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ABSTRACT

Availability analysis is based on the combination of First and Second Laws of Thermodynamics. Availability is defined as the maximum amount of potential work in relation to the surrounding environment. In the present paper, availability loss method was applied to evaluate a dual-evaporator vehicle air conditioning (A/C) system in order to identify a critical component that had led to the poor system performance. Second Law Efficiency analysis was also used to evaluate a vehicle A/C system at different operating conditions. It was found that A/C systems always display better Second Law Efficiencies at highway running conditions than at other operating conditions. In the calculations provided in this paper, availability analysis identified that a new prototype slimline Thermal Expansion Valve (TXV) in a new A/C system had caused lower Second Law Efficiency as compared with the current block TXV A/C system. Consequently, it was concluded that revisions be made to the slimline TXV for optimal performance.

NOMENCLATURE

a_f: specific fluid flow availability
A_f: flow availability transfer
A_W: availability transfer due to work interaction
h: specific enthalpy
q: specific heat transfer rate
o: dead state (environment)
T: temperature
OSA: outside supply air mode
R/D: receiver and dryer
A: fluid flow availability
A_q: availability transfer due to heat flow
ε: Second Law Efficiency
I: availability loss
$\overline{Q}$: time average parameter
s: specific entropy
t: time
REC: recirculated air mode

INTRODUCTION

Due to concerns of fuel economy and emissions, automotive industries are focusing more on the fuel consumption caused by vehicle air conditioning systems. Fuel consumption resulting from A/C system usage could be up to 6-8% of the total vehicle fuel consumption in truck and SUV applications. Availability analysis can identify the A/C system availability loss for each component and the Second Law Efficiency of the system. The analysis can thus point in the direction of potential A/C system improvements.

In this paper, attempts were made to answer three questions: (1) What is the definition of availability loss for an automobile A/C system? (2) How to use the availability analysis to help identify problems in vehicle A/C system design? (3) How and to what extent can changing one of the A/C components change the system characteristics?

THEORY

Assuming the changes in kinetic and potential energies to be negligible, the flow availability per unit mass, a_f of refrigerant R134a is given as[1]

$$a_f = h - h_o - T_o * (s - s_o) \qquad (1)$$

Availability is physically defined as the maximum amount of a material or a form of energy in relation to surrounding environment. In general, the availability balance of a control volume undergoing a steady-state and steady-flow process can be given as[1]

$$\frac{dA}{dt} = A_q - A_w + A_f - I \qquad (2)$$

Where $\frac{dA}{dt}$ is the system or component availability rate of change with respect to time. For steady state or quasi-steady state, this value is zero. For a certain operating point, quasi steady state can be assumed for A/C systems. Availability destruction, I, symbolizes the irreversibility of thermal processes.

By applying the availability balance equation (2) to the individual components of automobile A/C system, the availability loss of compressor, condenser, evaporator, TXV and hoses are derived as follows:

$$I_{condenser} = T_o * (s_{cond2} - s_{cond1}) + q_{cond} \qquad (3)$$
$$I_{compressor} = T_o * (s_{com2} - s_{com1}) \qquad (4)$$
$$I_{evaporator} = T_o * (s_{evpout} - s_{evpin}) - (T_o/T_{cold}) * q_{evp} \qquad (5)$$
$$I_{txv} = T_o * (s_{txv2} - s_{txv1}) \qquad (6)$$
$$I_{hose} = T_o * (s_{hose2} - s_{hose1}) \qquad (7)$$
$$I_{R/D} = T_o * (s_{R/D2} - s_{R/D2}) \qquad (8)$$

The availability transfer due to heat transfer is given as

$$A_q = q * (1 - T_o/T_{cold}) \qquad (9)$$

T_{cold} is the ambient temperature of a component. T_0 is the dead state temperature. In this study, wind tunnel ambient is assumed to be the dead state. For evaporator, the T_{cold} is the vehicle interior temperature. For compressor, since it is located inside the engine compartment where temperature is very hot, very close to the compressor body temperature, we assume the compressor to be adiabatic. Similar assumptions can be applied to all A/C hoses, receiver/dryer and the TXV, its throttling process is assumed as iso-enthalphic. Finally, for condenser, since it is located in front of vehicle where the temperature is very close to wind tunnel ambient temperature, the availability transfer due to heat flow between condenser airside and the wind tunnel ambient can be neglected.

In a vehicle A/C system, the availability transfer of evaporators due to heat flow is desired availability flow. Second Law Efficiency ε is defined as the ratio of the desired availability out flow to compressor input availability (purchased availability inflow). First Law Efficiency (COP) is defined as the ratio of evaporator cooling capacity (desired energy flow) to compressor input work (purchased energy flow).

