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Design Analysis of Car Radiator in an Engine Cooling System

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Abstract

This paper refers to the design analysis of automotive radiator in engine cooling system. This analysis aims to design the more compact radiator that transfers the equivalent amount of heat of the existing radiator. Both LMTD (Log Mean Temperature Difference) and ϵ -NTU (effectiveness-Number of Transfer Units) methods are commonly used for design and thermal analysis of radiator. In this paper, the design analysis of automotive radiator is described by using ϵ -NTU method. The results obtained from the analysis are presented. Finally, calculated results with actual values have been compared. This calculation can be done using MATLAB software.

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Keywords: Automotive radiator; design analysis; ϵ -NTU method; MATLAB

1. Introduction

Nowadays, several types of internal combustion engines have been invented and widely used in many countries. Most automotive internal combustion engines generate a large amount of heat. An automotive engine requires the cooling system because the burning of air and fuel mixture produces much more heat than the engine can alter into useful power. About one-third of heat created in the engine must be away by the cooling system [5]. Most engine cooling systems consist of the following components: radiator, water pump, cooling fan, radiator pressure cap, and thermostat.

Radiator is the main component of the engine cooling system because it transfers heat. Radiators are heat exchangers used for cooling internal combustion engines, mostly in automobiles but also in piston-engine airplane, railway locomotives, motorcycles, stationary generating plant or any similar use of such an engine [8]. There are five types of heat exchanger. They are: (1) Double-pipe heat exchanger, (2) Shell and tube heat exchanger, (3) Compact heat exchanger, (4) Gasket plate heat exchanger, and (5) Condenser and evaporator.

Automotive radiator is a cross-flow compact heat exchanger with unmixed fluids [1]. It is a type of heat exchanger, transferring heat from the engine to the air passing through it. It consists of three main parts: radiator core, inlet tank and outlet tank. One tank holds hot coolant and the other holds the cooled coolant. Cores are normally comprised of flattened aluminium tubes surrounded by thin aluminium fins [7]. It includes two sets of passages: a set of tubes and a set of fins attached to the tubes (shown in Fig. 1). One set is for coolant and the other for outside air. Coolant flows through the tubes and air flows between the fins.



Fig. 1. Fins and tubes of automotive radiator

2. Types of Engine Cooling Systems

There are two basic types of engine cooling systems: direct or air cooling system and indirect or liquid cooling system.

2.1. Air Cooling System

The air-cooled system is used in tractors of less horsepower, motorcycles, scooters, small aircraft engines where the forward motion of the machine gives good velocity to cool the engine. Air cooled engines is facilitated with metal fins covering the outside of the cylinder head and cylinders which increase the surface area that air can act on. In this system, the heat generated due to combustion in the engine cylinder will be conducted to the fins and when the air flows over the fin, heat will be dissipated to the air.

2.2. Liquid Cooling System

In liquid-cooled systems, water is generally used as a cooling medium. However, other liquids or a mixture of water and other liquids may also be used in the system to prevent freezing of the coolant at lower temperatures [7]. Liquid cooling system is commonly used for cooling automobile internal combustion engines and large industrial facilities such as steam electric power plants, hydroelectric generators, petroleum refineries and chemical plants. In this system, the engine has water jackets that surround the cylinders and combustion chambers. These are cast into the cylinder head and most cylinder blocks. In this system, heat is removed from around the combustion chambers by a heat-absorbing liquid (water/coolant) circulating inside the engine. This liquid is pumped through the engine and, after absorbing the heat of combustion, flows into the radiator where

the heat is transferred to the atmosphere. The cooled liquid is then returned to the engine to repeat the cycle. These systems are designed to keep the engine temperatures within a range where they provide peak performance. Fig. 2 shows the working operation of liquid cooling system for automobile.

