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Performance Enhancement in Automotive Radiators with Different Configurations

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Abstract—*Power requirement in automobiles have increased drastically, with the advent of new technologies. However the space available for cooling systems in vehicles is limited and hence there is a need to improve cooling capacity of modern day radiators. In this paper, use of counter flow heat exchangers have been proposed in vehicle radiators as they are the most effective heat exchangers among all. Furthermore, a theoretical performance analysis is carried out for different configurations of heat exchangers including a cross flow radiator, a counter flow radiator installed at the roof of heavy duty automobiles and a combination of both cross and counter flow heat exchangers (CCFC) used in a single vehicle radiator unit, which is optimised for better performance.*

Present analysis shows that CCFC radiator has 35.61% and 27.44% better cooling capacity than conventional cross flow radiators at a vehicle speed of 40 km/hr and 80 km/hr respectively with mass flow rate of water as 2 kg/s. Also, when the air velocity ratio of counter flow to cross flow radiator is 1.2, CCFC radiator has 28.11% higher cooling capacity than cross flow radiator. The CCFC radiator gives same performance as cross flow radiator by occupying 40.85% less volume, for same mass flow rate of water as well as air which makes them the best radiator in present scenario.

Nomenclature

V	Total Volume of the radiator
A	Total Heat Transfer Area
A_f	Fin area on one side
C	Heat capacity Rate (W/K)
C_p	Specific heat (J/kg-K)
C^*	C_{min}/C_{max}
D_h	Hydraulic Diameter (m)
ΔP	Pressure Drop (Pa)
f_f	Fanning Friction Factor
G	Mass Velocity (kg/m^2s)
H	Water flow length inside HEX (m)
h	Heat Transfer Coefficient (W/m^2 K)
j	Colburn factor
k	Thermal conductivity (W/mK)
L	Fin length for heat conduction
NTU	Number of heat transfer units
Nu	Nusselt number
P	Pumping power
Pr	Prandtl number
Re	Reynolds number
t	Fin thickness
T	Temperature (K)
U	Overall heat transfer coefficient (W/m^2K)
θ	Angle of inclination of Counter flow Heat Exchanger from horizontal
θ_o	Angle of orientation of streamlines near Counter flow heat exchanger
m	Mass flow rate
σ	Minimum free flow area/frontal area
η_f	Fin efficiency
η_o	Total surface temperature effectiveness
μ	Dynamic viscosity (Ns/m^2)
ρ	Density, (kg/m^3)
ε	Heat exchanger effectiveness
α	Total one side of heat transfer area/total volume

<u>Subscripts</u>

Fr	Frontal area
a	Air
f	Fluid
I	Inlet
o	Outlet

1. INTRODUCTION

Improving the heat dissipation systems in automotive engines have been one of the major challenges faced by researchers over time. Ever since the inception of radiators, many methods have been used to improve their heat transfer rate. Earliest approaches used were to use fins to increase the heat exchange surface area between the two fluids leading to better heat transfer. But this method has already been exhausted for improving the radiator [1]. Addition of nanoparticles to the coolant was proposed initially by Choi [2] and then implemented by many others. The use of nanofluids improved the heat transfer coefficient of the cooling system and consecutively lead to better heat exchange.

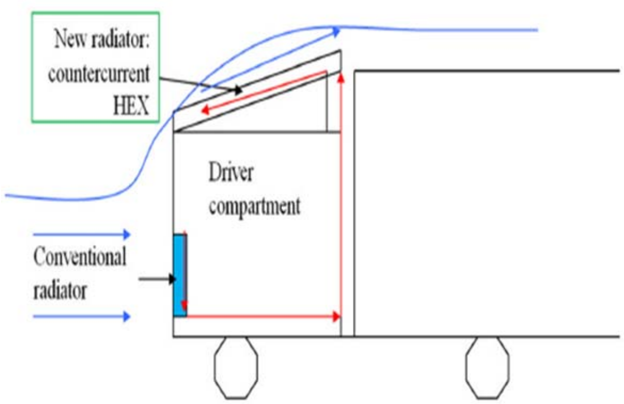

Fig. 1: Arrangement of cross flow and counter flow heat exchangers in a heavy load automobile [5]