The availability loss is an index of irreversibility of a thermal process. The Second Law Efficiency links an actual system performance to that of the best possible system, whereas the First Law Efficiency cannot measure how close the system is from an ideal system.

CALCULATION METHOD

The calculation program was coded using a mathematical software with refrigerant properties and thermal physical properties available. The test data was imported directly into the parametric table of the code that could simultaneously calculate multiple equation sets. The cabin average temperature was selected to be the temperature surrounding evaporators. The wind tunnel ambient temperature was selected to be the surrounding temperature for condenser. Since availability loss (I), Second Law Efficiency (ε), First Law Efficiency (COP) were all calculated for each testing time period, the time average method was introduced to account for this effect:

$$\overline{Q} = \frac{\int_{t1}^{t2} Q(t) \bullet dt}{t_{total}} \qquad (10)$$

$\overline{Q}$ is a time-averaged parameter, which can be heat transfer rate, availability loss, Second Law Efficiency, COP, etc. It is calculated from each data point measured.

CASE STUDY DESCRIPTION

Vehicle A/C System Description

Figure 1 is a schematic of a dual evaporator vehicle A/C system. The baseline A/C system consists of a 158 cc fixed swash plate piston compressor, copper round tube/fin evaporators (front 234x261x80, rear 208x451x64 integrated with heater core) for both front and rear air handling units, a six pass parallel flow flat tube condenser with louvered fins (800x507.8x16), and 1.5 ton block type TXV's for both front and rear units (front TXV with 2.8 ^{o}C Superheat, 0.1 ton bleeding and 0.38 Mpa MOP, rear TXV with 2.8 ^{o}C Superheat and 0.43 Mpa MOP setting). The new A/C system uses the same fixed swash plate compressor and six pass parallel flow condenser, but both evaporators were replaced with flat tube type evaporators (front 261x235x65, rear 235x212x65, louvered fins) and both block type TXV's were replaced with slimline fitting TXV's from two different manufacturers. These TXV's provide the same 1.5 ton capacity but with different settings (front TXV with –0.5 ^{o}C SH liquid cross charge, 0.1 ton bleeding and 0.68 bar/10 ^{o}K slop, rear TXV with 5.5 ^{o}C SH and 0.38 Mpa MOP setting).

Measurement and Test Procedure

Instrumentation

Pressure probes and T-type thermocouples were installed at each refrigerant component inlet and outlet. Two mass flow meters were installed at the outlet of receiver and dryer and the inlet of front TXV. Over 100 thermocouples and 8 relative humidity sensors were placed inside the vehicle cabin and on exterior walls to monitor vehicle interior comfort level.

Test Procedure

The A/C performance validation testing was performed in a climate wind tunnel. Vehicle was hot-soaked until the average interior temperature reached 60 ^{O}C. Then the test started with the designed test sequence. During testing, the wind tunnel ambient was controlled at 37.8 ^{O}C temperature, 40% RH and 1000 W/m^{2} sunload. In this study, both vehicles with the baseline A/C system and the new A/C system were tested to run five hours with simulating vehicle speed from 50 KPH, 80 KPH and 105 KPH and air circulation mode started as recirculation (REC) for the first three hours then changed to fresh air mode (OSA). Over 200 points of temperature, pressure, relative humidity, voltage, current, engine speed, compressor speed for refrigerant side and cabin airside were collected using a high speed data acquisition system.

RESULTS AND DISCUSSION

Figure 2 shows availability loss distribution of the baseline A/C system at different vehicle speed and air circulation modes. Figures 3 and 4 show the system coefficient of performance COP and Second Law Efficiency ε profiles of the baseline A/C system. Figure 5 shows the percentage change of availability loss, total desired availability flow out and efficiencies from the baseline system to the new one.

