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AUTOMOTIVE RADIATOR - DESIGN AND EXPERIMENTAL VALIDATION

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ABSTRACT

In automotive, radiator is a base component of engine cooling system. It extracts heat from engine and keeps engine surface temperature at optimum level for better engine efficiency. Radiator development consists of its size and design aspects. Size provides heat rejection area and its performance. Design is related to its robustness. This paper focuses radiator design validation through finite element analysis as well size and heat rejection validation by experimental test.

KEYWORDS: Automotive Radiator, Heat Transfer, Simulation, Sizing, Performance

INTRODUCTION

Radiator is a key component of engine cooling system. Coolant surrounding engine passes through radiator. In radiator coolant gets cooled down and re-circulated into the system. Radiator size is controlled by heat load and packaging space availability. In this paper ε-NTU method is described to do heat transfer calculations and to decide radiator size. Size is verified through 1-D simulation.

Table 1: Heat Rejection Requirement

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.2
4	8	16.5
6	12	22.8

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). 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 [1-3, 6]

Hydraulic diameter

Dhc = 4*Ait/Pit (1)

Reynolds number

Rec = (Vc*Dhc)/Sc (2)

Prandtl number

Prc = (Sc*Cpc)/Kc (3)

Nusselt number for 2300<Re<10000

$$Nuc = [(Rec-1000)*Prc*(FF/2)]/\{1.07+[(12.7*(FF/2)^{1/2}*(Prc^{2/3}-1)]\} \quad (4)$$

where Friction factor

$$FF = [1.58*\ln(Rec)-3.28]^{-2} \quad (5)$$

Heat transfer coefficient

$$hc = (Nuc*Kc)/(Dhc) \quad (6)$$

Heat transfer coefficient air

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

Hydraulic diameter

$$Dha = 4*Cd*Ara/Aa \quad (7)$$

Reynolds number

$$Rea = (Vaf*Dha)/Sa \quad (8)$$

Prandtl number

$$Pra = (Sa*Cpa)/Ka \quad (9)$$

Colburn factor

$$J = 0.174/Rea^{0.383} \quad (10)$$

Heat transfer coefficient

$$ha = (J*Vaf*Cpa)/Pra^{2/3} \quad (11)$$

Heat rejection calculations

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

Factor to calculate fin efficiency

$$F = [(2*ha)/(Kf*Thf)]^{0.5}*(Fh/2) \quad (12)$$

Temperature effectiveness of fins (fin efficiency)

$$Ef = [TanH(F)]/F \quad (13)$$

Total surface temperature effectiveness of fins

$$Eft = 1-[(1-Ef)*(Af/Aa)] \quad (14)$$

Overall thermal resistance

$$R = [1/(Eft*ha)]+\{1/\{[(Ac/Cv)/(Aa/Cv)]*hc\}\}+(Tht/Kt) \quad (15)$$

Overall heat transfer coefficient

$$U = 1/R \quad (16)$$

Stream heat capacity rate for air

Ca = Ma*Cpa (17)

Stream heat capacity rate for coolant

Cc = Mc*Cpc (18)

Stream heat capacity rate ratio

Cr = minimum of Ca or Cc/maximum of Ca or Cc (19)

Number of transfer units

NTUmax = [U*(Aa/2)]/minimum of Ca or Cc (20)

Heat exchanger effectiveness

$E = 1\text{-}\exp\{[\exp(-Cr*NTUmax^{0.78})-1]/(Cr*NTUmax^{-0.22})\}$ (21)

Total heat transfer rate

Q = E*minimum of Ca or Cc*(Tic-Tia) (22)

Heat Rejection Summary

Table 2: Heat Rejection Analytical Results

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	10.14
4	8	19.62
6	12	28.91

VERIFICATION OF HEAT TRANSFER AREA THROUGH 1-D SIMULATION

Cooling system is modeled as shown in Figure according to following steps:

- Heat source is selected as a radiator. Core dimensions specified.
- Input and output nodes set for air and coolant inlet and outlet parameters.
- Air and coolant flow direction given through network lines.
- 50% / 50% water and ethylene glycol coolant is selected accordingly its thermo-physical properties like inlet temperature, viscosity, density etc. prescribed.
- Similarly for air thermo-physical properties given.

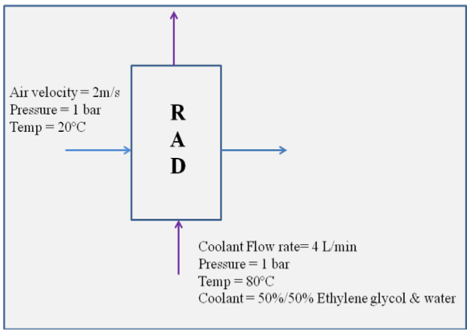

Figure 1: 1-D Simulation Cooling System Model

Simulation Results

Size = 142.3 x 665 x 60 mm3 [Fin Density 950 fins/cm]

Table 3: Heat Rejection Simulation Results

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.34
4	8	16.88
6	12	23.45

Heat exchanging surface is verified and it seems enough to achieve required heat rejection.