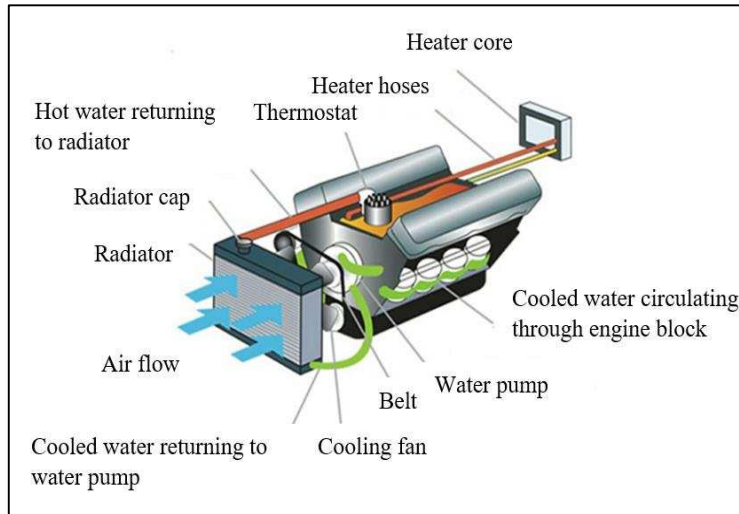


Fig. 2 Components of water cooling system [5]

3. Calculation of Heat Transfer Rate and Outlet Temperature

In this paper, the design data is obtained from 1500 cc petrol engine. These specifications are as follows:

Table 1. Specifications of the Radiator

No.	Descriptions	Symbols	Dimensions
1	Radiator Length	L_r	487.85 mm
2	Radiator Height	H_r	360 mm
3	Radiator Width	W_r	16 mm
4	Tube Length	L_t	2 mm
5	Tube Height	H_t	360 mm
6	Tube Width	W_t	16 mm
7	Fin Length	L_f	8 mm
8	Fin Distance	D_f	1.5 mm
9	Fin Width	W_f	16 mm
10	Number of Tubes	N_t	47

Once the temperature of the coolant give rises to between 82°C and 91°C, the thermostat starts to open, allowing the coolant to flow through the radiator [10]. Therefore the coolant inlet temperature ($T_{c,i}$) is taken from the above limitation. The air inlet temperature ($T_{a,i}$) is obtained from the surrounding temperature.

The thermal fluid properties of coolant at $T_{c,i} = 90^\circ\text{C}$ are shown in Table II. [4, 9]

Table 2. Thermal Fluid Properties of Coolant (Water)

Properties	Values	Units
Thermal conductivity (k_c)	676×10^{-6}	kW/m. K
Specific heat capacity ($C_{p,c}$)	4.208	kJ/kg. K
Density (ρ_c)	965.06	kg/m ³
Dynamic viscosity (μ_c)	311×10^{-6}	kg/m. s

The thermal fluid properties of air at $T_{a,i} = 30^\circ\text{C}$ are described in Table III. [4, 9]

Table 3. Thermal Fluid Properties of Air

Properties	Values	Units
Thermal conductivity (k_a)	2.6482×10^{-5}	kW/m. K
Specific heat capacity ($C_{p,a}$)	1.0050764	kJ/kg. K
Density (ρ_a)	1.165534	kg/m ³
Dynamic viscosity (μ_a)	1.8606×10^{-5}	kg/m. s
Kinematic viscosity (ν_a)	1.5981×10^{-5}	m ² /s

3.1. Assumptions

The heat transfer analysis of automotive radiator is done by considering the following assumptions.

- (1) The cooling system operates under steady-state conditions that are constant coolant flow-rate and fluid temperatures at both inlets.
- (2) Air velocity must be changed for constant the air flow rate with the changing of the radiator height.
- (3) There are no phase changes in the fluid streams flowing through the radiator.
- (4) Pure water is used as a coolant.
- (5) The thermal conductivity of the radiator material is constant.
- (6) Heat conduction in the wall is negligible.

3.2. Calculation of Relevant Heat Transfer Areas

The coolant and air surface areas can be calculated from equations (1) and (4),
Coolant surface area,

$$A_c = N_t \times [2(L_t \times H_r) + 2(W_t \times H_r)] \quad (1)$$

Number of fins per column,

$$N_f = \frac{H_r}{D_f} \quad (2)$$

Total number of air passages,

$$N_{a,p} = \text{Number of column of fins} \times \frac{H_r}{D_f} \quad (3)$$

Air surface area,

$$A_a = N_{a,p} \times [2(L_f \times D_f) + 2(L_f \times W_f)] \quad (4)$$

3.3. Calculation of Heat Transfer Coefficients

For internal flow of coolant,

The hydraulic diameter ($D_{h,c}$) must be used because it is a non-circular cross section. The hydraulic diameter can then be used to calculate the Reynolds number and the convective heat transfer coefficient of coolant.