Table 1and 2 list the availability loss, Second Law Efficiency, and COP comparison between both A/C systems. It was found that both A/C systems had very close First Law Efficiencies (COP), but the Second Law Efficiency of the new system was less than that of the baseline system. This indicated a poor A/C system configuration compared to the baseline system, especially during the early stage of pull down and fresh air mode (22.03% lower in 50REC, 13%, 14.09% and 12.23% respectively lower in 50OSA, 80OSA and 105OSA). From the availability loss point of view, flat tube evaporators of the new system have a lower availability loss than that of the round tube evaporators of the baseline system, which meant that selecting a flat tube evaporator was an improvement to the baseline system. For condensers, both systems used the same type of parallel flow condenser with six passes. The availability loss of the condenser in the new A/C system was

Table 1. Availability Loss Comparison Between The New And Base A/C Systems

Item	Rear TXV (%)	Front TXV (%)	Rear Evaporator (%)	Front Evaporator (%)	Condenser (%)	Compressor (%)
50REC	27.03	12.84	-15.65	-13.55	1.13	-17.17
80REC	11.35	2.76	-11.3	-8.68	-3.9	-12.78
105REC	11.4	3.15	-12.31	-10.82	-5.43	-8.14
50OSA	30.36	19.7	-30.27	-26.44	7.27	-20.22
80OSA	15.23	5.56	-12.73	-7.23	7.89	-10.98
105OSA	9.24	-1.02	-9.35	-5.94	6.16	-8.14

very close to that of the baseline system in air recirculated mode and was slightly higher (<8%) in fresh air mode. Overall, the condenser is not a major factor in lowering the Second Law Efficiency of the new A/C system. The new system has much lower total desired availability flow than that of the baseline system (50REC: 34.17% lower; fresh air mode: 16.49%-22.74% lower). In thermal fluid systems, the desired availability flow is an important index and every system designer wants to design a system with the higher availability flow output and Second Law Efficiency.

For compressor, the same fixed swash plate compressor was used in both systems. The compressor availability loss in the new system was lower than that in the baseline system, which means the compressor performed better in the new system compared to the baseline system.

For the TXV, the availability loss of both front and rear TXV's of the new system was higher than that in the baseline system. The new system used the slimline TXV but the baseline system used the block TXV. The rear TXV of the new system always had much higher availability loss in all vehicle speeds and air circulation modes than that of the baseline system. The maximum percentage increase of availability loss was about 30.36%. It is this higher availability loss that primarily contributes to a lower Second Law Efficiency in the new system.

Table 2: Total Desired Availability Flow And Coefficient Comparison Between The New And Base A/C systems

Item	Total Desired Availability Flow (%)	Coefficient Of Performance (%)	Second Law Efficiency (%)
50REC	-34.17	-2.34	-22.03
80REC	-16.29	0.11	-7.41
105REC	-9.24	-1.88	-1.67
50OSA	-22.74	-0.54	-13.00
80OSA	-19.69	-0.73	-14.09
105OSA	-16.49	0.2	-12.23

From the availability analysis, the TXV tuning was identified to be the critical factor in order to raise Second Law Efficiency of the new system. The proper refrigerant control could also eliminate the slugging flow at the compressor suction and the flooding at the evaporator outlet. Optimizing both front and aux TXV's could reduce the TXV availability loss and increase the A/C system desired availability flow from the evaporators.

CONCLUSIONS

From this work, we conclude:

(1) The availability analysis is a very useful method to assess vehicle A/C performance.
(2) With the help of this analysis, it was possible to identify, in a particular system, which components play a key role in affecting the A/C system performance.

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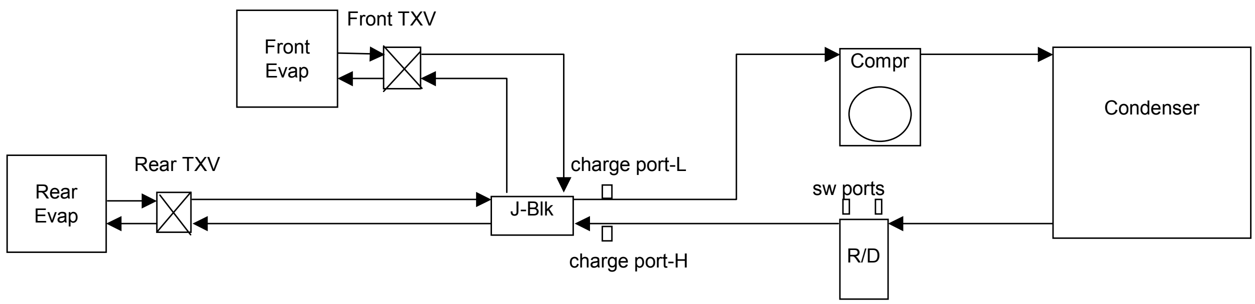

