International Journal of Scientific Research and Engineering Development-– Volume 4 Issue 5, Sep- Oct 2021

Available at www.ijsred.com

RESEARCH ARTICLE OPEN ACCESS

The Design and Analysis of An Automobile Radiator with a 14ºC Cooling Capacity

Paul O. Okhiria*, Olumide A. Towoju**

*(Mechanical Engineering, Adeleke University, Ede, Nigeria.
Email: okhiriapaul@gmail.com)

** (Mechanical Engineering, Lead City University, Nigeria.
Email: olumidetowo@yahoo.com)

--************************----------------------------------

Abstract:

In a country such as Nigeria, automobile use is at a high rate. About 11.7 million of the population are assumed to have or make use of it. Automobile engines produce heat, and the country prevailing hot weather conditions compounds this. Quality radiators are of paramount importance in regard to expelling this combined heat. Also, the radiator performance and effectiveness affect the engine performance and lifespan. To effectively expel the heat produced in the automobile engine, the reduction of the coolant temperature is necessary. Studies have shown that a 14ºC cooling capacity is considered the minimum for effective dissipation of combustion engine heat in Nigeria. A design and analysis of an automobile radiator to achieve this cooling capacity was carried out. This was achieved by material selection, theoretical heat exchanger investigation to determine radiator parameters, acquiring of the radiator according to the determined parameters, and evaluation of the performance of the developed automobile radiator using the Effectiveness - NTU method in an experimental set up.

Keywords **—Cooling Capacity, Effectiveness – NTU Method, Heat Exchanger, Radiator.**

--************************----------------------------------

I. INTRODUCTION

Radiators are heat exchangers that transmit thermal energy from one medium to another for cooling and heating purposes. Its function is hinged on the transfer of heat across tube bundles as fluid flows[1]. They are mostly used to cool internal combustion engines in automobiles, but they are also used in piston-engine aircraft, railway locomotives, motorbikes, stationary generating plants, and engines with comparable characteristics. In general, internal combustion engines are cooled by passing a liquid known as engine coolant through the engine block, where it is heated, then through the radiator, where it loses heat to the atmosphere, and finally back to the engine in a closed loop. Engine coolant is usually made of water, although it can also be made of oil. A water pump is commonly used to push the engine coolant to circulate, and an axial fan is used to blow air through the radiator[2].

Knocking, piston distortion, cylinder deformation, and other negative impacts of a car engine without a radiator exist. If the radiator is functioning properly, the cooling system will as well, resulting in improved engine performance.

Automobile radiators have two variants based on material: copper-brass radiators and aluminium radiators. For many years in the past, copper and brass (copper as the core and brass as the tanks) were the choice materials when developing radiators; but within the last two decades, aluminium (aluminium as the core and plastic as the tanks) has become the new material of choice. They are classified as single or dual pass radiators depending on their layouts. In a single pass radiator, the cooling fluid crosses the core once, whereas in a dual pass radiator, it crosses the core twice.

Downflow and crossflow designs are also available, based on combinations[3].

Radiators for automotive engine cooling are typically crossflow heat exchangers that make the internal combustion engine run at a much lower temperature due to high amount of heat it produces while working. This temperature is called engine working temperature a safe temperature for the engine components without being overheated[4].

The radiator is made up of tubes, fins, a protective cap that serves as a pressure valve, and a tank on either side. The radiator tank receives coolant fluid from the internal combustion engine, which is then transferred across the radiator core via tubes to another tank on the opposite side of the radiator. While passing through the radiator tubes on its route to the opposite tank, the coolant sends much of its heat to the tubes, which then transfers the heat to the fins that are stuck between each row of tubes. Finally, with the help of the cooling fan, this heat is evacuated into the atmosphere[5].

In thermodynamics, the burning gasoline inside the cylinder of a car engine is a thermodynamic system, whereas the piston, the exhaust system, the radiator, and the air outside form its surroundings[6].

The Radiator can also be considered a thermodynamic system because it permits mass flow (hot coolant goes in and cold coolant flows out) as well as heat transfer (hot coolant passes heat to the air) [7].

This study seeks to design, fabricate, and test an automobile radiator with a 14°C capacity which can be employed in engine cooling. The remaining sections discusses the methodology employed and the results. The conclusion forms the last section.

II. METHODOLOGY

A. Components/Materials Selection

The protective case, core (tubes and fins) will both be made from aluminium materials and the tanks from plastic is chosen for this radiator design.

