EXPERIMENTAL VALIDATION OF RADIATOR EFFECTIVENESS

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Abstract

It is difficult to imagine modern vehicles without a cooling system. The cooling system is based on the radiator. Scientists have done various researches to improve radiator efficiency and these are still ongoing. This paper shows both theoretical and experimental methods for determining the effectiveness of radiator.

Key words: Cooling system, vehicle, effectiveness, coolant, Arduino uno

Introduction

Vehicle radiator efficiency is determined by examining components of the cooling system. It is mainly determined by studying the parameters of the cooling system (radiator, coolant etc.). This paper provides an alternative and experimental methods of effectiveness. By increasing the effectiveness of car radiator fuel consumption of cars is reduced as only one cooling system consumes more than 30% of all fuel.

Define effectiveness of the radiator by alternative way

From the laws of thermodynamics, we know that heat transfer increases as we increase the surface area of the radiator assembly. That said the demand for more powerful engines in smaller hood spaces has created a problem of insufficient rates of heat dissipation in automotive radiators. As a result, many radiators must be redesigned to be more compact while still having sufficient cooling power capabilities. This application proposes a new design for a smaller radiator assembly. The new design is capable of dissipating the same heat as the original, given a set of operating conditions.

Figure 1 Schematic of single tube and fins of Radiator [3]
Original Spark Radiator dimensions using by ruler in normal condition

All measurements were determined using the Chevrolet Spark car radiator in the center of Mechatronics in TTPU.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiator length (rL)</td>
<td>0.532 m</td>
</tr>
<tr>
<td></td>
<td>1.74541 ft</td>
</tr>
<tr>
<td>Radiator width (rW)</td>
<td>0.411 m</td>
</tr>
<tr>
<td></td>
<td>1.34843 ft</td>
</tr>
<tr>
<td>Radiator height (rH)</td>
<td>0.0148 m</td>
</tr>
<tr>
<td></td>
<td>0.04593176 ft</td>
</tr>
<tr>
<td>Tube width (tW)</td>
<td>0.0148 m</td>
</tr>
<tr>
<td></td>
<td>0.04593176 ft</td>
</tr>
<tr>
<td>Tube height (tH)</td>
<td>0.0017 m</td>
</tr>
<tr>
<td></td>
<td>0.005577428 ft</td>
</tr>
<tr>
<td>Fin width (fW)</td>
<td>0.0148 m</td>
</tr>
<tr>
<td></td>
<td>0.04593176 ft</td>
</tr>
<tr>
<td>Fin height (fH)</td>
<td>0.0065 m</td>
</tr>
<tr>
<td></td>
<td>0.02132546 ft</td>
</tr>
<tr>
<td>Fin thickness (fT)</td>
<td>0.00005 m</td>
</tr>
<tr>
<td></td>
<td>0.000164042 ft</td>
</tr>
<tr>
<td>Distance Between Fins (fD)</td>
<td>0.0015 m</td>
</tr>
<tr>
<td></td>
<td>0.00492126 ft</td>
</tr>
<tr>
<td>Number of tubes (ntube)</td>
<td>42</td>
</tr>
</tbody>
</table>

Table 1: Measured dimensions of real Chevrolet Spark radiator, Mechatronics center at TTPU, 2018

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolant volumetric flow(Vfc)</td>
<td>0.0008 m³/s</td>
</tr>
<tr>
<td>Air volumetric flow(Vfa)</td>
<td>0.816 m³/s</td>
</tr>
<tr>
<td>Air velocity(Va)</td>
<td>4.5 m/s</td>
</tr>
<tr>
<td>Heat transfer performance(q)</td>
<td>18600 J/s</td>
</tr>
</tbody>
</table>

Table 2: Radiator operating conditions

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity(kc)</td>
<td>0.634 $\frac{W}{m*K}$</td>
</tr>
<tr>
<td>Specific heat (Cc)</td>
<td>4179 $\frac{J}{kg*K}$</td>
</tr>
<tr>
<td>Density(pc)</td>
<td>996.5 $\frac{kg}{m^3}$</td>
</tr>
<tr>
<td>Dynamic viscosity(µc)</td>
<td>0.00068 Pa*s</td>
</tr>
<tr>
<td>Coolant temperature(Tc)</td>
<td>355 K</td>
</tr>
</tbody>
</table>

Table 3: Water properties as a coolant at 355 K

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal conductivity (ka)</td>
<td>0.0276 $\frac{W}{m*K}$</td>
</tr>
</tbody>
</table>
Let us now determine the radiator’s Effectiveness (ε) using all the available information.

