

Exergy Analysis of A Thermal Energy System

Oleksandr Azarnyi

Founder & Lead Engineer

Advanced Flow Engineering

Email: contact@advancedflowengineering.com

Web: advancedflowengineering.com

Location: London, UK

1. Analysis of Heat Exchangers in an Engineering Application (Automotive Radiator)

1.1 Selected Thermal Energy System

The thermal energy system examined in this study is the liquid-cooling circuit of a passenger vehicle. The system operates as a closed-loop arrangement in which heat generated in the engine block is absorbed by a water-glycol coolant, transported to a crossflow radiator, and rejected to ambient air. The principal components of this system are summarised in Table 1 and include the coolant loop, pump, thermostat, radiator core, cooling fan, and connecting hoses. The radiator is the main heat exchanger in the circuit and ensures stable engine temperatures within the typical operating band of 90-105°C.

Table 1. Components of the automotive cooling system

Component	Function
Water-glycol coolant loop	Transfers thermal energy from engine to radiator
Water pump	Drives coolant circulation
Thermostat	Regulates coolant routing based on temperature
Radiator (water-air HE)	Rejects heat to ambient air
Cooling fan	Enhances air flow through fins
Piping and hoses	Connects system components

1.2 System Description and Operation

During engine operation, a significant portion of fuel energy appears as waste heat. A fraction of this heat is absorbed by the coolant flowing through the engine jackets, typically raising its temperature to approximately 90°C. This heated coolant is delivered to the radiator inlet by the water pump. Inside the radiator, coolant flows through an array of flat aluminium tubes joined to louvered fins. Heat is conducted through the tube walls and distributed across the extended fin surfaces, where it is removed by air flowing transversely through the core. The airflow arises from a combination of ram flow during vehicle motion and the electric cooling fan (Kays & London, 1984). As heat transfer occurs, the coolant temperature decreases to about 80°C before returning to the engine. This continuous cycle maintains stable engine operation, prevents overheating, preserves lubricant integrity, and maintains favourable thermodynamic properties of the coolant.

1.3 Functions of the Radiator

The radiator ensures proper thermal regulation of the engine by rejecting waste heat to the surrounding air. Maintaining the coolant within a safe temperature range prevents excessive thermal stresses, reduces the risk of knock, preserves lubricant quality, and ensures reliable engine performance under both steady-state and transient conditions.

1.4 Justification for the Selected Heat Exchanger Type

Automotive radiators universally employ crossflow, finned-tube, water-air heat exchangers due to their balance of compactness, manufacturability, and heat-transfer effectiveness (Kays & London, 1984). Coolant possesses a high heat capacity, whereas air has a much lower convective capability (Bahador & Behnia, 2001). The louvered fins dramatically increase the effective heat-transfer area, compensating for air-side limitations and improving overall performance. The suitability of this configuration is summarised in Table 2.

Table 2. Suitability of the crossflow finned radiator configuration

Requirement	Rationale
High heat-transfer area	Louvered fins provide extensive extended surface
Low mass and compact design	Aluminium fins and tubes provide low weight and high conductivity
Handling fluids with different heat capacities	Crossflow geometry accommodates water's high cp and air's low cp
Durability	Brazed aluminium construction provides rigidity and vibration resistance
Acceptable pressure drop	Fin and tube geometry optimised to control flow resistance

1.5 Structure, Configuration, and Operating Data

The geometric and operational data for a typical mid-size automotive radiator are presented in Table 3. These values reflect commonly reported radiator characteristics and are consistent with heat-exchanger design literature (Kays & London, 1984; Bahador & Behnia, 2001).