Hydraulic Diameter,

$$D_{h,c} = \frac{4 A_{\min}}{P} \quad (5)$$

Where, A_{\min} = Flow cross-sectional area (m^2)
 P = Wetted perimeter (m)

Reynolds Number,

$$Re_c = \frac{\rho_c v_c D_{h,c}}{\mu_c} \quad (6)$$

Prandtl Number,

$$Pr_c = \frac{\mu_c c_{p,c}}{k_c} \quad (7)$$

From equation (6), as Re_c for coolant flow in the tube is greater than 10,000, this flow is turbulent. Therefore, the Dittus-Boelter Equation is used to find the Nusselt Number.

Nusselt Number,

$$Nu_c = 0.023 \times Re_c^{0.8} \times Pr_c^n \quad (8)$$

This equation is valid for

$$0.7 \leq Pr_c \leq 160$$

$$Re_c \geq 10,000$$

Then the convective heat transfer coefficient of coolant can be calculated from equation (9),

$$h_c = \frac{Nu_c k_c}{D_{h,c}} \quad (9)$$

Then, the convective heat transfer coefficient of air can be obtained from the heat transfer rate of the current radiator design by using $\epsilon - NTU$ method. The energy rejected to the cooling system of the existing radiator is about 35 % of energy supplied from fuel. The existing radiator is capable of heat transfer rate 29.1333 kW with the vehicle speed of 100 km/hr and fuel consumption of 1/11 Li/km.

3.4. Calculation of Heat Capacity Ratio

The heat capacity rates for coolant and air flows are:

$$C_c = \dot{m}_c \times c_{p,c} \text{ and } C_a = \dot{m}_a \times c_{p,a} \quad (10)$$

Where,

\dot{m}_c, \dot{m}_a = mass flow rates of coolant and air (kg/s)

$C_{p,c}, C_{p,a}$ = the specific heat capacities of coolant and air (kJ/kg. K)

The mass flow rates of coolant and air (\dot{m}_c and \dot{m}_a) can be determined from equation (11),

$$\dot{m}_c = \dot{V}_c \times \rho_c \text{ and } \dot{m}_a = \dot{V}_a \times \rho_a \quad (11)$$

Where,

\dot{V}_c = the volumetric flow rate of coolant (m³/s)

= 0.0014 m³/s)

\dot{V}_a = the volumetric flow rate of air (m³/s)

Then \dot{V}_a becomes,

$$\dot{V}_a = [(L_r \times H_r) - (N_t \times L_t \times H_r)] \times v_a \quad (12)$$

Where,

v_a = air velocity = 5 m/s

The mean velocity of the air referred to the stream section at the radiator face is within 7 to 12 m/sec [2]. The velocity (v_a) can be specified before in designing a radiator. When the heat dissipation rate is calculated, the velocity of the approaching air stream to get the required volumetric flow rate of air is within 4.5 to 5.5 m/s. Therefore, the average air velocity taken from the above range is 5 m/s.

By comparing the values of the heat capacity rates of the two flows, minimum and maximum heat capacity rates (C_{min} and C_{max}) can be obtained.

The heat capacity rate ratio can be determined as:

$$C_r = \frac{C_{min}}{C_{max}} \quad (13)$$

3.5. Calculation of Heat Transfer Rate by using ϵ -NTU Method

Neglecting the sediment factor and thermal resistance in the tubes, the overall heat transfer coefficient can be expressed as in equation:

$$\frac{1}{UA} = \frac{1}{h_c A_c} + \frac{1}{h_a A_a} \quad (14)$$

Where,

UA = the overall conductance (kW/K)

h_c, h_a = the convective heat transfer coefficients of coolant and air (kW/m² K)

A_c, A_a = the coolant and air surface areas (m²)

And the number of heat transfer units can also be expressed as:

$$NTU = \frac{UA}{C_{min}} \quad (15)$$

Considering the values of C_r and NTU calculated from equations (13) and (15), the effectiveness of the radiator based on a cross-flow heat exchanger (both fluids unmixed) can be determined from equation (16):

$$\epsilon = 1 - \exp\left\{\frac{0.22 \cdot NTU}{C_r} [\exp(-C_r \cdot NTU^{0.78}) - 1]\right\} \quad (16)$$

