

Design and Thermal Performance Testing of Radiator of High Altitude Engine

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Abstract: Till now there are many interventions have been made in the area of thermal performance enhancement of radiator which is cross flow type of heat exchanger. It is only because the radiator is key component of engine cooling system. These interventions include changes in material, changes in shape, various types of coolants, variations in air velocity and so on. And these interventions improve efficiency of automotive cooling system. Radiator thermal analysis consists of sizing and rating of heat exchanger. The radiator size mainly depends on heat rejection requirement and it leads the importance of heat transfer calculations to optimize radiator size. This paper focuses on theoretical thermal analysis of radiator using Effectiveness-No of transfer Units (ϵ -NTU) method and its validation by experimentation. The theoretical analysis can be validated furthermore with Computational Fluid Dynamics (CFD) based analysis. The designed radiator is used for 65 HP rotary engine of Unmanned Air Vehicle (UAV)

Keywords: Thermal Analysis, Effectiveness, Heat Dissipation, Heat Reception, Effectiveness

I. INTRODUCTION

The key component of automotive cooling system is the radiator. The problem of insufficient heat dissipation rates in automotive radiators has been created because of the demand for more powerful engines in smaller hood spaces. More than 33% of the energy generated by the engine through combustion of fuel is lost in heat^[4]. Overheating of the engine that leads to the improper functioning of lubricating oil, engine parts weakening, and much wear between engines parts can be resulted from insufficient heat dissipation. Therefore to minimize the stress on engine that results of heat generation, automotive radiators must be redesign to be more compact while still maintaining better heat transfer performance^[5].

Coolant surrounding engine passes through radiator. Coolant flown through the radiator gets cooled down and re-circulated into system again and again. Radiator sizing is the important factor while designing cooling system. The radiator size depends mainly on heat load and packaging space availability. Heat load depends on rejection of heat required to keep engine surface at optimum temperature^[7]. Generally, Log Mean Temperature Difference (LMTD) or Effectiveness-No of Transfer Units (ϵ -NTU) methods is used for heat transfer calculations of heat exchanger. Both methods have their own advantages and they can be preferred according to data availability. When radiator inlet and outlet temperatures are known, faster solution can be meeting from LMTD method. When any of the temperature is unknown, more iteration is required to find solution while using LMTD method^[8]. In this case ϵ -NTU method is described for heat transfer calculations because it gives more accurate solution.

As this is the sponsored project, there was requirement to design radiator for 65 HP rotary engine of Unmanned Air Vehicle (UAV). For that we have specifications of engine that are required for radiator and the space available to place the radiator. In this project work, approximate size of radiator has been assumed according to space availability. Based on this size the theoretical calculations have been made by using ϵ -NTU method. Radiator size and heat transfer rate have been finalized accordingly. The

experimentation has been made on experimental set up available is with proper provision for appropriate coolant and air supply, temperature measurement sensors for both coolant and air. And then thermal performance has been validated by experimental testing.

The purposes of doing this project are to Design radiator for 65 HP rotary engine with given specifications of engine and for expected requirements; to provide radiator that will be more efficient and compact; to assess heat rejection performance of designed radiator by experimental testing; and to compare heat dissipation rate by theoretical data and that of by experimental data.

II. EXPERIMENTAL SETUP LAYOUT

To achieve above stated objectives, experimental set up containing space for radiator and required measuring instruments is available at VRDE workshop itself. The heat rejection performance has been investigated by using this experimental setup.

A. Terminology

Coolant side Heat Dissipation Rate: Under test conditions, the heat dissipation rate given as the quantity of heat that water losses under, and is expressed by the unit of Kilograms per second (Kg/s).

Airside Heat Reception Rate: Under test conditions, the heat rate that the cooling air receives and it is expressed by the unit of Kilograms per second (Kg/s).

Inlet temperature difference (ITD): The difference between coolant inlet temperature and air inlet temperature is expressed by the unit of degree Celsius ($^{\circ}\text{C}$).

Coolant Flow Rate: The coolant flow rate that passes through the radiator expressed in meter cube per second (m^3/s).

