THERMAL ANALYSIS OF CAR AIR COOLER

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Abstract

People more and more time spend in vehicles (cars, trains, planes, buses or subway). This is the reason why the thermal comfort has more and more paid attention. In one hand people try to make comfort (in each situation) whatever they are at home, office or in car. In the other hand the thermal conditions in the cabin of vehicles directly influences on the driver's and passengers safety.

The investigations presented in this paper are the part of larger project, which assumes complex modelling of thermal state of car interior. First part assumes creation of CFD model of car interior. Second part is thermodynamic modelling of air cooling unit in order to estimate the influence of basic cabin parameters on the A/C unit COP, power consumption of the unit and fuel consumption of the vehicle.

In the paper thermodynamic analysis of car air cooler is presented. Typical refrigerator cycles are studied: one with uncontrolled orifice and non controlled compressor, second with thermostatic controlled expansion valve and externally controlled compressor. The influence of refrigerant charge and the inlet air temperature on the coefficient of performance, exergy efficiency, heat flux and temperature in evaporator and compressor net power were investigated. The impact of improper refrigerant charge on the performance of A/C systems was also checked.

Keywords: *car air conditioning, refrigerant, thermal comfort, thermodynamic cycle*

1. Thermal comfort in vehicles

Car compartment is a place where often thermal discomfort is obvious. In summer, the most important phenomenon of energy transfer is sun radiation. In hot summer day radiation heat flux can be even several times higher than convection heat flux. It can be easy to notice when one takes car to shady road after driving in the sun. Coldness and freshness feeling is almost immediate. Temperature in a vehicle cabin is closely related with the occurrence of traffic accidents [2]. In hot summer days internal temperature often exceeds +30°C. Zlatoper [8] has created the ranking list of the factors which affect the traffic accidents in United States and placed the temperature on the third position. So it is obvious, that the thermal conditions in the cabin of vehicles directly influences on the driver's and passengers safety.

Both too high and too low ambient temperature influences human physical and mental state. Driver's efficiency researches indicate that it can be even 35% higher at +20°C than at +35°C. Decrease of efficiency at +5°C can be the same as that at +35°C [8][8].

It is impossible to ensure temperature at the same level as outside compartment using only ventilation, even with the strong flow. The internal temperature is almost always higher. Radiation heat flux with green house effect in car compartment is higher that heat flux which can be refuse with ventilation. Situation is critical during car parking in hot clearly day with direct sun exposure. In summer, internal temperature can even reach 70^{o}C with 30^{o}C outside. It is very dangerous for animals or children left inside car [3]. The techniques of achieving quite good effects of thermal comfort are well recognized in the habitats, but in mobile spaces, like cars, trains and buses are still under development.

There are also additional parameters, which influence on the thermal comfort: air flow speed, air humidity, outer wall temperature and, what is important in vehicles cabins, sun radiation. In many cases thermal parameters are controlled only by regulation of the air temperature and the mass flow rate. Due to that, air flow speed can locally exceed its reasonable value.

It is hard to strictly define the thermal comfort. Usually thermal comfort means that temperature is between 20°C and 22°C, humidity is about 50% and air velocity is under 0.5 m/s. This can be called independent factors. There is also second group of factors affecting thermal comfort – individual human feelings which are much harder to define, because each person has their own preferences for thermal comfort. One can say there is thermal comfort when amount of people saying “I fell badly here” is the lowest [2]. The symptoms of thermal discomfort are intensive sweat production, increment of heart beat frequency, and as a result, the decrease of driver concentration and efficiency.