The effectiveness (ϵ), is the ratio between the actual heat transfer rate and the maximum possible heat transfer rate. The effectiveness of the radiator can also be obtained from equation (17),

$$\epsilon = \frac{\text{Actual heat transfer rate}}{\text{Maximum possible heat transfer rate}} = \frac{q}{q_{max}} \quad (17)$$

Therefore, the actual heat transfer rate of the radiator can be calculated by equation (18),

$$q = \epsilon C_{min} (T_{c,i} - T_{a,i}) \quad (18)$$

3.6. Calculation of Outlet Temperatures

The outlet temperatures of coolant and air can be calculated by equations (19) and (20),

$$T_{c,o} = T_{c,i} - \frac{q}{(\dot{m}_c \times c_{p,c})} \quad (19)$$

$$T_{a,o} = T_{a,i} + \frac{q}{(\dot{m}_a \times c_{p,a})} \quad (20)$$

4. Results and Discussion

The new design parameters are the same as the original design, except it is smaller in height and has more fins per column. In this analysis, the design of a new smaller radiator assembly is capable of the same heat dissipation as the existing design.

Table 4 shows the values of the outlet temperatures, the heat transfer rates and the effectiveness of automotive radiator by reducing the height of the existing radiator.

Table 4. Result Data of Automotive Radiator obtained from changing the Radiator Height

H_r (mm)	ϵ	q (kW)	$T_{c,o}$ (K)	$T_{a,o}$ (K)	ΔT_w (K)
360	0.5847	29.1333	358.0257	338.2302	5.1243
340	0.5650	28.1515	358.1984	337.0481	4.9516
320	0.5442	27.1175	358.3803	335.8030	4.7697
300	0.5224	26.0281	358.5719	334.4911	4.5781
280	0.4993	24.8799	358.7739	333.1086	4.3761
260	0.4750	23.6694	358.9868	331.6509	4.1632

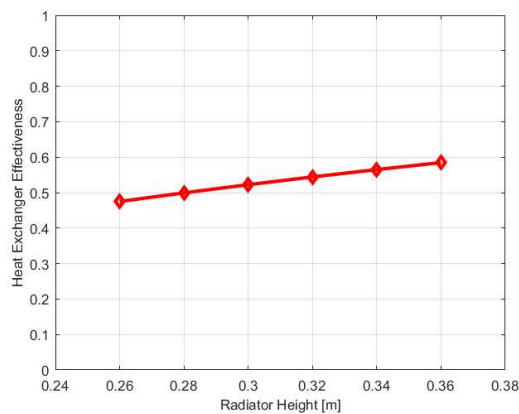


Fig. 3 Variation of the Heat Exchanger Effectiveness with the Height of Automotive Radiator

