viscosity, and Prandtl number.

Velocity

$$\mathrm{v_{air}} = \frac{\mathrm{Q_{air}}}{\mathrm{A_{radiator}} - (\mathrm{N_{tube}H_{tube}L_{radiator}})} \tag{6}$$

Reynolds Number

$$\mathrm{Re_{air}} = \frac{\mathrm{v_{air}W_{fin}}}{\nu_{\mathrm{air}}} \tag{7}$$

Nusselt Number

Looking at the geometry of the tubes, it can be assumed that the flow of air is similar to parallel flow over a flat plate. Since the flow never reaches the critical Reynolds number for a flat plate, Re = 5x10^5, it is said to be laminar for the entire process.

$$\mathrm{Nu_{air}} = .664\mathrm{Re_{air}}^{\frac{1}{2}}\mathrm{Pr_{air}}^{\frac{1}{3}} \tag{8}$$

Convective Heat Transfer Coefficient for Air Flow

$$\mathrm{h_{air}} = \frac{\mathrm{Nu_{air}k_{air}}}{\mathrm{W_{tube}}} \tag{9}$$

Fin Dimensions and Efficiency

The geometry of the fins on the radiator is sinusoidal. The troughs of the fins touch the lower adjacent tube and the peaks of the fins touch the upper adjacent tube. The heat from the tubes emanates through the fins. The fins and tubes are then cooled by the air from the fan, which is traveling across the radiator. To simplify the geometry for the ease of calculations, the fins are assumed to be straight instead of sinusoidal. This can be seen in Fig. 6. This is a minor transition in geometry since the shape and position of the actual fins are so close to the straight configuration. The following formulas are given below to calculate the fin efficiency. The fin efficiency equation takes into account the geometry of the fin and its dimensions to find the efficiency the fin will have.

$$\eta_{\mathrm{fin}} = \frac{\tanh(\mathrm{mL_c})}{\mathrm{mL_c}} \tag{10}$$

Overall Surface Efficiency

The overall surface efficiency is needed for the external flow of air because the imperfections of the flow around the fins must be considered.

$$\eta_{\mathrm{o}} = 1 - \frac{\mathrm{N_{fin}A_f}}{\mathrm{A_{fin,base}}}(1 - \eta_{\mathrm{fin}}) \tag{11}$$

Effectiveness-NTU Method

The Effectiveness-NTU method is used to find the effectiveness of the system. The overall heat transfer coefficient is needed. The surface efficiency is needed for the external flow of air because the imperfections of the flow around the fins must be considered. Using the convective heat transfer coefficients of both the internal and external flows, the UA is calculated. This value is then used to calculate the NTU.

Overall Heat Transfer Coefficient

$$\mathrm{UA} = \frac{1}{\left(\frac{1}{\eta_o h_{air} A_{external}} + \frac{1}{h_{water} A_{internal}}\right)} \tag{14}$$

Number of Transfer Units

$$\mathrm{NTU} = \frac{\mathrm{UA}}{C_{min}} \tag{13}$$

Effectiveness

The radiator utilizes a cross-flow single pass design where both fluids remain unmixed. This correlates to a specific equation to calculate effectiveness. However, this equation requires the heat capacity ratio, C_r, to be equal to 1. The calculated heat capacity ratio is 0.455; therefore, the effectiveness is only a close approximation instead of the true value.

$$\varepsilon = 1 - \exp^{\left[\left(\frac{1}{C_r}\mathrm{NTU}^{0.22}\right)\left(\exp^{\left(-C_r \mathrm{NTU}^{0.78}\right)} - 1\right)\right]} \tag{14}$$

Heat Transfer Rate

The maximum heat transfer rate must be found to find the predicted heat transfer rate. Once this is known, the final output temperature of both the hot and cold fluid is calculated using a modified version of the initial thermal energy equation. These outlet temperatures must be iterated with the initially guessed outlet temperatures until the numbers are equivalent. The iterated outlet temperatures for both air and water are the theoretical values, which are used to compare with the experimental results.

Max Heat Transfer Rate

$$q_{max} = C_{min}(T_{water,in} - T_{air,in}) \tag{15}$$

Predicted Heat Transfer

$$q_{predicted} = \varepsilon q_{max} \tag{16}$$

Temperature Out

$$T_{water,out} = T_{water,in} - \frac{q_{predicted}}{C_{water}} \tag{17}$$

$$T_{air,out} = T_{air,in} - \frac{q_{predicted}}{C_{air}} \tag{18}$$

Experiment

Setup

An aluminum stock radiator was tested with a 2.5 L Subaru engine at idle conditions. The coolant used in the radiator was pure water. The inlet and outlet temperatures for both the water and the air were measured using a thermocouple. For the water, a probe can be inserted in the tube right before the fluid enters the radiator and right after it exits. The inlet temperature of air will be assumed to equal the ambient. A probe was placed approximately five inches from the fan on the back side of the radiator to measure the outlet air temperature. In addition, the flow rate of the air across the radiator was measured using an air flow meter. Lastly, the flow rate through the radiator was measured by attaching a rotameter just before the coolant enters the radiator.

Procedure

The engine ran without the radiator fan until it reached 200 degrees Fahrenheit. Once the engine reached this temperature, the fan on the radiator was turned on to begin cooling the engine. The radiator, along with the fan, then cooled the engine until the temperatures reached steady state, which took approximately six minutes. The inlet and outlet temperatures and the flow rates for air and water were then recorded.