Table 3. Geometric and operating characteristics of a typical radiator

Category	Parameter	Value
Geometry	Core size	600 × 400 × 26 mm
	Tube count	40-60
	Tube hydraulic diameter	~3 mm
	Fin type	Louvered
	Fin pitch	1-2 mm
	Heat-transfer area	~1.2 m ²
Coolant side	Inlet temperature	90°C
	Outlet temperature	80°C
	Mass flow rate	0.40 kg/s
	Heat capacity	3.6 kJ/kg·K
Air side	Inlet temperature	25°C
	Mass flow rate	1.50 kg/s
	Heat capacity	1.005 kJ/kg·K

The heat-transfer rate obtained from the coolant-side balance is:

$$\dot{Q} = \dot{m}_w c_{p,w} (T_{w,in} - T_{w,out}) = 0.40 \cdot 3.6 \cdot 10 = 14.4 \text{ kW.}$$

The corresponding air outlet temperature is:

$$T_{a,out} = 298 + \frac{14.4}{1.5 \cdot 1.005} \approx 307.55 \text{ K} \approx 34.6^\circ\text{C.}$$

2. Exergy Analysis of the Thermal Energy System

2.1 Governing Equations

The exergy analysis is based on several standard thermodynamic assumptions that are appropriate for automotive cooling systems. The radiator is treated as a steady-flow control volume, implying that all properties remain constant in time and that no accumulation of energy or mass occurs. Variations in kinetic and potential energy of the coolant and air streams are negligible compared with thermal energy and are therefore omitted from the governing equations. Pressure losses across the radiator are small relative to

absolute pressure and do not significantly influence the thermal exergy; hence, the physical exergy is modelled using only temperature-entropy relations. Furthermore, the specific heats of coolant and air are assumed constant over the operating temperature range, which is justified by the relatively narrow variation in temperature for typical engine-cooling conditions. These assumptions simplify the formulation while preserving the accuracy required for second-law evaluation of the radiator's performance. For a steady-flow system, the **first law** gives the heat-transfer rate from the coolant:

$$\dot{Q} = \dot{m}_w c_{p,w} (T_{in,w} - T_{out,w}).$$

The **second law** states that any real heat-transfer process generates entropy. The specific entropy change of a fluid stream is:

$$\Delta s = c_p \ln \left(\frac{T_{out}}{T_{in}} \right).$$

The total entropy generation within the radiator is therefore:

$$\dot{S}_{gen} = \dot{m}_w \Delta s_w + \dot{m}_a \Delta s_a.$$

Using the Gouy-Stodola relation, the associated exergy destruction is:

$$\dot{E}_D = T_0 \dot{S}_{gen}.$$

The **specific physical exergy** of a stream at temperature T is expressed as:

$$ex = c_p \left[(T - T_0) - T_0 \ln \left(\frac{T}{T_0} \right) \right].$$

Finally, the **second-law (exergy) efficiency** of the radiator is defined as:

$$\eta_{II} = \frac{\dot{E}_{a,gain}}{\dot{E}_{w,loss}},$$

which represents the fraction of the available thermal exergy in the coolant that is successfully transferred to the air stream.

2.2 Flow Chart for Exergy Computation

A structured computational sequence was followed to ensure consistency with standard exergy-analysis methodology. The flow chart in Figure 1 summarises the calculation steps, starting from measured input data and progressing through energy balances, entropy generation, exergy destruction, and evaluation of the second-law efficiency.