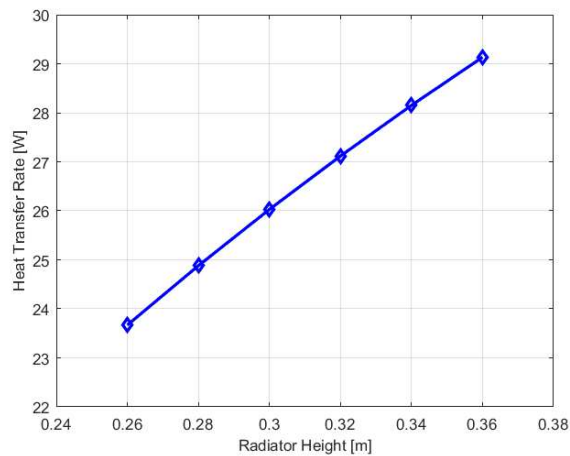


Fig. 4 Variation of heat transfer rate with the height of radiator

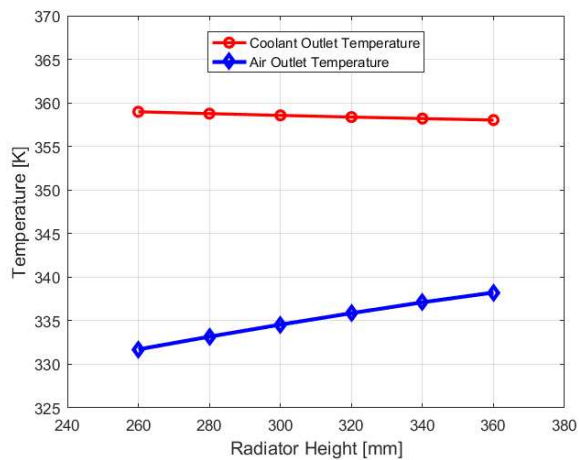


Fig. 5 Variation of Outlet Temperatures with the Height of Automotive Radiator

Fig. 3 shows the variation of heat exchanger effectiveness depends on the radiator height. If the height of the radiator is increased, the heat exchanger effectiveness is increased. Fig. 4 shows the variation of heat transfer rate depending on the radiator height. If the radiator height increases, the heat transfer rate is also increased. If the height of the radiator is reduced nearly 30%, the heat transfer rate also will be reduced almost 19% as shown in Fig. 4. Fig. 5 shows the variation of temperatures with the height of radiator. The height of the radiator increases, the outlet temperatures of air increases. But the coolant outlet temperature is slightly decreased.

To get same heat transfer rate of the existing radiator, the number of fins per column must be changed for the proposed radiator height. Table 5 shows the comparison of the heat transfer rate of the two radiator heights by

changing the number of fins per column. This calculation can be done by changing the number of fins per column using MATLAB software.

Table 5. Variation of the Heat Transfer Rate with the Number of Fins per Column

N_f	q (kW)	
	$H_r = 360$ mm	$H_r = 260$ mm
170	24.5773	23.4256
190	26.0238	24.8331
210	27.3480	26.1180
230	28.5631	27.2942
250	29.6804	28.3736
270	30.7099	29.3665
290	31.6603	30.2822
310	32.5394	31.1283
330	33.3540	31.9119
350	34.1102	32.6390
370	34.8131	33.3150
390	35.4678	34.9446
410	36.0783	34.5320

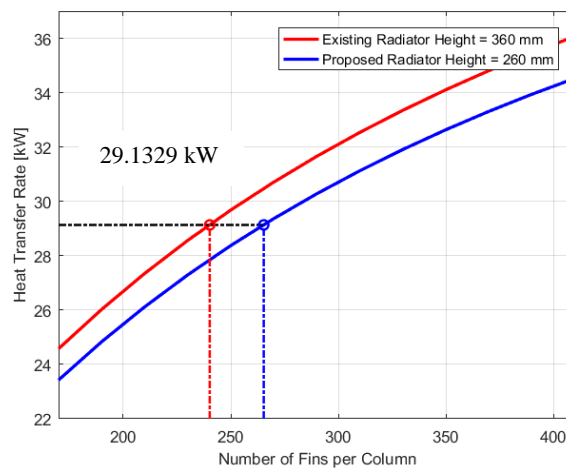


Fig. 6 Variation of the Heat Transfer Rate of the Automotive Radiator by Changing the Number of Fins per Column

Fig. 3 shows the variation of the heat transfer rate of the automotive radiator with the number of fins per column for the height of the existing radiator (360 mm) and the proposed radiator (260 mm). If the number of fins per column is increased, the heat transfer rate of the automotive radiator is also increased in both radiator heights. But the fin distance is decreased. When the height of the existing radiator is reduced from 360 mm to 260 mm without changing the fin distance, the heat transfer rate is also reduced from 29.1333 kW to 23.6694 kW (shown in Fig. 4 and Table 4). To reach the required heat transfer rate (29.1333 kW) of the automotive radiator, the existing number of fins per column is 240 at the radiator height ($H_r = 360$ mm) and the proposed radiator height ($H_r = 260$ mm), the number of fins per column must be 265. Thus, the fin distance is decreased from 1.5 mm to 0.9811 mm.

And then, the comparison between the existing design and the proposed design of automotive radiators are shown in Table 6.

Table 6. Comparison between the Result Parameters of Proposed Design and Existing Design

Parameters	Existing Design	Proposed Design
H_r	360 mm	260 mm
D_f	1.5 mm	0.9811 mm
N_f	240	265

5. Conclusions

An existing radiator size (487.85 mm \times 360 mm \times 16 mm) can produce as a heat transfer rate of 29.1333 kW. If the height of the existing radiator is reduced to 260 mm, the heat transfer rate is also reduced to 23.6694 kW. Although reducing the radiator height, the heat transfer of the existing radiator can be obtained by adding the number of fins per column. By choosing the optimum number of fins, the heat transfer rate of the existing radiator obtained from the observation research.

Subscripts:

r : Radiator

t : Tube

f : Fin

c : Coolant (Water)

a : Air

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