This experimental process was repeated four times in order to give a range of results to compare with one another. These experimental results were then compared with the inlet and outlet temperatures found in the theoretical analysis of the problem.

Results and Discussion

All of the dimensions for the radiator were carefully measured and are recorded below in Table 1. Certain material properties, given in Tables 2 and 3, were needed for water and air for the theoretical calculations. The values of these properties were found using the average temperature of the fluid. [1] An iteration process involving the inlet and outlet fluid temperatures was needed to calculate the final absolute value for the outlet temperatures. To complete this process the convective heat transfer coefficients, overall heat transfer coefficient, number of transfer units, effectiveness, and heat transfer rate for the radiator were needed.

Table 1: Basic Radiator Dimensions

$L_{radiator}$	$H_{radiator}$	$W_{radiator}$	W_{tube}	H_{tube}	L_{fin}	W_{fin}	H_{fin}	N_{tube}	N_{fin}
inches	inches	inches	inches	inches	inches	inches	inches		
26.125	18	2.375	1	0.083	0.156	2.3	0.003	86	780

Table 2: Properties of Water at Average Temperature

ρ_{water}	$c_{p,water}$	Pr_{water}	k_{water}	μ_{water}
kg/m^3	J/kgK	unitless	W/mK	kg/sm
982.20	4185	5.26	0.59	7.61E-4

Table 3: Properties of Air at Average Temperature

ρ_{air}	$c_{p,air}$	Pr_{air}	k_{air}	ν_{air}
kg/m^3	J/kgK	unitless	W/mK	m^2/s
1.16	1007	.74	2.50E-2	2.20E-5

Table 4: Final Results for Radiator

h_{water}	h_{air}	UA	NTU	ε	$q_{predicted}$
W/m^2K	W/m^2K	M^2kg/Ks^3	unitless	%	W
609.27	45.13	836.34	0.59	40	23670

The final results, given in Table 4, for the theoretical calculations based on the given inlet temperature for air and water, yielded the actual outlet temperature of the same fluids and are shown in Table 5. However, these results are based only on theory. The experimental values for the inlet and outlet temperatures of air and water are recorded below in Table 6.

Table 5: Theoretical Temperature of Fluids through Radiator

$T_{water,in}$	$T_{water,out}$	$T_{air,in}$	$T_{air,out}$
F	F	F	F
151.7	138.9	77.0	107.4

Table 6: Experimental Temperatures and Flow Rates through Radiator

Trial	$T_{water,in}$	$T_{water,out}$	$T_{air,in}$	$T_{air,out}$	m_{water}	v_{air}
	F	F	F	F	gpm	m/s
1	147.7	138.0	77.0	124.8	12.0	9.6
2	155.5	145.3	77.0	126.4	12.0	9.6
3	152.2	141.3	77.0	125.2	12.0	10.9
4	151.4	140.5	77.0	124.4	12.0	10.2
Average	151.7	141.3	77.0	125.2	12.0	10.1

Using Equation 1, the experimental value for the heat transfer rate can be found. The results of the heat transfer rate for water and air are shown in Table 7. There are numerous possible reasons for the different values between the experimental heat transfer rate for water and air. The internal flow analysis of the water through the radiator is operating in a closed system, as opposed to the open system for the air flow in the external analysis. Therefore, the experimental heat transfer rate for water is expected to be close to the theoretical predicted heat transfer rate.

Table 7: Experimental Heat Transfer Rate for Air and Water

$q_{experimental}$	
Water	**Air**
W	W
17997	37667

The experimental values for the outlet temperature and the heat transfer rate for air are different from the theoretical predicted values for numerous possible reasons. The external analysis of the air flow is operating under an open system. The radiator was tested close to the engine and exhaust pipe, which added surplus heat to the external system. This raised the temperature of the outlet temperature of air. Another reason for a difference between experimental and theoretical values has to do with the assumptions made for the tubes of the radiator. There are two tubes in parallel that carry the water across the radiator. The air at the inlet temperature is assumed to flow over both tubes before it is heated to the outlet temperature. Realistically, the air approaches the first tube at the inlet temperature of air. The air is then heated to a different temperature as it flows across the first tube. Therefore, the second tube of the radiator is not cooled as much as the first. This occurrence raises the outlet temperature of air, which also raises the heat transfer rate. Another assumption that could possibly have affected the results was using an estimated value for the effectiveness. The equation for the effectiveness is only exact when the heat capacity ratio equals one. However, the heat capacity ratio for the radiator is 0.455. The effectiveness equation is only a good approximation in this instance.

Conclusion

The heat transfer processes for the radiator are analyzed in a real life situation. The objectives of the project, to find and compare the inlet and outlet temperatures of the fluids in the radiator, were accomplished successfully. There were numerous assumptions that were necessary to complete the theoretical calculations. Although these assumptions changed the final values for the theoretical outlet temperatures and heat transfer rate, the differences are expected. The theoretical values are good approximations of the real values found experimentally. When first analyzing the radiator, there were many challenges and obstacles that hindered the advancement of the project. These challenges presented the students with opportunities to learn from mistakes and link concepts into an integrated whole. This project provided an in depth understanding of the theoretical knowledge learned in heat transfer and offered a chance to use this information to solve real world problems.

References

[1] Incropera, Frank P. *Introduction to Heat Transfer*. 5th ed. Hobokenm NJ: Wiley, 2007. Print.

[2] Munson, Bruce R., Donald F. Young, and Theodore H. Okiishi. *Fundamentals of Fluid Mechanics.* New York: Wiley, 1998. Print.