Formula Student - Engine Cooling

Radiator Design

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Declaration

I certify that this research work titled "*Formula Student – Engine Cooling: Radiator Desing"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

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Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Copyright Statement

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Abstract

The Formula Student competition challenges students to conceive, design, fabricate and compete with small Formula style race cars. Gasoline engines have improved significantly over the years, but they are still not very efficient at turning chemical energy into mechanical power. Most of the energy in the gasoline (perhaps 70%) is converted into heat, and it is the job of the cooling system to take care of that heat. The demand for more powerful engines in smaller spaces has created a problem of insufficient heat dissipation in automotive radiators. Almost of 33% of the energy generated by the engine through combustion is lost in heat. Insufficient heat dissipation can result in the overheating of the engine, which leads to the breakdown of lubricating oil, metal weakening of engine parts, and significant wear between engine parts.

The main functions of an Engine Cooling system is to remove excess heat from engine and keep the engine at optimum working temperature (also called Normal Operating Temperature).

A radiator is a compact cross-flow heat exchanger in which the coolant from engine flows through in tubes and a pull-type fan forces air to flow over fins (covering the tubes, and increasing the overall surface area) for heat exchange.

The E-NTU (effectiveness – no. of transfer units) method is a mathematical model used to design heat exchangers when the sink temperatures of the working fluids (coolant & air) are unknown.

The radiator's heat transfer depends on the many factors such as radiator's outer dimensions, fin and tube dimensions, and water and air flow-rates.

The main mode of heat transfer in a radiator is convection, with minimal conduction, and small radiation (depending upon the engine type).

The mathematical model has been made in MATLAB to perform calculations and calculate the radiator effectiveness and heat dissipated. The model calculates the heat for the default dimensions and then compares this value to the required value, iterating the dimensions to get the minimum dimensions to get the job done.

The math model has been tested experimentally on a test engine (different than the design engine). Some errors arose due unaccounted factors and experimental errors.

Key Words: *Engine Cooling, Radiator, Heat Exchanger Design, Mathematical Model, MATLAB*

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List of Symbols

<u>Heat Transfer</u>
Q = Heat Dissipated
Q_max = Maximum Heat Transfer
Q_cal = Calculated Heat Transfer
Q_total = Total Heat Power
E_power = Total Engine Power
FOS = Factor of Safety
E = Radiator Effectiveness
dTmax = Maximum Temperature Gradient
NTU = No. of Transfer Units
Cr = Heat Capacity Ratio
C_min = Minimum Heat Capacity
C_max = Maximum Heat Capacity
U = Overall heat transfer coefficient
h= convective heat transfer coefficient
Re = Reynolds No.
f = Friction factor
Nu = Nusselt No.

<u>Dimensions</u>
L = length
W = width
H = height
N_tube = No. of tubes
Cf = No. of Columns of Fins
N_fins = No. of Fins on both sides of 1 Tube
Dh = hydraulic diameter
Lc = characteristic length
As = Total Surface Area
Ai = Internal Surface Area
Ae = External Surface Area
<u>Temperatures</u>
T_in = Inlet Temperature (Water= hot, Air= cold)
T_out = Outlet Temperature (Water= cold, Air= hot)

<u>Flow-rates</u>
V = Volume flow-rate
m = mass flow-rate

<u>Physical Properties</u>
p = density of fluid
u = kinematic viscosity
r = dynamic viscosity

cp = specific heat
Pr = Prandtl no.

Other Parameters
h_L = Head Loss
dP = Pressure loss
W_p = Pump load
per_diff = Percentage Difference b/w Estimated and Calculated Cooling load

Chapter 1: Introduction

1.1 Formula Student Competition

Formula Student (FS) is one of the world's most established educational motorsport competitions, run by the Institution of Mechanical Engineers (IMechE). Backed by industry and high profile engineers, the competition aims to inspire and develop enterprising and innovative young engineers. Universities from across the globe are challenged to design and build a single-seat racing car in order to compete in static and dynamic events, which demonstrate their understanding and test the performance of the vehicle.

The participating teams design a Formula-style vehicle which is judged in various static and dynamic events with respective points awarded for the events. The team with the most points wins.

Rules and Regulations

The vehicles competing in the FS competition must follow strict regulations, otherwise they are disqualified. There are specific rules for all aspects of the vehicle (chassis, suspension, fuel etc.).

The rules dealing with the engine cooling are:

1. Coolant to be used is Pure Water (no anti-freeze or other mixture)
2. The fasteners used for attaching different parts should be of 6mm Metric Grade 8.8
3. Catch cans must be installed in order to prevent leakage of fluids
4. The vehicle needs to pass the Tilt Test (in which the vehicle's roll-over stability is tested by tilting it 60^0 w.r.t horizontal plane)
5. The Engine Power should be less than 100hp (75 kW)
6. Scatter-shields need to be installed for chain and belt drives

1.2 Engine Cooling System

Engine cooling system ensures that the engine does not overheat and runs at Normal Operating Temperature (optimum working temperature).

For the FS design, we will only consider the Water cooled system.

1.2.1 Functions

Engine cooling system has the following functions:

1. **Primary Functions:** The primary functions are:
    a. Removal of excess heat from the engine
    b. Keeping the engine at optimum operating temperature
2. **Secondary Function:** The secondary function is to perform quick warm-up of the engine to achieve the optimum operating temperature quickly during start-up.

1.2.2 Heat Load

The distribution of the Engine Power is as:
(Engine power) = [(1/3)*(Shaft Power)] + [(1/3)*(**Cooling Load**)] + [(1/3)*(Heat carried away by Exhaust system)]

1.2.3 Types

There are two types of engine cooling systems:

1. **Air-cooled:** Older car models, and very few modern cars, are air-cooled. Instead of circulating fluid through the engine, the engine block is covered in aluminum fins that conduct the heat away from the cylinder. A powerful fan forces air over these fins, which cools the engine by transferring the heat to the air.
   Coolant: Air

2. **Water-cooled:** It is the prevalent system in modern cars. The cooling system on liquid-cooled cars circulates a fluid through pipes and passageways in the engine. As this liquid passes through the hot engine it absorbs heat, cooling the engine. After the fluid leaves the engine, it passes through a heat exchanger, or radiator, which transfers the heat from the fluid to the air blowing through the exchanger.

   Coolant: Most commonly used coolants are:
   a. **Water:** One of the most effective fluids for holding heat is Water, but it freezes at too high a temperature to be used in car engines.
   b. **Antifreeze:** Ethylene Glycol ($C_2H_6O_2$) also called Antifreeze is mixed with water to reduce the water's boiling temperature. It is mixed with water in ratios of 50/50 and 70/30 ($C_2H_6O_2$ / H_2O).

   Characteristics: A good coolant has:
   a. Very low freezing point
   b. High boiling point
   c. Capacity to hold a large amount of heat

1.2.4 Components

Most modern cars are liquid-cooled, with main components like:

1. **Radiator**
   A radiator is a compact cross-flow heat exchanger with finned surfaces. Cooling water after absorbing heat from the engine is sent to the Radiator where the hot water is cooled by forced convection through the Fan. The radiator is pressurized so that the water flowing through it does not boil.

a. **Types:** Most common types of radiators are:

   i. **Down-flow Radiator:** A conventional vertical-flow design, with inlet tank located at the top of the core and connected by a hose to the coolant outlet housing on the engine. Coolant passes from the inlet tank and down through the core to the bottom (outlet) tank, also connected by a hose to the water pump inlet port. This permits coolant circulation through the radiator when the thermostat is open.
   This design is losing ground in modern vehicles, with its high profile limiting its use in the low profile front vehicle air flow dynamics; but it is still popular with heavy equipment manufactures.

   ii. **Cross-flow Radiator:** This design has the header tanks on each side (instead of top and bottom), the coolant travels horizontally instead of vertically. The header tank fitted with the radiator cap is the outlet tank, equivalent to the lower tank of the down flow design.
   The cross- flow design has two distinct advantages of permitting the use of a lower styling profile, and reducing pressure against the radiator cap, which prevents the cap from blowing if a blockage occurs and the radiator overheats.

b. **Parts**: A radiator consists of:

   i. **Core:** The radiator core consists of fins brazed on flattened tubes (through which the coolant flow) mounted in a parallel arrangement.The core is made up of:

1. **Aluminum (Al):** Most modern cars use Al radiators.
   Merits: Light weight; high heat transfer co-efficient.
   De-merits: Difficult to machine; easily deformed.
2. **Copper (Cu):** Older vehicles mostly used Cu radiators.
   Merits: Higher heat transfer co-efficient than Al; easy to machine.
   De-merits: Much heavier than Al (nearly 8 times); more susceptible to corrosion.

   ii. **Tank (Inlet & Outlet):** A radiators has tanks on each side (inlet and outlet).They are made usually made of the same material as the core (sometimes, plastic tanks are used with Al radiators).

2. **Cooling Fan**
   The Cooling Fan induces forced convection to the Radiator where it forces air to flow pass the Radiator tubes to absorb the heat from the water, thus cooling it down. The fans are controlled either with a thermostatic switch

or by the ECU, and they turn on when the temperature of the coolant goes above a set point. They turn back off when the temperature drops below that point.

3. **Fan Motor**
   The Fan-Motor is a DC motor which can rotate in both clockwise and anti-clockwise directions. The fan is fixed on the motor via press-fit.

4. **Plumbing**
   Engine cooling system's plumbing consists of thick-walled (with little flexibility) rubber pipes.

5. **Fan Shroud**
   The Fan Shroud is a metal covering that hold the fan and motor. The motor is screwed on the shroud before the fan is fixed on it. The shroud is then joined to the Radiator with screws.

6. **Condensate Catch-can**
   The Condensate Catch-can is attached to the water inlet of radiator via a small opening. If the water in the Radiator reaches near its boiling point, some steam is produced creates extra pressure in the Radiator pressure. After a certain limit, this steam is forced to move into the catch-can where it cools off and becomes water, after which it is forced back into the radiator.

7. **Pressure Cap**
   The Pressure Cap keeps the radiator pressurized, and sets the pressure limit (higher the pressure, higher the coolant's boiling point). When the fluid in the cooling system heats up, it expands, causing the pressure to build up. The cap is the only place where this pressure can escape, so the setting of the spring on the cap determines the maximum pressure in the cooling system. When the pressure reaches the set-point, the pressure pushes the valve open, allowing coolant to escape from the cooling system. This coolant flows through the overflow tube into the condensate catch-can. This arrangement also keeps air out of the system. When the radiator cools back down, a vacuum is created in the cooling system that pulls open another spring loaded valve, sucking water back in from the bottom of the overflow tank to replace the water that was expelled.

8. **Thermostat**
   The thermostat valve is placed before the radiator's water inlet. Its main job is to keep the engine at optimum operating temperature. It does this by regulating the amount of water that goes through the radiator. At low temperatures, the outlet to the radiator is completely blocked; all of the coolant is re-circulated back through the engine.

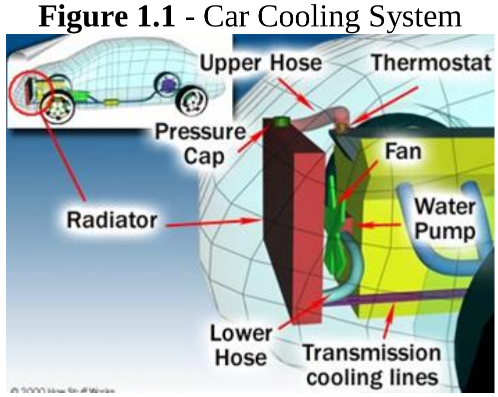
9. **Water Pump**
   The Water Pump keeps the water flowing in the engine cooling system and the engine. It is of two types:
   a. **Mechanical Pump:** It is a centrifugal pump belt-driven by the crank-shaft and takes a small portion of the engine's shaft power (thus reducing the overall output power). However, it is a tried-&-tested system, readily available, and most employed.
   b. **Electrical Pump:** It is employed in special cases. It is driven by an electric motor (thus the shaft power remains unaffected), and requires less power than a mechanical pump. However, it is not as effective as a mechanical pump.

10. **Oil Cooling System**
    Oil cooling system is used to cool the engine oil. It has a separate oil pump, and oil cooler (a small heat exchanger, that maybe air or water cooled).

11. **Quick Warm-up System**
    Quick warm-up (pre-heating) system heats up the engine during start-up in cold ambient conditions (winter). This circuit takes fluid from the cylinder head and passes it through a heater core and then back to the pump.
    This system is a reverse cooling system. A heating coil heats up the surrounding air, the heater fan forces this hot air to flow through a Heater core (a small radiator, through which coolant flows). The hot coolant then circulates through the engine block heating it. The heater core draws its coolant from the cylinder head and returns it to the pump, so the heater works regardless of whether the thermostat is open or closed.

12. **Transmission Cooling System**
    Vehicles with automatic transmission have a separate circuit for cooling the transmission fluid inside the main radiator. Transmission coolers are usually placed inside the radiator tanks. So, it is cooled through coolant-to-oil interaction.

Figure 1.1 - Car Cooling System



1.2.5 Heat Transfer

It is the energy in transit due to spatial temperature difference.
Heat transfer occurs when a temperature difference occurs between two or more media, or inside the medium.

- **Modes:** There are three modes of heat transfer:
  - **Conduction:** Heat transfer through molecular motion within a body (or multiple bodies in direct contact) due to temperature gradient.
    Assuming infinitesimally small Radiator tubes' thickness, the Conduction heat transfer can be neglected.
  - **Convection:** Heat transfer between two mediums due to motion of fluid (forced or natural) and temperature gradient.
    It is the most prominent heat transfer mode and transfers the most heat.
  - **Radiation:** Heat transfer caused by photons in electromagnetic waves due to temperature difference.
    Radiation heat transfer is accounts for less than 10% of total heat transfer in Spark Ignition engines, whereas, it is more prominent in CI engines (nearly 25%).
- **Overall Heat Transfer Coefficient:** It is a measure of the overall ability of a series of conductive and convective barriers to transfer heat.
  It is commonly applied to the calculation of heat transfer in heat exchangers.
  $UA_s = 1/((1/(h_1*A_1)) + (dx/k*A_w) + (1/(h_2 *A_i)))$

- **Nusselt No.:** It is the ratio of convective to conductive heat transfer across the boundary.
  $Nu = h.L_c / k$

- **Prandtl No.:** It is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity.
  Pr = cp. u / k

- **Reynolds No.:** It is the ratio of inertial forces to viscous forces. It tells whether a fluid flow is laminar, turbulent or transitional (different ranges for internal & external flows).
  Re = p.v.Dh / u (or Re = v.Dh / r)

- **Heat Exchanger Design Methods:** Radiator is a compact cross-flow heat exchanger. The following generic methods are for designing all types of heat exchangers.
  - **LMTD Method:** The **Log Mean Temperature Difference** (**LMTD**) is used to determine the temperature driving force for heat transfer in flow systems, most notably in heat

exchangers. The LMTD is a logarithmic average of the temperature difference between the hot and cold streams at each end of the exchanger. The larger the LMTD, the more heat is transferred. The use of the LMTD arises straightforwardly from the analysis of a heat exchanger with constant flow rate and fluid thermal properties.

- **E-NTU Method:** The **Number of Transfer Units (NTU) Method** is used to calculate the rate of heat transfer in heat exchangers (especially counter current exchangers) when there is insufficient information to calculate the Log-Mean Temperature Difference (LMTD).
  In heat exchanger analysis, if the fluid inlet and outlet temperatures are specified or can be determined by simple energy balance, the LMTD method can be used; but when these temperatures are not available **The NTU** or **The Effectiveness** method is used.

Chapter 2: Literature Review

2.1 Topics Reviewed

- Engine Cooling System
  - Basics
  - Components
  - Different Arrangements (Parallel vs. Series etc.)
- Heat Transfer
  - Modes (Conduction, Convection, Radiation)
  - Boundary Layer (Velocity, Temperature)
  - Constants (Nusselt, Reynolds, Prandtl Numbers)
  - Heat Exchangers
    - Types
    - Designing
      - Assumptions
      - Logarithmic Mean Temperature Difference (LMTD) Method
      - Effectiveness – No. of Transfer Unit (E-NTU) Method
- Internal Combustion Engines
  - Total Heat Load
  - Cooling System Load
  - Cooling Load Calculations
  - Effect of Radiation on Spark-Ignition & Compression Ignition Engines

2.2 Books Consulted

- Chapters 1, 2, 3, 6, 7, 8, 11 - Heat and Mass Transfer (Cengel)
- Engine Cooling – Bosch Automotive Handbook (Bosch)
- Chapter 10 – Engineering Fundamentals of Internal Combustion Engine (Pulkrabek)
- Chapter 12 - Internal Combustion Engine Fundamentals (Heywood)

2.3 Research Papers Consulted

- **Title:** Designing a More Effective Car Radiator
  Author: Maplesoft
  Affiliation: Waterloo Maple Inc.
  Abstract: The demand for more powerful engines in smaller hood spaces

has created a problem of insufficient rates of heat dissipation in automotive radiators. Upwards of 33% of the energy generated by the engine through combustion is lost in heat. Insufficient heat dissipation can result in the overheating of the engine, which leads to the breakdown of lubricating oil, metal weakening of engine parts, and significant wear between engine parts. To minimize the stress on the engine as a result of heat generation, automotive radiators must be re-designed to be more compact while still maintaining high levels of heat transfer performance. Most four-cylinder automobiles, depending on their size, have radiator cores that vary from 19" x 11.5" x 0.7" to 27" x 17" x 0.9". We believe that we can greatly reduce the size of automotive radiators while maintaining the current levels of heat transfer performance expected. Moreover, this can be done without significant modification to the existing internal radiator structure. There are several different approaches that one can take to optimize the heat transfer performance of a smaller radiator design. These include:
1) Changing the fin design
2) Increasing the core depth
3) Changing the tube type
4) Changing the flow arrangement
5) Changing the fin material
6) Increasing the surface area to coolant ratio (chosen for proposed design)

- **Title:** The Theoretical and Experimental Investigation of the Heat Transfer Process of an Automotive Radiator (No.31, 2012 ASEE Radiator Final)
  Authors: Mathew Carl, Dana Guy, Brett Leyendecker, Austin Miller and Xuejun Fan
  Affiliation: Dept. of Mechanical Engineering, Lamar University, USA
  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.

- **Title:** Automotive Radiator Sizing and Rating – Simulation Approach
  Authors: P. S. Armutkar and S. R. Patil
  Affiliation: Dept. of Mechanical Engineering, Sinhgad Academy of Engineering, University of Pune, India
  Abstract: Automotive radiator is key component of engine cooling system. Coolant surrounding engine passes through radiator. In radiator coolant gets cooled down and re-circulated into system. Radiator sizing is important factor while designing cooling system. Radiator size depends on heat load as well packaging space availability. Heat load depends on heat rejection required to keep engine surface at optimum temperature. Generally LMTD or E-NTU method is used to do heat transfer calculations of radiator. Both methods have its own advantages and preferred according to data availability. When radiator inlet and outlet temperature are known LMTD gives faster solution. When any of the temperature is unknown LMTD method undergoes iterations to find solution. In this case E-NTU is better. In this paper E-NTU method is described to do heat transfer calculations.
- **Title:** Automotive Cooling System in Industry
  Author: Adel Alkhodairy (IE-499)
  Abstract: Modern automotive internal combustion engines generate a huge amount of heat. This heat is created when the gasoline and air mixture is ignited in the combustion chamber. This explosion causes the piston to be forced down inside the engine, levering the connecting rods, and turning the crankshaft, creating power. Metal temperatures around the combustion chamber can exceed 1000° F. In order to prevent the overheating of the engine oil, cylinder walls, pistons, valves, and other components by these extreme temperatures, it is necessary to effectively dispose of the heat.
  Approximately 1/3 of the heat in combustion is converted into power to drive the vehicle and its accessories. Another 1/3 of the heat is carried off into the atmosphere through the exhaust system. The remaining 1/3 must be removed from the engine by the cooling system.
  Modern automotive engines have basically dumped the Air Cooled System for the more effective Liquid Cooled System to handle the job. In a liquid cooled system, heat is carried away by the use of a heat absorbing coolant that circulates through the engine, especially around the combustion chamber in the cylinder head area of the engine block. The coolant is pumped through the engine, then after absorbing the heat of combustion is circulated to the radiator where the heat is transferred to the atmosphere. The cooled liquid is then transferred back into the engine to repeat the process.
  Excessive cooling system capacity can also be harmful, and may affect engine life and performance. You must understand that coolant temperatures also affect oil temperatures and more engine wear occurs when the engine oil is below 190° F. An effective cooling system controls

the engine temperature within a specific range so that the engine stays within peak performance.