Frontal Area Air Velocity: The air flow rate that passes through the radiator divided by the frontal area and is expressed in meter per second (m/s).

Coolant side Pressure Loss: The difference of static pressure between the coolant side inlet and outlet that measured at the test conditions and it is expressed by the unit of mercury column height in millimeters (mm Hg).

Airside Pressure Loss: The difference of static pressure between the airside inlet and outlet of the radiator that measured at the test conditions and it is expressed by the unit of water column height in millimeters (mm Aqua).

Upstream End: Before the radiator the area that permits entry of air into the radiator.

Downstream End: After the radiator the area that permits exit of air away from the radiator.

B. Testing and Measuring Arrangement

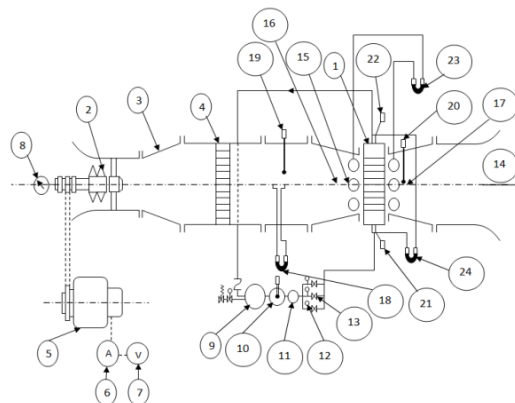


Fig. 1: Line Diagram of Experimental Testing Setup

Fig.1 shows the typical experimental setup. It contains Test Radiator; Fan; Wind Tunnel Body; Rectifying Lattice; Ampere Meter; Shunt Motor; Voltmeter; Speed Counter For Fan; Hot Coolant Tank; Supplementary Hot Coolant Tank; Coolant Pump And Motor; Coolant Flow meter; Coolant Flow Adjusting Valve; Wind Direction; Connecting Tube; Downstream End; Upstream End; Liquid Column Gauge (Water) For Air Flow meter; Thermometer For Inlet Air Temperature; Thermometer For Outlet Air Temperature; Thermometer For Inlet Coolant Temperature; Thermometer For Outlet Coolant Temperature; Liquid Column Gauge (Mercury) For Coolant Side Pressure Loss; Liquid Column Gauge (Water) For Air Side Pressure Loss.

III. HEAT TRANSFER CALCULATIONS

Purpose of thermal analysis of heat exchanger is to determine the heat transfer surface area (sizing) and performance calculations to determine rate of heat transfer (rating). The ϵ -NTU method is based on the concept of effectiveness of heat exchanger. Heat transfer requirement is decided as per engine specifications, operating conditions of engine and vehicle.

Table 1: Requirements for Engine Cooling System

Parameter	Value	Unit
Total Heat Transfer	29	KW
Height	225	Mm
Length	350	Mm
Depth	25	Mm

Table 2: Input Data for Theoretical Calculations

Description	Parameter	Value	Unit
Coolant	Density	1028.55	Kg/m ³
	Specific Heat	3.644	KJ/Kg-K
	Dynamic Viscosity	0.00077	N-s/m ²
	Thermal conductivity	0.37974	W/m-K
	Prandtl no.	7.163	-
Air	Density	1.11	Kg/m ³
	Specific Heat	1.007	KJ/Kg-K
	Dynamic Viscosity	19.8*10 ⁻⁶	N-s/m ²
	Thermal conductivity	28*10 ⁻³	W/m-K
	Prandtl no.	0.7214	-
Tube	Width	1.5	mm
	Thickness	0.06	mm
	Height	25	mm
	Length	225	mm
	Numbers	29	-

Calculations to find out required effectiveness [8]:

i. Heat transfer rate

$$Q = m * C_p * \Delta T \quad (1)$$

ii. Heat capacity rate

$$C_h = m * C_p \quad (2)$$

iii. Heat capacity rate ratio

$$C_r = C_{min} / C_{max} \quad (3)$$

iv. Required effectiveness

$$\varepsilon_{reqd} = [C_h * (T_{h1} - T_{h2})] / [C_{min} * (T_{h1} - T_{c1})] \quad (4)$$