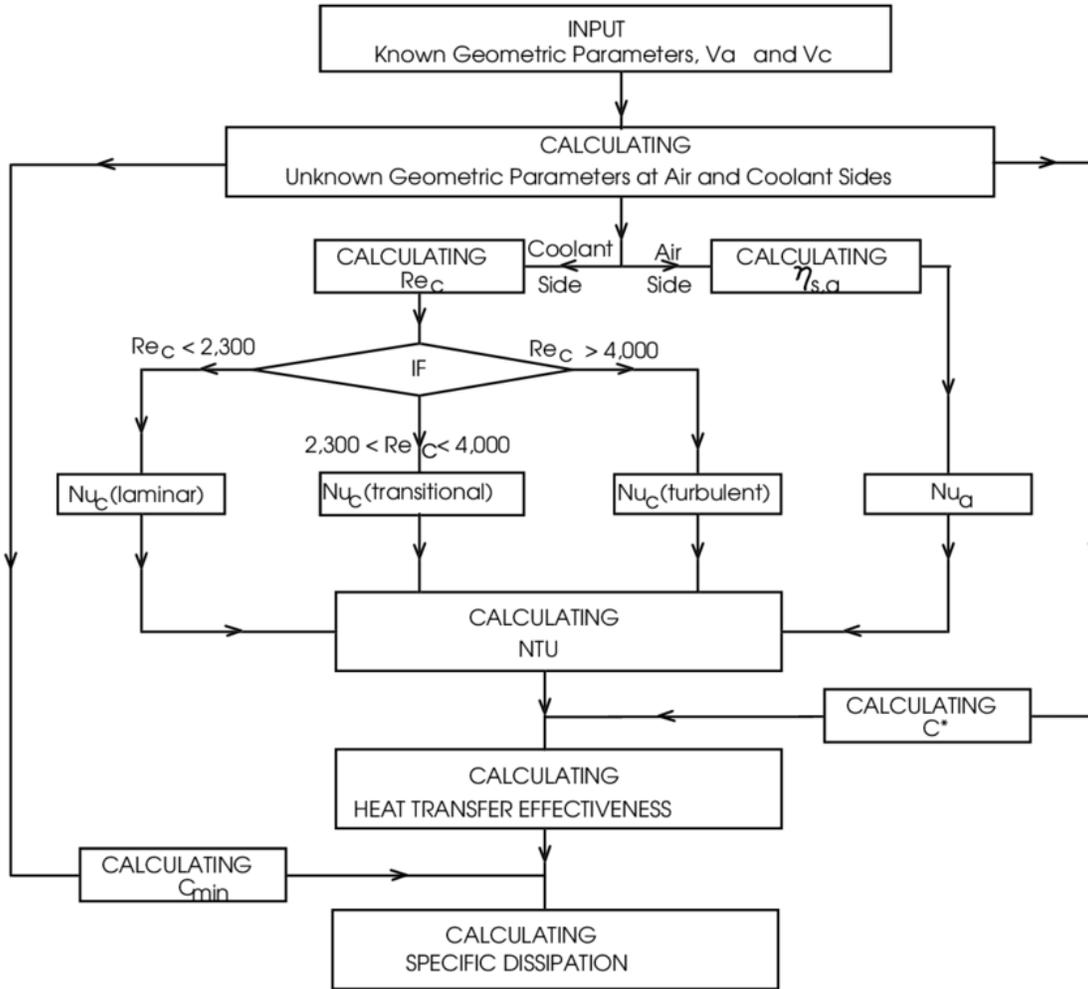


Figure 1. Flow chart of the exergy-analysis calculation procedure for the automotive radiator.

2.3 Numerical Results and Discussion

Entropy generation

Coolant entropy change:

$$\Delta s_w = 3.6 \ln \left(\frac{353}{363} \right) = -0.1004 \text{ kJ/kgK}, \dot{S}_w = -0.0402 \text{ kW/K.}$$

Air entropy change:

$$\Delta s_a = 1.005 \ln \left(\frac{307.55}{298} \right) = 0.0318 \text{ kJ/kgK}, \dot{S}_a = 0.0477 \text{ kW/K.}$$