B. Design analysis (Theoretical heat exchanger investigation

Radiators work under different conditions such as the temperature and properties of the coolant coming from the engine, temperature and properties of the air being axially passed through the radiator, water and air volume, mass flow rates, material used etc. Certain conditions were chosen which were theoretically calculated alongside random dimensions of the automobile radiator to determine the dimensions (by iteration and interpolation) which will give a 14°C cooling capacity. These conditions are:

i. Water is assumed to enter the radiator at 355K (82ºC)
ii. Air is assumed to flow through the radiator at ambient temperature of 300K (27 ºC)
iii. The water volumetric flow rate is gotten from a water pump of 40 litre/min (0.00067 m³/s). The radiator fan rotates with speed of 3950 rpm, diameter 12 inches, an effective pitch of 8 inches and a CFM rating of 2000. (0.944 m³/s) which is common in different modern automobiles.
iv. Material used is aluminum which has a thermal conductivity of 237 W/m·k.

Properties such as Prandtl number, thermal conductivity, density, dynamic viscosity, kinematic viscosity, and specific heat are determined for both given temperatures of air and water that will pass through the radiator. This will aid in design calculations. The equations involved in determining the 14°C cooling capacity are given below alongside any assumptions made.

<u>Internal Flow of Water</u>: As the water flows through the radiator, the area and hydraulic diameter of each tube, Reynolds number, velocity of the water, Nusselt number, and convective heat transfer coefficient are determined using these formulas:

$$D_{hydraulic} = \frac{4A_{tube}}{P_{tube}} = \frac{4W_{tube}H_{tube}}{2W_{tube}+2H_{tube}} \quad (1)$$

$$V_{water} = \frac{Q_{water}}{N_{tube} \times A_{tube}} \quad (2)$$

$$Re_{water} = \frac{\rho_{water} \times v_{water} \times D_{hydraulic}}{\mu_{water}} \quad (3)$$

$$h_{water} = \frac{Nu_{water} \times k_{water}}{D_{hydraulic}} \quad (4)$$

The Nusselt number is a constant of 3.96 due to the laminar flow of rectangular cross section of the radiator.

External Flow of Air: Water is assumed to already be present in all the tubes and air from fan blows across the tubes and fins. The Reynolds number, air velocity, Nusselt number, and convective heat transfer coefficient are determined using these formulas;

$$v_{air} = \frac{Q_{air}}{A_{radiator} - (N_{tube} \times H_{tube} \times L_{radiator})} = \frac{Q_{air}}{H_{radiator} L_{radiator} - (N_{tube} \times H_{tube} \times L_{radiator})} \quad (5)$$

$$Re_{air} = \frac{v_{air} \times W_{fin}}{\nu_{air}} \quad (6)$$

$$Nu_{air} = 0.664 \times Re_{air}^{0.5} \times Pr_{air}^{\frac{1}{3}} \quad (7)$$

$$h_{air} = \frac{Nu_{air} \times k_{air}}{W_{tube}} \quad (8)$$

Fin Dimension and Efficiency: Fins help to dissipate the heat as they give space for the tubes to cool off when the fan blows. To simplify the fin efficiency equation, the fin is assumed to be straight rather than sinusoidal. The fin's efficiency is expressed as

$$\eta_{fin} = \frac{\tanh(mL_c)}{mL_c} \quad (9)$$

Where $m = \frac{2h_{air}}{K_{aluminum} \times H_{fin}}$, (10)

and $L_c = L_{fin} + \frac{H_{fin}}{2}$ (11)

Overall Surface Efficiency & Heat Transfer Coefficient (UA): Finding the overall surface efficiency for external air flow is critical due to air loss around the radiator's fins. It is written as

$$\eta_o = 1 - \frac{N_{fin} \times A_f}{A_{fin.base}}(1 - \eta_{fin}) \quad (12)$$

$$A_f = 2 \times W_{fin} \times L_c \quad (13)$$

$$A_b = 2L_{radiator}W_{tube} - H_{fin}W_{fin}N_{fin} \quad (14)$$

$$A_{fin.base} = N_{fin}A_f + A_b \quad (15)$$

Subsequently,

$$UA = \frac{1}{\left(\frac{1}{\eta_o \times h_{air} \times A_{external}}\right) + \left(\frac{1}{h_{water} \times A_{internal}}\right)} \quad (16)$$

$$A_{external} = A_{fin.base} N_{tube} \quad (17)$$

$$A_{internal} = (2W_{tube} + 2H_{tube}) L_{radiator} N_{tube} \quad (18)$$

Effectiveness-NTU method: This method is key to determining the performance rate of the radiator. This combines the value of the UA, the mass flow rates and heat capacity of air and water, and number of transfer units (NTU).