Heat transfer coefficient calculations [8]:

i. Hydraulic diameter

$$D_h = (4 * A_o) / P \quad (5)$$

ii. Mass flow rate per unit area

$$G = m / A_o \quad (6)$$

iii. Reynolds no.

$$Re = (G * D_h) / \mu \quad (7)$$

iv. Nusselt no. for $2300 < Re < 1000$

$$Nu = 0.0265 * Re^{0.8} * Pr^{0.3} \quad (8)$$

v. Heat transfer coefficient

$$h = (Nu * k) / D_h \quad (9)$$

Radiator effectiveness calculations [8]:

i. Number of transfer units

$$NTU = (U_o * A_c) / C_{min} \quad (10)$$

ii. Required Constants

$$A = C_r * NTU^{0.78} \quad (11)$$

$$B = C_r * NTU^{-0.22} \quad (12)$$

$$D = (e^A - 1) / B \quad (13)$$

iii. Calculated radiator effectiveness

$$\varepsilon_{cal} = 1 - e^D \quad (14)$$

If the calculated effectiveness for selected radiator size is greater than that of required effectiveness the design is said to be safe in thermal design point of view.

IV. EXPERIMENTATION

By connecting the radiator and blower with the connecting tube, the air side circuit has been completed. The coolant side circuit of the test apparatus has been connected to the outlet and inlet pipes of the radiator. When radiator has reached the stable conditions with specified air mass flow rate and coolant mass flow rate, the required tests have been conducted.

During experimental testing the following parameters have been measured:

- i. Pressure and humidity at ambient conditions
- ii. Mass flow rate of air and coolant
- iii. Inlet and outlet coolant temperatures
- iv. Inlet and outlet air temperatures
- v. Air velocity

A. Comparison between analytical and experimental results

After calculations all analytical and experimental results are listed in **Table 3** and **Table 4** respectively.

Table 3: Analytical Results

Parameter		Value	Unit
Coolant inlet temperature	T_{h1}	105	$^{\circ}\text{C}$
Coolant outlet temperature	T_{h2}	98.37	$^{\circ}\text{C}$
Air inlet temperature	T_{c1}	45	$^{\circ}\text{C}$
Air outlet temperature	T_{c2}	55.98	$^{\circ}\text{C}$
Heat dissipated by coolant	Q_h	29	KW
Heat received by air	Q_c	29	KW
Required Effectiveness	ϵ_{reqd}	0.1831	-
Calculated Effectiveness	ϵ_{cal}	0.2347	-

Table 4: Experimental Results

Parameter		Value	Unit
Coolant inlet temperature	T_{h1}	101.3	$^{\circ}\text{C}$
Coolant outlet temperature	T_{h2}	94.8	$^{\circ}\text{C}$
Air inlet temperature	T_{c1}	36.8	$^{\circ}\text{C}$
Air outlet temperature	T_{c2}	45	$^{\circ}\text{C}$
Heat dissipated by coolant	Q_h	28.42	KW
Heat received by air	Q_c	21.63	KW
Required Effectiveness	ϵ_{reqd}	0.1623	-
Calculated Effectiveness	ϵ_{cal}	0.2305	-

The above comparison (for reading no 11) shows that both analytical and experimental results for heat dissipation from coolant are closely matched with each other. Thus, theoretical thermal analysis of radiator by using ϵ -NTU method is validated using experimental approach. Size of radiator is fixed from these results and to be used while designing radiator.

B. All Experimental Results

The readings have been taken for eleven coolant inlet temperatures and the variation of heat transfer and effectiveness with increasing coolant inlet temperature is shown in Fig 2.