Siginer [3] concluded that counter flow heat exchangers lead to higher heat transfer coefficient in comparison to cross flow heat exchangers. However, conventional engines used in practice in automobiles today, consist of cross flow compact heat exchangers to cool the coolant primarily because cross flow heat exchangers have an orientation which allows heat exchanger to take in maximum mass of air. Lin [5] proposed a different arrangement of heat exchanger which consists of a counter flow heat exchanger installed at the top of heavy load automobiles such as trucks and buses. This increases the heat energy lost by the coolant to the air molecules.

This study uses a different approach for heat transfer enhancement. An analysis of different configurations of radiator in an automobile has been carried out and henceforth, compared for better performance. These radiators use different types of heat exchangers (having cross or counter flow mechanisms), installed at different places in the vehicle. Less volume is one of the essential characteristics of a good radiator. So, a comparison between different radiators occupying same volume, has been carried out and their cooling capacity is compared. The better radiator can give the same performance by occupying less volume. All the heat exchangers under consideration of this study have fins to increase the heat exchange surface area. The fins are made of aluminium with thermal conductivity 205 W/m-K at 298 K.

The radiator configurations considered in this study are suitable for heavy load automobiles like trucks and buses. They are as follows-

- *Configuration 1:* Cross flow heat exchanger with both fluids unmixed, installed in the front of the automobile occupying some volume and using water as a coolant.
- *Configuration 2:* Counter flow heat exchanger installed on the roof of the automobile at an angle to the horizontal, parallel to the flow direction of air and using water as a coolant, having same volume as first configuration.
- *Configuration 3:* Combination of both the above systems i.e. a single pass, cross flow Heat Exchanger with both fluids unmixed, installed in the front of the automobile with half the volume and a counter flow heat exchanger installed on the roof of the automobile at an angle parallel to the flow direction of air having the remaining volume.

Fig. 1 above illustrates the position of Heat exchangers used in the above three configurations. In the last configuration, known as Cross and Counterflow Combination (CCFC) radiator, coolant is processed first through cross flow radiator, it then passes through the red flow directions as shown in Fig. 1 and it is then cooled through Counter Flow Heat exchanger at rooftop.

2. MATHEMATICAL FORMULATION

Mathematical formulae taken to compare different arrangement of radiators have been taken from references [5] and [6]. Both air side and coolant side calculations have been done with MATLAB software. On the basis of these calculations overall heat transfer coefficient, NTU, effectiveness and cooling capacity have been calculated for each configuration and there performance is validated with those of Lin [5].

The input data used for comparing different radiators are taken from Table 1 and Table 2. Cross flow or Counter Flow Heat exchangers used in any configuration have some common characteristics as mentioned in table 1. Characteristics specific to any particular configuration are listed down in Table 2. All heat exchangers use louver fins.

2.1 Air side calculation

i) Heat capacity rate C_a is calculated as-

$$C_a = m_a C_{p,a} \tag{1}$$

ii) Mass velocity and subsequently Reynold's Number is found out using the relation

$$G_a = \frac{m_a}{A_{fr,a}\sigma_a} \tag{2}$$

$$Re_a = \frac{G_a D_{h,a}}{\mu_a} \quad (3)$$

Table 1: Characteristics of Cross Flow/ Counter Flow Heat Exchanger used in any of the configurations