Ac is coolant surface area: \( Ac = n_{\text{tube}} \times (2 \times \text{tH} \times \text{rL}) + 2 \times (\text{tW} \times \text{rL}) = 0.737 \text{m}^2 \)  

(1)

Aa is air surface area: \( Aa = \text{TotNumAirPassages} \times (2 \times (\text{fD} \times \text{fH}) + 2 \times (\text{fH} \times \text{fW})) = 3.0813 \text{m}^2 \)  

(2)

\[ \text{TotNumAirPassages} = \text{NumRowsOfFin} \times \left( \frac{\text{rL}}{\text{fD}} \right) = 41 \times \frac{0.532}{0.0015} = 145.4 \]

(3)

Solve for \( hc \):

\[ \text{W}_{\text{P}} = 2 \times (\text{tW} + \text{tH}) = 2 \times (0.0148 + 0.0017) = 0.033 \text{ m} \]

\[ \text{Dh} = \frac{4 \times \text{Amin}}{\text{W}_{\text{P}}} = 0.00304 \text{ m} \]

(5)

\[ \text{Vc} = \frac{\text{vf}}{n_{\text{tube}} \times \text{Amin}} = 1.9 \text{ m/s} \]

(6)

\[ \text{ReynoldsNum} = \frac{\rho \times \text{Vc} \times \text{Dh}}{\mu} = 7926.93 \]

(7)

From the DittusBoelterEquation:

\[ \text{NusseltNum} = 0.023 \times \text{ReynoldsNum}^{0.8} \times \text{PrandtlNum}^{1/3} \]

PrandtlEquation:

\[ \text{PrandtlNum} = \frac{\text{C} \times \mu}{\text{k}} = 6.6 \]

(8)

NusseltEquation:

\[ \text{NusseltNum} = \frac{\text{hc} \times \text{Dhe}}{\mu} \]

(9)

Nusselt number is known from DittusNoelter Equation an is equal to 45.34

\[ \text{hc} = \frac{\text{NusseltNum} \times \mu}{\text{Dhe}} \]

(10)

\[ \text{hc} = 6190 \]

Determine \( \text{ReynoldsNum} \)

We solve ha in a similar manner as I did for hc

\[ \text{Amin} = \text{fH} \times \text{fD} = 0.00000975 \text{ m}^2 \]

(11)

\[ \text{W}_{\text{P}} = 2 \times (\text{fD} + 8 \times \text{fD}) = 0.027 \text{ m}^2 \]

(12)

\[ \text{DHa} = \frac{4 \times \text{Amin}}{\text{W}_{\text{P}}} = 0.00144 \text{ m} \]

(13)

\[ \text{ReynoldsNum} = \frac{\rho \times \text{Vc} \times \text{Dhe}}{\mu} = 384 \]

(14)

Calculate for Cratio

\[ \text{Ntu} = \frac{\text{UA}}{\text{Cmin}} \]

Thermal Capacity Rate: \( \text{CR} = \text{C} \times \text{mfr} \)

MassFlowRate: \( \text{mfr} = \text{FluidViscosity} \times \text{p} \)

\[ \text{mfa} = \text{vf} \times \text{pa} = 0.98 \text{kg/s} \]

(15)

\[ \text{mfc} = \text{vf c} \times \text{pc} = 2.03 \text{ kg/s} \]

(16)

\[ \text{CRa} = \text{Ca} \times \text{mfa} = 985 \text{ J/s*K} \]

(17)

\[ \text{CRc} = \text{Cc} \times \text{mfc} = 7474. \text{ J/s*K} \]

(18)

\[ \text{CRc} > \text{CRa} \text{ so, Cmin} = \text{CRa} \text{ and Cmax} = \text{CRc} \]

(19)

Now, we need to calculate Number of Transfer Unit (Ntu), ITD and Effectiveness (ε)

\[ \text{ITD} = \text{CoolantTemperature} – \text{AirTemperature} = 60 \text{ K} \]

(20)

\[ \varepsilon \text{Ntu} = \frac{\text{q}}{\text{cmin} \times \text{ITD}} \]

\[ 0.314 \text{ or } 31.4\% \]

(21)
Experimental validation of radiator effectiveness

The main purpose of the experiment is determining inlet and outlet temperatures of coolant at different points.