2.4 FS Reports Reviewed

- **Title:** Cooling System Analysis (109-829-1-PB)
  Author: Lt. Andrew Jiear
  Affiliation: University of New South Wales, Australia
  Abstract: The Formula SAE competition challenges students to conceive, design, fabricate and compete with small formula style race cars. The aim of this thesis is to construct a robust process for gathering experimental data and to conduct analysis in order to determine the most efficient location and size of the radiator core on SAE vehicles. Data from experiments on coolant flow and radiator characteristics were used to calculate the system's flow rate and heat load capacity. The dynamic test results were unable to provide relevant data to pass judgment on the most efficient radiator location and core size. The experimental and simulation data from experiments on cooling system performance and coolant flow characteristics led to the recommendation to use an electrical water pump on ACME racing's 2009 vehicle, the WS05.

- **Title:** FSAE Cooling System Design
  Author: Nathan Marcus
  Affiliation: University of Pennsylvania, USA
  Abstract: Overall goals of this subsystem are:
    - Provide exceptional protection from thermal damage to the engine.
    - In design, consider this a candidate to be a high-reliability subsystem.
    - Packaging of this subsystem should blend in as smooth as possible with the vehicle aerodynamics packaging.

- **Title:** FSAE Cooling System Report
  Authors: Craig Mclain, Reuben Ness and Riki Hopkins
  Affiliation: Portland State University, USA
  Abstract: Formula Society of Automotive Engineers (FSAE) is an international engineering competition where students design, build, and test small-scale autocross racing vehicles. Competitions are held annually with regulations that create a real-world engineering challenge. Cooling related problems, ranging from relatively minor problems of hot starting issues and suboptimal performance of the car during competition to catastrophic engine failures due to overheating, are not uncommon amongst competitors.
  PSU's 2010 car had inadequate cooling capacity due to undersized

radiator and fan, and improper airflow due to poor radiator positioning. The car faced challenges such as:

- Running at temperature hotter than that for optimal performance
- The car tended to overheat when idled for extended time or brought to an idle shortly after it was ran hard, as the undersized radiator and fan was not able to produce enough air flow in order to reject the required heat load of 2 hp
- The car had difficulties starting in competition due to thermal expansion of the engine components from excessive heat.

A properly engineered solution for a cooling system will allow the car to run at the temperature for optimal performance, and prevent problems during expected and routine procedures such as overheating during idle or hot starting issues during testing and competition. Because, the radiator was an afterthought for this team, not enough time was allocated in analyzing the necessary cooling loads. The radiator design and sizing relied heavily on broad assumptions that were not well understood. Radiator placement and orientation were packaged with little consideration of the fluid dynamics of airflow, and since the team was short on resources, ducting and fan placement were neglected. In 2010, the importance of the cooling system was indeed underrated and inadequate resources were allocated to its design and build process.

- **Title:** Analysis and Design of FSAE Racecar Cooling System
  Author: Jesse Hastings, Pat Howe
  Abstract: The objective of this project is to compare analysis between series and parallel radiator set ups for the 2010 Formula SAE car. Data will be collected on water pump output at a range of different engine speeds. From this information and that of known engine power output and other parameters, each model will be configured and the results will be compared to determine which system will function properly for the desired requirements of the car.

Chapter 3: Designing the FS Vehicle Radiator

3.1 Project Scope

Aim
The aim of the project is to design the Engine Cooling system of Formula Student vehicle, focusing on Radiator Design.

Objectives
The main objectives of the project are:

1. Making a Generic Mathematical Model for Radiator design
2. Designing a Radiator for the required conditions
3. Experimentally validating the Mathematical model

Initial vs. Final Aim
The initial aim of the project was to:

1. Design the Engine Cooling System of Formula Student vehicle
2. Implementing the design on the vehicle with Electronic Temperature Control and Electric Pump

Re-definition: Due to unavailability of the design engine and funds, the vehicle could not be manufactured, and the project's aim had to be re-defined.

3.2 Mathematical Model

3.2.1 Assumptions

For developing the mathematical model, some assumptions had to be made for simplicity. These assumptions were taken through the literature review of Heat Exchanger and Radiator design, which are:

1. **Engine**
    - Estimated Cooling Load = (Total Engine Power)/3
    - No heat gain due to friction
    - No radiation losses
    - Flow (Water / Air)
    - Steady-state Flow
    - Fully developed Water flow in Radiator

2. **Flow-rates**
    - Water = 36 lit/min (0.6 kg/s)
    - Air = 1000 CFM (0.5 kg/s)

3. **Properties**
   - Properties for both Water and Air are taken at STP conditions
     - Ambient Temperature= 25^{o}C
     - Pressure= 1 atm
   - These properties are assumed to be constant throughout.
   - Density
   - Specific Heat
   - Thermal Conductivity (Water, Air, Radiator Material)
   - Viscosity (Kinematic for Air, Dynamic for Water)
   - Prandtl No.

Table 1.1 - Fluid Properties (STP)

Parameters	**Symbols**	**Units**	**Value**
Water			
Density	p_water	kg/m^3	997
Specific Heat	cp_water	J/kg.K	4180
Thermal Conductivity	k_water	W/m.K	0.607
Dynamic Viscosity	u_water	kg/m.s	0.891e-3
Prandtl Number	Pr_water	-	6.14
Air			
Inlet Temperature	T_air_in	^{o}C	25
Density	p_air	kg/m^3	1.184
Specific Heat	cp_air	J/kg.K	1007
Thermal Conductivity	k_air	W/m.K	0.0251
Kinematic Viscosity	u_air	kg/m.s	1.562e-5
Prandtl Number	Pr_air	-	0.7296
Gravitational Acceleration	g	m/s^2	9.81

4. Radiator Parameters
   - Radiator Operating Conditions
     - Normal Operating Temperature (Radiator Inlet Temperature) =
       $T_{water-in}$ = 95^{o}C
     - Limiting Pressure = 1.5 bar
   - Temperature Gradient ($T_{water-in} - T_{water-out}$) = 10^{o}C
   - Smooth Rectangular Fins
   - Insulated Fin Tips
   - Internally Smooth Tubes
   - Constant Fluid Flow-rates (Air/Water)
   - Negligible Tube Wall Thickness
   - No Ram Air (the vehicle is assumed to be stationary)

3.2.2 Algorithm

E-NTU (Effectiveness – No. of Transfer Units)

The Effectiveness NTU method is used to predict the heat transfer performance of a system. In this method we have the dimensions and properties of a radiator as an input while total heat to be removed and temperature gradient across the radiator is calculated. The E-NTU (Effectiveness – No. of Transfer Units) method is used for calculating the Cooling load dissipated by the Radiator, because the Exiting Temperatures of Water and Air are unknown.

Advantage: The reason is that The **NTU** method is more convenient than the **LMTD** method for cases in which outlet temperature(s) are not known. Even though iterative calculations for the LMTD method are not as cumbersome as they used to be without modern computational equipment, the NTU method still provides a useful formalism for designing heat exchangers.

Basic Equations: Some of the basic equations used in this method are:

- Q=m*cp*dT
- Q_max=C.min*dT.max
- Q_cal=E*Q_max
- E = 1-exp(((NTU^0.22)/Cr)*(exp(-Cr*(NTU^0.78))-1))
- NTU = UAs/C_min

For water, internal convection equations are used.
For air, external convection equations are used.

Parameters

Inputs: Input parameters are:

- Air & Water properties at S.T.P (p, μ, r, cp, k, V, Pr, T_in)
- Thermal conductivity of radiator (k)
- Gravitational Acceleration (g)
- Dimensions of radiator: See Figure-
    - Outer: L_rad, H_rad, W_rad
    - Tube: W_tube, H_tube, L_tube, N_tube
        - Down-flow: L_tube = H_rad
        - Cross-flow: L_tube = L_rad
    - Fin: W_fin, H_fin, L_fin, N_fin, d_fin
        - N_fin = No. of Fins per Tube (both sides)
        - d_fin = Distance between 2 fins
        - W_fin = W_rad

Figure 3.1 - Radiator Outer Dimensions

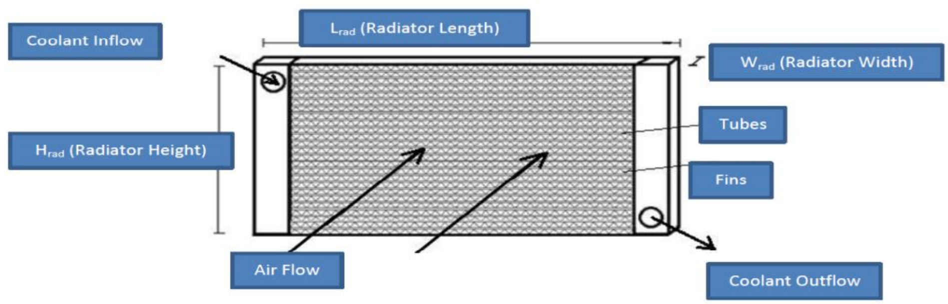


Figure 3.2 - Radiator Tube Dimensions

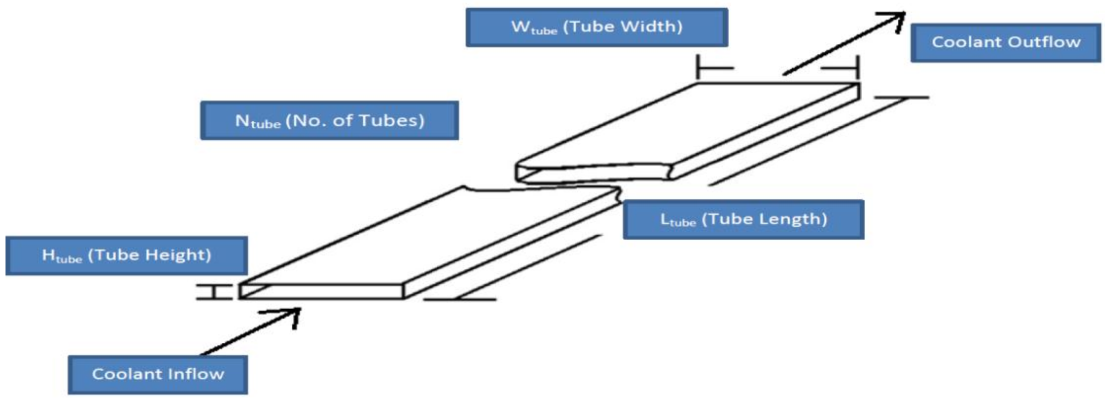
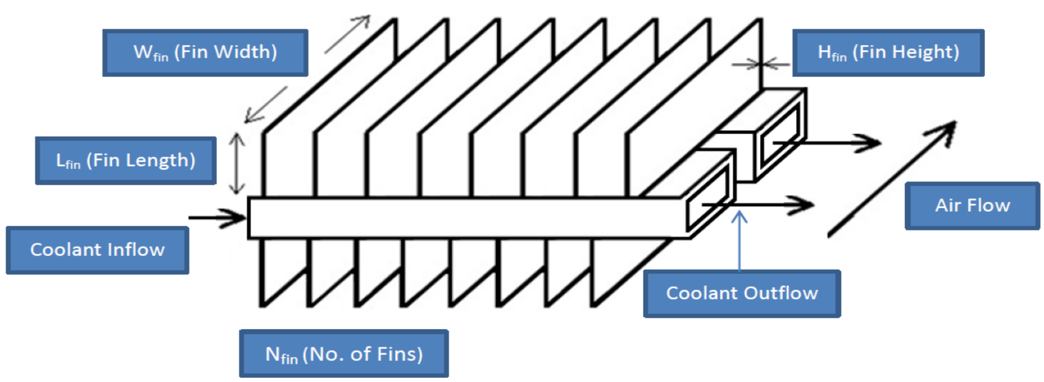


Figure 3.3 - Radiator Fin Dimensions



- Total engine power
    - E_Power=75000
    - FOS=0.2
    - Q_total=E_Power+(E_Power*FOS)

Calculations: Calculated parameters are:

- **Reynolds Number**
  - Re_water = ρ.v.Lc / μ
  - Re_water = v.Lc / r
  - Characteristic Length
    - Water:
      - Lc = Dh_water = (4*A_tube)/P_tube
      - A_tube = W_tube*H_tube
      - P_tube = 2*(W_tube+H_tube)
    - Air: Lc_air = Dh_water = W_tube
  - Fluid Velocity
    - Water
      - v_water = V_water/(N_tube*A_tube)
      - A_rad = H_rad*L_rad
    - Air: v_air = V_air/(A_rad - (N_tube*H_tube*L_tube))

- **Nusselt Number**
  - Water: Water in the tubes is assumed to be in steady-state fully developed flow.
    - For Re_water < 2300, see Table-XX for Rectangular configuration &
q_s= constant.
    - For Re_water > 2300 & Re_water > 5E6
      - Nu_water = ((f/8) * (Re_water -1000) * Pr_water) / (1+(12.7 * ((f/8)^0.5)) * ((Pr_water^(2/3))-1))
      - f = (0.79*log(Re_water-1.642))^(-2)
  - Air: Air is assumed to be flowing over a horizontal flat plate.
    - For Re_air < 5E5
Nu_air = 0.664*(Re_air^0.5)*(Pr_air)^(1/3)
    - Re_air < 5E5
Nu_air = 0.037*(Re_air^0.8)*(Pr_air)^(1/3)

- **Overall Heat Transfer Coefficient**
  - UAs = 1/((1/(h_air*Ae)) + (1/(h_water*Ai)))
  - Convection Heat Transfer Coeficient
    - h = (Nu_water * k_water) / Lc_water
  - Areas
    - Ai = 2*(W_tube+H_tube)*L_tube*N_tube

- Ae: Two methods are used to calculate the 'External Surface Area'. The basic difference is that one uses 'Number of Fins' as input while other uses 'Distance between Fins'.
  - 1st Method: No. of Fins

    Ae = A_unfinned + (n_fin*A_finned)
    where,
    Lc = L_fin + (H_fin/2)
    m = ((2*h_air)/(k_rad*H_fin))^0.5 (This is not Mass flow-rate, but a Fin constant)
    n_fin = (tanh(m*Lc))/(m*Lc)
    A_finned = (2*W_fin*Lc*(N_fin/2))*(N_tube +1)
    A_unfinned = ((2*L_tube*W_tube)-(N_fin*H_fin*W_fin))*N_tube

  - 2nd Method: Distance of Fins
    Ae = ((L_tube/d_fin)*Cf)*(2*L_fin)*(d_fin+W_fin)
    Cf = N_tube+1

- **NTU (Number of Transfer Units)**
  - NTU = UAs/C_min
  - Heat Capacity:
    - C_water = m_water.cp_water
    - C_air = m_air.cp_air
    - C_min = C_air if C_air < C_water (& vice versa)
    - C_max = C_air if C_air > C_water (& vice versa)
    - Cr = Heat Capacity Ratio = C_min / C_max
  - Mass Flow-rates
    - Water: m_water = p_water*V_water
    - Air: m_air = p_air*V_air

- **Effectiveness: Radiator Effectiveness of Cross-flow Heat Exchanger**
  E = 1-exp(((NTU^0.22)/Cr)*(exp(-Cr*(NTU^0.78))-1))

- **Cooling load**
    - Estimated cooling load: Q_est = Q_total/3
    - Max temperature difference: dT_max = T_water_in-T_air_in
    - Maximum Cooling load: Q_max = C_min*dT_max
    - Calculated Cooling load: Q_cal = E*Q_max
    - Percentage Difference: per_diff = ((Q_cal – Q_est)/Q_est)*100

- **Outgoing Temperatures**
    - Water: T_water_out = T_water_in-(Q_cal/C_water)
    - T_air_out = (Q_cal/C_air)+T_air_in

- **Other Parameters**
    - h_L = f*(L_tube/Dh_water)*((v_water^2)/(2*g))
    - dP = f(y)*(L_tube/Dh_water)*((p_water*(v_water^2))/2)
    - W_p = m_water*g*h_L

<u>Procedure</u>

1. First of all, Reynolds number is calculated to classify flow as either laminar or turbulent (both for air and water).
2. After calculating this, Nusselt number is calculated for air and water by different formulas.
3. Heat transfer for both air and water is calculated separately.
4. Overall heat transfer coefficient is calculated.
5. Then, NTU (number of transfer units) are calculated.
6. Effectiveness of radiator is then calculated using NTU.
7. Cooling load is calculated using effectiveness.
8. Temperature for both air and water is calculated at outlet of radiator.
9. Iterations are done in order to get optimized dimensions of a radiator under given properties and flow-rates.
    a. L_rad(y+1) = L_rad(y) + (iteration step)
    b. H_rad(y+1) = H_rad(y) + (iteration step)
    c. L_tube(y+1) = H_rad(y+1)
    d. N_tube(y+1) = 2*((L_rad(y+1)-L_fin)/(H_tube+L_fin))
    e. N_fin(y+1) = 2*((L_tube(y+1)+d_fin)/(H_fin+d_fin))

3.3 Proposed Design

The proposed design based on the Literature Review and the Algorithm is as follows:

- Design Engine: CBR600RR 2008 Model
    - Engine Type: Petrol

- Cooling System: Liquid
    - No. of Cylinders: 4
    - Swept Volume: 600cc
    - Peak Power: The engine's peak power is 76 kW (@ 13,900 rpm), but as per FS rules, a Restrictor at the Intake is used to reduce power below 75 kW (100 hp).
- Radiator Type: Down-flow, with Double Tube Rows
- Radiator Material: Copper (because of ease of welding, brazing and machining)
- Radiator Arrangement: Parallel (2 radiators working in parallel receiving half the total water flow-rate (assuming that both are equidistant from the engine) and dissipating half the total heat)
- Radiator Positioning: Side-mounted (outside the chassis, attached to the body; common arrangement in Formula Cars)

Figure 3.4 - Proposed Design

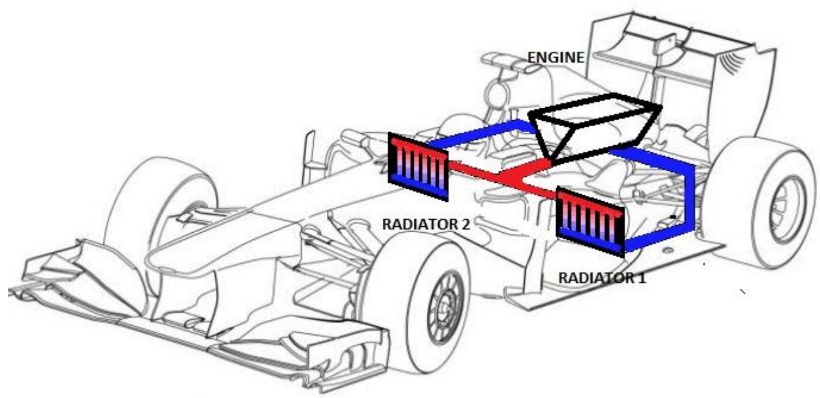
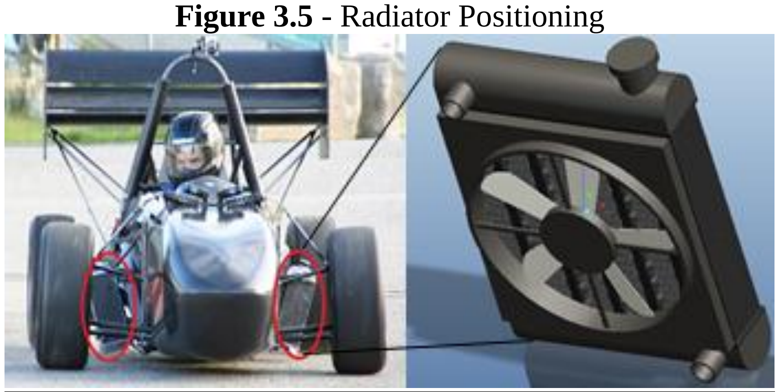


Figure 3.5 - Radiator Positioning



Radiator Dimensions

The dimensions of one radiator (based on side-pod dimensions) are given below.