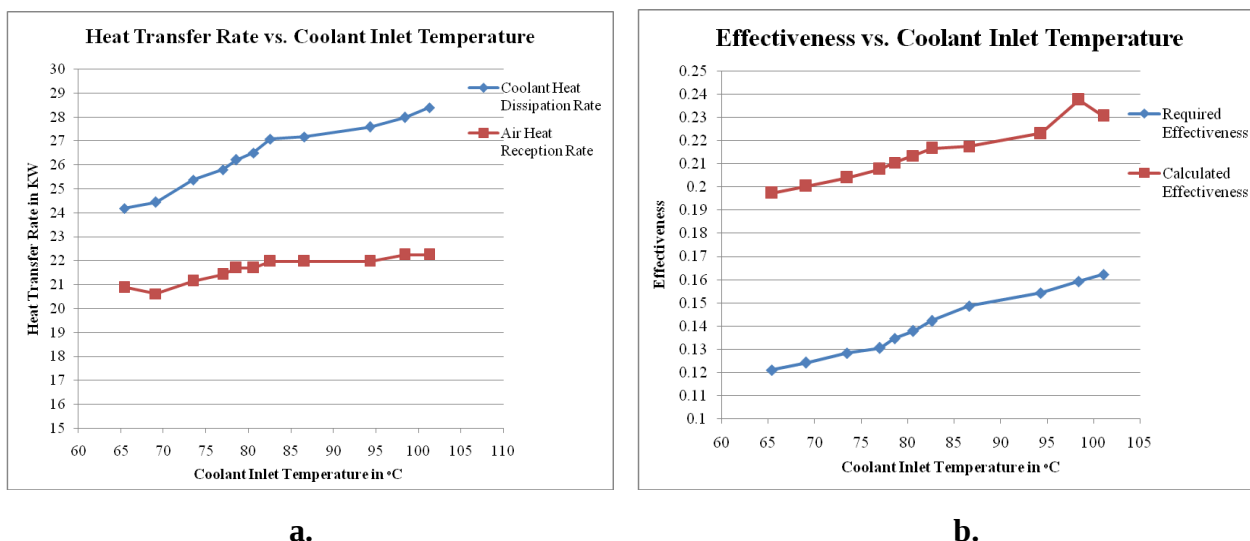


Fig. 2: Experimental Results (a. Heat Transfer Rate vs. Coolant Inlet Temperature, b. Effectiveness vs. Coolant Inlet Temperature)

From Fig. 2 it is observed that the heat dissipation rate as well as effectiveness increases with increasing coolant inlet temperature. But the heat dissipated by coolant is not received by air totally.

Some of the heat is lost while transferring from coolant to air. Out of these heat losses near about 10% to 15% heat losses are due to radiation heat transfer to atmosphere and the remaining are unpredictable heat losses. These losses are increasing with increase in coolant inlet temperature because radiative heat transfer is proportional to wall surface temperature and as the coolant inlet temperature increases wall surface temperature also increases.

C. Effect of coolant inlet temperature on radiator performance parameters

It is found from these results that all radiator performance parameters increase with increasing coolant inlet temperature. But it satisfies the basic requirement i.e. the calculated effectiveness is greater than that of required effectiveness which proves that the design is safe.

Table 5: Variation of Radiator Effectiveness and Cooling Capacity with Coolant Inlet Temperature

Sr. No	Coolant Inlet Temperature in °C	Required Effectiveness (ϵ_{reqd})	Calculated Effectiveness (ϵ_{cal})	Cooling Capacity in KW
1	65.4	0.1211	0.1973	24.212
2	69.1	0.1243	0.2003	24.462
3	73.5	0.1284	0.2039	25.405
4	77	0.1306	0.2077	25.824
5	78.6	0.1348	0.2104	26.236
6	80.6	0.1379	0.2134	26.536
7	82.6	0.1423	0.2166	27.111
8	86.6	0.1487	0.2175	27.205
9	94.3	0.1544	0.2230	27.611
10	98.4	0.1593	0.2300	28.017
11	101.3	0.1623	0.2305	28.391

V. HIGH ALTITUDE ANALYSIS

It is necessary know the performance of the designed radiator at high altitude, the ambient temperature decreases with increase in altitude. Accordingly the thermo physical properties of coolant and air will change considerably. Here, the cooling capacity of the heat exchanger is estimated by up to 4000 meters altitude as ceiling altitude of the UAV is 3600 meters. The variation of radiator performance parameters with altitude is shown in **Table 6** and **Fig. 3** (for reading no 11).