Figure 1: Vehicle A/C System Schematic

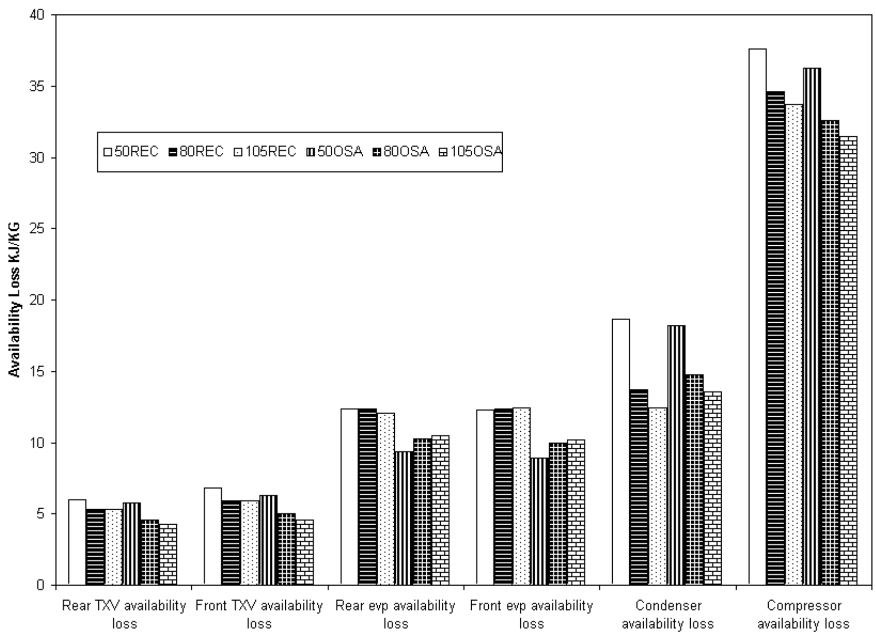

Figure 2: The Baseline A/C System Availability Loss Distribution.

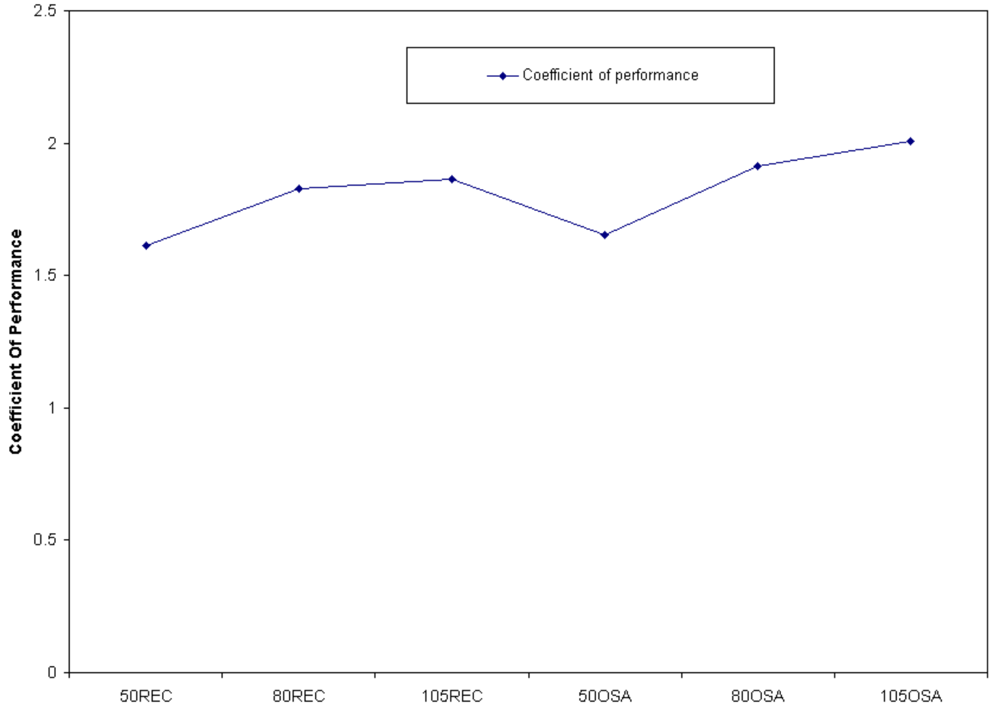

Figure 3: The Baseline A/C System Coefficient of Performance.

