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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
   Dhc = 4*Ait/Pit
2. Reynolds number
   Rec = (Vc*Dhc)/Sc
3. Prandtl number
   Prc = (Sc*Cpc)/Kc
4. Nusselt number for 2300<Re<10000
   $Nuc = [(Rec–1000)*Prc*(FF/2)]/\{1.07+[(12.7*(FF/2)^{1/2}*(Prc^{2/3}-1)]\}$
   where Friction factor
   $FF = [1.58*\ln(Rec)–3.28]^{-2}$
5. Heat transfer coefficient
   hc = (Nuc*Kc)/(Dhc)

Heat transfer coefficient air
Mathematical expressions are taken from references [2,3,5,6]

1. Hydraulic diameter
   Dha = 4*Cd*Ara/Aa
2. Reynolds number
   Rea = (Vaf*Dha)/Sa
3. Prandtl number
   Pra = (Sa*Cpa)/Ka

4. Colburn factor
   $J = 0.174/Rea^{0.383}$
5. Heat transfer coefficient
   $ha = (J*Vaf*Cpa)/Pra^{2/3}$

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

1. Factor to calculate fin efficiency
   $F = [(2*ha)/(Kf*Thf)]^{0.5}*(Fh/2)$
2. Temperature effectiveness of fins (fin efficiency)
   $Ef = [TanH(F)]/F$
3. Total surface temperature effectiveness of fins
   $Eft = 1-[(1-Ef)*(Af/Aa)]$
4. Overall thermal resistance
   $R = [1/(Eft*ha)]+\{1/\{[(Ac/Cv)/(Aa/Cv)]*hc\}\}+(Tht/Kt)$
5. Overall heat transfer coefficient
   $U = 1/R$
6. Stream heat capacity rate for air
   $Ca = Ma*Cpa$
7. Stream heat capacity rate for coolant
   $Cc = Mc*Cpc$
8. Stream heat capacity rate ratio
   Cr = minimum of Ca or Cc/maximum of Ca or Cc
9. Number of transfer units
   NTUmax = [U*(Aa/2)]/minimum of Ca or Cc
10. Heat exchanger effectiveness
    $E = 1-\exp\{[\exp(-Cr*NTUmax^{0.78})-1]/(Cr*NTUmax^{-0.22})\}$
11. Total heat transfer rate
    Q = E*minimum of 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.

Table 1: Requirement of engine cooling system

Parameter	**Unit**	**Value**
Total heat transfer	KW	38.93
Height	m	0.390
Length	m	0.343
Depth	m	<=0.032

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

Description	**Parameter**		**Unit**	**Value**
Core	Width	Cw	m	0.3423
	Length	Cl	m	0.39
	Depth	Cd	m	0.032
Fin	Density	Gf	Per m	850
	Height	Fh	m	0.0063
	Thickness	Thf	m	0.001
	Thermal conductivity	Kf	W/mK	200
Tube	Number	Nt	-	42
	Rows	Ntr	-	1
	Thermal conductivity	Kt	W/mK	200
Coolant	Volume flow rate	Wc	l/h	4600
	Density	Gc	Kg/m^3	1037.5
	Dynamic viscosity	Sc	Kg/ms	0.001209
	Specific heat	Cpc	J/KgK	3504.97
	Thermal conductivity	Kc	W/mK	0.4375
	Inlet temperature	Tic	K	383
Air	Velocity	Va	m/s	6
	Density	Ga	Kg/m^3	1.057
	Dynamic viscosity	Sa	Kg/ms	0.00002
	Specific heat	Cpa	J/KgK	1009.95
	Thermal conductivity	Ka	W/mK	0.002014
	Inlet temperature	Tia	K	323

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

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

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.

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.

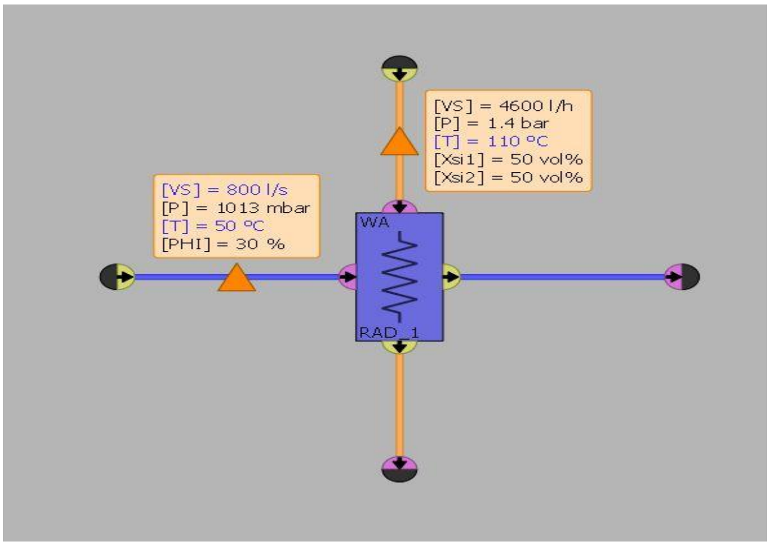

Fig.1: 1-D simulation cooling system model

V. RESULTS AND DISCUSSION

Comparison of analytical and simulation results

Table 4: Analytical results

Parameter		**Unit**	**Value**
Total heat transfer	Q	KW	42.368
Coolant outlet temperature	Toc	K	374.4
Air outlet temperature	Toa	K	372.54

Table 5: Simulation results

Parameter		**Unit**	**Value**
Total heat transfer	Q	KW	41.944
Coolant outlet temperature	Toc	K	374.02
Air outlet temperature	Toa	K	372.0

Comparison shows that both results closely matched with each other. Thus theoretical thermal analysis of radiator using ε-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

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

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