S. No.	Description	Cross flow Heat Exchanger		Counter Flow Heat Exchanger	
		Air Side	Coolant Side	Air Side	Coolant Side
1	Fin Pitch	4.46 fins/cm		4.32 fins/cm	
2	Fin Thickness	0.1mm		0.1mm	
3	Hydraulic Diameter	0.003663 m	0.004226m	0.004044m	0.003114m
4	Free Flow Area/Frontal Area	0.786	0.8	0.8094	0.8
5	Heat Transfer Area / Total Volume	1030.288m^2/m^3	132.7 m^2/m^3	938.93m^2/m^3	72.67 m^2/m^3
6	Fin Area/ Total Area	0.8712		0.9237	

iii) Colburn factor for louver fin and Prandtl Number for air is calculated using

$$j_a = \frac{0.26712}{Re_a^{0.1944}}\left(\frac{L_a}{90}\right)^{0.257}\left(\frac{F_P}{L_p}\right)^{-0.5177}\left(\frac{F_h}{L_p}\right)^{-1.9045} * \left(\frac{L_h}{L_p}\right)^{1.7159}\left(\frac{L_d}{L_p}\right)^{-0.2147}\left(\frac{t}{L_p}\right)^{-0.05} \quad (4)$$

$$Pr_a = \frac{C_{p,a}\mu_a}{k_a} \quad (5)$$

iv) Heat transfer coefficient is found using Colburn factor and Prandtl Number as-

$$h_a = \frac{j_a G_a C_{p,a}}{Pr_a^{2/3}} \quad (6)$$

v) Fin efficiency of louver fin is found out using,

$$\eta_f = \frac{\tanh wl}{wl} \quad (7)$$

Where, $w = \sqrt{\frac{2h_a}{k_a t}}$ (8)

2.2 Coolant Side Calculation

i) Heat capacity rate C_f is calculated as

$$C_f = m_f C_{p,f} \quad (9)$$

ii) Mass velocity and Reynold's number are found out from mass flow rate as-

$$G_f = \frac{m_f}{A_{fr,f}\sigma_f} \quad (10)$$

$$Re_f = \frac{G_f D_{h,f}}{\mu_f} \quad (11)$$

iii) The Prandtl number of water is calculated as-

$$Pr_f = \frac{C_{p,f}\mu_f}{k_f} \quad (12)$$

iv) Nusselt number for the coolant is calculated from Reynold's Number as

$$Nu_f = 0.023 Re_f^{0.8} Pr_f^{0.3} \quad (13)$$

v) Heat transfer coefficient of fluid is calculated using Nusselt number through the equation-

$$h_f = \frac{Nu_f k_f}{D_{h,f}} \quad (14)$$

2.3 Performance Analysis

To predict the heat exchange rate between air and water and the temperature change of the fluids, effectiveness-NTU method is applied.

Table 2: Specific characteristics of the three radiator configurations

	Configuration I (Cross flow Radiator)	Configuration II (Counter Flow Radiator)	Configuration III (CCFC Radiator)	
			Cross flow Heat Exchanger	Counter Flow Heat Exchanger
Core Dimensions	0.8m*0.14m*0.5m	0.8m*0.2m*0.35m	0.8m*0.07m*0.5m	0.8m*0.1m*0.35m
No. of Tubes	1215 (81 across length * 15 layers across width)	1326 (51 across length *26 layers across height)	648 (81 across length * 8 layers across width)	1326 (51 across length * 26 layers across height)

In general, the effectiveness of a counter flow heat exchanger is better than a cross flow heat exchanger, which is the primary reason to introduce them in automobile radiators.

i) Overall heat transfer coefficient is calculated after neglecting fouling factor and the wall resistance using the relation

$$\frac{1}{U_a} = \frac{1}{\eta_o h_a} + \frac{1}{(\frac{\alpha_f}{\alpha_a})h_f} \quad (15)$$

NTU is calculated from overall heat transfer coefficient as-

$$NTU = \frac{U_a A}{C_{min}}$$

ii) Effectiveness of a single pass cross flow heat exchanger with both fluids unmixed is given as

$$\varepsilon = 1 - \exp[\frac{NTU}{C^*}\{\exp(-C^* NTU^{0.78}) - 1\}] \quad (16)$$