Side-pod Dimensions: The side-pod dimensions given by the Body-works team are:

- L_rad = 258.49 mm
- H_rad = 288.91 mm
- W_rad = 34.17 mm

Tube & Fin Dimensions: The Tube and Fin Dimensions are taken equal to the Mehran's Radiator dimensions:

- Tubes
  - L_tube = 316 mm
  - H_tube = 1 smm
  - W_tube = 15 mm
- Fins
  - L_fin = 8.7 mm
  - W_fin = 38 mm
  - H_fin = 0.5mm
  - d_fin = 2 mm

With these dimensions, the calculated dimensions are:

- N_tube = 56
- N_fin = 232

Cooling Load: One Radiator is expected to dissipate half the total cooling load, so:

- Engine Peak Power = 75 kW
- Total Cooling Load = 75/3 = 25 kW
- Cooling Load of 1 Radiator = 25/2 = **12.5 kW**

Flow-rates: The flow-rates of water and air are assumed to be:

- Water = 18 Lit/min
- Air = 1000 CFM

Heat Dissipated and Radiator Effectiveness calculated:

- E = 0.4126
- Q_est = 12.5 kW
- Q_cal = 16.18 kW
- per_diff = 29.45%

Minimum Dimensions: For a Radiator that dissipates around 12.5 kW, the dimensions are:

- L_{rad} = 193 mm

- H_{rad} = 223 mm
- W_{rad} = 34.17mm
- N_tube = 40
- N_fin = 180

The results of this Radiator are:

- E = 0.3174
- Q_est = 12.5 kW
- Q_cal = 12.45 kW
- per_diff = -0.38 %

3.4 Constraints

The constraints in the prototype design and the math model are as follows:

- **Coolant:** Only Water can be used as coolant as per Formula Student rules.
- **Math Model:**
  - **Fully Developed Flow:** The flow inside the radiator tubes is considered to be fully developed throughout, and Entry length is not considered.
  - **Flow over Fins:** The air flow over fins is considered to be the same as air flow over a flat plate, and the respective Heat Transfer relations are used (Nusselt No., Friction factor, Reynolds No. etc.).
  - **Fixed Inner Dimensions:** Some of the Tube and Fin dimensions are considered to be fixed for all sizes of Radiator (outer dimensions). These dimensions are taken from the Mehran Radiator.
    - H_tube = 1 mm
    - W_tube = 15 mm
    - L_fin = 8.7 mm
    - H_fin = 0.5 mm
  - **Un-accounted Factors:** The math model does not contain factors to incorporate:
    - Ram Air
    - Radiation Heat Transfer

Chapter 4: Sensitivity Analysis

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs.
The sensitivity Analysis is done using both methods of Fins (Fin distance & Fin Height). The radiator dimensions are taken for the Mehran car. For all the parameters these inputs are the same unless where it is required to change:

```
k_rad = 401;          % Thermal conductivity of Radiator Material (copper)

V_air    = 0.47;        % Volume flow rate
V_water    = 0.0006;     % Volume flow rate of water

T_air_in = 298;         % Air inlet temp
T_water_in = 368;       % water inlet temp

L_rad =0.347;           % Outer dimensions
H_rad =0.316 ;
W_rad =0.038 ;

W_tube =0.015 ;          % Tube dimensions
H_tube =0.001 ;
L_tube = H_rad;

L_fin =0.0087;           % Fin dimensions
W_fin =0.038 ;
H_fin =0.0005 ;
d_fin = 0.002;
N_tube=2*((L_rad-L_fin)/(H_tube+L_fin));
N_tube=round(N_tube)                          % N_tube=70
N_fin=2*((L_tube+d_fin)/(H_fin+d_fin));
N_fin=round(N_fin)                      %N_fin=254
```

4.1 Thermal Conductivity of Material

By changing the material i.e. thermal conductivity is changed the Effect on heat dissipation and Effectiveness is negligible because this factor is not incorporated in calculating heat dissipation or Effectiveness rather it is incorporated only for fin Efficiency.

Table 4.1 - Al vs. Cu

Material	Thermal conductivity (W/m.K)	Heat dissipated (kW)	Effectiveness
Aluminum	205	17.64	0.4498
Copper	401	17.80	0.4540

4.2 Radiator Dimensions

4.2.1 Outer Dimensions

1. **Length of Radiator:** With increasing the length of a radiator the heat dissipation decreases to a certain point and then start to increase. This is because by increasing length different parameters like number of tubes, Reynolds number for air and water etc. are affected. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
   L_rad =0.347:0.0005:0.372 (initial value: iteration step: final value)

Figure 4.1.1 - Q_cal vs. L_rad

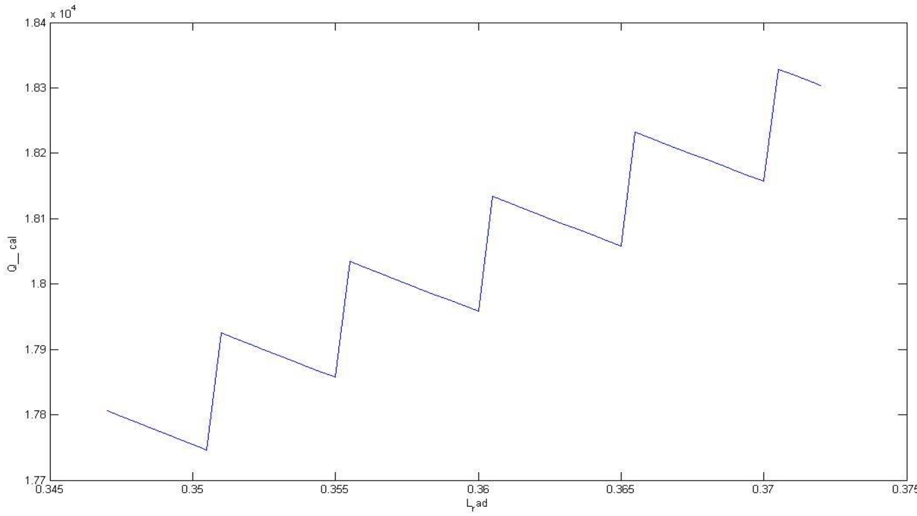
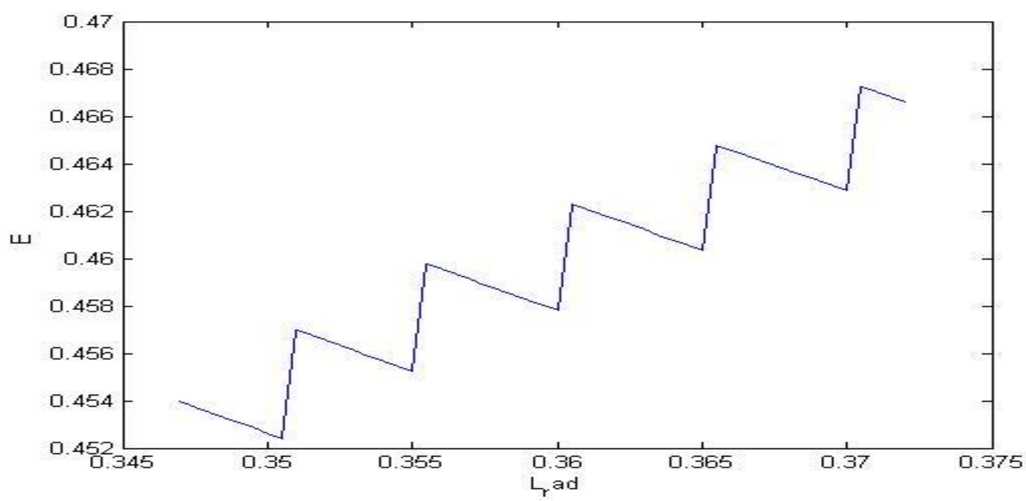


Figure 4.1.2 - E vs. L_rad



2. **Height of Radiator:** Both the graph shows that by increasing the height of a radiator the heat dissipation and Effectiveness increases. The slight disturbance is due to that by changing height of radiator, length of tube is changed and all the parameters related to it like number of fins etc. are changed.
   H_rad =0.316:0.0005:0.341 (initial value: iteration step: final value)

Figure 4.2.1 - Q_cal vs. H_rad

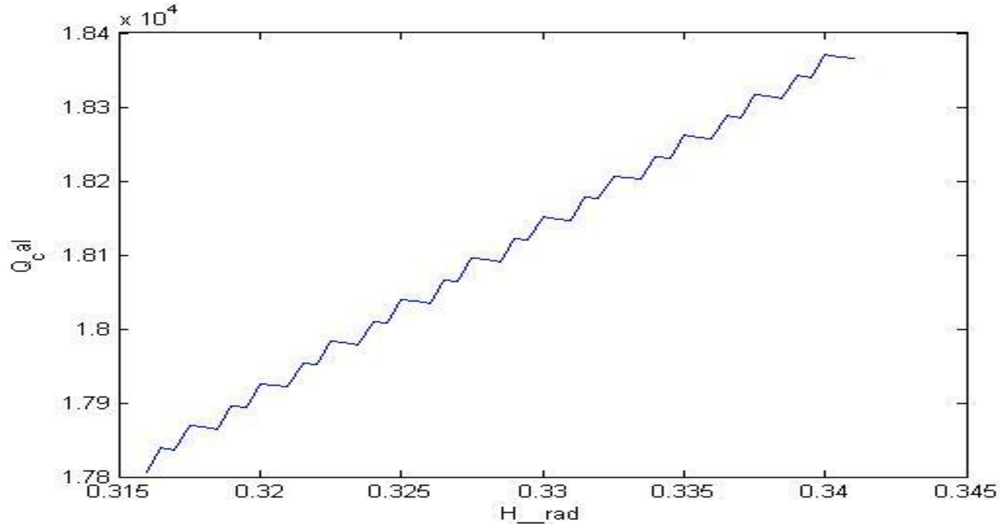
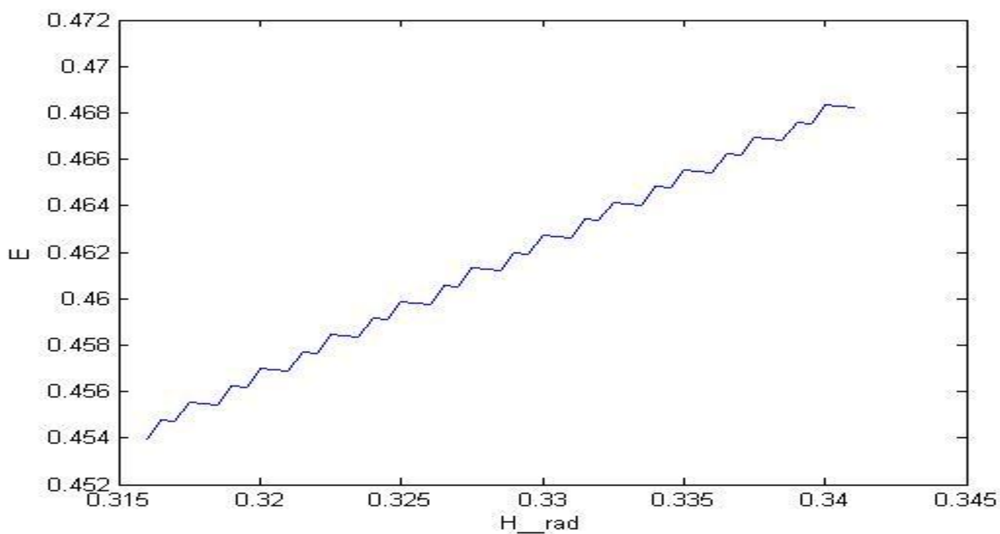


Figure 4.2.2 - E vs. H_rad



3. **Width of Radiator:** By increasing the width of radiator there is no effect on the heat dissipation and Effectiveness as all others parameters area same and width does not affect any other parameter which has effect on heat dissipation or Effectiveness.
   W_rad =0.038:0.00005:0.0405 (initial value: iteration step: final value)

Figure 4.3.1 - Q_cal vs. W_rad

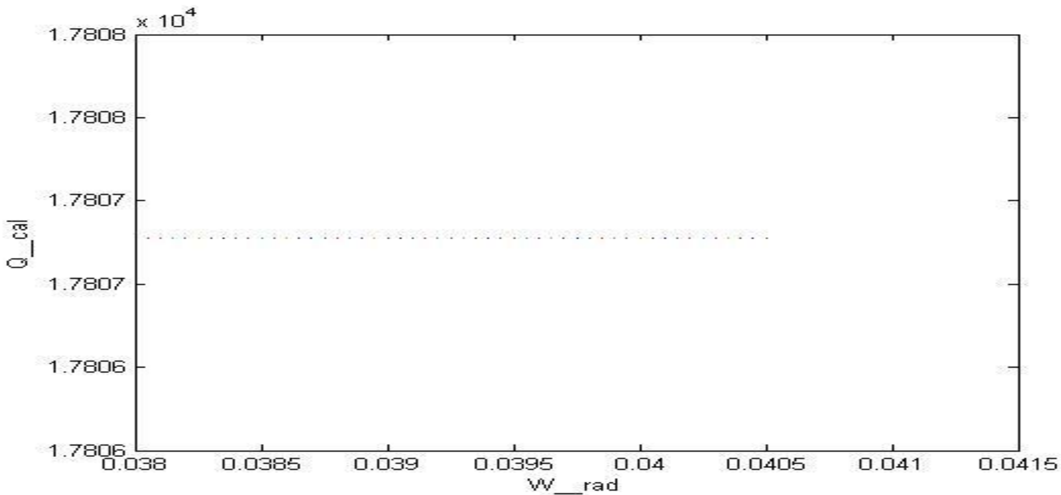
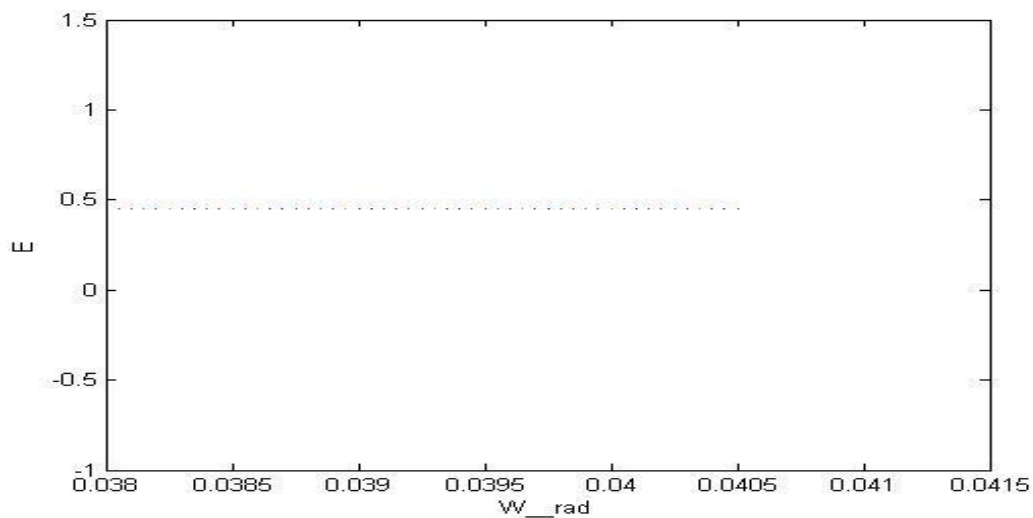


Figure 4.3.2 - E vs. W_rad



4.2.2 Tube Dimensions

1. **Length of Tube:** As L_tube=H_rad so the graph of L_tube is same as that of H_rad.
   L_tube=H_rad =0.316:0.0005:0.341 (initial value: iteration step: final value)

Figure 4.4.1 - Q_cal vs. L_tube

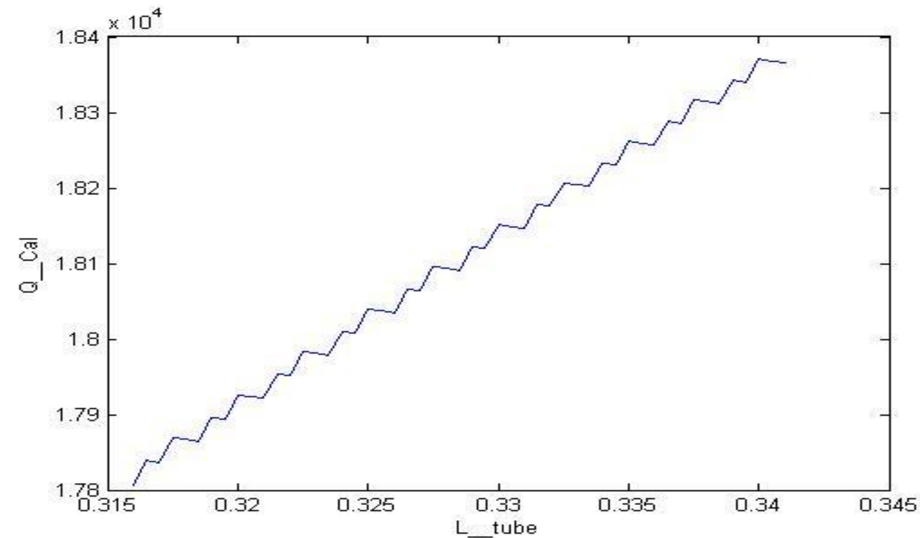
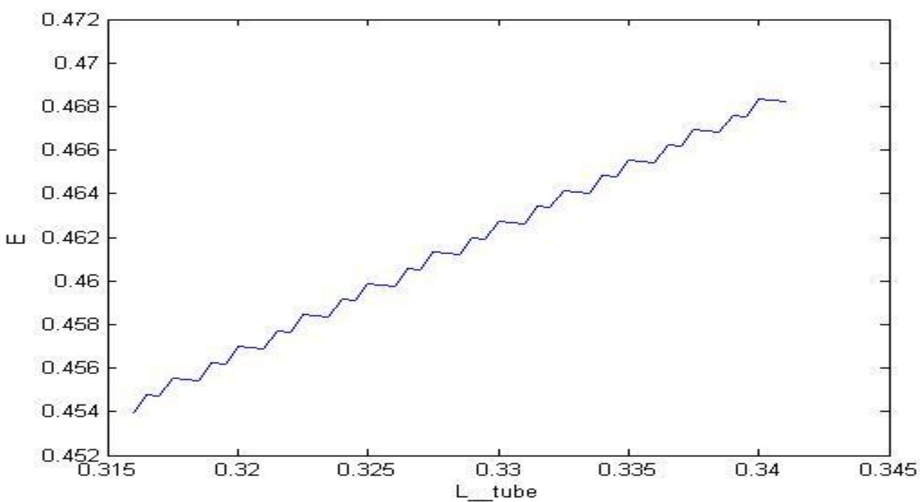