The mass flow rate is obtained as follows;

$$\dot{m}_{water} = Q_{water} \times \rho_{water} \quad (19)$$

$$\dot{m}_{air} = Q_{air} \times \rho_{air} \quad (20)$$

The heat capacity of the fluids is derived using the relations;

$$C_{air} = \dot{m}_{air} \times C_{P.air} \quad (21)$$

$$C_{water} = \dot{m}_{water} \times C_{P.water} \quad (22)$$

The number of transfer units is obtained as follows;

$$NTU = \frac{UA}{C_{min}} \quad (23)$$

The radiator has a crossflow single pass design with both fluids remaining unmixed, and the graph below can be used to measure its effectiveness;

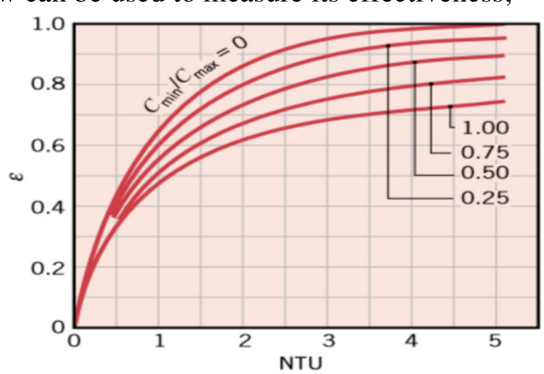

Fig.1With both fluids unmixed, the effectiveness of a single-pass, crossflow heat exchanger is shown[8].

Heat Transfer Rate: For both air and water, the maximum heat transfer rate is utilized to calculate the expected heat transfer rate in terms of both output temperatures. The radiator's cooling capacity may now be determined.

The heat transfer rate is obtained thus;

$$q_{max} = C_{min}(T_{water.in} - T_{air.in}) \quad (24)$$

And the predicted heat transfer is;

$$q_{predicted} = \varepsilon \times q_{max} \quad (25)$$

Final Temperature;

$$T_{water,out} = T_{water,in} - \frac{q_{predicted}}{C_{water}} \quad (26)$$

$$T_{air,out} = T_{air,in} + \frac{q_{predicted}}{C_{air}} \quad (27)$$

C. *Mathematical Analysis*

The radiator parameters, properties of water and air at chosen temperatures gotten after iteration and interpolations with the use of the theoretical heat exchanger analysis are depicted in Tables 1, 2, and 3, respectively. These parameters and conditions are able to successfully achieve a 14ºC cooling capacity.

TABLE 1
RADIATOR PARAMETERS

Lradiator (m)	0.5842
Hradiator(m)	0.508
Wradiator(m)	0.0508
Htube(m)	0.002286
Wtube(m)	0.0508
Ntube	48
Wfin(m)	0.0508
Lfin(m)	0.00762
Nfin	16,800
Hfin(m)	0.0000254

TABLE 2
PROPERTIES OF WATER AT 255K OR 82 ℃

$\rho_{water}\ (\frac{Kg}{m^3})$	970.518
$C_{P.water}\ (\frac{KJ}{kgk})$	4.199
Pr_{water} (unitless)	0.951
$k_{water} (W/mk)$	0.67
$\mu_{water}\ (kg/m.s)$	343×10⁻ □

TABLE 3
PROPERTIES OF AIR AT 300K OR 27 ℃

$\rho_{air}\ (\frac{Kg}{m^3})$	1.1614
$C_{P.air}\ (\frac{KJ}{kgk})$	1.007
Pr_{air} (unitless)	0.707
$k_{air}\ (\frac{W}{mk})$	0.0263
$v_{air}\ (\frac{m^2}{s})$	15.89×10⁻ □

