Automotive Radiator Sizing and Rating – Simulation Approach

P. S. Amrutkar, S. R. Patil
(Department of Mechanical Engineering, Sinhgad Academy of Engineering, University of Pune, India)

ABSTRACT: Automotive radiator is key component of engine cooling system. Radiator thermal analysis consist sizing and rating of heat exchanger. Radiator size mainly depends on heat rejection requirement. Heat transfer calculations are important fundamentals to optimize radiator size. Automotive manufacturers use 1-D simulation software to decide radiator size. This paper focuses on thermal analysis of radiator theoretically using ε-NTU method and its validation by simulation approach.

Keywords - Automotive radiator, Heat transfer, Rating, Simulation, Sizing

I. INTRODUCTION

Automotive radiator is key component of engine cooling system. Coolant surrounding engine passes through radiator. In radiator coolant gets cooled down and re-circulated into system. Radiator sizing is important factor while designing cooling system. Radiator size depends on heat load as well packaging space availability. Heat load depends on heat rejection required to keep engine surface at optimum temperature. Generally LMTD or ε-NTU method is used to do heat transfer calculations of radiator. Both methods have its own advantages and preferred according to data availability. When radiator inlet and outlet temperature are known LMTD gives faster solution. When any of the temperature is unknown LMTD method undergoes iterations to find solution. In this case ε-NTU is better. In this paper ε-NTU method is described to do heat transfer calculations.

II. HEAT TRANSFER CALCULATIONS

Purpose of thermal analysis of heat exchanger is to determine heat transfer surface area (sizing) and performance calculation to determine heat transfer rate (rating). It is necessary to find out amount of heat transfer, outlet temperatures of both fluids. ε-NTU method is based on concept of heat exchanger effectiveness. [6] Here approximate size is assumed according to space availability. Based on this size heat transfer rate is calculated which should fulfill the requirement. Radiator size and heat transfer rate finalized accordingly.

Coolant side heat transfer coefficient calculations

Mathematical expressions are taken from references [1,2,3,6]

1. Hydraulic diameter
   \[ \text{Dhc} = \frac{4 \times A_{it}}{P_{it}} \]
2. Reynolds number
   \[ \text{Rec} = \left( \frac{V_{c} \times \text{Dhc}}{\text{Sc}} \right) \]
3. Prandtl number
   \[ \text{Prc} = \left( \frac{\text{Sc} \times \text{Cpc}}{K_{c}} \right) \]
4. Nusselt number for 2300<Re<10000
   \[ \text{Nuc} = \left\{ \frac{(\text{Rec} - 1000) \times \text{Prc} \times (FF/2)}{[1.07 + (12.7 \times (FF/2)^{1/2} \times (\text{Prc}^{2/3} - 1))]} \right\} \]
   where Friction factor
   \[ FF = \left[ 1.58 \times \ln(\text{Rec}) - 3.28 \right]^{2} \]
5. Heat transfer coefficient
   \[ h_{c} = \left( \frac{\text{Nuc} \times K_{c}}{\text{Dhc}} \right) \]

Heat transfer coefficient air

Mathematical expressions are taken from references [2,3,5,6]

1. Hydraulic diameter
   \[ \text{Dha} = \frac{4 \times C_{d} \times A_{ra}}{A_{a}} \]
2. Reynolds number
   \[ \text{Rea} = \left( \frac{V_{af} \times \text{Dha}}{S_{a}} \right) \]
3. Prandtl number
   \[ \text{Pra} = \left( \frac{S_{a} \times \text{Cpa}}{K_{a}} \right) \]
Automotive Radiator Sizing and Rating – Simulation approach

4. Colburn factor
   \[ J = \frac{0.174}{Re^{0.383}} \]

5. Heat transfer coefficient
   \[ ha = \frac{(J*Val*Cpu)}{Pra^{0.23}} \]

Heat rejection calculations
Mathematical expressions are taken from references [1,3,5,6]