2. Thermal analysis of refrigerator cycle

The heat flux which should be transferred out of the car cabin is about 2 kW [5][6]. The only way to achieve internal temperature at desire level is use air conditioning systems. An optimum A/C unit should assure thermal comfort under time varying thermal loads with minimal energy consumption. Compressor in the unit is driven by the vehicle engine and therefore considerably increases the fuel consumption. In the paper three types of unit are considered. First with uncontrolled orifice and non controlled compressor (fixed piston displacement, R134a as refrigerant – non controlled cycle), second with thermostatic controlled expansion valve assuring 1K superheating of refrigerant at compressor inlet and externally controlled compressor (piston displacement from 60 to 120 cm^3, R134a – controlled cycle), third with thermostatic controlled expansion valve assuring 1K superheating of refrigerant at compressor inlet and externally controlled compressor (piston displacement from 10 to 50 cm^3, R744 – controlled cycle). All cases work with compressor speed 1000 and 3000 rev/min. Nominally refrigerant charge R134a is 0.44 kg. The charges 0.22 kg (50% nominal) and 0.055 kg (12% nominal) were also considered. For R744 nominally refrigerant charge is 0.15 kg. The charges 0.3 kg (200% nominal), 0.225 kg (150% nominal) and 0.075 kg (50% nominal) were considered. Air temperature changes from 20°C to 45°C. The refrigerator scheme is shown in figure 2. For the simulations commercial software Kuli was used [4]. As it was mentioned, the aim of the investigations was the influence of refrigerant charge and inlet air temperature on the air A/C unit parameters: COP (1), exergy efficiency - η_{Carnot} (2), heat transferred in evaporator - Q_{evap} (3), refrigerant temperature inside evaporator and compressor driving power. The parameters are defined in the following way [6]:

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{comp}}, \tag{1}$$

$$\eta_{carnot} = COP\frac{T_{cond} - T_{evap}}{T_{evap}}, \tag{2}$$

$$\dot{Q}_{evap} = \dot{M}(h_4 - h_3), \qquad (3)$$

where:
T_{cond} - condenser temperature, K,
T_{evap} - evaporator temperature, K,
h_4 - refrigerant enthalpy at the evaporator outlet, kJ/kg,
h_3 - refrigerant enthalpy at the evaporator inlet, kJ/kg,
$\dot{M}$ - refrigerant factor mass flow rate, kg/s.

3. Non controlled cycle

In this case as expansion valve is orifice and everything depends on orifice effective throttle area. If the area is too high the compressor works properly (without fluid droplets) only in some range. If effective throttle area is too low the refrigerant at evaporator outlet is always superheated but the temperature at compressor outlet can be too high. That high temperature involves other problems. First is higher compressor material durability, second is a problem with liquid phase at condenser outlet, especially with higher ambient air temperature.

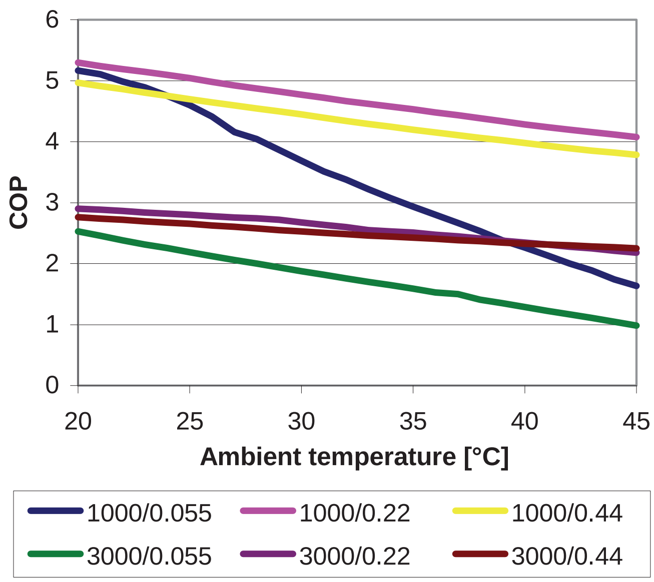

Fig. 1. COP as a function of ambient temperature

When the refrigerant is not liquid or subcooled, efficiency of the system decreases significantly. In this case, at 20°C irrespectively of refrigerant charge, COP is about 5 for 3000 rev/min and 3 for 1000 rev/min and decreases of 1 at 45°C air temperature. For 0.055 kg charge the drop is about 3 for 1000 rev/min and 2 for 3000 rev/min. It is shown in figure 1.