Internal Flow of Water

$$D_{hydraulic} = \frac{4 \times 0.0508 \times 0.002286}{(2 \times 0.0508) + (2 \times 0.002286)} = 0.0044$$

$$h_{water} = \frac{3.96 \times 0.671}{0.0044} = 603W/m^2k$$

External Flow of Air

$$v_{air} = \frac{0.944}{(0.5842 \times 0.508) - (50 \times 0.002286 \times 0.5842)} = 4.1m/s$$

$$Re_{air} = \frac{4.1 \times 0.0508}{0.00001589} = 13{,}107.6$$

$$Nu_{air} = 0.664 \times 114.5 \times 0.8909 = 67.7$$

$$h_{air} = \frac{67.7 \times 0.0263}{0.0508} = 35.05\ W/m^2k$$

Fin Dimensions and Efficiency

$$m = \frac{2 \times 35.05}{237 \times 0.0000254} = 107.9$$

$$L_c = 0.00762 + \frac{0.0000254}{2} = 0.0076m$$

$$\eta_{fin} = \frac{\tanh(107.9 \times 0.0076)}{(107.9 \times 0.0076)} = 0.823$$

Overall Surface Efficiency

$$A_f = 2 \times 0.0508 \times 0.0076 = 0.00077m^2$$

$$A_b = (2 \times 0.5842 \times 0.0508) - (0.0000254 \times 0.0508 \times 16800) = 0.0377m^2$$

$$A_{fin.base} = (16{,}800 \times 0.00077) + 0.0377 = 12.97m^2$$

$$\eta_o = 1 - \frac{(16{,}800 \times 0.00077)}{12.97}(1 - 0.823) = 0.82$$

Overall Heat Transfer Coefficient

$$A_{external} = 12.97 \times 48 = 622.56m^2$$

$$A_{internal} = [(2 \times 0.0508) + (2 \times 0.002286)] \times (0.5842 \times 48) = 2.977m^2$$

$$UA = \frac{1}{\frac{1}{0.82\times622.56\times35.05} + \frac{1}{603\times2.977}} = 1631.4W/k$$

Mass flow rate

$$\dot{m}_{water} = 0.00067 \times 970.518 = 0.65\ kg/s$$

$$\dot{m}_{air} = 1.1614 \times 0.944 = 1.096\ kg/s$$

Heat capacity

$$C_{air} = 1.096 \times 1007 = 1103.672\mathrm{W/k}$$

$$C_{water} = 0.65 \times 4199 = 2729.35W/k$$

Number of Transfer Units

$$NTU = \frac{1631.4}{1103.672} = 1.478$$

Effectiveness-NTU Method

Using Figure 1 with the heat capacity ratio $\frac{c_{min}}{c_{max}}$ and the NTU gotten, $\varepsilon = 0.65$

Max Heat Transfer Rate

$$q_{max} = 1103.672(355 - 300) = 60701.96$$

Predicted Heat Transfer

$$q_{predicted} = 0.65 \times 60701.96 = 39{,}456.274$$

Temperature Out

$$T_{water,out} = 340.5k,$$

$$T_{air,out} = 335.75k$$

$$cooling\ capacity = 355 - 340.5 = 14.5℃$$

D. Performance Evaluation

The performance evaluation of the automobile radiator is done in an experimental set-up using the Effectiveness – NTU analytical method to determine its cooling capacity from the derived outlet air and water temperatures. The same conditions used when designing the radiator was also used as parameters during this experimental setup. The components involved in this experimental set up are thermometers, water pump, reservoir tank with heating element, hose and pipes, radiator and radiator fan, tachometer, and a 12V car battery. Other assumptions were established to carry out the experiment:

i. Steady state conditions.
ii. In the coolant, there were no phase transitions.
iii. Heat conduction through the coolant tube's walls was insignificant.
iv. No additional heat transfer route, such as radiation, was addressed because heat loss through coolant was only transported to the cooling air.
v. In each tube, the coolant fluid flow was fully established.
vi. The radiator's dimensions were consistent throughout, and the heat transmission surface area was uniformly distributed.
vii. The radiator material's heat conductivity was constant.
viii. Within the radiator, there were no heat sources or sinks.