Figure 4.4.2 - E vs. L_tube



2. **Height of Tube:** The graph shows that overall by increasing height of tube, heat dissipation decreases. This is due to the reason that by reducing the height of a tube its un-finned area increases which result in poor heat dissipation. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
H_tube =0.001:0.0001:0.006 (initial value: iteration step: final value)

Figure 4.5.1 - Q_cal vs. H_tube

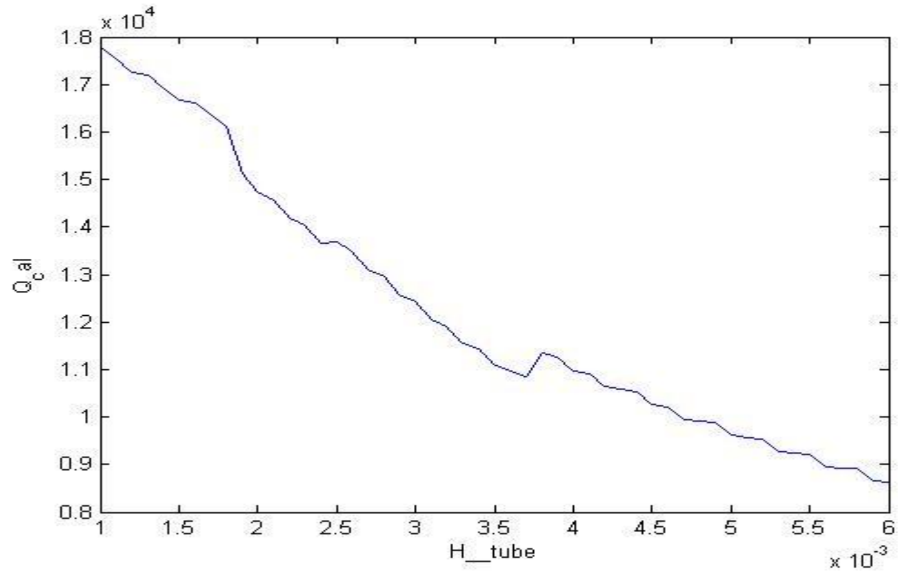
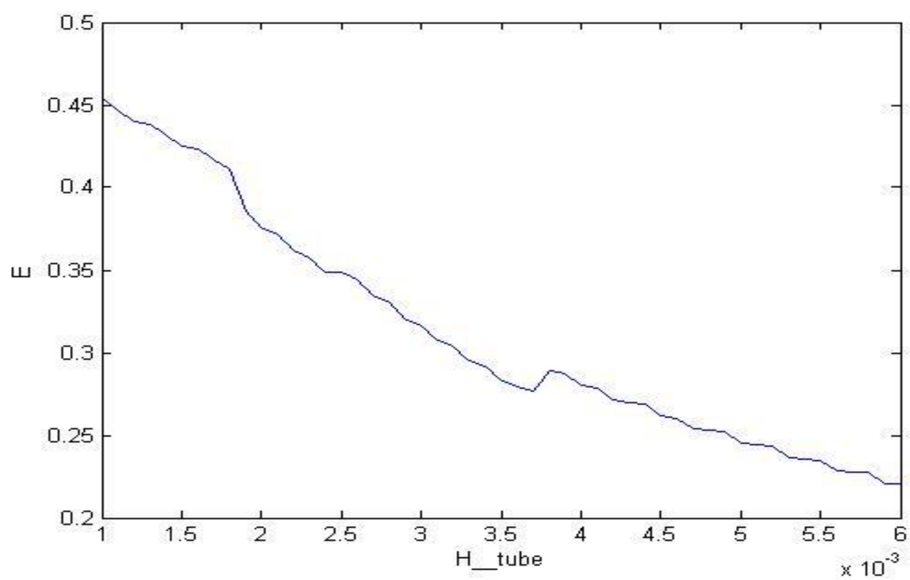


Figure 4.5.2 - E vs. H_tube



3. **Width of Tube:** The graph shows that relation is linear and by increasing width of tube, heat dissipation decreases. The relation is clear as reducing the width of tube reduces the area from which heat is to be dissipated. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
   W_tube =0.015:0.0001:0.02 (initial value: iteration step: final value)

Figure 4.6.1 - Q_cal vs. W_tube

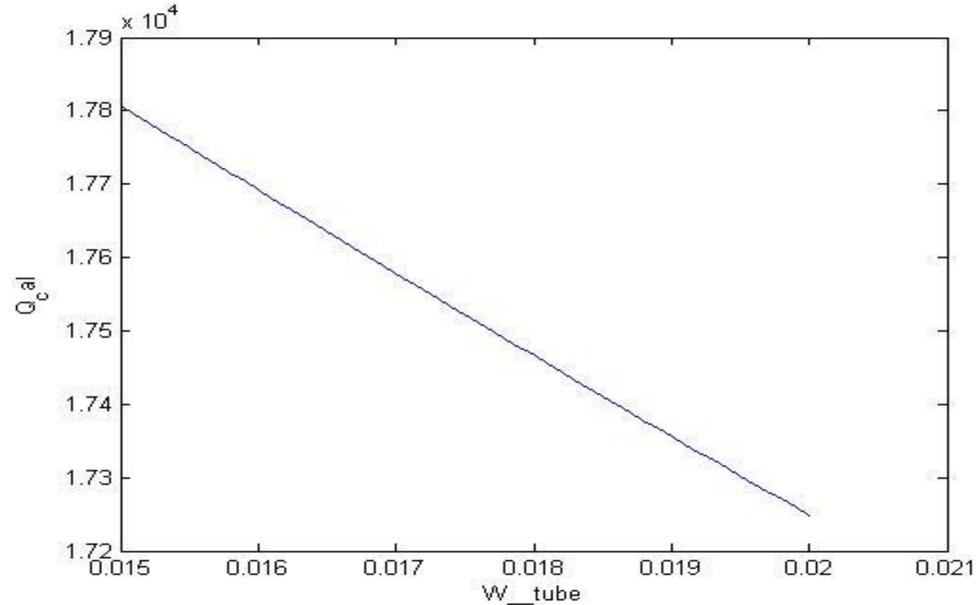
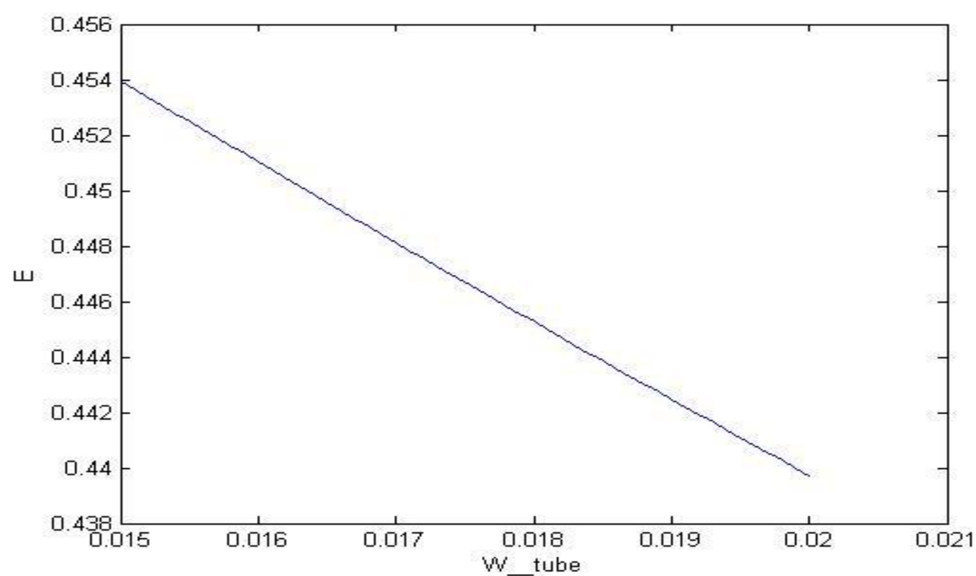


Figure 4.6.2 - E vs. W_tube



4. **Number of Tubes:** By increasing number of tubes the heat dissipation graph shows that heat dissipation also increases. The sudden decrement is due to change in other parameters like Reynolds number and Nusselt number for water and air. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.

Figure 4.7.1 - Q_cal vs. N_tube

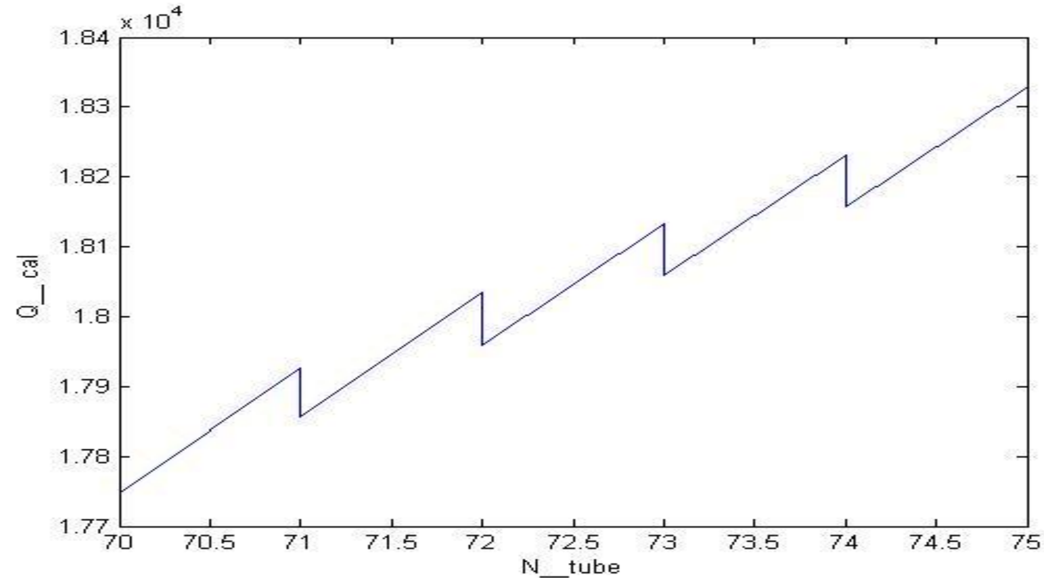
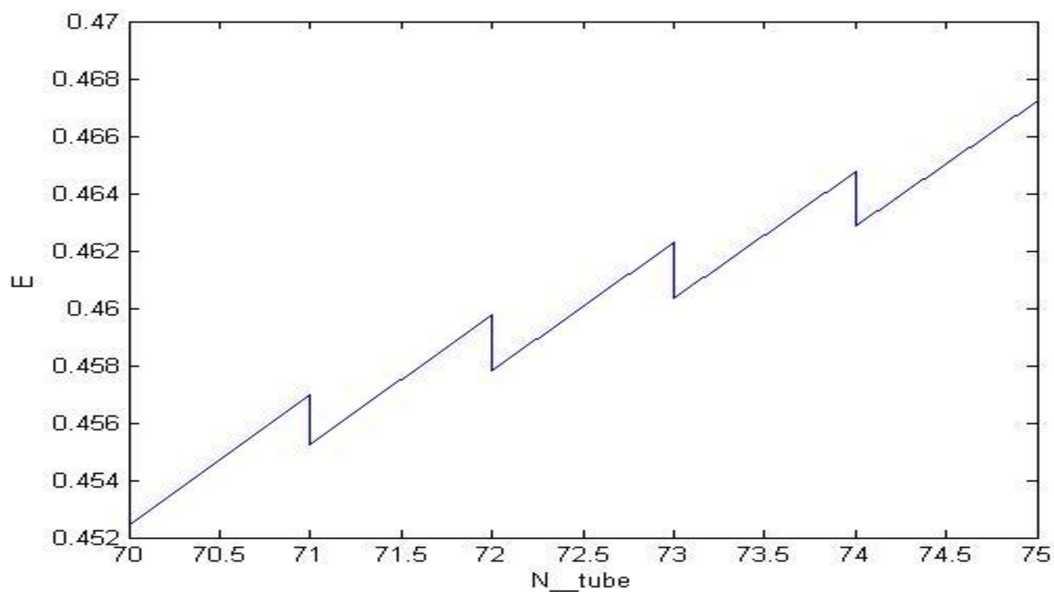


Figure 4.7.2 - E vs. N_tube



4.2.3 Fin Dimensions

1. **Length of Fin:** There is irregularity in the graph but the overall trend shows that by increasing length of fins the heat to be dissipated decreases. The reason is that by increasing length of fin for the same length of tube it decreases the number of fins on the tube hence heat dissipation decreases. . The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
   L_fin =0.0087:0.0001:.0137 (initial value: iteration step: final value)

Figure 4.8.1 - Q_cal vs. L_fin

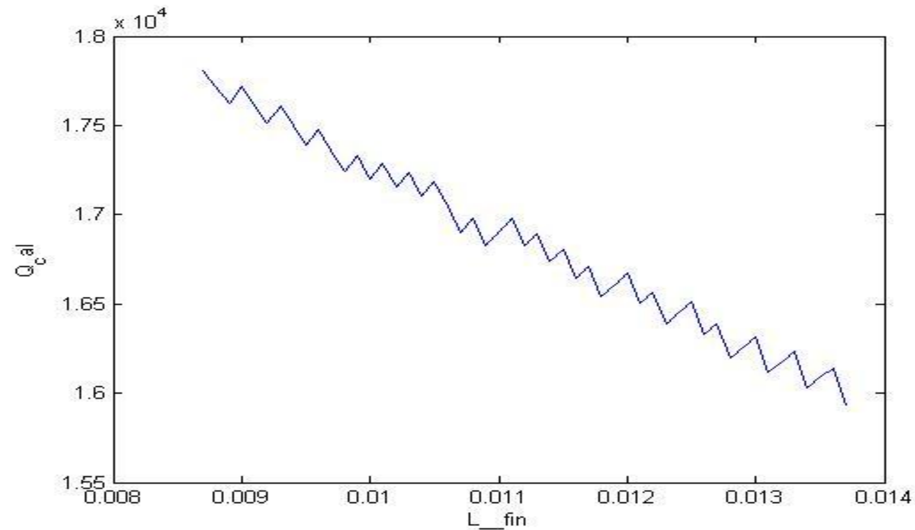
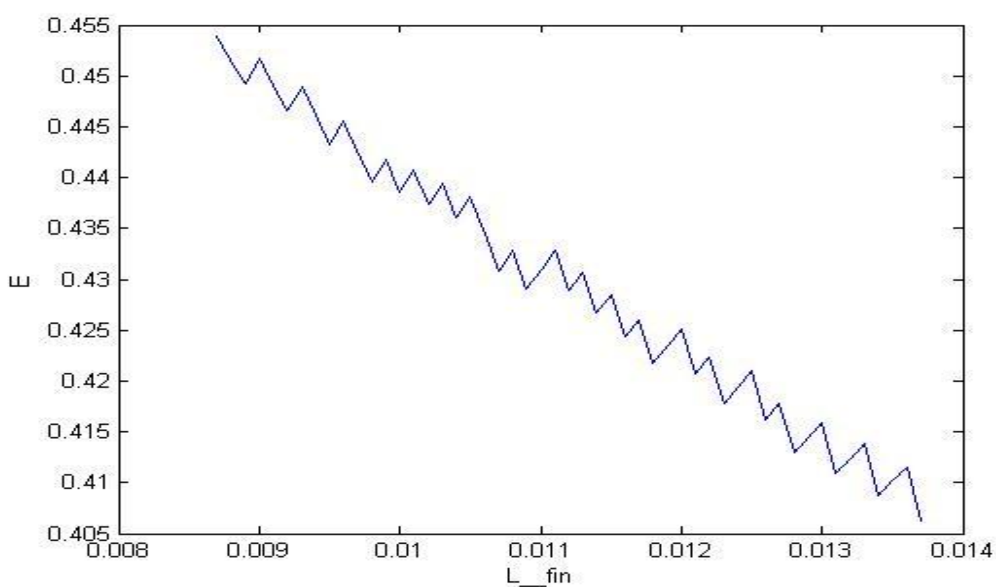


Figure 4.8.2 - E vs. L_fin



2. **Width of Fin:** The graph shows almost linear behavior between the two parameters. By increasing the width of fin, the area of fin increases through which heat transfer takes place hence the heat dissipation increases. . The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
   W_fin =0.038:0.001:0.088 (initial value: iteration step: final value)

Figure 4.9.1 - Q_cal vs. W_fin

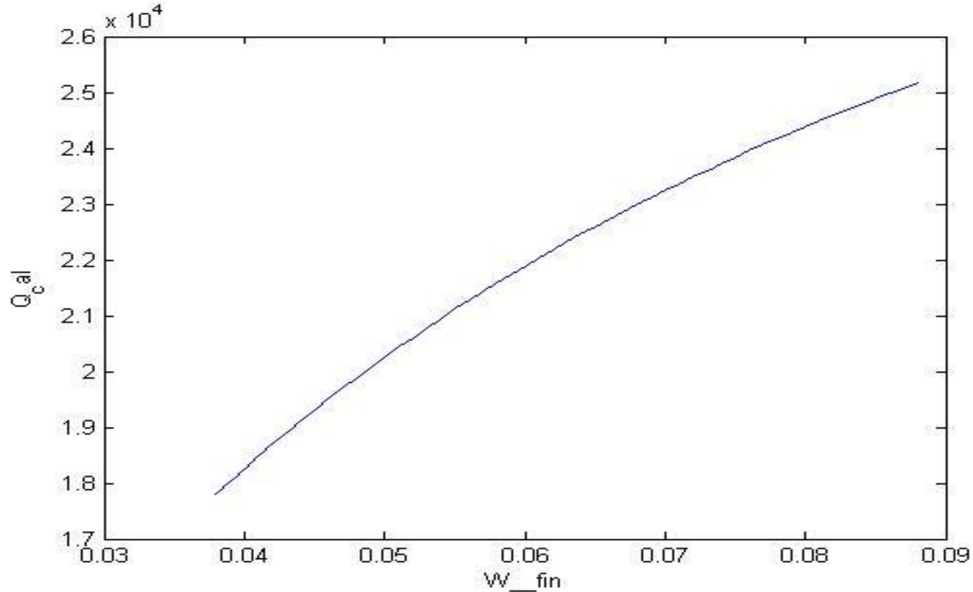
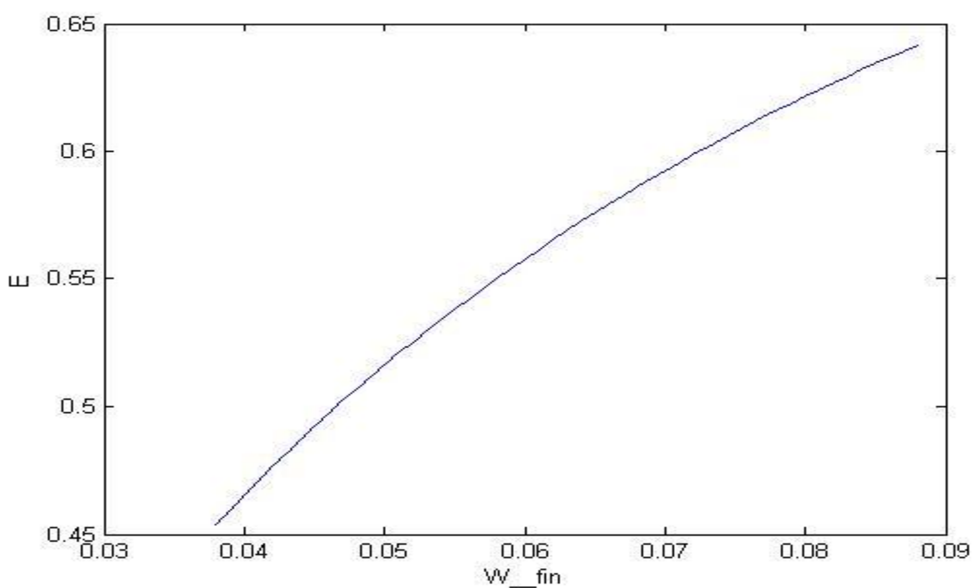