Similar trend can be observed with heat transferred in evaporator. For the charge 0.44 kg and 0.22 kg, the heat flux increases with air temperature. It is shown in figure 6. For 45°C the heat flux is two times higher than for 20°C. For the charge 0.055 kg the situation is opposite – heat flux decreases with air temperature.

There is one advantage of 0.055 kg charge case: compressor power is low: at 3000 rev/min is below 1 kW while for 0.44 kg is twice higher. But here is almost impossible to achieve required temperature inside car cabin in this case. Heat transferred in the evaporator is just too low (figure 2).

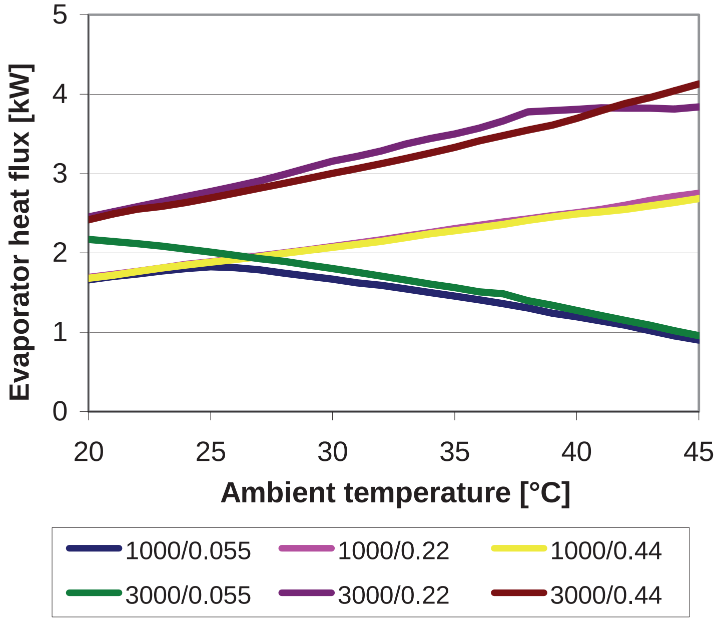

Fig. 2. Evaporator heat flux as a function of ambient temperature

For the 0.22 and the 0.44 kg charge exergy is at the same level in whole temperature range and is about 45-50%. For the 0.055 kg, charge decreases to 25% at 45^{o}C air temperature. It is shown in figure 3.

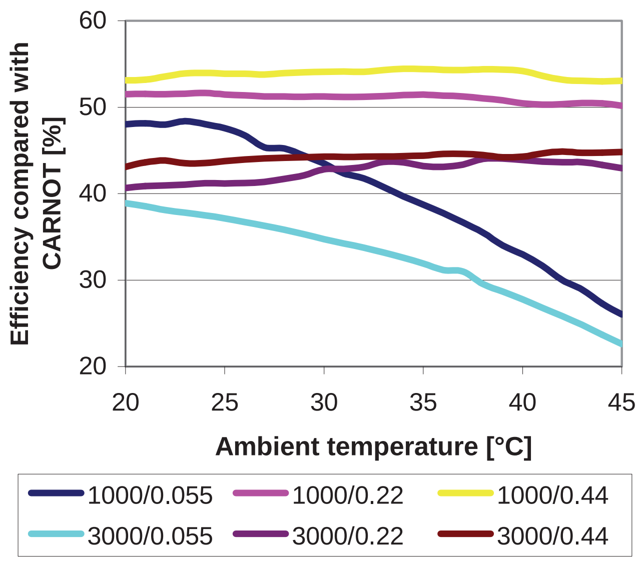

Fig. 3. Exergy efficiency as a function of ambient temperature

4. Controlled cycle

In this case there is no problem with too high temperature, because expansion valve always assures 1K of superheating. So there is no problem with high temperature material durability, because temperature at compressor outlet is lower too. If the temperature at compressor outlet is lower it is also easier to obtain liquid phase at condenser outlet.

One can say the controlled cycle is more “flexible”. In this case heat flux in evaporator can be about 1.5 kW higher than in non controlled one, which means that we can reject 1.5 kW of heat flux more from car compartment. For 0.055 kg charge, compressor inlet (evaporator outlet) temperature is about 40°C at 45°C air temperature.