1. Factor to calculate fin efficiency
   \[ F = \frac{2*ha}{(Kf*Thf)^{0.5}}/(Ph/2) \]

2. Temperature effectiveness of fins (fin efficiency)
   \[ Ef = \frac{[TanH(F)]}{F} \]

3. Total surface temperature effectiveness of fins
   \[ Eft = 1-[(1-Ef)*(Af/Aa)] \]

4. Overall thermal resistance
   \[ R = \frac{1}{[1/(Eft*ha)]+\frac{1}{[[([Ac/Cv)/(Aa/Cv)]*hc}\}}+(Tht/Kt) \]

5. Overall heat transfer coefficient
   \[ U = \frac{1}{R} \]

6. Stream heat capacity rate for air
   \[ Ca = Ma*Cpu \]

7. Stream heat capacity rate for coolant
   \[ Cc = Mc*Cpc \]

8. Stream heat capacity rate ratio
   \[ Cr = \min\{Ca or Cc\}/\max\{Ca or Cc\} \]

9. Number of transfer units
   \[ NTUmax = \frac{U*(Aa/2)}{\min\{Ca or Cc\}} \]

10. Heat exchanger effectiveness
    \[ E = 1-\exp\{\exp\{-Crc*NTUmax^{0.78}\}-1\}/(Crc*NTUmax^{0.22}) \]

11. Total heat transfer rate
    \[ Q = E*\min\{Ca or Cc\}*(Tic-Tia) \]

Coolant Outlet Temperature
1. \[ Toc = Tic-(Q/Cc) \]

Air Outlet Temperature
1. \[ Toa = Tia+(Q/Ca) \]

III. 1-D SIMULATION SOFTWARE

One-dimensional simulation software is used to design and perform thermal analysis of cooling system. The cooling system is represented as a network of various parts like pipes, heat source etc. Inputs include fluid flow rates and temperatures, core dimensions, fins and tubes details like thickness, thermal conductivities, number of tubes etc. It is also possible to specify different coolant types or other system combinations or different concepts and compare them with each other. System can be analyzed at constant or variable operating conditions. Cooling system performance can be estimated independent of the vehicle measurements, earlier in development phase. Analysis accuracy can be increased by incorporating Computational Fluid Dynamics results into cooling system 1-D model design. Simulation software offers great saving in terms of cost and development time while designing cooling systems.

IV. RADIATOR SIZING AND RATING

Actual thermal analysis is performed first theoretically and then by simulation approach for following requirement. It includes heat rejection requirement, space available under hood to mount radiator on vehicle chassis. Heat transfer requirement is decided as per engine specification, engine operating conditions and vehicle operating conditions. Cooling system design should fulfill all these requirements.
Automotive Radiator Sizing and Rating – Simulation approach

Table 1: Requirement of engine cooling system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heat transfer</td>
<td>KW</td>
<td>38.93</td>
</tr>
<tr>
<td>Height</td>
<td>m</td>
<td>0.390</td>
</tr>
<tr>
<td>Length</td>
<td>m</td>
<td>0.343</td>
</tr>
<tr>
<td>Depth</td>
<td>m</td>
<td>&lt;=0.032</td>
</tr>
</tbody>
</table>

Analytical approach

Following parameters are considered for analytical approach. First radiator core size is assumed and heat transfer calculations done.

Table 2: Inputs for theoretical calculations

<table>
<thead>
<tr>
<th>Description</th>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>Width</td>
<td>Cw m</td>
<td>0.3423</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>Cl m</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>Depth</td>
<td>Cd m</td>
<td>0.032</td>
</tr>
<tr>
<td>Fin</td>
<td>Density</td>
<td>Gf Per m</td>
<td>850</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>Fh m</td>
<td>0.0063</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>Thf m</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>Kf W/mK</td>
<td>200</td>
</tr>
<tr>
<td>Tube</td>
<td>Number</td>
<td>Nt</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>Rows</td>
<td>Ntr</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>Kt W/mK</td>
<td>200</td>
</tr>
<tr>
<td>Coolant</td>
<td>Volume flow rate</td>
<td>Wc l/h</td>
<td>4600</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>Gc Kg/m³</td>
<td>1037.5</td>
</tr>
<tr>
<td></td>
<td>Dynamic viscosity</td>
<td>Sc Kg/ms</td>
<td>0.001209</td>
</tr>
<tr>
<td></td>
<td>Specific heat</td>
<td>Cpc J/KgK</td>
<td>3504.97</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>Kc W/mK</td>
<td>0.4375</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature</td>
<td>Tic K</td>
<td>383</td>
</tr>
<tr>
<td>Air</td>
<td>Velocity</td>
<td>Va m/s</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Density</td>
<td>Ga Kg/m³</td>
<td>1.057</td>
</tr>
<tr>
<td></td>
<td>Dynamic viscosity</td>
<td>Sa Kg/ms</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>Specific heat</td>
<td>Cpa J/KgK</td>
<td>1009.95</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>Ka W/mK</td>
<td>0.002014</td>
</tr>
<tr>
<td></td>
<td>Inlet temperature</td>
<td>Tia K</td>
<td>323</td>
</tr>
</tbody>
</table>

Simulation approach

Cooling system modeled as shown in Fig.1 according to following parameters and steps.