Table 6: Variation of Radiator Performance Parameter with Altitude

Sr. No.	Altitude (m)	Required Effectiveness (ϵ_{reqd})		Calculated Effectiveness (ϵ_{cal})		Heat Load (KW)	
		Analytical	Experimental	Analytical	Experimental	Analytical	Experimental
1	0	0.1832	0.1623	0.2347	0.2305	37.1471	40.3174
2	1000	0.1817	0.1548	0.2471	0.2371	39.4178	43.4953
3	2000	0.1860	0.1736	0.2618	0.2571	40.8138	42.0398
4	3000	0.1876	0.1786	0.2745	0.2696	42.4112	42.8428
5	3600	0.1849	0.1757	0.2843	0.2803	44.5834	45.2997
6	4000	0.1790	0.1729	0.2899	0.2858	46.9582	46.9193

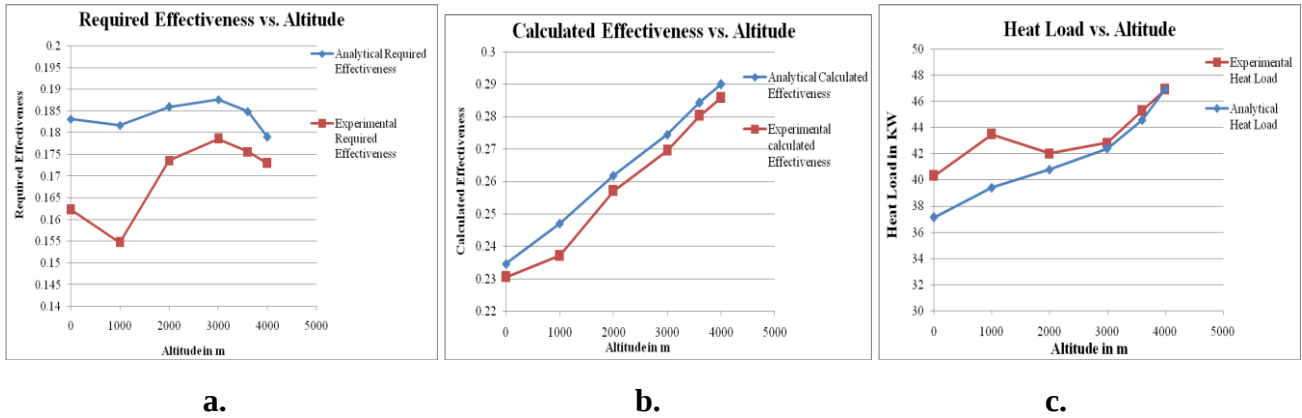


Fig. 3: Variation of Radiator Performance Parameters with Altitude (**a.** Required Effectiveness vs. Altitude, **b.** Calculated Effectiveness vs. Altitude, **c.** Heat Load vs. Altitude)

From **Fig. 3**, it is observed that as the altitude increases the radiator performance parameters also increases but it still shows that the calculated effectiveness is greater than that of required effectiveness. That means the designed radiator will work at high altitude without creating any problem.

VI. CONCLUSION

After completing the study, the following conclusion can be made:

1. The heat transfer rate increases with coolant mass flow rate in the range of 0.5% to 1% per lpm of coolant mass flow rate.
2. There are 16% to 24% heat transfers losses while transferring heat from coolant to air; out of these losses some heat transfer losses are due to radiative heat transfer to atmosphere and remaining heat transfer losses are unpredictable heat transfer losses.
3. As the coolant inlet temperature increases the wall temperature also increases. The radiative heat transfer proportional to wall temperature. Hence the radiative heat transfer losses increases with increase in coolant inlet temperature i.e. wall surface temperature.
4. The main expectation from this project was that the radiator must withstand to transfer maximum 29 KW at 70 lpm coolant mass flow rate. And designed radiator is enabling to transfer 28.3909 KW at 70 lpm coolant mass flow rate.
5. The radiator which is designed for worst condition ambient temperature will work at high altitude without creating any problem.

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