Figure 4.9.2 - E vs. W_fin



3. **Height of Fin:** This graph shows that increasing the height of fin, heat dissipation decreases. The reason is that by increasing height/thickness of fins, the conduction start to take place in fin which is not required. The fin should dissipate heat as soon as possible so that better heat dissipation can be done. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
H_fin =0.0005:0.00005:0.003 (initial value: iteration step: final value)

Figure 4.10.1 - Q_cal vs. H_fin

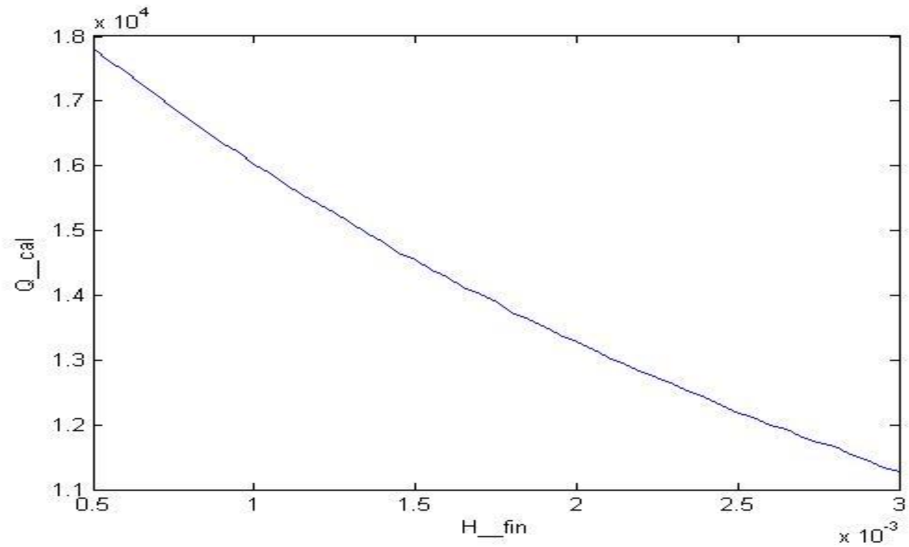
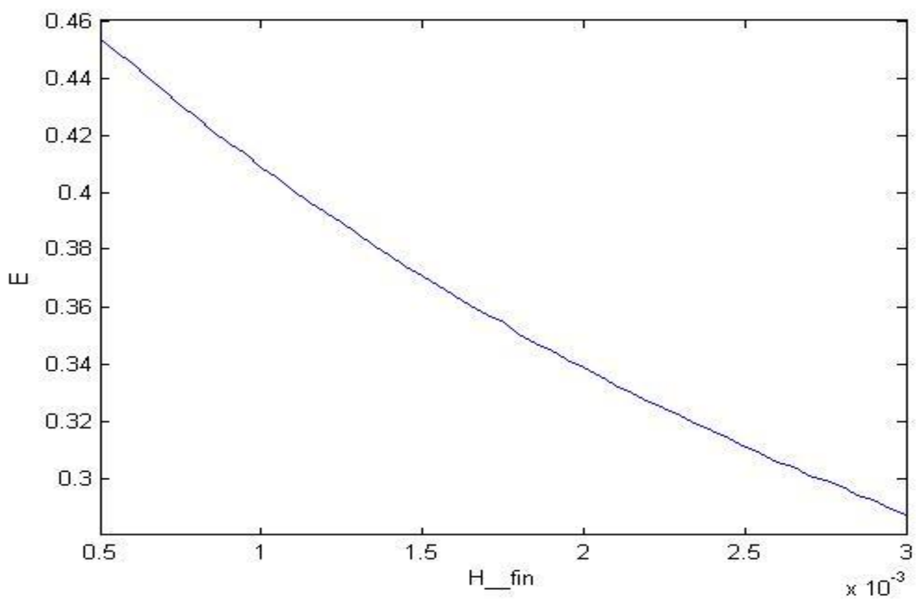


Figure 4.10.2 - E vs. H_fin



4. **Distance between Fins:** As the distance between fins increases, for the same length of tube the number of fins decreases. Hence by decrement in the number of fins, the heat dissipation also decreases. The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.
d_fin = 0.002:0.0001:0.007 (initial value: iteration step: final value)

Figure 4.11.1 - Q_cal vs. d_fin

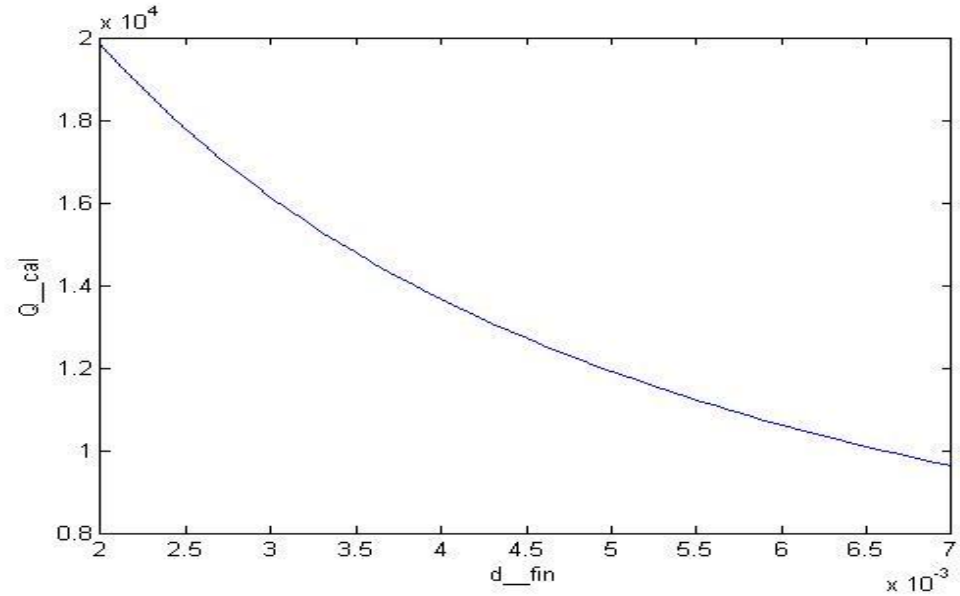
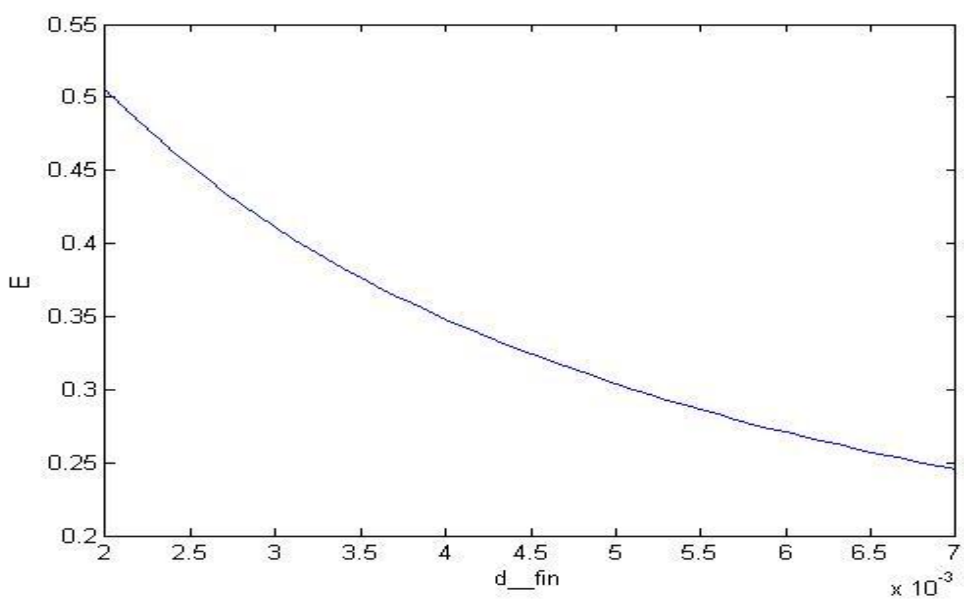


Figure 4.11.2 - E vs. d_fin



4.3 Volume Flow-rates

4.3.1 Air

Here the graph between heat dissipation and Effectiveness show opposite trends. By increasing volume flow rate of air (CFM) the heat dissipation increases. The reason is obvious because as the flow rate increases the air will flow fast across the radiator so the new air will take place of old air and there will be large temperature gradient between the air and water temperature so heat dissipation increases. For Effectiveness, although it is directly proportional to heat dissipated but here another parameter is effected by CFM i.e. Heat Capacity of air (Cp_air). It affects Q_max which has also direct relation with heat dissipation.

1. Q_cal = E *Q_max
2. Q_max = C_min*dT_max
3. C_min = C_air if C_air < C_water (& vice versa)
4. C = m*cp

V_air = 0.47:0.12:1.91(initial value: iteration step: final value)

Figure 4.12.1 - Q_cal vs. V_air

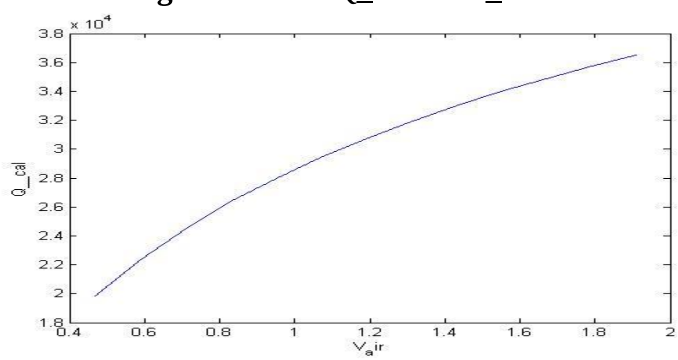
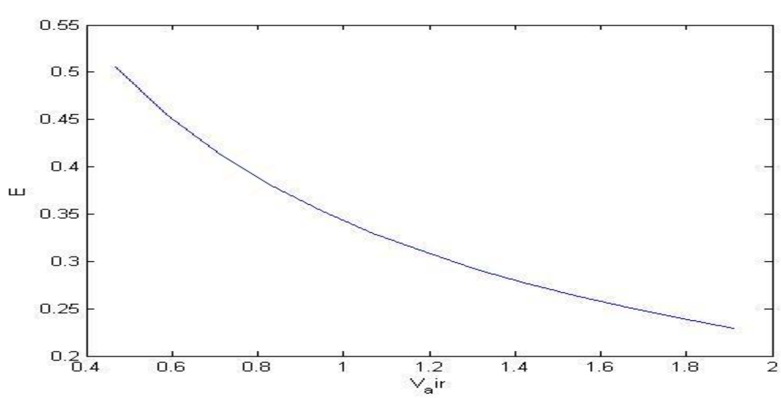


Figure 4.12.2 - E vs. V_air



4.3.2 Water

By increasing water flow rate of water the heat dissipation increases. The reason is that increasing the volume flow rate of water, mass flow rate is increased which in turns increases the heat dissipation as

Q=m*cp*dT

The Effectiveness graph follows the same trend as that of heat dissipation because they are directly proportional to each other.

V_water = 0.0002:0.0001:0.001(initial value: iteration step: final value)

Figure 4.13.1 - Q_cal vs. V_water

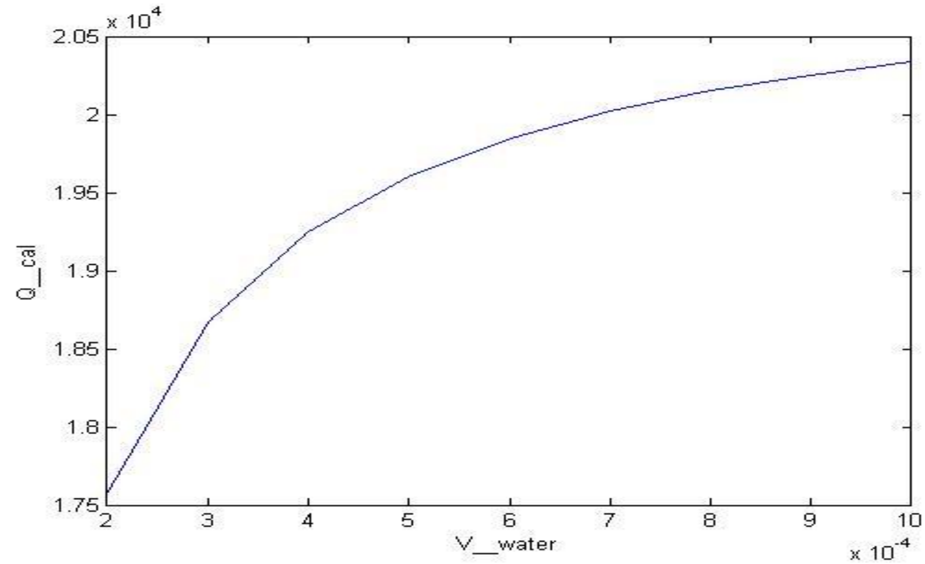
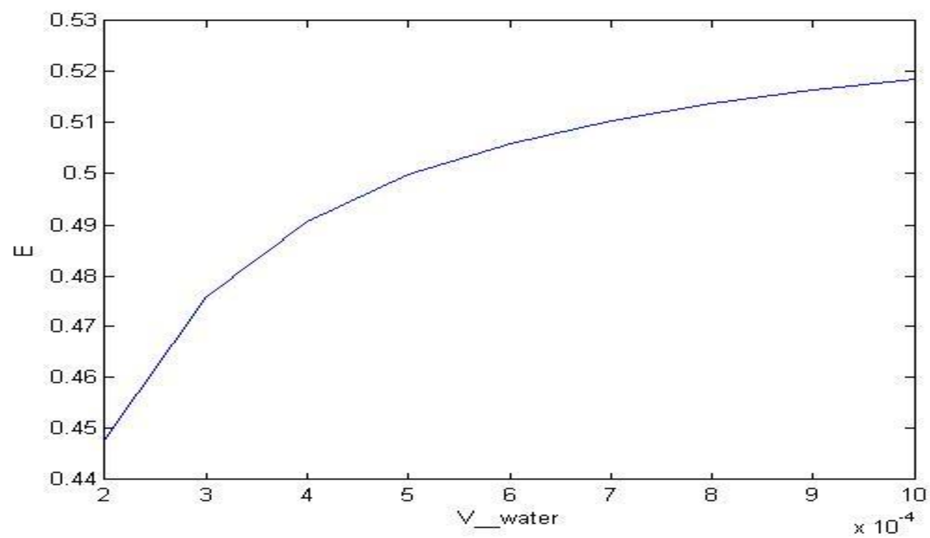


Figure 4.13.2 - E vs. V_water

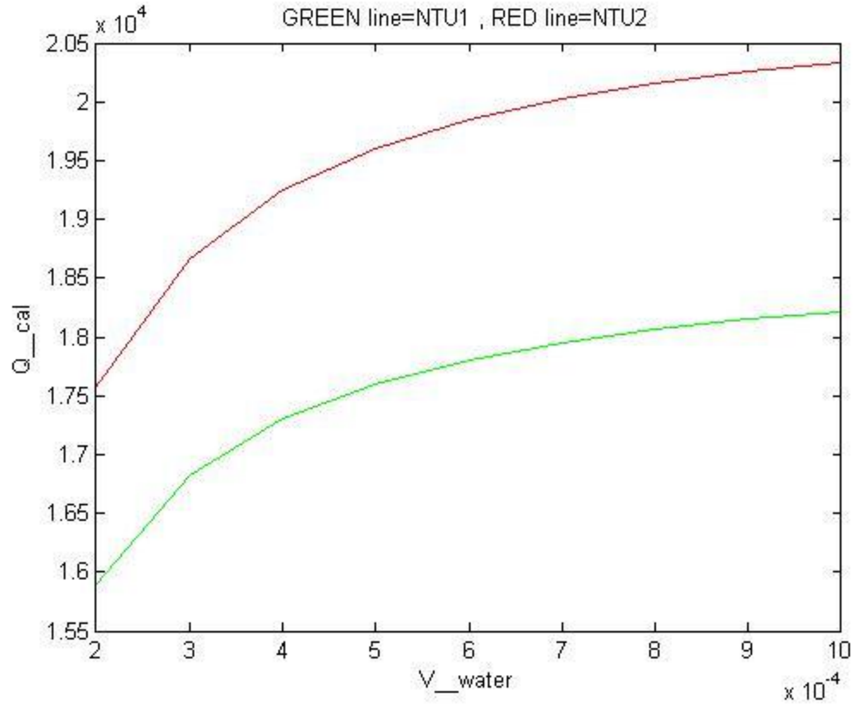


4.4 Comparison of Methods 1 & 2 of Fins

The graph of comparison between Method-1 (NTU 1) and Method-2 (NTU 2) shows that heat dissipation is more for NTU 2 as compared to NTU 1.The reason is that in NTU 2 , fin efficiency is ignored which is incorporated in NTU 1 method.

V_water = 0.0002:0.0001:0.001(initial value: iteration step: final value)

Figure - 4.14 - Fins Methods 1 vs. 2



4.5 Conclusion

By summing up all the results above we can conclude that although the relation between heat dissipation and Effectiveness vs. different physical parameters (length, height, width etc) of radiator/tube/fin seems quite simple, in real the relation between these quantities are quite complicated. The reason is that one cannot simply change one parameter by keeping all the other parameters constant. All the parameters are such interlinked with each other that by changing only one parameter, various other parameters are automatically changed due to which the results are affected and irregularities and errors are introduced.

Hence to do sensitivity analysis, all these considerations should be accounted to get best possible results.

Chapter 5: Experimentation

5.1 Aim

The aim of the experimentation is to provide experimental validation for the mathematical model's results.

5.2 Test Engine

The Test Radiator is available in Tribology Lab, SMME.
Characteristics:
The Test Engine has the following characteristics:

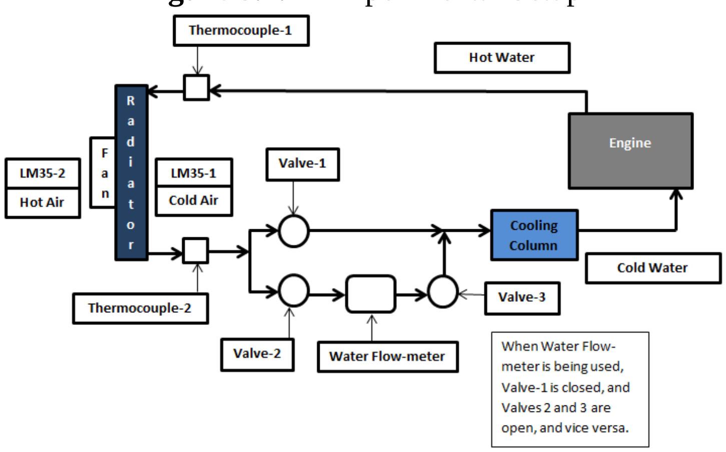
1. Engine type: Diesel
2. Engine Power: 80kW
3. Swept Volume: 5000cc
4. No. of Cylinders: 6
5. Default Cooling System: This engine's default cooling system is a cooling column which receives hot water from the engine, mixes it with cold water (coming from an external cooling tower) and sends the cooled water back to the engine.