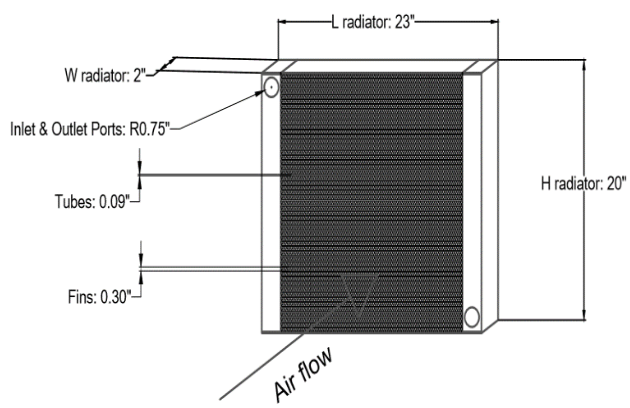

Fig. 2Schematic of designed radiator

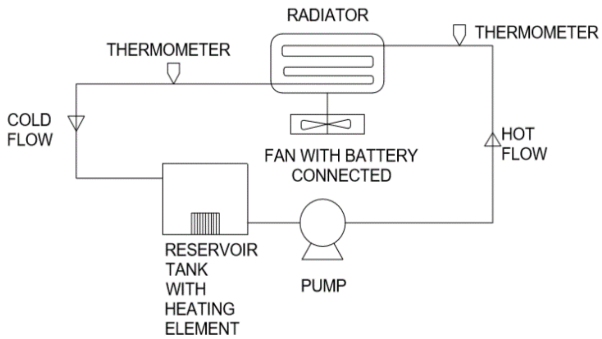

Fig. 3 Experimental Layout


Fig.4 Experimental Setup

The coolant enters the radiator from the reservoir tank and is heated by a heating element, which keeps the coolant at a constant temperature in hot conditions. The radiator distributes the heated coolant into its branching tubes, where the coolant transmits its heat to the environment through the fins with the help of the radiator fan blowing air axially across it. The coolant then leaves the radiator at a lower temperature back to the reservoir tank where it will be reheated. The coolant is pumped back into the radiator by a water pump in hot condition and the cycles continues [9], [10].

III. RESULTS AND DISUSSION

After carrying out the experiment, the results gotten of the temperature difference of water in 3 attempts are as follows:

TABLE 4
EXPERIMENTAL RESULTS

Attempts	1	2	3
Inlet temperature (K) [water, air]	355, 300	355, 300	355, 300
Outlet temperature (K) [water, air]	342, 333	341, 335	341, 334
Temperature difference (K) [water, air]	13, 33	14, 35	14, 34

Using $cooling\ capacity\ (K) = T_{water,in} - T_{water,out}$,the average temperature difference or cooling capacity of the designed radiator is 13.67K for water and 34K for air.

From the heat capacities $C_{air} = 1103.672W/k$ and $C_{water} = 2729.35W/k$, the max possible heat transfer is calculated;

$$q_{max} = C_{min}(T_{water.in} - T_{air.in}) = 1103.672(355 - 300) = 60{,}701.96$$

Actual heat transfer

$$q = C_{water} \times (T_{water,in} - T_{water,out}) = 2729.35(13.67) = 37{,}310.2$$

Effectiveness of the radiator

$$\varepsilon = \frac{q}{q_{max}} = \frac{37310.2}{60701.96} = 0.615 = 61.5\%$$

TABLE 5
PERFORMANCE OF RADIATOR IN DESIGN ANALYSIS VERSUS ACTUAL EXPERIMENT.

Parameters	Design calculation result	Experimental result
Heat transfer, q (W)	39,456.274	37,310.200
Effectiveness, ε	0.650	0.615
Air outlet temperature(K)	335.75	334.00
Water outlet temperature(K)	340.50	341.33

The results show that the radiator dissipates heat close to the capacity designed for. The assumptions decreased the final values for the experimental temperature difference by 2.4 percent and the heat transfer rate by 5.4 percent. The experimental approach's errors, such as ambient air changes, are negligible, and the theoretical method can be used to design a radiator with great precision.

Comparing testing data to design calculations has proven to be a more efficient approach of designing vehicle radiators, saving the designer time. Furthermore, this article demonstrates that ε – NTU approach is a reliable method of designing cross flow type heat exchanger radiators [9].

IV. CONCLUSIONS

The ε – NTU methods of design was used to design a radiator with 14°C cooling capacity. This involves material selection, determination of parameters, and performance evaluation through experiments. Several mass flow rate parameters for coolant (water) and air, as well as geometrical factors were iterated to arrive at optimized values based on the design aim [1].

REFERENCES

[1] Petinrin, M. O., Towoju, O. A., Ajiboye, S. A., & Zebulun, O. E. (2019). Numerical Study of the Effect of Changing Tube Pitches on Heat and Flow Characteristics from Tube Bundles in Cross Flow. *Journal of Engineering Sciences*, 10.

[2] Ladumor, R. J., Gajjar, V. J., & Araniya, K. K. (2014). A Review Paper on Analysis of Automobile Radiator. *International Journal of Research and Scientific Innovation*, 388-393.