For a counter flow heat exchanger, the effectiveness is,

$$\varepsilon = \frac{1-\exp(-NTU(1-C^*))}{1-C^*\exp(-NTU(1-C^*))} \quad (17)$$

iii) Total heat transfer rate is then calculated from effectiveness as

$$Q = \varepsilon C_{min}(T_{f,in} - T_{a,in}) \quad (18)$$

iv) Fanning friction factor and pressure drop of a heat exchanger is given as,

$$\Delta P = \frac{G_f^2 f_f H}{2\rho_f(\frac{D_{h,f}}{4})} \quad (19)$$

$$f_f = \frac{0.079}{Re^{0.25}} \quad (20)$$

v) Pumping power is calculated from pressure drop ΔP as

$$P = V_f(\Delta P) \quad (21)$$

3. RESULTS AND DISCUSSIONS

3.1 Influence of speed of air (vehicle) on relative performance of different configuration of radiators

After optimising the counter flow heat exchanger for maximum cooling capacity, different configurations of radiators have been compared at mass flow rate of fluid of 2 kg/s. Heavy vehicles usually runs between 20 km/hr and 80 km/hr depending upon the traffic conditions. Due to change in the speed of the vehicle, the mass flow rate of air also changes in both counter flow and cross flow heat exchangers. As a result, with increase in vehicle speed, heat capacity rate, mass velocity and Reynold's number increases with slight decrease in Colburn factor, due to which the heat transfer coefficient of air increases and it also leads to increase in the overall heat transfer coefficient which also results in increase in cooling capacity.

The cooling capacity increases by different rates for different configurations as shown in Fig. 2. CCFC radiators dissipate maximum heat, for all vehicle speeds whereas the counter flow radiator dissipates the minimum. For example, At 11.11 m/s, cross flow heat exchanger dissipates 123.36 KW of heat whereas CCFC dissipates 167.29 KW of heat, which leads to an improvement of 43.93 KW of cooling capacity.