5.3 Setup

The Radiator is joined with the Cooling column in series, with the radiator placed first.
A Stand was made for the Radiator by welding Iron strips together; holes were drilled and internally threaded, and the Radiator was clamped on to the Stand.

Water Flow-meter Cut-off Circuit: As the Water flow-meter could not be used at high temperatures, a cut-off circuit was implemented to re-route water flowing through the flow-meter directly to the cooling column.
It consists of three 1-Way Valves for controlling the direction of water flow.

Figure 5.1.1 - Experimental Setup



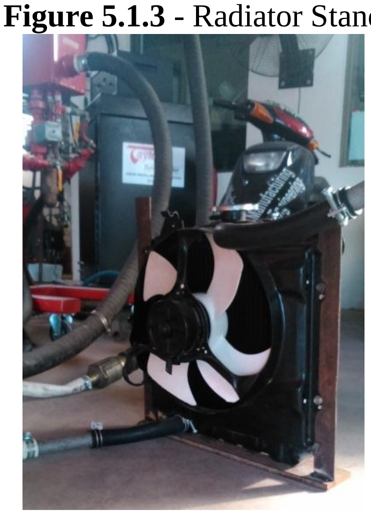
Pipe Reduction Nozzles:

- The default pipes of the test engine's cooling column were much larger than the pipes of radiator (Cooling Column Pipe diameter = 1.5"; Radiator Pipe diameter = 0.75"), so two pipe reduction nozzles (with one wide end and one small end) to attach the radiator pipes with the engine water outlet and the cooling column water inlet.
- The inlet and outlet of Water flow- meter were slightly smaller than the radiator pipes so small pipe reduction nozzles with similar sized pipes were used to connect them (Water Flow-meter inlet diameter = 0.5"; Radiator pipe diameter = 0.75").

Figure 5.1.2 - Pipe Reduction Nozzle

Radiator Stand: A metal stand was made to hold the radiator upright during the experiment. It was made of three iron strips welded together.

Figure 5.1.3 - Radiator Stand



5.4 Instrumentation

5.4.1 Temperatures

- **Water**
  - **Sensor:** K-type Thermocouple
  - **Calibration:** The Thermocouple is calibrated by heating water in a kettle from 40-100^{o}C, and noting the Voltage against Temperature (measured by a Thermometer). (see Appendix C)
  - **Placement:** The Thermocouple is screwed in metal pipe (by drilling a hole and threading it) and sealed with Teflon tape. The metal pipe is then fixed between two rubber pipes with clips.

Figure 5.2.1 - Thermocouple Fixture

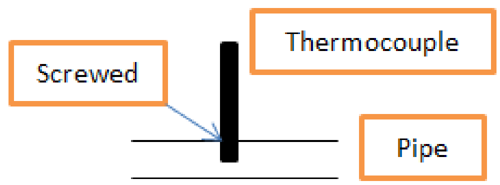
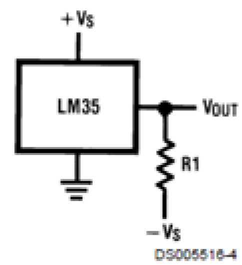


Figure 5.2.2 - Thermocouple in Pipe (1)

Figure 5.2.3 - Thermocouple in Pipe (2)

- **Air**
  - **Sensor:** LM35
  - **Calibration:** The LM35 is calibrated using the standard circuit from the LM35 datasheet using 100 kΩ Resistor. The LM35 gives has the sensitivity of 10mV/^{0}C.
  - **Placement:** 2 LM35 sensors are used by placing one in-front, and the other one behind the Radiator Fan.

Figure 5.3 - LM35 Circuit



(+Vs = 5V, -Vs = 0V, R1 = 100 kΩ)

5.4.2 Flow-rates

- **Water:** The Water Flow-rate can be measured using a Water Flow-meter, which directly measures the flow-rate.
  Advantages
  i. Flow-rate is measured during the main experiment in a closed circuit.
  ii. Losses in pipes are already incorporated.
  Disadvantages: The Water Flow-meter cannot be used at high temperatures.

Figure 5.4 - Water Flow-meter

- **Air:** The Air Flow-rate is measured implicitly by measuring the Heat released by the water and absorbed by the air.

5.5 Equations

Q = m_water * cp_water * (T_water_in – T_water_out)
Q = m_air * cp_air * (Tair_out – Tair_in)

5.6 Experimental Run

The experiment was performed on a cold engine. After 1 minute of the start-up, the water was cut-off from the Water Flow-meter and went directly to the Cooling Column.
The experiment was concluded after 20 minutes of start-up when the Radiator Outlet Temperature reached nearly 65^oC.

5.7 Data

5.7.1 Temperatures

a. **Water:** The voltages from thermocouples were interpolated against the calibrated voltages at 80 & 90^oC (because these values are the closest to the trend-line) to get the required temperatures.

Table 5.1 - Thermocouple Readings

Thermocouple-1 (mV)	T_water_in (^oC)	Thermocouple-2 (mV)	T_water_out (^oC)
1.4	38.1	1.24	36.7
1.55	44.0	1.37	41.1
1.63	46.9	1.45	43.7
1.71	50.1	1.52	46.4
1.79	53.0	1.6	49.0
1.98	60.4	1.76	54.4

b. Air

Table 5.2 - LM35 Readings

LM35-1 (mV)	T_air_in (^oC)	LM35-2 (mV)	T_air_our (^oC)
338	33.8	385	38.5
337	33.7	419	41.9
337	33.7	432	43.2
337	33.7	439	43.9
344	34.4	468	46.8
346	34.6	484	48.4

5.7.2 Flow-rates

a. **Water:** The water flow-rate was measured within 1 minute after starting the cold engine. Due to complications, flow-rate was measured within 30 seconds.
The initial and final positions of the dials of the water flow-meter were noted to measure the volume flow-rate of water.
V_water = 0.01865 m^3/ 30 sec = 6.22E-4 m^3/s = **37.32 Lit/min**
m_water = 0.622 kg/s

b. **Air:** The air flow-rate was found implicitly after measuring the Temperatures, Water flow-rate, and Heat dissipated, using the equations mentioned above.
(see Results)

5.8 Cost Estimate

Table 5.3 - Experiment Cost Estimate

S.No.	Component	No. of Components	Individual Component Price (PKR)	Total Cost (PKR)
1	Mehran Radiator	1	5000	5000
2	Pressure Cap	1	290	290
3	Fan	1	290	290
4	Fan Shield	1	750	750
5	Fan Motor	1	2500	2500
6	Catch-can (Radiator	1	150	150

	Bottle)			
7	Radiator Stand Metal Strips	3	400	400
8	Thermocouple	2	250	500
9	LM35	2	100	200
10	Various Electronics (Wire, Resistors)	Various	20	20
11	Plumbing	Various	1320	1320
12	Various (Transport, Plumbing)	Various	2000	2000
13	Engine Parts	Various	3000	9000
			Total	**22,440**

Chapter 6: Results

6.1 Experimental Results

6.1.1 Equations

1. Q = m_water * cp_water * (T_water_in – T_water_out)
2. Q = m_air * cp_air * (T_air_out – T_air_in)
3. Q_max = C_min*dT_max
4. E = Q / Q_max

6.1.2 Heat Dissipated

Table 6.1 - Heat Dissipated

m_water (kg/s)	cp_water (kJ/kg.K)	C_water (kW/K)	T_water_in (^oC)	T_water_out (^oC)	Q (kW)
0.622	4.180	2.60	38.1	36.7	3.64
0.622	4.180	2.60	44.0	41.1	7.54
0.622	4.180	2.60	46.9	43.7	8.32
0.622	4.180	2.60	50.1	46.4	9.62
0.622	4.180	2.60	53.0	49.0	10.4
0.622	4.180	2.60	60.4	54.4	15.86

6.1.3 Air Flow-rate

Table 6.2 - Air Flow-rate

Q (kW)	cp_air (kJ/kg.K)	T_air_in (^oC)	T_air_out (^oC)	m_air (kg/s)	V_air (m^3/s)	V_air (CFM)	C_air (kW/K)
3.64	1.007	33.8	38.5	0.77	0.64	1280	0.76
7.54	1.007	33.7	41.9	0.91	0.76	1520	0.92
8.32	1.007	33.7	43.2	0.87	0.72	1440	0.88
9.62	1.007	33.7	43.9	0.94	0.78	1560	0.95
10.4	1.007	34.4	46.8	0.83	0.69	1380	0.84
15.86	1.007	34.6	48.4	1.14	0.95	1900	1.15

6.1.4 Effectiveness

Table 6.3 - Experimental Effectiveness

C_min (kW/K)	T_water_in (^oC)	T_air_in (^oC)	dT_max (K)	Q_max (kW)	Q (kW)	E
0.76	38.1	33.8	4.3	3.27	3.64	1.11
0.92	44.0	33.7	10.3	9.48	7.54	0.795
0.88	46.9	33.7	13.2	11.62	8.32	0.716
0.95	50.1	33.7	16.4	15.58	9.62	0.617
0.84	53.0	34.4	18.6	15.62	10.4	0.666
1.15	60.4	34.6	25.8	29.67	15.86	0.534

6.2 Theoretical vs. Experimental Results

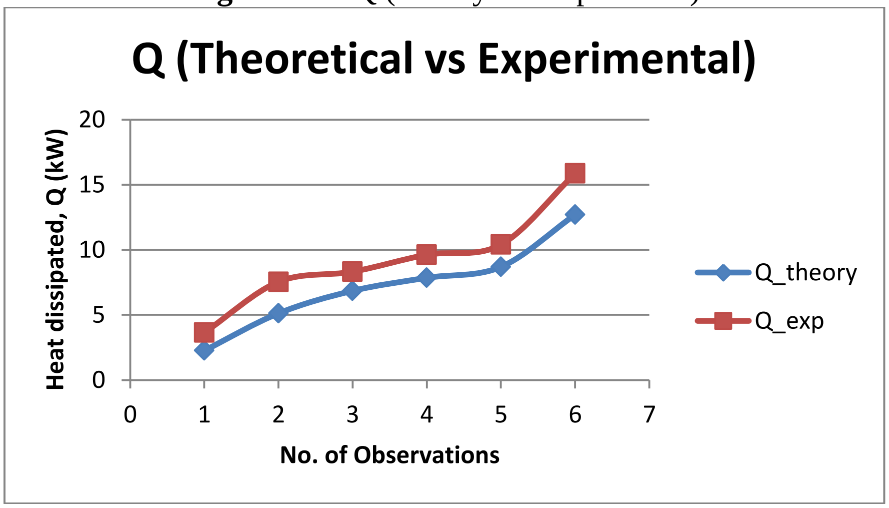
The Temperatures and Flow-rates form the experiment were put into the MATLAB program and run to achieve the theoretical results. These results were then compared with the experimental results.

6.2.1 Heat Dissipated

Table 6.4 - Q (Theory vs. Experiment)

Q_est	(kW)	Error
Theoretical	**Experimental**	**(%)**
2.26	3.64	38
5.12	7.54	32.1
6.85	8.32	17.7
7.85	9.62	18.4
8.69	10.4	16.4
12.7	15.86	20

Figure 6.1 - Q (Theory vs. Experiment)

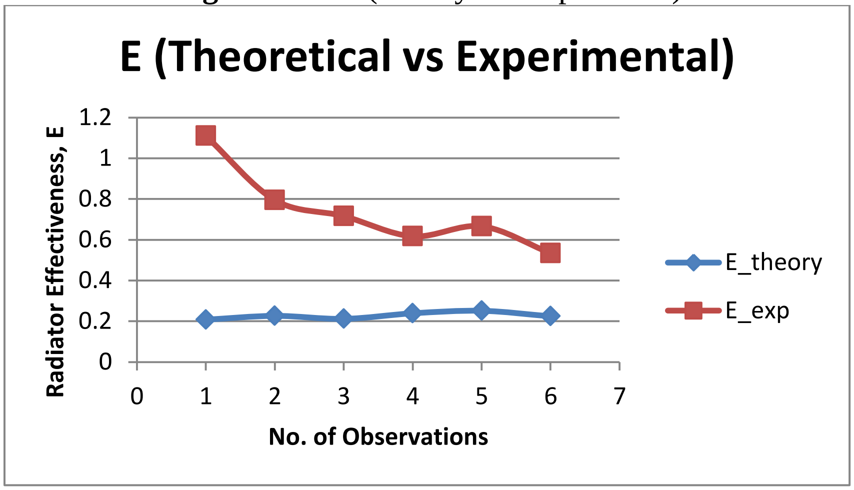


6.2.2 Effectiveness

Table 6.5 - E (Theory vs. Experiment)

E		Error
Theoretical	**Experimental**	**(%)**
0.2077	1.11	82
0.2264	0.795	72
0.2117	0.716	70.4
0.2390	0.617	61
0.2512	0.666	61
0.2241	0.534	58

Figure 6.2 - E (Theory vs. Experiment)



6.2.3 Out-going Temperatures

Table 6.6 - Outgoing Temperatures

T_water_out	(°C)	T_air_out	(°C)
Theoretical	**Experimental**	**Theoretical**	**Experimental**
37.13	36.7	34.62	38.5
42	41.1	36	41.9
44.36	43.7	36.52	43.2
46.97	46.4	37.60	43.9
49.65	49.0	39.07	46.8
55	54.4	40.3	48.4

6.3 Discussion

6.3.1 Error

By comparing the theoretical and experimental values of the Heat dissipated and Effectiveness, we come to know that:

1. Average Error of Heat Dissipated = 23%
2. Average Error of Heat Dissipated = 67.4%

Reasons: The main reasons for this large amount of error are due to:

- System was not stable while taking the readings; as we had limited time to perform our test during which the system was not properly stable.
- We considered Water flow rate as constant, although in practical it was not constant and varies with rpm.
- We did not consider the phenomena of radiation whereas in real it dissipates about 25-30% of the heat.
- Friction losses were not taken into account while performing test although there was friction due to usage of valves and different components like pipes, nozzles etc.
- There were certain leakages in pipe joints and thermocouple joints.
- Thermocouples although calibrated, but gave garbage values at the beginning of the test.

6.3.2 Limitations

There were certain limitations while performing our test due to which we could not reduce the error:

- As we were performing test on high powered engine and its heat dissipation was also very high, we had a limited time to perform our test after which we had to disconnect our system from the engine so that no damage would be done to our system as the temperature goes very high with increasing rpm.
- The Thermocouples used were bought locally so their reliability was also questionable.
- The Water flow-meter used was not able to withstand high temperature so we had to measure the flow at the very beginning for a short time when the temperature was low.

6.3.3 Deductions

By looking into the experimental results and their comparison with the theoretical ones, we can deduce that:

- Although there is an error in values of heat dissipated, the experimental and theoretical values follow the same trend.

- The experimental value of heat dissipation is greater than the theoretical one because in real heat is also dissipated by radiation which is not considered in theoretical method.
- The difference in Effectiveness value at the start of test is due to the instability of the system although it became stable with passage of time.

Chapter 7: Conclusion

7.1 Sensitivity Analysis

By summing up all the results above we can conclude that although the relation between heat dissipation and Effectiveness vs. different physical parameters (length, height, width etc) of radiator/tube/fin seems quite simple, in real the relation between these quantities are quite complicated. The reason is that one cannot simply change one parameter by keeping all the other parameters constant. All the parameters are such interlinked with each other that by changing only one parameter, various other parameters are automatically changed due to which the results are affected and irregularities and errors are introduced.
Hence to do sensitivity analysis, all these considerations should be accounted to get best possible results.

7.2 Error (Theory vs. Experiment)

By comparing the theoretical and experimental values of the Heat dissipated and Effectiveness, we come to know that:

3. Average Error of Heat Dissipated = 23%
4. Average Error of Heat Dissipated = 67.4%

Reasons: The main reasons for this large amount of error are due to:

- System was not stable while taking the readings; as we had limited time to perform our test during which the system was not properly stable.
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- Friction losses were not taken into account while performing test although there was friction due to usage of valves and different components like pipes, nozzles etc.
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- Thermocouples although calibrated, but gave garbage values at the beginning of the test.

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There were certain limitations while performing our test due to which we could not reduce the error:

- As we were performing test on high powered engine and its heat dissipation was also very high, we had a limited time to perform our test after which we had to disconnect our system from the engine so that no damage would be done to our system as the temperature goes very high with increasing rpm.

- The Thermocouples used were bought locally so their reliability was also questionable.
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By looking into the experimental results and their comparison with the theoretical ones, we can deduce that:

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- The experimental value of heat dissipation is greater than the theoretical one because in real heat is also dissipated by radiation which is not considered in theoretical method.
- The difference in Effectiveness value at the start of test is due to the instability of the system although it became stable with passage of time.

7.5 Recommendations

To reduce the error and to get more realistic results following recommendations should be made:

- Increase the number of observations while performing test.
- Instead of taking values of temperatures at discrete points, the readings should be taken after a defined time interval e.g. after 30 seconds or 1 minute.
- The readings should be recorded after ensuring that the system is stable.
- More than one experimental run should be performed.
- Factor of safety (30% to 50%) should be incorporated while doing calculations.
- Reliable instruments should be used.
- Every possible leakage should be plugged and addressed.
- Test engine should be as close as possible to the real one (for which system is to be designed) to get realistic results.
- By introducing a Factor of Safety (30-50%), the theoretical results come closer to the experimental ones.