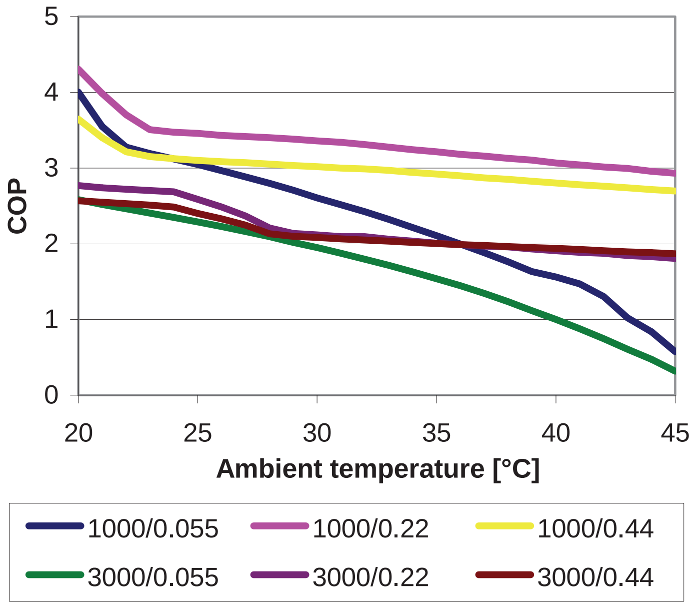

Fig. 4. COP as a function of ambient temperature

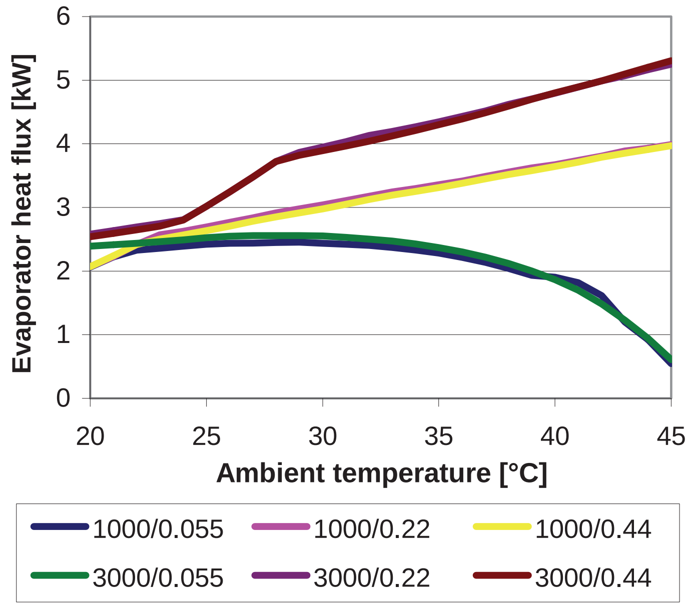

Fig. 5. Evaporator heat flux as a function of ambient temperature

It means that temperature at compressor outlet can be about 100°C. For other charges, inlet temperatures are similar and always below 15°C.

COP tendency is similar to non controlled cycle but the values are a little bit lower (figure 4). The compressor power is always higher than in non controlled cycle. There is also higher heat flux in evaporator for both 1000 and 3000 rev/min cases (figure 5). For the charge 0.055 kg COP is equal to 0.25 at 45°C air temperature.

Efficiency trend is similar to non controlled cycle. For 0.22 and 0.44 kg charge values are a little bit higher than in non control cycle. Opposite situation is for 0.055 kg charge, efficiency decreases to zero with air temperature. It is shown in figure 6.

Comparing the cases one can say that non controlled case is better than controlled one. COP values are higher for uncontrolled, compressor power is lower (lower fuel consumption), but on the other hand heat flux in evaporator is lower and refrigerant temperature is higher.

Additionally it should be stressed out, that for the charge 0.055 kg compressor works only with vapour phase. For the charge 0.11 kg it works with vapour phase above 35°C air temperature. For the charge 0.44 kg liquid always appears in compressor.