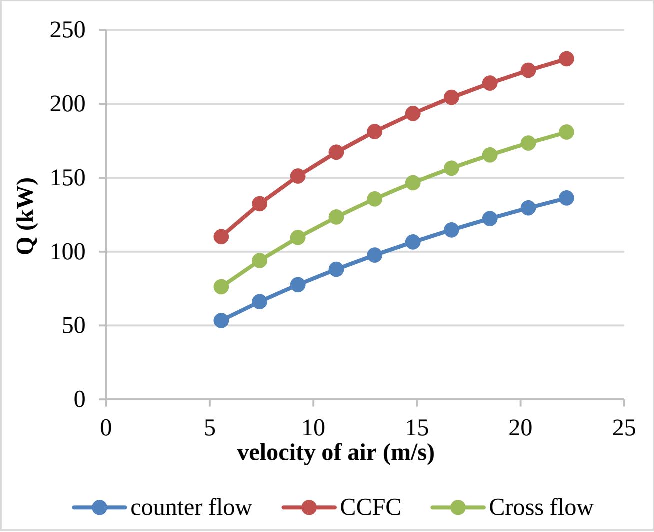

Fig. 2: Effect of velocity of vehicle on cooling capacity of radiator

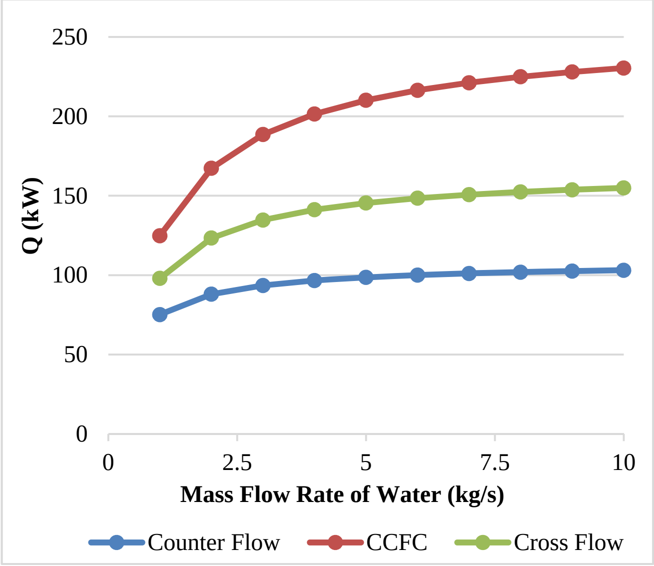

Fig. 3: Effect of mass flow rate of coolant on cooling capacity of radiator

3.2 Influence of mass flow rate of coolant on relative performance of radiators, keeping speed of air constant

Mass flow rate of water is another important factor for cooling capacity of an engine. On increasing the mass flow rate of coolant, mass velocity increases and increase in mass velocity also leads to increase in Reynold's number and hence Nusselt's number. Increase in Nusselt's number leads to increase in heat transfer coefficient of air, which triggers an improvement in overall heat transfer coefficient and therefore cooling capacity of radiator as shown in Fig. 3. At mass flow rate of water between 2 kg/s and 4 kg/s which is the engine operating range, the cooling capacity of CCFC radiators turns out to be better than other radiator configurations.

3.3 Influence of mass flow rate of coolant on Pumping Power for different configurations of radiator

Pressure drop through pipes in a heat exchanger should be as low as possible, as it demands power from pump to maintain the coolant flow in the radiator. The pumping power required for cross and counter flow combination (CCFC), is more than the other two basic configurations, for all values of mass flow rate of fluid. In fact the difference between the required pumping power in CCFC and other two configurations, increase with increase in mass flow rate of fluid. However, for practical uses, the amount of fluid required to be cooled for an engine is roughly 2-4 kg/s. From Fig. 4, it is clear that in this range, for all configurations, the pumping power required is less than 3 KW which is quite less in comparison to the net engine power of trucks and buses. Hence higher pumping power for CCFC is not a big disadvantage for it compared to the improvement in radiator it provides.

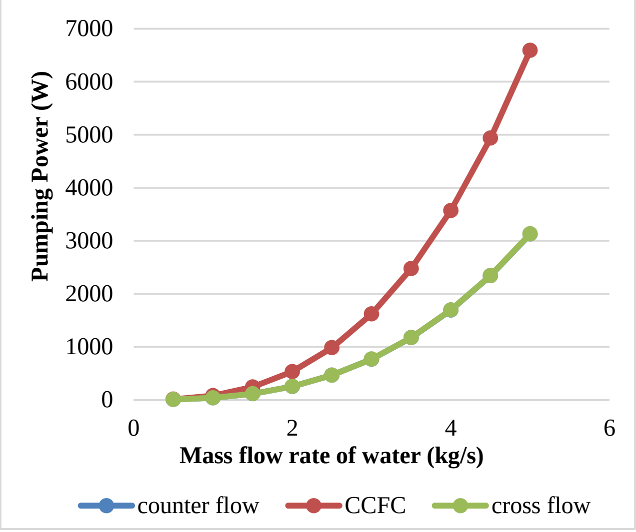

Fig. 4: Effect of mass flow rate of coolant on pumping power

3.4 Effect of ratio of input air velocities of counter flow and cross flow configurations on cooling capacity of radiator