- CFD (Computational Fluid Dynamics) analysis should be done to get better understanding of the heat transfer and design refinement.
- Mathematical Model should be refined.
- Radiation Heat Transfer and Ram Air effects should be incorporated,

Appendices

Appendix-A: MATLAB Code

```
                         % INPUT DATA
% All values are in SI units
% Air properties (at S.T.P)
clear all
clc

V_air    = 0.47;            % Volume flow rate
p_air    = 1.184;           % Density of air
cp_air   = 1007;            % Specific heat of air
k_air    = 0.0251;          % Thermal conductivity of air
r_air    = 1.562E-5;        % Kinematic viscosity of air
Pr_air   = 0.7296;          % Prandtl number
T_air_in = 298;             % Air inlet temp

% Water properties (at S.T.P)
V_water    = 0.0006;        % Volume flow rate of water
p_water    = 997;           % Density of water
cp_water   = 4180;          % Specific heat of water
k_water    = 0.607;         % Thermal conductivity of water
u_water    = 0.891E-3;      % Dynamic viscosity of water
Pr_water   = 6.14;          % Prandtl number
T_water_in = 368;           % water inlet temp

% Radiator
k_rad = 401;                % Thermal conductivity of Radiator Material
(copper)
disp('Initially:')
L_rad(1)=0.341                  % Outer dimensions
H_rad(1)=0.316
W_rad =0.038 ;

W_tube =0.015 ;             % Tube dimensions
H_tube =0.001 ;

L_tube(1) = H_rad(1);
% For Down-flow Radiator (L_tube= H_rad, for Cross-flow Radiator)
%N_tube(1) =70

L_fin =0.0087;              % Fin dimensions
W_fin =0.038 ;
H_fin =0.0005 ;
d_fin = 0.002;
```

```
 N_tube(1)=2*((L_rad(1)-L_fin)/(H_tube+L_fin));
   N_tube(1)=round(N_tube(1))
   N_fin(1)=2*((L_tube(1)+d_fin)/(H_fin+d_fin));
   N_fin(1)=round(N_fin(1))

% Total engine power
E_Power=75000
FOS=0.5                                   % Factor of Safety
Q_total=E_Power+(E_Power*FOS)
g = 9.18;                                 % Gravitational Acceleration
Q_est  = Q_total/3
                          % CALCULATIONS
% Radiator
y=1;
A_rad(y)  = H_rad(y)*L_rad(y);              % Radiator area
A_tube = W_tube*H_tube;                   % Tube area
P_tube = 2*(W_tube+H_tube);               % Wetted Perimeter of tube

% Water
m_water  = p_water*V_water;                 % Mass flow rate of water
v_water(y)  = V_water/(N_tube(y)*A_tube);              % Velocity of water
Dh_water = (4*A_tube)/P_tube;
 % Hydraulic diameter of pipe containing water
Lc_water = Dh_water;
Re_water(y) = (p_water*v_water(y)*Lc_water)/u_water;
% Reynolds number for water flow

if(Re_water(y)<=2300)                       % Laminar Flow
   z = W_tube/H_tube;
% Ratio of Tube width to Tube height, Assuming Constant Heat Flux

      if (z==1)
        Nu_water(y) = 3.61;
        f(y) = 56.92/Re_water(y);

      elseif(z>1 && z<=2)
        Nu_water(y) = 4.12 - 0.96*(2-z) ;
        f(y) = (62.2 - 5.28*(2-z))/Re_water(y);

      elseif(z>2 && z<=3)
        Nu_water(y) = 4.79 - 0.67*(3-z) ;
        f(y) = (68.36 - 6.16*(3-z))/Re_water(y);

      elseif(z>3 && z<=4)
        Nu_water(y) = 5.33 - 0.54*(4-z) ;
        f(y) = (72.92 - 4.56*(4-z))/Re_water(y);
```

```
        elseif(z>4 && z<=6)
          Nu_water(y) = 6.05 - 0.72*(6-z) ;
          f(y) = (78.8 - 5.88*(6-z))/Re_water(y);

        elseif(z>6 && z<=8)
          Nu_water(y)= 6.49 - 0.44*(8-z) ;
          f(y) = (82.32 - 3.52*(8-z))/Re_water(y);

        elseif(z>8)
          Nu_water(y) = 8.24;
          f(y) = 96/Re_water(y);
       end
elseif(Re_water(y)>2300 && Re_water(y)<5E6)      % Turbulent Flow

    f(y) = (0.79*log(Re_water(y)-1.642))^(-2);
% Friction factor for Smooth Tubes

  Nu_water(y) = ((f/8)*(Re_water(y)-
1000)*Pr_water)/(1+(12.7*((f/8)^0.5))*((Pr_water^(2/3))-1));
end
h_water(y)=(Nu_water(y)*k_water)/Lc_water;
% Heat transfer coefficient for water

h_L(y) = f(y)*(L_tube(y)/Dh_water)*((v_water(y)^2)/(2*g));
% Head Loss

dP (y) = f(y)*(L_tube(y)/Dh_water)*((p_water*(v_water(y)^2))/2);
% Pressure Loss
W_p(y) = m_water*g*h_L(y);                          % Pump Load

% Air
m_air  = p_air*V_air;                      % Mass flow rate of air
v_air(y)  = V_air/(A_rad(y)-(N_tube(y)*H_tube*L_tube));
% Velocity of air
Lc_air = W_tube;
 % Characteristic length

Re_air(y) = (v_air(y)*Lc_air)/r_air;        % Reynold number for air
if(Re_air(y)<5E5)
      Nu_air(y) = 0.664*(Re_air(y)^0.5)*(Pr_air)^(1/3);
    elseif(Re_air(y)>=5E5 && Re_air(y)<1E7)
      Nu_air(y) = 0.037*(Re_air(y)^0.8)*(Pr_air)^(1/3);
    end
h_air(y)=(Nu_air(y)*k_air)/Lc_air;     % Heat transfer coefficient of air
```

```
% Surface area
Ai(y) = 2*(W_tube+H_tube)*L_tube(y)*N_tube(y);
% Total Internal Surface Area
Cf(y)=N_tube(y)+1;                     % No. of column of fins
Ae(y) = ((L_tube(y)/d_fin)*Cf(y))*(2*L_fin)*(d_fin+W_fin) ;
% Total External Surface Area

% Overall heat transfer coefficient
UAs(y) = 1/((1/(h_air(y)*Ae(y))) + (1/(h_water(y)*Ai(y))));

% NTU (Number of Transfer Units)

C_air   = m_air*cp_air;                % Heat capacity of air
C_water = m_water*cp_water;       % Heat capacity of water

if(C_air < C_water)
   C_min = C_air;
   C_max = C_water;
else
   C_min = C_water;
   C_max = C_air;
end
Cr = C_min/C_max;                  % Heat capacity ratio
NTU(y) = UAs(y)/C_min;
% Effectiveness
E(y) = 1-exp(((NTU(y)^0.22)/Cr)*(exp(-Cr*(NTU(y)^0.78))-1))

% Cooling load
Q_est  = Q_total/3                       % Estimated cooling load
dT_max = T_water_in-T_air_in;            % Max temperature difference
Q_max  = C_min*dT_max ;                  % Maximum cooling load
Q_cal(y)  = E(y)*Q_max                    % calculated cooling load

% Temperatures
T_water_out(y) = T_water_in-(Q_cal(y)/C_water);
 % Temperature of water at outlet
T_air_out(y)   = (Q_cal(y)/C_air)+T_air_in;
% Temperure of air at outlet

  % Conclusion
per_diff(y)=((Q_cal(y)-Q_est)/Q_est)*100
% Difference between calculated and estimated

while (Q_cal(y) < Q_est )
   L_rad(2)=L_rad(1);
   H_rad(2)=H_rad(1);
```

```
   L_tube(2)=L_tube(1);
   N_tube(2)=N_tube(1);
   N_fin(2)=N_fin(1);
y=y+1;
A_rad(y)  = H_rad(y)*L_rad(y);                    % Radiator area
A_tube = W_tube*H_tube;                           % Tube area
P_tube = 2*(W_tube+H_tube);           % Wetted Perimeter of tube

% Water
m_water  = p_water*V_water;                    % Mass flow rate of water
v_water(y)  = V_water/(N_tube(y)*A_tube);         % Velocity of water
Dh_water = (4*A_tube)/P_tube;
% Hydraulic diameter of pipe containing water
Lc_water = Dh_water;
Re_water(y) = (p_water*v_water(y)*Lc_water)/u_water;
% Reynolds number for water flow

if(Re_water(y)<=2300)        % Laminar Flow
   z = W_tube/H_tube;
 % Ratio of Tube width to Tube height, Assuming Constant Heat Flux
      if (z==1)
        Nu_water(y) = 3.61;
        f(y) = 56.92/Re_water(y);

      elseif(z>1 && z<=2)
        Nu_water(y) = 4.12 - 0.96*(2-z) ;
        f(y) = (62.2 - 5.28*(2-z))/Re_water(y);

      elseif(z>2 && z<=3)
        Nu_water(y) = 4.79 - 0.67*(3-z) ;
        f(y) = (68.36 - 6.16*(3-z))/Re_water(y);

      elseif(z>3 && z<=4)
        Nu_water(y) = 5.33 - 0.54*(4-z) ;
        f(y) = (72.92 - 4.56*(4-z))/Re_water(y);

      elseif(z>4 && z<=6)
        Nu_water(y) = 6.05 - 0.72*(6-z) ;
        f(y) = (78.8 - 5.88*(6-z))/Re_water(y);

      elseif(z>6 && z<=8)
        Nu_water(y)= 6.49 - 0.44*(8-z) ;
        f(y) = (82.32 - 3.52*(8-z))/Re_water(y);

      elseif(z>8)
        Nu_water(y) = 8.24;
```

```
     f(y) = 96/Re_water(y);
    end

elseif(Re_water(y)>2300 && Re_water(y)<5E6)         % Turbulent Flow
   f(y) = (0.79*log(Re_water(y)-1.642))^(-2);
% Friction factor for Smooth Tubes
   Nu_water(y) = ((f(y)/8)*(Re_water(y)-
1000)*Pr_water)/(1+(12.7*((f(y)/8)^0.5))*((Pr_water^(2/3))-1));
end
h_water(y)=(Nu_water(y)*k_water)/Lc_water;          % Heat transfer
coefficient for water

h_L(y) = f(y)*(L_tube(y)/Dh_water)*((v_water(y)^2)/(2*g));        % Head Loss
dP (y) = f(y)*(L_tube(y)/Dh_water)*((p_water*(v_water(y)^2))/2);
 % Pressure Loss
W_p(y) = m_water*g*h_L(y);                     % Pump Load

% Air
m_air  = p_air*V_air;             % Mass flow rate of air
v_air(y)  = V_air/(A_rad(y)-(N_tube(y)*H_tube*L_tube(y)));
 % Velocity of air
Lc_air = W_tube;               % Characteristic length
Re_air(y) = (v_air(y)*Lc_air)/r_air;      % Reynold number for air
if(Re_air(y)<5E5)
  Nu_air(y) = 0.664*(Re_air(y)^0.5)*(Pr_air)^(1/3);
elseif(Re_air(y)>=5E5 && Re_air(y)<1E7)
  Nu_air(y) = 0.037*(Re_air(y)^0.8)*(Pr_air)^(1/3);
end
h_air(y)=(Nu_air(y)*k_air)/Lc_air;    % Heat transfer coefficient of air

% Surface area
Ai(y) = 2*(W_tube+H_tube)*L_tube(y)*N_tube(y);
  % Total Internal Surface Area
Cf(y)=N_tube(y)+1;      % No of column of fins
Ae(y) = ((L_tube(y)/d_fin)*Cf(y))*(2*L_fin)*(d_fin+W_fin) ;
% Total External Surface Area

% Overall heat transfer coefficient
UAs(y) = 1/((1/(h_air(y)*Ae(y))) + (1/(h_water(y)*Ai(y))));

% NTU (Number of Transfer Units)
C_air   = m_air*cp_air;          % Heat capacity of air
C_water = m_water*cp_water;         % Heat capacity of water

if(C_air < C_water)
   C_min = C_air;
```

```
   C_max = C_water;
else
   C_min = C_water;
   C_max = C_air;
end

Cr = C_min/C_max;                        % Heat capacity ratio
NTU(y) = UAs(y)/C_min;

% Effectiveness
E(y) = 1-exp(((NTU(y)^0.22)/Cr)*(exp(-Cr*(NTU(y)^0.78))-1));

% Cooling load
Q_est  = Q_total/3;                      % Estimated cooling load
dT_max = T_water_in-T_air_in;            % Max temperature difference
Q_max  = C_min*dT_max ;                  % Maximum cooling load
Q_cal(y)  = E(y)*Q_max;                  % calculated cooling load
% Temperatures
T_water_out(y) = T_water_in-(Q_cal(y)/C_water);     % Temperature of water
at outlet
T_air_out(y)   = (Q_cal(y)/C_air)+T_air_in;    % Temperature of air at outlet

 % Conclusion
per_diff(y)=((Q_cal(y)-Q_est)/Q_est)*100;
% Difference between calculated and estimated

if(Q_cal(y) < Q_est)
   L_rad(y+1)=L_rad(y) + 0.005;
   H_rad(y+1)=H_rad(y)+0.005;
   L_tube(y+1)=H_rad(y+1);
   N_tube(y+1)=2*((L_rad(y+1)-L_fin)/(H_tube+L_fin));
   N_tube(y+1)=round(N_tube(y+1));
   N_fin(y+1)=2*((L_tube(y+1)+d_fin)/(H_fin+d_fin));
   N_fin(y+1)=round(N_fin(y+1));
else
   break ;
end
end
t=1;
while (Q_cal(t) > Q_est )
  L_rad(2)=L_rad(1);
   H_rad(2)=H_rad(1);
   L_tube(2)=L_tube(1);
   N_tube(2)=N_tube(1);
   N_fin(2)=N_fin(1);
 t=t+1;
```

```
A_rad(t)  = H_rad(t)*L_rad(t);                    % Radiator area
A_tube = W_tube*H_tube;                           % Tube area
P_tube = 2*(W_tube+H_tube);                      % Wetted Perimeter of tube

% Water
m_water  = p_water*V_water;                        % Mass flow rate of water
v_water(t)  = V_water/(N_tube(t)*A_tube);     % Velocity of water
Dh_water = (4*A_tube)/P_tube;                    % Hydraulic diameter of pipe
containing water
Lc_water = Dh_water;
Re_water(t) = (p_water*v_water(t)*Lc_water)/u_water;
% Reynolds number for water flow
if(Re_water(t)<=2300)          % Laminar Flow
  z = W_tube/H_tube;
 % Ratio of Tube width to Tube height, Assuming Constant Heat Flux
       if (z==1)
         Nu_water(t) = 3.61;
         f(t) = 56.92/Re_water(t);

       elseif(z>1 && z<=2)
         Nu_water(t) = 4.12 - 0.96*(2-z) ;
         f(t) = (62.2 - 5.28*(2-z))/Re_water(t);

       elseif(z>2 && z<=3)
         Nu_water(t) = 4.79 - 0.67*(3-z) ;
         f(t) = (68.36 - 6.16*(3-z))/Re_water(t);

       elseif(z>3 && z<=4)
         Nu_water(t) = 5.33 - 0.54*(4-z) ;
         f(t) = (72.92 - 4.56*(4-z))/Re_water(t);

       elseif(z>4 && z<=6)
         Nu_water(t) = 6.05 - 0.72*(6-z) ;
         f(t) = (78.8 - 5.88*(6-z))/Re_water(t);

       elseif(z>6 && z<=8)
         Nu_water(t)= 6.49 - 0.44*(8-z) ;
         f(t) = (82.32 - 3.52*(8-z))/Re_water(t);

       elseif(z>8)
         Nu_water(t) = 8.24;
         f(t) = 96/Re_water(t);
       end
elseif(Re_water(t)>2300 && Re_water(t)<5E6)       % Turbulent Flow
   f(t) = (0.79*log(Re_water(t)-1.642))^(-2);          % Friction factor for
Smooth Tubes
```

```
   Nu_water(t) = ((f(t)/8)*(Re_water(t)-
1000)*Pr_water)/(1+(12.7*((f(t)/8)^0.5))*((Pr_water^(2/3))-1));
end
h_water(t)=(Nu_water(t)*k_water)/Lc_water;
% Heat transfer coefficient for water

h_L(t) = f(t)*(L_tube(t)/Dh_water)*((v_water(t)^2)/(2*g));
% Head Loss
dP (t) = f(t)*(L_tube(t)/Dh_water)*((p_water*(v_water(t)^2))/2);
% Pressure Loss
W_p(t) = m_water*g*h_L(t);          % Pump Load

% Air
m_air  = p_air*V_air;               % Mass flow rate of air
v_air(t)  = V_air/(A_rad(t)-(N_tube(t)*H_tube*L_tube(t)));
 % Velocity of air
Lc_air = W_tube;    % Characteristic length

Re_air(t) = (v_air(t)*Lc_air)/r_air;        % Reynolds number for air
if(Re_air(t)<5E5)
  Nu_air(t) = 0.664*(Re_air(t)^0.5)*(Pr_air)^(1/3);
elseif(Re_air(t)>=5E5 && Re_air(t)<1E7)
  Nu_air(t) = 0.037*(Re_air(t)^0.8)*(Pr_air)^(1/3);
end
h_air(t)=(Nu_air(t)*k_air)/Lc_air;     % Heat transfer coefficient of air

% Surface area
Ai(t) = 2*(W_tube+H_tube)*L_tube(t)*N_tube(t);
% Total Internal Surface Area

Cf(t)=N_tube(t)+1;                 % No of column of fins
Ae(t) = ((L_tube(t)/d_fin)*Cf(t))*(2*L_fin)*(d_fin+W_fin) ;
% Total External Surface Area

% Overall heat transfer coefficient
UAs(t) = 1/((1/(h_air(t)*Ae(t))) + (1/(h_water(t)*Ai(t))));

% NTU (Number of Transfer Units)
C_air   = m_air*cp_air;                  % Heat capacity of air
C_water = m_water*cp_water;        % Heat capacity of water
if(C_air < C_water)
   C_min = C_air;
   C_max = C_water;
else
   C_min = C_water;
   C_max = C_air;
```

```
end
Cr = C_min/C_max;                          % Heat capacity ratio
NTU(t) = UAs(t)/C_min;

% Effectiveness
E(t) = 1-exp(((NTU(t)^0.22)/Cr)*(exp(-Cr*(NTU(t)^0.78))-1));

% Cooling load
Q_est  = Q_total/3 ;                       % Estimated cooling load
dT_max = T_water_in-T_air_in;   % Max temperature difference
Q_max  = C_min*dT_max ;         % Maximum cooling load
Q_cal(t)  = E(t)*Q_max;         % Calculated cooling load

% Temperatures
T_water_out(t) = T_water_in-(Q_cal(t)/C_water);
% Temperature of water at outlet
T_air_out(t)   = (Q_cal(t)/C_air)+T_air_in;
% Temperure of air at outlet

 % Conclusion
per_diff(t)=((Q_cal(t)-Q_est)/Q_est)*100;
 % Difference between calculated and estimated

if(Q_cal(t) > Q_est)
   L_rad(t+1)=L_rad(t) - 0.005;
   H_rad(t+1)=H_rad(t)- 0.005;
   L_tube(t+1)=H_rad(t+1);
   N_tube(t+1)=2*((L_rad(t+1)-L_fin)/(H_tube+L_fin));
   N_tube(t+1)=round(N_tube(t+1));
   N_fin(t+1)=2*((L_tube(t+1)+d_fin)/(H_fin+d_fin));
   N_fin(t+1)=round(N_fin(t+1));
else
   break ;
end
end
  if(y>1)
 disp('After iterations the results are:')
 disp('L_rad')
 L_rad(y)
 disp('H_rad')
 H_rad(y)
 disp('N_tube')
 N_tube(y)
 disp('N_fin')
 N_fin(y)
 disp('E')
```

```
 E(y)
 disp('Q_cal')
 Q_cal(y)
 disp('per_diff')
 per_diff(y)
 K={'L_rad';'H_rad';'N_tube';'N_fin';'E';'Q_cal';'per_diff'};
  xlswrite('raddata',K,'radiator','A2')
  I={'Initial','Final';L_rad(1) L_rad(y);H_rad(1) H_rad(y);N_tube(1)
N_tube(y);N_fin(1) N_fin(y);E(1) E(y);Q_cal(1) Q_cal(y);per_diff(1)
per_diff(y)};
  s = xlswrite('raddata.xls', I, 'radiator', 'B1')
  elseif(t>1)
 disp('After iterations the results are:')
 disp('L_rad')
 L_rad(t)
 disp('H_rad')
 H_rad(t)
 disp('N_tube')
 N_tube(t)
 disp('N_fin')
 N_fin(t)
 disp('E')
 E(t)
 disp('Q_cal')
 Q_cal(t)
 disp('per_diff')
 per_diff(t)
 K={'L_rad';'H_rad';'N_tube';'N_fin';'E';'Q_cal';'per_diff'};
  xlswrite('raddata',K,'radiator','A2')
  I={'Initial','Final';L_rad(1) L_rad(t);H_rad(1) H_rad(t);N_tube(1)
N_tube(t);N_fin(1) N_fin(t);E(1) E(t);Q_cal(1) Q_cal(t);per_diff(1) per_diff(t)};
  s = xlswrite('raddata.xls', I, 'radiator', 'B1')
  end
```

% Note 1: ‘y’ and ‘t’ are used to read/write the element of matrix . The value of ‘y’ and ‘t’ depends upon number of iterations.