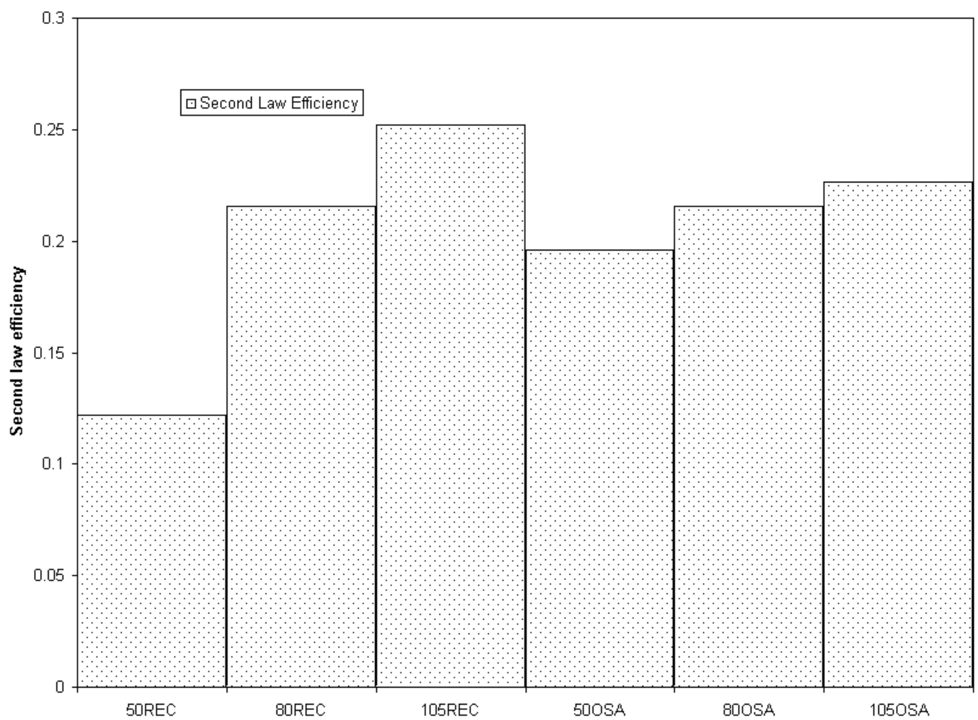

Figure 4: The Baseline A/C System Second Law Efficiency.

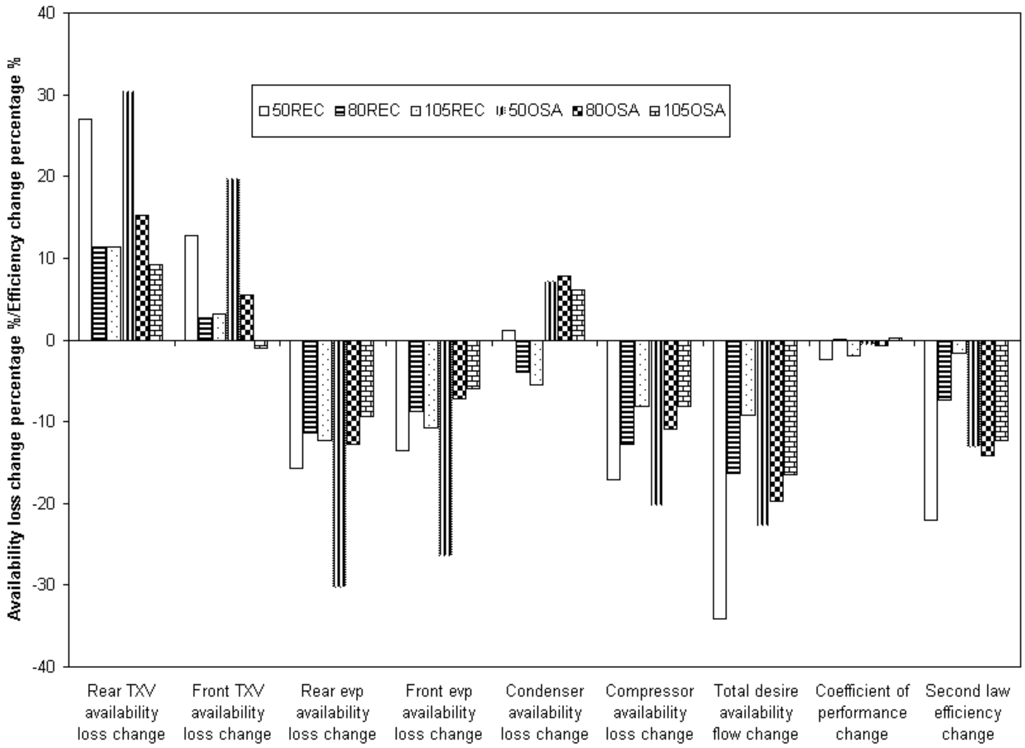

Figure 5: Availability Loss And Efficiency Comparison Between New And Base Systems.