First law of thermodynamics for the system:
\[ Q = C_a(T_{a,i} - T_{c,o}) = C_c(T_{c,o} - T_{c,i}) = \varepsilon*C_{\text{min}}(T_{a,o} - T_{c,i}) \]  
(22)

- \( T_{c,i} \) - coolant inlet temperature, \( T_{a,i} \) – air inlet temperature
- \( T_{c,o} \) – coolant output temperature, \( T_{a,o} \) – air output temperature

By measuring inlet and outlet temperatures for both fluids, it is possible to see which side has higher difference. The one that has higher difference in temperature, has \( C_{\text{min}} \) from above equation, since \( C_{\text{min}} = \min(C_a, C_c) \). If mass flow rate of engine coolant is also measurable (from pump speed), it is possible to find numerical value of \( C_{\text{min}}, C_{\text{max}} \) and consequently \( \varepsilon \), using the first law of thermodynamics only.

\[ C_c(T_{c,o} - T_{c,i}) = \varepsilon*C_{\text{min}}(T_{a,o} - T_{c,i}) \]  

(24)

\( C_{\text{min}} = \min(C_a, C_c) \)

\( C_a = \text{mass flow rate of air} \times \text{Specific heat capacity of the air} \)

(25)

\( C_c = \text{mass flow rate of coolant} \times \text{Specific heat capacity of the coolant} \)

(23)

Equipments for experiment: Arduino uno, breadboard, temperature sensors (Dallas 18 b 20), resistor (10kohm), automobile radiator with an electric fan, water pump, anemometer (TSI), coolant and metal wires. Temperature sensors are connected to Arduino uno board as follows and result should appear on the screen.

\( C_c \) is a coolant heat capacity; it can be calculated by the following formula:

\[ C_c = \text{mass flow rate} \times \text{Specific heat capacity of the coolant} \]

(23)

\( C_a = \text{mass flow rate of air} \times \text{Specific heat capacity of the air} \)

(25)

\( C_{\text{min}} = \min(C_a, C_c) \)

(24)

\( C_{\text{max}} = \max(C_a, C_c) \)

(26)

In Table 8, there is average velocity is 4.3 m/s. By the calculation active surface of air has been obtained and it is equal to 0.532m * 0.411m = 0.22m²

density of air = 1.2041 kg/m³ from these calculations volume was obtained

volumetric flow rate of air =

\[ = 0.22m^2 \times 4.3 \text{ m/s} = 0.82 \text{ m}^3/\text{s} \]

(29)

mass flow rate of air =

\[ = 0.82 \text{ m}^3/\text{s} \times 1.2041 \text{ kg/m}^3 = 0.98 \text{ kg/s} \]

(30)

Specific heat capacity of air is 717 J/(kg*K) [TTPG84] Specific heat capacity of coolant (water) is 4180 J/(kg*K). The Arduino Uno board is dependent on MS Excel for real-time viewing and control to the result. As a result of experiment, effectiveness of the car radiator is determined by the temperature of coolant input and outputs from the radiator [Table 10].

Now, Calculate the effectiveness obtained the results from the experiment using the formula above:
Figure 3 Temperature sensors (ds 18 b 20) connected to Arduino Uno.

Figure 4 Real time analyzing of temperature of the coolant.

\[
\varepsilon = \frac{C_c (T_{c,d} - T_{c,o})}{C_{\text{min}} (T_{a,d} - T_{a,o})} = \frac{C_{\text{coolant}} M_{\text{coolant}} (T_{c,o} - T_{c,d})}{C_{\text{air}} M_{\text{air}} (T_{a,o} - T_{a,d})} = \frac{4180 \frac{J}{kg \cdot K} * 0.05 \frac{kg}{s} * (308.5K - 318K)}{717 \frac{J}{kg \cdot K} * 0.98 \frac{kg}{s} * (307K - 318K)} = \frac{1985.5 \frac{J}{s}}{7729 \frac{J}{s}} = 0.265 \text{ or } 26.5\% 
\]
b) $T_{c,i} = 46^\circ C = 319K$, $T_{c,o} = 37^\circ C = 310K$

$$\varepsilon = \frac{C_c (T_{c,o} - T_{c,i})}{C_{min} *(T_{a,o} - T_{c,i})} = \varepsilon = \frac{1881}{6950} \frac{J}{s} = 0.2706$$

or 27%

c) $T_{c,i} = 45.5^\circ C = 318.5K$, $T_{c,o} = 35.5^\circ C = 308.5K$

$$\varepsilon = \frac{C_c (T_{c,o} - T_{c,i})}{C_{min} *(T_{a,o} - T_{c,i})} = \varepsilon = \frac{4179}{8080.6} \frac{J}{s} = 2089.5 \frac{J}{s} = 0.259 \text{ or } 26\%$$
Results and discussion