Table 3: Inputs / Boundary Conditions for 1-D simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Width</td>
<td>Cw m</td>
<td>0.3423</td>
</tr>
<tr>
<td>Core Length</td>
<td>Cl m</td>
<td>0.390</td>
</tr>
<tr>
<td>Core Depth</td>
<td>Cd m</td>
<td>0.032</td>
</tr>
<tr>
<td>Fin Density</td>
<td>Gf Per m</td>
<td>850</td>
</tr>
<tr>
<td>Number of tubes</td>
<td>Nt</td>
<td>42</td>
</tr>
<tr>
<td>Coolant Volume flow rate</td>
<td>Wc l/h</td>
<td>4600</td>
</tr>
<tr>
<td>Coolant Inlet temperature</td>
<td>Tic K</td>
<td>383</td>
</tr>
<tr>
<td>Air volume flow rate</td>
<td>Wa l/s</td>
<td>800</td>
</tr>
<tr>
<td>Air inlet temperature</td>
<td>Tia K</td>
<td>323</td>
</tr>
</tbody>
</table>

Steps:
1. Heat source is selected as a radiator. Core dimensions specified.
2. Input and output nodes set for air and coolant inlet and outlet parameters.
3. Air and coolant flow direction given through network lines.
Automotive Radiator Sizing and Rating – Simulation approach

4. 50% / 50% water and ethylene glycol coolant is selected accordingly its thermo-physical properties like inlet temperature, viscosity, density etc. prescribed.

5. Similarly for air thermo-physical properties given. Thermal analysis is performed on cooling system model.

![Fig.1: 1-D simulation cooling system model](image)

V. RESULTS AND DISCUSSION

Comparison of analytical and simulation results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heat transfer</td>
<td>Q</td>
<td>42.368</td>
</tr>
<tr>
<td>Coolant outlet temperature</td>
<td>Toc</td>
<td>374.4</td>
</tr>
<tr>
<td>Air outlet temperature</td>
<td>Toa</td>
<td>372.54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total heat transfer</td>
<td>Q</td>
<td>41.944</td>
</tr>
<tr>
<td>Coolant outlet temperature</td>
<td>Toc</td>
<td>374.02</td>
</tr>
<tr>
<td>Air outlet temperature</td>
<td>Toa</td>
<td>372.0</td>
</tr>
</tbody>
</table>

Comparison shows that both results closely matched with each other. Thus theoretical thermal analysis of radiator using $\varepsilon$-NTU method is validated using simulation approach. Core dimensions are fixed from these results and to be used while designing radiator.

VI. FUTURE SCOPE

In broad manner simulation approach is useful tool for thermal analysis of cooling system. It is more helpful when cooling system involves more than one heat exchanger. With the help of advance simulation software it is possible to analyze complete vehicle thermal management.

Nomenclature

- A : Total heat transfer area
- Ar : Free flow area
- Ai : Inside cross-section area
- Pi : Inside perimeter
- Fh : Fin height

Second National Conference on Recent Developments in Mechanical Engineering
M.E. Society's College of Engineering, Pune, India
Automotive Radiator Sizing and Rating – Simulation approach

G : Density
Cl : Core length
Cd : Core depth
Cw : Core width
Cv : Total volume of core
Nt : Number of tubes
Ntr : Number of tube rows
Dh : Hydraulic diameter
Th : Thickness
K : Thermal conductivity
FF : Friction factor
F : Factor to calculate fin efficiency
Q : Total amount of heat transfer
E : Effectiveness of heat exchanger
Eft : Total surface temperature effectiveness of fin
Ef : Temperature effectiveness of fin
C : Heat capacity rate
Cr : Heat capacity rate ratio
Ti : Inlet temperature
To : Outlet temperature
NTU : Number of transfer units
M : Mass flow rate
W : Volume flow rate
Cp : Specific heat
U : Overall heat transfer coefficient
R : Overall thermal resistance
h : Heat transfer coefficient
Nu : Nusselt number
Re : Reynolds number
Pr : Prandtl number
V : Velocity
Vaf : Air mass flow velocity
S : Dynamic viscosity
J : Colburn factor

Subscripts :
c : Coolant
a : Air
t : Tube
f : Fin

REFERENCES