[3] Contributors, W. (2020, May 16). *Radiator (engine cooling)*. Retrieved from Wikipedia: https://en.wikipedia.org/w/index.php?title=Radiator_(engine_cooling)&oldid=957090192

[4] Prakesh, P. L., Selvam, M., Pandian, A. S., Palani, S., & Harish, K. A. (2016). Design and Modification of Radiator in I.C. Engine Cooling System for Maximizing Efficiency and Life. *Indian Journal of Science and Technology*, 1-7.

[5] Mounika, P., Sharma, K. R., & Kishore, P. (2016). Performance Analysis of Automobile Radiator. *International Journal on Recent Technologies in Mechanical and Electrical Engineering (IJRMEE)*, 35-38.

[6] Samuel, L. J., Jeff, S., & Bill , M. (2020, January 20). *LibreTexts*. Retrieved from LibreTexts website: https://phys.libretexts.org/Bookshelves/University_Physics/Book%3A_University_Physics_(OpenStax)/Map%3A_University_Physics_II_-_Thermodynamics%2C_Electricity%2C_and_Magnetism_(OpenStax)/03%3A_The_First_Law_of_Thermodynamics/3.02%3A_Thermodynamic_System

[7] Yadav, S. (2016, December 11). *Quora*. Retrieved from Quora Website: https://www.quora.com/Can-a-car-radiator-be-considered-as-a-closed-system-or-an-open-system-Thermodynamics

[8] Incropera, F. P., Dewitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of Heat and Mass Transfer*. Hoboken: John Wiley & Sons, Inc.

[9] Arasu, K., & Ramesh, T. (2017). Validation of Design Parameters of Radiator using Computational tool . *International Research Journal of Engineering and Technology (IRJET)*, 825-830.

[10] Vashist, D., Bhatia, S., & Kalra, A. (2013). Some Studies on the Performance of Automotive Radiator at Higher Coolant Temperature. Journal of Basic and Applied Engineering Research, 41-46.

[11] Chukwudi, B. C., & Ogunedo, M. B. (2018). Design and Construction of a Shell and Tube Heat Exchanger. *Elixir International Journal*, 50687-50691.

[12] Eke, C. (2019, August 13). *Export.Gov*. Retrieved from A Export.Gov Website: https://www.export.gov/apex/article2?id=Nigeria-Automobiles

[13] Matthew , C., Dana, G., Brett , L., Austin , M., & Xuejen, F. (2012). The Theoriticaland Experimental Investigation of the Heat Tranfer Process of an Automobile Radiator. 128-140.

NOMENCLATURE

Hradiator	Height of radiator	Lradiator	Radiator length
Wradiator	Width of radiator	Wtube	Tube width
Htube	Tube height	Wfin	Fin width
Twater,in	Temperature of the inlet	water Lfin	Fin length
Twater,out	Temperature of the outlet water	Hfin	Fin thickness
Tair,in	Temperature of the inlet air	Ptube	Tube perimeter
Tair,out	Temperature of the outlet air	Vwater	Water velocity
mair	Total air mass flow rate	Vair	Air velocity
cp,air	Air specific heat	Ab	Base surface area
mwater	Total water mass flow rate	Ntube	Number of tubes
cp,water	Water specific heat	ρwater	Density of water
Atube	Tube cross-sectional area	Aradiator	Total radiator area
Qwater	Total water volumetric flow rate	Nuwater	Nusselt number of water
Rewater	Reynolds number of water	Nuair	Nusselt number of air
µwater	Dynamic viscosity of water	ηfin	Fin efficiency
kwater	Thermal conductivity of water	Prair	Prandtl number of air
Qair	Total air volumetric flow rate	νair	Kinematic viscosity of air
Reair	Reynolds number of air	kair	Thermal conductivity of air
UA	Overall heat transfer coefficient	Aexternal	Total external surface area
NTU	Number of transfer units	Ainternal	Total internal surface area
Cmin	Minimum heat capacity	Lc	Corrected fin length
Cmax	Maximum heat capacity	ηo	Overall surface efficiency
m	Coefficient for calculating efficiency	ε	Effectiveness
Af	Single fin surface area	Cair	Air's total heat capacity
Cr	Heat capacity ratio	Cwater	Water's total heat capacity
qmax	Maximum heat transfer rate	qpredicted	Predicted heat transfer rate
kaluminum	Thermal conductivity of aluminum		
hair	Air's convective heat transfer coefficient		
hwater	Water's convective heat transfer coefficient		
Nfin	Fin count per tube, top and bottom		
Afin,base	A single tube's total fin/base surface area		