% Note 2: ‘xlswrite’ command is used to write data from MATLAB to Excel file.

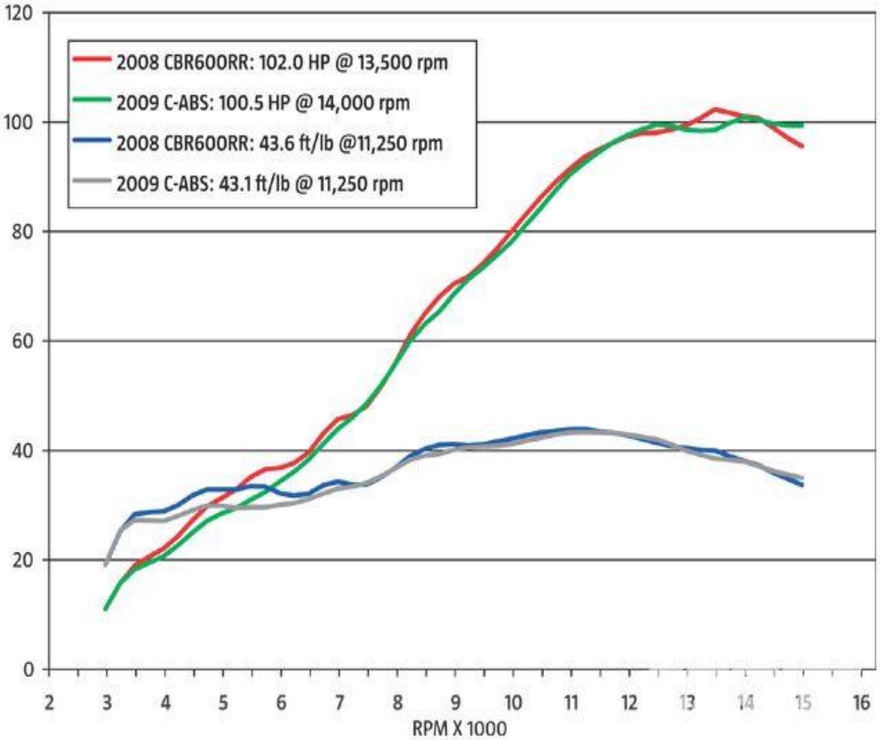
Appendix-B: CBR600rr (Design Engine) 2008 Model Specs.

1. Specifications

Engine Configuration	Inline Four, 4 Stroke
Engine Displacement	599 cc
Engine Cooling System	Liquid
Compression Ratio	12.2:1
Combustion Chamber Design	Pentroof
Valves per Cylinder	4
Intake Valves per Cylinder	2 (Steel)
Exhaust Valves per Cylinder	2 (Steel)
Bore x Stroke	67 x 42.5 mm
Connecting Rod Length (center to center)	91.8 mm
Connecting Rod Material	Steel
Measured Peak Horsepower	102.8 bhp @ 13,900 rpm
Measured Peak Torque	42.61 lbs-ft @ 11,400 rpm
Measured Horsepower to Weight Ratio	3.98 pounds per horsepower
Engine Redline	15,000 rpm
Valve Angle (included)	11.5 degrees intake, 12 degrees exhaust (23.5 degrees)
Combustion Chamber Volume	13.4 cc
Valve Train Type	DOHC, Link-plate Chain Drive, Bucket Followers, Shim-under Buckets Lash Adjustment
Valve Adjustment Interval	16,000 miles
Intake Valve Diameter	27.5 mm
Exhaust Valve Diameter	22 mm
Intake Valve Stem Diameter	4 mm
Exhaust Valve Stem Diameter	4 mm
Intake Valve Maximum Lift	8.3 mm
Exhaust Valve Maximum Lift	7.2 mm
Intake Valve Timing	
Open BTDC	21 degrees
Closed ABDC	45 degrees
Duration	245 degrees
Exhaust Valve Timing	
Open BBDC	40 degrees
Closed ATDC	5 degrees
Duration	225 degrees
Valve Timing Measuring Point	1 mm
Fuel Delivery System	Keihin Fuel Injection
Throttle Body Venturi Size	40 mm

Air Filter Type	Pleated Paper
Exhaust System Type	4-2-1
Ignition System	Digital
Lubrication System	Wet Sump
Oil Capacity	3.6 quarts
Fuel Capacity	4.8 gallons
Transmission Type	6-speed, Constant Mesh
Clutch Type	Multi-plate, Wet
Clutch Actuation System	Cable
Clutch Spring Type	Coil
No. of Clutch Springs	5
No. of Clutch Plates	15
Drive Plates	8
Driven Plates	7
Primary Drive	Gear (Straight Cut)
Primary Drive Gear Teeth (Ratio)	76 / 36 (2.111 : 1)
Final Drive Sprocket Teeth (Ratio)	42 / 16 (2.625 : 1)
Transmission Gear Teeth (Ratios)	
6th	29 / 24 (1.208 : 1)
5th	30 / 23 (1.304 : 1)
4th	26 / 18 (1.444 : 1)
3rd	30 / 18 (1.666 : 1)
2nd	32 / 16 (2.000 : 1)
1st	33 / 12 (2.750 : 1)
Transmission Overall Ratios	
6th	6.693 : 1
5th	7.225 : 1
4th	8.001 : 1
3rd	9.237 : 1
2nd	11.082 : 1
1st	15.238 : 1

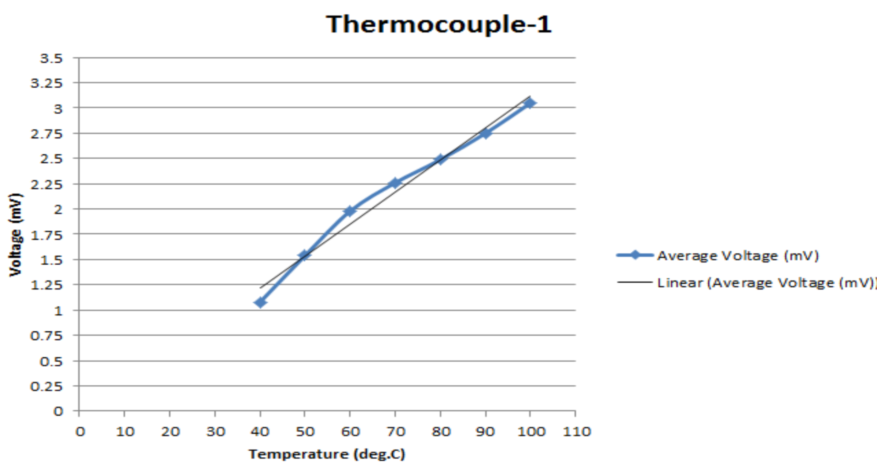
2. Power Curves



Appendix-C: Thermocouples' Calibration Data

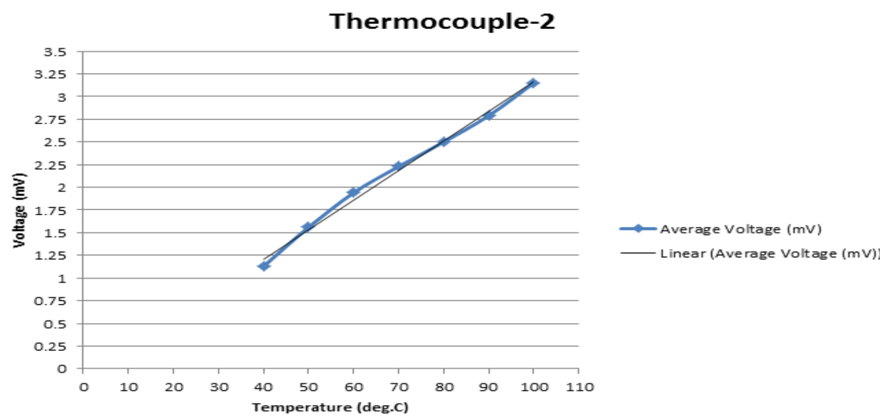
1. Thermocouple-1

Temperature (^oC)	Average Voltage (mV)
40	1.08
50	1.54
60	1.98
70	2.26
80	2.49
90	2.75
100	3.05

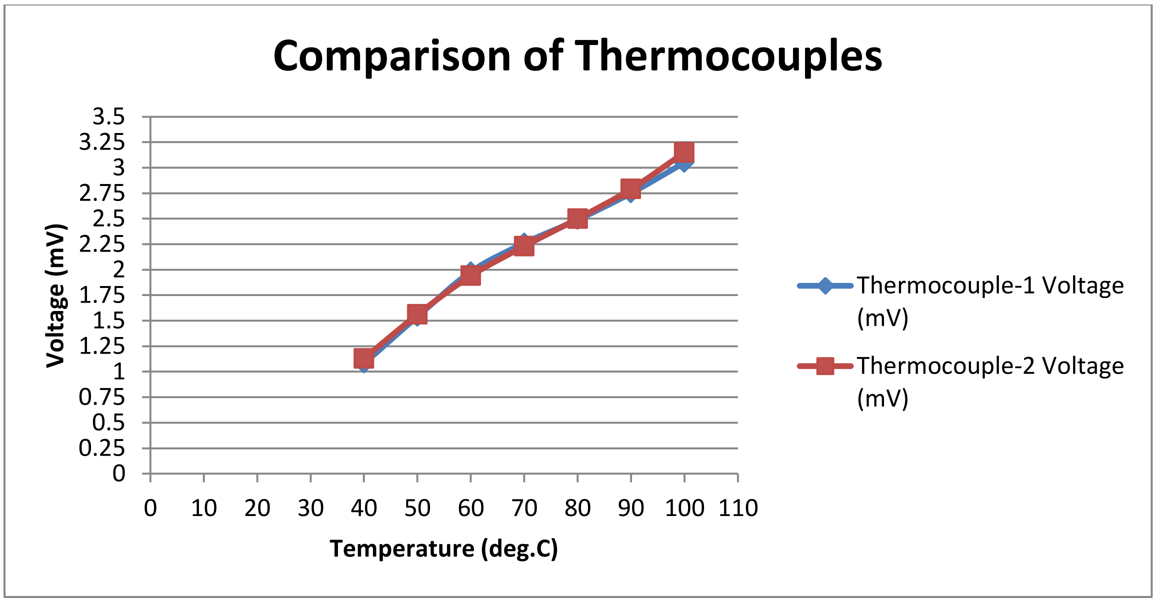


2. Thermocouple-2

Temperature (^oC)	Average Voltage (mV)
40	1.13
50	1.56
60	1.94
70	2.23
80	2.5
90	2.79
100	3.15

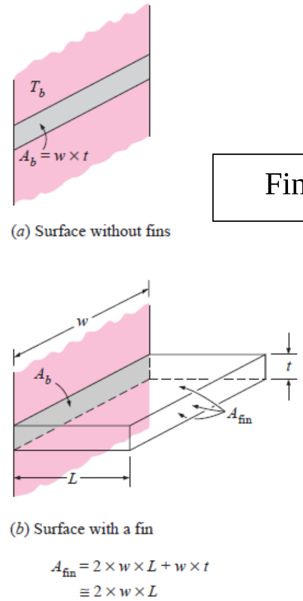


3. Comparison

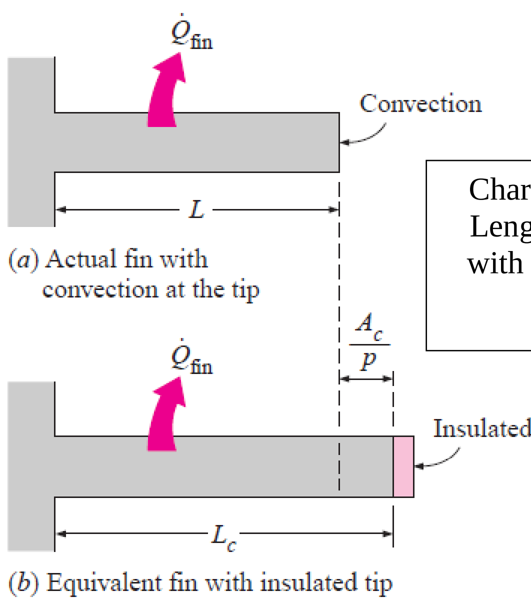


Appendix-D: Miscellaneous Heat Transfer Relations

1. Fins



Finned Area



Characteristic Length of Fin with Insulated Tip

2. Effectiveness of Various Types of Heat Exchangers

TABLE 13–4

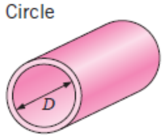
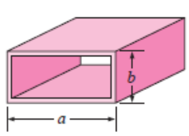
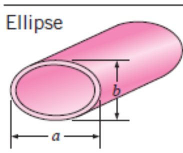
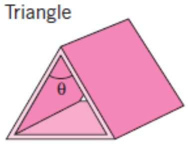
Effectiveness relations for heat exchangers: $\text{NTU} = UA_s/C_{\min}$ and $c = C_{\min}/C_{\max} = (\dot{m}C_p)_{\min}/(\dot{m}C_p)_{\max}$ (Kays and London, Ref. 5.)

Heat exchanger type	Effectiveness relation
1 *Double pipe:*	
Parallel-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1+c)]}{1+c}$
Counter-flow	$\varepsilon = \dfrac{1 - \exp[-\text{NTU}(1-c)]}{1 - c\exp[-\text{NTU}(1-c)]}$
2 *Shell and tube:*	
One-shell pass 2, 4, . . . tube passes	$\varepsilon = 2\left\{1 + c + \sqrt{1+c^2}\,\dfrac{1+\exp[-\text{NTU}\sqrt{1+c^2}]}{1-\exp[-\text{NTU}\sqrt{1+c^2}]}\right\}^{-1}$
3 *Cross-flow (single-pass)*	
Both fluids unmixed	$\varepsilon = 1 - \exp\left\{\dfrac{\text{NTU}^{0.22}}{c}\left[\exp(-c\ \text{NTU}^{0.78}) - 1\right]\right\}$
$C_{\max}$ mixed, $C_{\min}$ unmixed	$\varepsilon = \dfrac{1}{c}(1 - \exp\{1 - c[1 - \exp(-\text{NTU})]\})$
$C_{\min}$ mixed, $C_{\max}$ unmixed	$\varepsilon = 1 - \exp\left\{-\dfrac{1}{c}[1 - \exp(-c\ \text{NTU})]\right\}$
4 *All heat exchangers with* $c = 0$	$\varepsilon = 1 - \exp(-\text{NTU})$

3. Nusselt No. & Friction Factor for Internal Flow

TABLE 8–1

Nusselt number and friction factor for fully developed laminar flow in tubes of various cross sections ($D_h = 4A_c/p$, $\text{Re} = \mathcal{V}_m D_h/\nu$, and $\text{Nu} = hD_h/k$)

Tube Geometry	a/b or θ°	Nusselt Number T_s = Const.	Nusselt Number $\dot{q}_s$ = Const.	Friction Factor f
Circle 	—	3.66	4.36	64.00/Re
Rectangle 	a/b			
	1	2.98	3.61	56.92/Re
	2	3.39	4.12	62.20/Re
	3	3.96	4.79	68.36/Re
	4	4.44	5.33	72.92/Re
	6	5.14	6.05	78.80/Re
	8	5.60	6.49	82.32/Re
	∞	7.54	8.24	96.00/Re
Ellipse 	a/b			
	1	3.66	4.36	64.00/Re
	2	3.74	4.56	67.28/Re
	4	3.79	4.88	72.96/Re
	8	3.72	5.09	76.60/Re
	16	3.65	5.18	78.16/Re
Triangle 	θ			
	10°	1.61	2.45	50.80/Re
	30°	2.26	2.91	52.28/Re
	60°	2.47	3.11	53.32/Re
	90°	2.34	2.98	52.60/Re
	120°	2.00	2.68	50.96/Re

4. Efficiency & Surface Areas of Common Fin Configurations

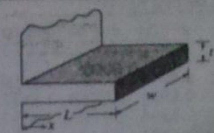
TABLE 3–3

Efficiency and surface areas of common fin configurations

Straight rectangular fins

$m = \sqrt{2h/kt}$
$L_c = L + t/2$
$A_{fin} = 2wL_c$

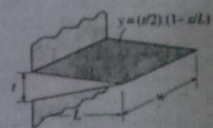
$$\eta_{fin} = \frac{\tanh mL_c}{mL_c}$$



Straight triangular fins

$m = \sqrt{2h/kt}$
$A_{fin} = 2w\sqrt{L^2 + (t/2)^2}$

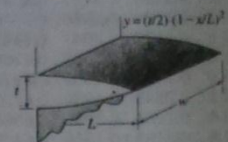
$$\eta_{fin} = \frac{1}{mL}\frac{I_1(2mL)}{I_0(2mL)}$$



Straight parabolic fins

$m = \sqrt{2h/kt}$
$A_{fin} = wL[C_1 + (L/t)\ln(t/L + C_1)]$
$C_1 = \sqrt{1 + (t/L)^2}$

$$\eta_{fin} = \frac{2}{1 + \sqrt{(2mL)^2 + 1}}$$

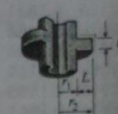


Circular fins of rectangular profile

$m = \sqrt{2h/kt}$
$r_{2c} = r_2 + t/2$
$A_{fin} = 2\pi(r_{2c}^2 - r_1^2)$

$$\eta_{fin} = C_2\frac{K_1(mr_1)I_1(mr_{2c}) - I_1(mr_1)K_1(mr_{2c})}{I_0(mr_1)K_1(mr_{2c}) + K_0(mr_1)I_1(mr_{2c})}$$

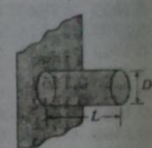
$$C_2 = \frac{2r_1/m}{r_{2c}^2 - r_1^2}$$



Pin fins of rectangular profile

$m = \sqrt{4h/kD}$
$L_c = L + D/4$
$A_{fin} = \pi DL_c$

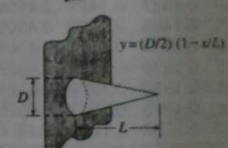
$$\eta_{fin} = \frac{\tanh mL_c}{mL_c}$$



Pin fins of triangular profile

$m = \sqrt{4h/kD}$
$A_{fin} = \frac{\pi D}{2}\sqrt{L^2 + (D/2)^2}$

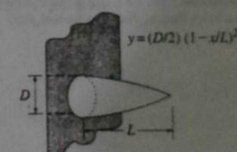
$$\eta_{fin} = \frac{2}{mL}\frac{I_2(2mL)}{I_1(2mL)}$$



Pin fins of parabolic profile

$m = \sqrt{4h/kD}$
$A_{fin} = \frac{\pi L^3}{8D}[C_3C_4 - \frac{L}{2D}\ln(2DC_4/L + C_3)]$
$C_3 = 1 + 2(D/L)^2$
$C_4 = \sqrt{1 + (D/L)^2}$

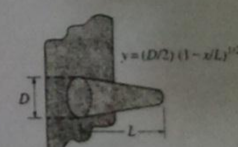
$$\eta_{fin} = \frac{2}{1 + \sqrt{(2mL/3)^2 + 1}}$$



Pin fins of parabolic profile (blunt tip)

$m = \sqrt{4h/kD}$
$A_{fin} = \frac{\pi D^4}{96L^2}\left\{[16(L/D)^2 + 1]^{3/2} - 1\right\}$

$$\eta_{fin} = \frac{3}{2mL}\frac{I_1(4mL/3)}{I_0(4mL/3)}$$



Appendix-E: Test Radiator

1. **Test Engine attached with Cooling Column**

2. **Test Engine attached with Dynamometer**

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