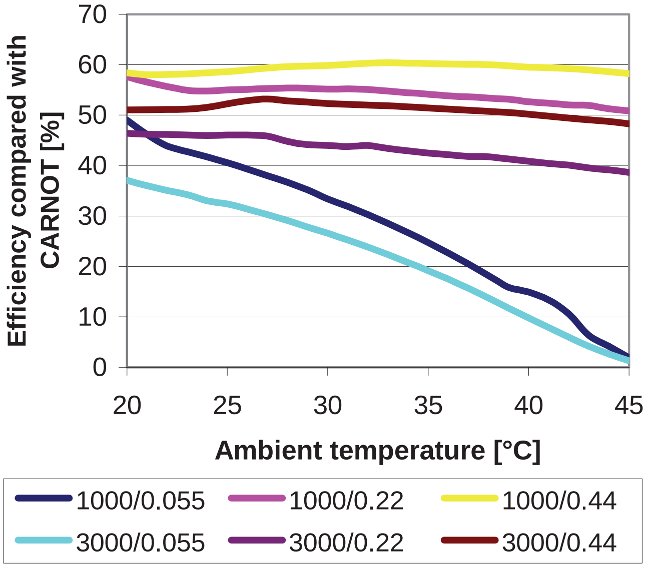

Fig. 6. Exergy efficiency as a function of ambient temperature

All the simulations show how important is proper refrigerant charge in A/C systems. It is impossible to estimate the amount of refrigerant in the cycle without special measuring instruments. There is only one symptom to say that refrigerant charge is too low – the outlet air temperature from A/C is too high.

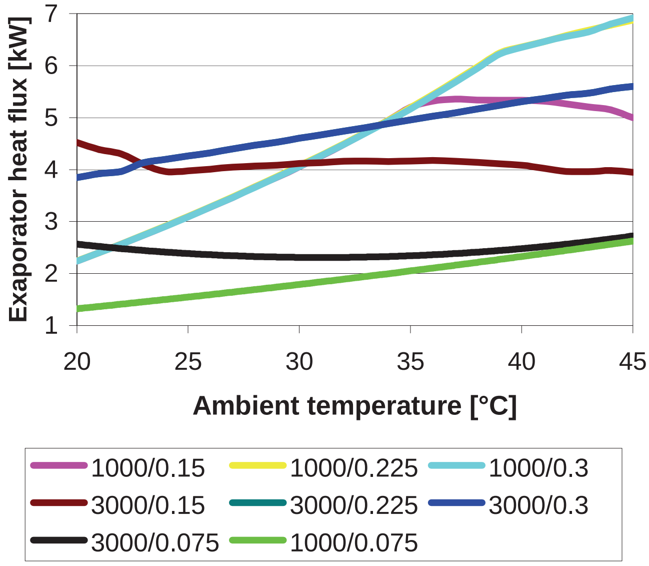

Fig. 7. Evaporator heat flux as a function of ambient temperature

A/C cycle with CO_2 (R744) as refrigerant was also considered. In this case refrigerant is in supercritical phase between compressor outlet and expansion valve inlet. Pressure levels are also different. At compressor outlet is up to 200 bar (about 15 bar for R134a cycle) and at evaporator outlet is about 80 bar (about 1.5 bar for R134a). This cycle can also be called "controlled cycle" because expansion valve always achieve 1K superheating at evaporator outlet.

It can be noticed that evaporator heat flux is much lower for 0.075kg charge both at 1000 and at 3000 rpm. The difference increases with air temperature. Heat flux is over twice lower for 0.075kg than for other charges. It is almost impossible to achieve required temperature inside car cabin in this case. Heat transferred in the evaporator is just too low. It is shown in figure 7. COP value is similar for all charges in whole air temperature range. Except 0.075 kg, it is between 1.5 and 2. This value is lower than R134a cycle but still over 1, even for 45°C air temperature. For 0.075kg charge COP value is near 1 at 1000 rpm and decrease to 0.5 at 3000 rpm (figure 8).