RADIATOR MODELING

- Following points taken care during design of Tank
  - Strength
  - Flow Optimization
  - Installation Space
  - Cost
- As radiator tank has to take all module weight, it needs to be robust in design to sustain load at the same time capable to sustain internal pressure.

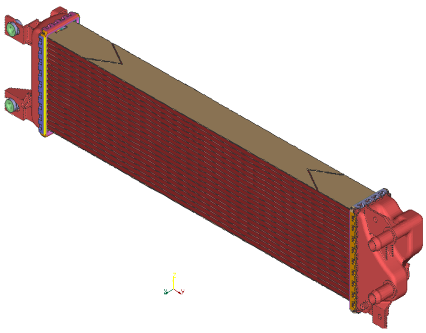

Figure 2: Radiator 3D Model

FINITE ELEMENT ANALYSIS

FE analysis was performed to check the stress and accordingly design modification for robust structure. An acceptance criterion is stress level below 60MPa.

Table 4: FEA – Geometry

Component	Part	Material
Radiator	Header	Aluminum
	Tanks	PA66-GF30%
	Tubes	Aluminum
	External Fin	Aluminum
Mounting bracket		Steel
Isolator		Rubber

Boundary Conditions

The model is fixed at left and right tank at the mounting points as shown below.

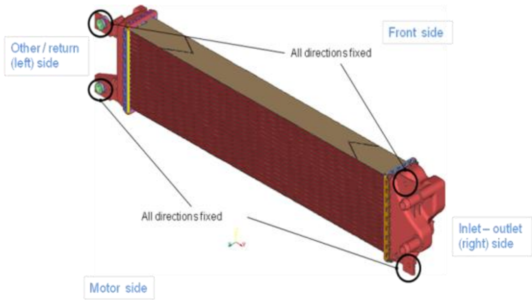

Figure 3: FEA Boundary Conditions

FEA Result

Table 5: Maximum Stress

Load Case (2 Bar)	Open Case	Close Case
Right Tank	52 MPa	53MPa
Left Tank	13 MPa	13 MPa

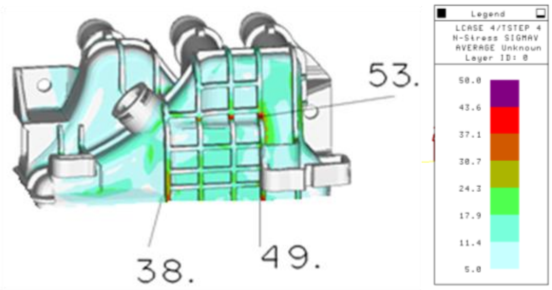

Figure 4: Maximum Stress

From above FEA results, tank design passes stress level so this geometry is considered to be ok.

TESTING AND VALIDATION

Prototype

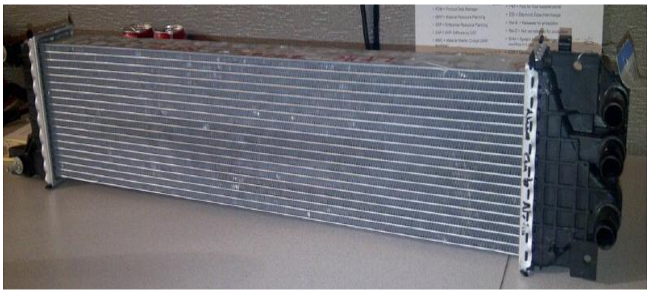

Figure 5: Prototype

Heat Rejection Test

Equipments used:

- Test bench
- Measuring equipment to measure coolant and air side mass flows, inlet and outlet temperatures
- Coolant-side inlet and outlet frames with ring ducts
- Mounting bolts for connection to test stands and connections or ducts

Testing Workbench

Figure 6: Test Set Up

Procedure

- This procedure is applied for preparation, supervising and evaluating measurements at test stands for determining coolant and air-side performance.
- Test is performed at radiator assembly level.
- A visual check is made of the radiator: any damage at fins, brazed joints, connections is checked.
- Full core matrix is exposed to air flow.
- **Test Conditions**
  - 50/50 coolant
  - 80+/-10°C inlet coolant temperature
  - 20°C inlet air temperature
- Coolant to air heat rejection balance is kept within 3% for each test point.
- Coolant side heat rejection results recorded.
- Air inlet end temperature measuring points are distributed uniformly ahead of the radiator core.
- The first measuring point is recorded after two minutes in the steady state condition, according to the equilibrium criteria defined for Coolant inlet temperature, Coolant inlet velocity, Air inlet temperature, Air mass flow rate.