Total entropy generation:

$$\dot{S}_{gen} = 0.0477 - 0.0402 = 0.0075 \text{ kW/K.}$$

Exergy destruction

$$\dot{E}_D = 298 \cdot 0.0075 = 2.24 \text{ kW.}$$

Exergy transfer
Coolant exergy decrease:

$$\dot{E}_{w,loss} = 0.40(22.33 - 16.29) = 2.41 \text{ kW.}$$

Air exergy gained:

$$\dot{E}_{a,gain} = 1.50 \cdot 0.151 = 0.226 \text{ kW.}$$

Second-law efficiency

$$\eta_{II} = \frac{0.226}{2.41} = 0.0937 \approx 9.4\%.$$

Discussion

The numerical results show that most irreversibility originates on the air side of the radiator. While the coolant undergoes a small entropy decrease, the air stream - entering close to the ambient dead-state temperature - experiences a proportionally much larger entropy rise. This imbalance results in a net entropy generation rate of 0.0075 kW/K, producing an exergy destruction of 2.24 kW according to the Gouy-Stodola relation. Although the radiator transfers a substantial amount of thermal energy, only 0.226 kW of exergy is gained by the air compared with a coolant exergy loss of 2.41 kW. This indicates that a large portion of the coolant's available work potential is degraded before reaching the air stream. The primary reasons are the large temperature difference between coolant and air and the inherently low air-side heat-transfer coefficient. The resulting second-law efficiency of $\approx 9.4\%$ lies within the 5-20% range typically reported for compact automotive radiators, confirming that the obtained results are physically realistic and reflect known thermodynamic limitations (Gölcü et al., 2007; Romero-Méndez et al., 2008).

3. Performance Optimisation of the Thermal Energy System

A parametric study was performed to investigate the influence of coolant and air mass-flow rates on the exergy efficiency of the radiator. The coolant mass flow was varied between 0.25-0.45 kg/s, while the air mass flow was varied between 1.0-2.5 kg/s. For each operating point, the energy balances, entropy generation, exergy destruction, and second-law efficiency were recomputed using the same procedure described in Section 2. All calculations were executed using a Python script, which automatically loops over all mass-flow combinations and stores the resulting exergy efficiency for each case. The results of this parametric sweep are summarised in Table 4 and further visualised using the exergy-efficiency map in Figure 2, demonstrating that higher coolant flow and lower air flow produce the highest second-law performance.

Table 4. Influence of coolant and air mass flow on radiator exergy performance

Case	Coolant flow (kg/s)	Air flow (kg/s)	Heat transfer (kW)	Air outlet (°C)	Exergy efficiency
1	0.25	1.0	9.0	33.8	0.088
2	0.25	1.5	9.0	30.8	0.059
3	0.25	2.0	9.0	29.3	0.044
4	0.25	2.5	9.0	28.4	0.036
5	0.30	1.0	10.8	35.6	0.105

Case	Coolant flow (kg/s)	Air flow (kg/s)	Heat transfer (kW)	Air outlet (°C)	Exergy efficiency
6	0.30	1.5	10.8	32.0	0.071
7	0.30	2.0	10.8	30.2	0.053
8	0.30	2.5	10.8	29.1	0.043
9	0.35	1.0	12.6	37.4	0.122
10	0.35	1.5	12.6	33.2	0.082
11	0.35	2.0	12.6	31.1	0.062
12	0.35	2.5	12.6	29.9	0.050
13	0.40	1.0	14.4	39.2	0.139
14	0.40	1.5	14.4	34.4	0.094
15	0.40	2.0	14.4	32.0	0.071
16	0.40	2.5	14.4	30.6	0.057
17	0.45	1.0	16.2	41.0	0.156
18	0.45	1.5	16.2	35.6	0.105
19	0.45	2.0	16.2	32.9	0.079
20	0.45	2.5	16.2	31.3	0.064

Summary of optimisation results

The highest exergy efficiency occurs when the coolant mass flow rate is at its maximum (0.45 kg/s) and the air mass flow is at its minimum (1.0 kg/s). Under these conditions (Case 17), the efficiency reaches approximately 0.156 because the coolant releases more exergy while the smaller air flow yields a greater exergy gain per unit mass.