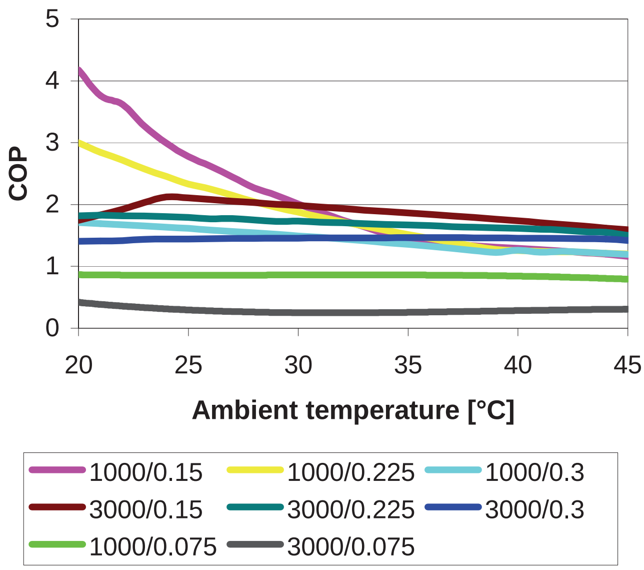

Fig. 8. COP as a function of ambient temperature (R744)

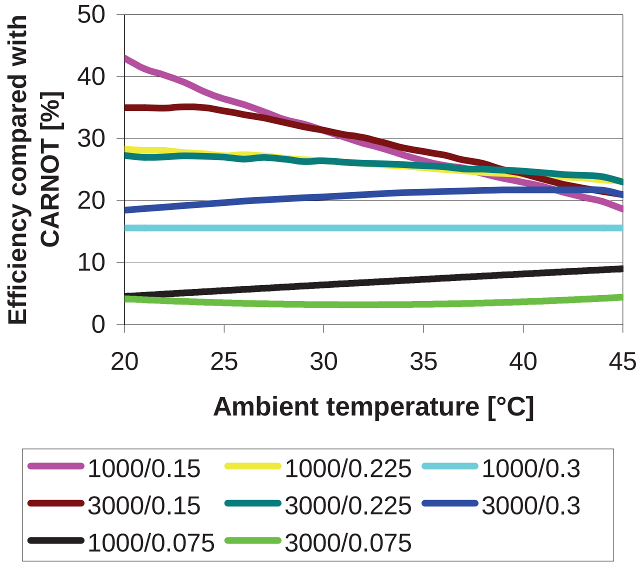

Fig. 9. Efficiency compared with CARNOT as a function of ambient temperature (R744)

Exergy efficiency of the cycle is lower than for R134a. Difference is significant at high air temperature. For R134a cycle efficiency is between 40 and 60% for whole air temperature range: only for the lowest charge decrease to 25%, for uncontrolled or near 0% for controlled cycle. For CO_2 cycle efficiency is lower. The efficiency is the highest for 0.15 kg charge at 20°C and decrease with air temperature, except 0.075 kg charge when is between 5 and 10% for whole air temperature range. It is shown in figure 9.

5. Conclusions

In the paper the thermal analysis of A/C unit cycle are presented. Basing on the simulations to date, it can be noticed that the decrease of the refrigerant charge decreases COP both for R134a and for CO_2 as refrigerant.. For R134a case, decrease is higher in controlled cycle because the temperature in evaporator is higher which causes lower heat flux in evaporator and higher compressor power. Beneficial is that compressor works always with gas phase. For non controlled R134a cycle efficiency is higher but the hazard of compressor work with liquid appears.

For CO_2 case COP values are on the same level for all temperature, except 0.15 kg charge when it decreases significantly with air temperature. It can be noticed that COP values are lower than for R134a cycle. In all cases COP is lower when refrigerant charge is below its nominal value.

There is one advantage of CO_2 usage as refrigerant over R134a. Global Warming Potential (GWP), which is measure representing potential of a substance to contribute to the global warming, is 1300 for R134a and only 1 for CO2. It means 1kg R134a emission is equal 1300 kg of CO_2. Ozone Depletion Potential is zero for both cases.

Car units are not so hermetic like home air conditioning. If it takes into account how many cars are equipped in A/C systems, emission from mobile systems has significant part in global green gas emission.

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