Testing Results

Sample 1

Table 6: Testing Result – Sample 1

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.3
4	8	16.7
6	12	23.0

Sample 2

Table 7: Testing Result – Sample 2

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.4
4	8	16.7
6	12	23.1

Sample 3

Table 8: Testing Result – Sample 3

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.3
4	8	16.7
6	12	23.0

Sample 4

Table 9: Testing Result – Sample 4

Air Flow (m/s)	Coolant Flow (L/min)	Heat Rejection (kW)
2	4	9.3
4	8	16.7
6	12	23.1

RESULTS & DISCUSSIONS

- Four 60 mm deep, U-flow, radiator with having fin density 95fpdm and 34 tubes were tested for heat performance. The tested radiators have similar heat performance.
- At all air flows, the heat-transfer is similar to the expectation.
- Results obtained confirmed design of radiator fulfills performance requirement and hence comply level of acceptance.

Comparison of Analytical, Simulation and Experimental Performance Results

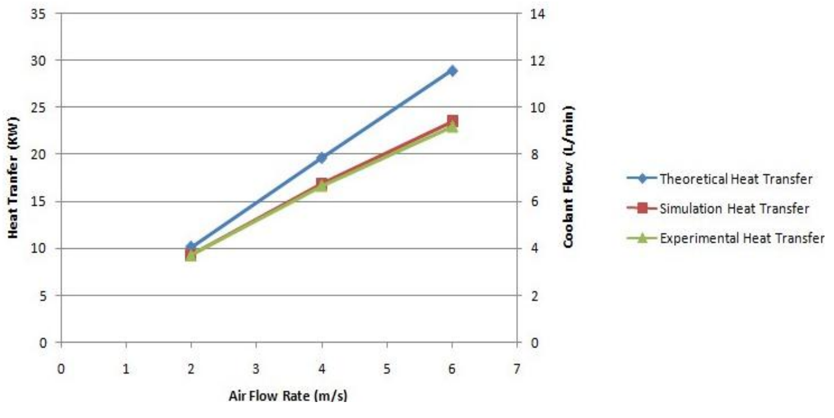

Figure 7: Comparison of Analytical, Simulation and Experimental Results

There were some assumptions made in analytical calculations like uniform coolant flow through tubes, uniform temperature of coolant and air throughout etc. so the analytical values are at higher than simulation and experimental values. As in practical conditions properties of air and coolant may differ from point to point. Temperature of coolant is changing throughout the core which affect heat transfer rate. Analytical values provide safer side radiator design as actual vehicle running conditions are unpredictable.

CONCLUSIONS

The heat transfer performance of the radiator is analyzed for theoretical, simulation and experimental values. FE Analysis result shows radiator design is safe and stress level observed is below maximum stress criteria. Performance test result shows radiator is able to deliver required heat rejection. Simulation results are good approximations of the tested values found experimentally. The objective to design and validate the radiator is accomplished successfully.

FUTURE SCOPE

Currently automotive industries use iteration methods to predict radiator performance in development phase.

- To develop core blocks of certain volume with combinations of different standard tubes and fins.
- Test the block for performance result for specific coolant and air supply.
- Block volume is integrated to obtain performance values for particular core size and then result is validated through actual test measurements.
- These results data is incorporated in simulation software and then it will integrate values over any defined core size and will give performance values.
- All such core combination blocks results will be useful in development phase to get performance values and iterations will be reduced as these values are already validated.

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

REFERENCES

1. Matthew Carl, Dana Guy, Brett Leyendecker, Austin Miller, and Xuejun Fan, The Theoretical and Experimental Investigation of the Heat Transfer Process of an Automobile Radiator, *ASEE Gulf Southwest Annual Conference, Texas*, 2012
2. R. Esmaeili Sany, M. H. Saidi, J. Neyestani,Experimental Prediction of Nusselt Number and Coolant Heat Transfer Coefficient in Compact Heat Exchanger Performed with *ε-NTU* Method, *The Journal of Engine Research, Vol.18, Spring,* 2010

3. K.Y. Leong, R. Saidur, S.N. Kazi, A.H. Mamun, Performance investigation of an automotive car radiator operated with nanofluid-based coolants (nanofluid as a coolant in a radiator), *Applied Thermal Engineering,30*, 2010

4. S. K. Saripella, W. Yu, J. L. Routbort, D. M. France, Rizwan-uddin, Effects of Nanofluid Coolant in a Class 8 Truck Engine, *SAE Technical Paper, 2141*, 2007

5. D. Ganga Charyulu, Gajendra Singh, J.K. Sharma, Performance evaluation of a radiator in a diesel engine- a case study, *Applied Thermal Engineering 19*, 1999

6. S. Kakac, H. Liu, *Heat Exchangers Selection Rating and Thermal Design*, (CRC Press LLC, 1998)

7. Pawan S. Amrutkar, Sangram R. Patil, Automotive Radiator Performance – Review, *International Journal of Engineering and Advanced Technology (IJEAT),* ISSN: 2249 – 8958, Volume-2, Issue-3, February 2013

8. P. S. Amrutkar, S. R. Patil, Automotive Radiator Sizing and Rating – Simulation Approach, *IOSR Journal of Mechanical and Civil Engineering (IOSR-JMCE,* ISSN(e) : 2278-1684, ISSN(p) : 2320–334X, 2013