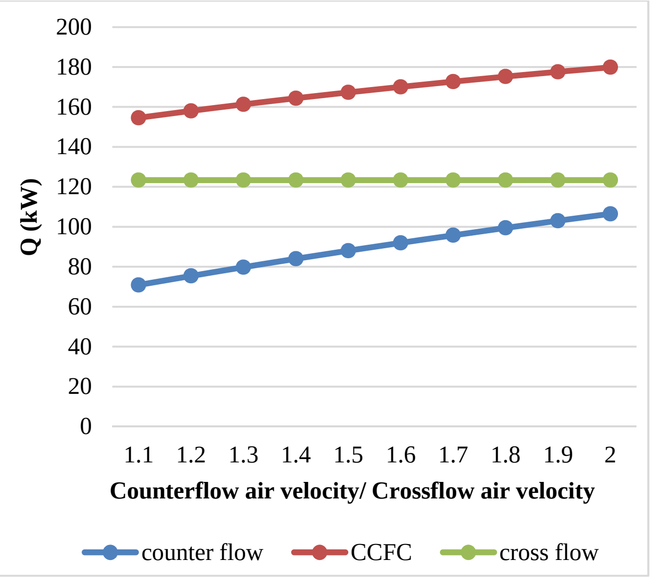

Fig. 5: Effect of ratio of counter flow air velocity/cross flow air velocity on cooling capacity of different radiators

The velocity of air near the roof of vehicle is more than that at the hood (where the cross flow heat exchanger is placed). The velocity of air near the roof is expressed as a multiple of the velocity of air near the hood with a multiplying factor between 1 and 2, depending on the shape of automobile. In this section, the cooling capacity of different configurations of radiators are compared by keeping speed of vehicle, input velocity of air at hood and mass flow rate of water fixed and varying the ratio of input air velocities between counter flow and cross flow heat exchangers.

As the ratio between the air velocity changes, there is no effect on cooling performance of cross flow radiators because they don't have a counter flow heat exchanger, and the input air velocity of cross flow heat exchanger remains fixed. However, the heat transfer rate of other configurations containing counter flow heat exchanger improves as the ratio increases. From Fig. 5 above it is evident that for all the ratios, the CCFC radiator has the highest heat transfer rate and hence proves to be better than conventional cross flow radiators.

4. CONCLUSIONS

From the above analysis it is concluded that although using a counter flow arrangement seems to be the best for car radiator as it has higher effectiveness values among all types of heat exchangers, a combination of counter flow heat exchanger and the cross flow heat exchanger called CCFC radiators are a better radiator configuration for cooling the engine. This result is strengthened by the following results about CCFC radiator-

i) For the same volume occupied by the cross flow radiator and CCFC radiator, the CCFC radiator has 35.61% better cooling capacity than conventional cross flow radiators at vehicle speed 11.11 m/s (40 km/hr) with mass flow rate of water 2 kg/s.

ii) At a higher vehicle speed of 80 km/hr, CCFC radiator has 27.44% better cooling capacity than cross flow radiator with mass flow rate of water as 2 kg/s.

iii) Air velocity ratio of counter flow and cross flow radiator is an important factor that depends on vehicle design etc. and is greater than 1. When this ratio is 1.2, CCFC radiator has 28.11% higher cooling capacity than cross flow radiator.

iv) The CCFC radiator gives same performance as cross flow radiator by occupying 40.85% less volume, for same mass flow rate of water as well as air.

v) CCFC uses two heat exchangers, whose volume is distributed in two places inside the vehicle. In any case, keeping two distinct units having a total volume V in a vehicle is easier than keeping a single unit of volume V because it is easy to find two small spaces inside the vehicle. Along with this, for both the heat exchangers in CCFC radiator, fresh air is taken and therefore air released through the radiator is less hot as well.

It is to be noted that a heat exchanger arrangement other than counter flow cannot be constructed at the roof of the vehicle, because the direction of flow of air and coolant automatically turn out to be opposite in direction. Hence it can be concluded that arrangements such as combination of cross flow and cross flow radiators, are difficult to construct. However, instead of dividing the radiators into two equal volumes, considerations can be given to dividing into unequal volumes, keeping the net volume same for even better radiator performance.

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