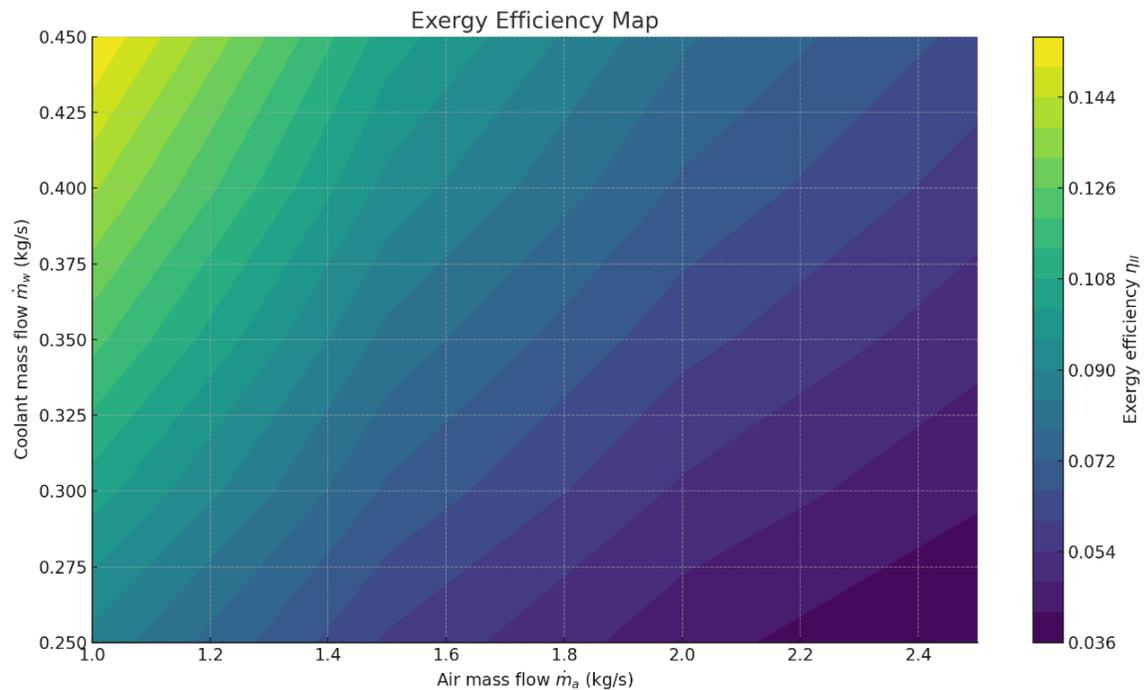


Figure 2. Exergy efficiency map as a function of coolant and air mass flow rates. Higher efficiency is obtained at high coolant flow and low air flow, while the opposite combination results in poor second-law performance.

The lowest exergy efficiency is observed for the lowest coolant flow and the highest air flow (Case 4), where the efficiency drops to approximately 0.036. In this condition, the coolant releases little exergy while the large air mass distributes the available exergy thinly.

Overall, increasing coolant flow enhances exergy efficiency, whereas increasing air flow reduces it. The radiator performs best when coolant flow is high and air flow is relatively low.

4. Conclusion

This investigation evaluated the thermodynamic performance of an automotive radiator through detailed exergy analysis and parametric optimisation. Under representative operating conditions, the radiator rejects approximately 14.4 kW of heat, raising the air temperature from 25°C to 34.6°C. The resulting entropy generation of 0.0075 kW/K leads to an exergy destruction of 2.24 kW. The second-law efficiency of the radiator was determined to be approximately 9.4%, consistent with reported values for compact coolant-air heat exchangers (Romero-Méndez et al., 2008). A parametric study covering twenty operating points revealed that the exergy performance is strongly dependent on the ratio of coolant to air mass flow rates. High coolant flow and low air flow yield the highest efficiencies, while the opposite combination results in the poorest performance. Optimisation efforts should therefore focus on improving coolant-side flow capacity and managing air-side flow to minimise unnecessary exergy dilution.

5. References

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