All of the dimensions for the radiator are carefully measured and recorded in Table 2. Properties coolant and air given in Tables 7 and 8. Average fluid temperature is used to determining their properties.

<table>
<thead>
<tr>
<th>Lradiator</th>
<th>Hradiator</th>
<th>Wradiator</th>
<th>Wtube</th>
<th>Htube</th>
<th>Lfin</th>
<th>Wfin</th>
<th>Hfin</th>
<th>Ntube</th>
<th>Nfin</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
<td>mm</td>
</tr>
<tr>
<td>532</td>
<td>14.8</td>
<td>411</td>
<td>14.8</td>
<td>1.7</td>
<td>3.4</td>
<td>14.8</td>
<td>6.5</td>
<td>42</td>
<td>780</td>
</tr>
</tbody>
</table>

Table 5: Basic Radiator Dimensions.

<table>
<thead>
<tr>
<th>ρwater</th>
<th>Cₚ,water</th>
<th>kwater</th>
<th>μwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg/m³</td>
<td>J/kgK</td>
<td>W/mK</td>
<td>kg/sm</td>
</tr>
<tr>
<td>998.8</td>
<td>4180</td>
<td>0.58</td>
<td>0.00076</td>
</tr>
</tbody>
</table>

Table 6: Properties of Water at Average Temperature

<table>
<thead>
<tr>
<th>ρair</th>
<th>Cᵥ,air</th>
<th>kair</th>
<th>νwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>kg/m³</td>
<td>J/kgK</td>
<td>W/mK</td>
<td>m²/s</td>
</tr>
<tr>
<td>1.16</td>
<td>717</td>
<td>0.025</td>
<td>0.000022</td>
</tr>
</tbody>
</table>

Table 7: Properties of Air at Average Temperature.

<table>
<thead>
<tr>
<th>Trial</th>
<th>Twater,in</th>
<th>Twater,out</th>
<th>Tair,in</th>
<th>Tair,out</th>
<th>Mwater</th>
<th>Vair</th>
<th>ε</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K</td>
<td>K</td>
<td>K</td>
<td>K</td>
<td>kg/s</td>
<td>m/s</td>
<td>%</td>
</tr>
<tr>
<td>1</td>
<td>318</td>
<td>308</td>
<td>296</td>
<td>306.2</td>
<td>0.05</td>
<td>4.28</td>
<td>26.5</td>
</tr>
<tr>
<td>2</td>
<td>318.5</td>
<td>308.5</td>
<td>296</td>
<td>307.1</td>
<td>0.05</td>
<td>4.32</td>
<td>27</td>
</tr>
<tr>
<td>3</td>
<td>318</td>
<td>308</td>
<td>296</td>
<td>307.2</td>
<td>0.05</td>
<td>4.25</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>319</td>
<td>308.5</td>
<td>296</td>
<td>307.5</td>
<td>0.05</td>
<td>4.35</td>
<td>27</td>
</tr>
<tr>
<td>Average</td>
<td>318.4</td>
<td>308.3</td>
<td>296</td>
<td>307</td>
<td>0.05</td>
<td>4.3</td>
<td>27</td>
</tr>
</tbody>
</table>

Table 8: Experimental Temperatures and Flow rates through Radiator

Conclusion

As you can see, the effectiveness found in alternative methods is different from the one found experimental way in the laboratory condition.

This can be explained by the following:

Problems connecting the hoses
Insufficient accuracy in measuring radiator sizes
The sensitivity level of the sensor used for temperature measurement is ± 0.5 °C
- Coolant parameters are not explicitly accounted and so on

References

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5. Sliding vane rotary pump in engine cooling system for automotive sector. R Cipollone, D Di Battista - Applied Ther-
