Energy saving measures for automotive air conditioning (AC) system in the tropics

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Energy Saving Measures for Automotive Air Conditioning (AC) System in the Tropics

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ABSTRACT

Automotive air conditioning (AC) in the tropics consumes a large amount of energy. In conventional internal combustion engine cars, it consumes up to 30% of the fuel, while in battery electric cars, AC may reduce the battery range by up to 40% in an urban driving cycle condition. Fortunately, there are various ways to improve the efficiency of automotive ACs in the tropics. In this paper, three energy saving measures are discussed. These include a higher indoor temperature setting, a smaller temperature lift and a separate dehumidification system. The study suggests that increasing the indoor temperature setting alone, from 20°C to 24°C, can save about 22% of the compressor power and increase the coefficient of performance (COP) by up to 13%. Reducing the temperature lift by reducing the temperature difference between the condensing and ambient temperatures can potentially save up to 30% of the compressor power and increase the COP by 45%. An important requirement of this method is the need for a compact and lightweight heat exchanger design. The separation of dehumidification and cooling is very effective as it reduces the thermal load and allows for a higher evaporating temperature. About 50% compressor power saving can be achieved with a dehumidification system. An important requirement is that the energy for regeneration of the dehumidifier must come from waste energy. Finally, combination of all the methods can save compressor power requirement of automotive AC systems in the tropics by up to 70%.

1. INTRODUCTION

Air conditioning (AC) is integral for modern cars, particularly in high-temperature regions like the tropics. Automotive AC regulates air condition in the cabin, particularly the temperature and humidity. This is not only to provide comfort, but also for health and safety reasons because a driver's concentration level changes with the air condition in the cabin (Norin and Wyon, 1992). However, due to the constantly high temperature and high humidity ambient conditions in the tropics, AC systems consume a large amount of energy. Farrington and Rugh (2000) reported that in conventional internal combustion engine (ICE) cars, AC systems consume up to 30% of the fuel; while in battery electric cars, AC may reduce the battery range by up to 40% in an urban driving cycle condition. Moreover, the tailpipe emissions of NO_x and CO increase by more than 70%. Weilenmann *et* al. (2005) reported comparable findings. With the urgent need to make cars more energy efficient due to ever increasing fuel prices and the harmful effects of greenhouse gases, it is important to reduce the energy consumption of automotive ACs.

A typical automotive AC system consists of a compressor, an expansion device, a condenser and an evaporator, as illustrated in Figure 1. In many applications, a dryer or a receiver is installed to increase the reliability of the system. The compressor circulates and compresses the working fluid (refrigerant) to the required pressure and temperature. It is coupled to the engine shaft in an ICE car or driven by an electric motor in an electric car. It takes up most of an AC system's total energy consumption. From the compressor, refrigerant enters the condenser, which is typically installed near the car radiator. Here, heat is rejected from the fluid to the ambient. The refrigerant changes phase from superheated gas to gas-liquid mixture or even to sub-cooled liquid. The fluid then enters the expansion device, where its pressure and temperature drop. This low-temperature fluid then flows into the evaporator, where heat load from the cabin is absorbed. The most common working fluid (refrigerant) is currently R134a. Unfortunately, it has a high global warming potential (GWP) and is being phased out as directed by the Kyoto Protocol. R1234yf has been proposed as the substitute due to its low GWP and ease of retrofitting with existing systems.

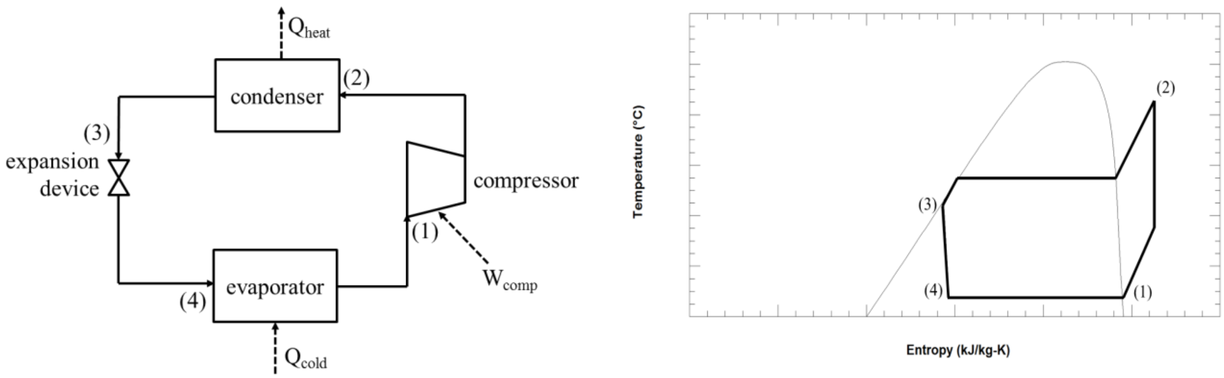


Figure 1: Schematic and temperature-entropy diagrams of a typical AC system

Thermal loads in a car cabin typically consist of four main sources: solar irradiation, enthalpy to cool and dehumidify the air in the cabin, passengers' body heat and heat conducted from car body. Solar irradiation and enthalpy of the air are the most significant heat loads, particularly in the tropics. When no recirculation of air is carried out, the air treatment consumes most of the AC power. For illustration, when the ambient temperature is 30°C and 90% relative humidity, air treatment accounts for more than 50% of the total thermal load, while solar irradiation only accounts for about 30%. This is because of the enthalpy difference that needs to be overcome to dehumidify the air as it has to be cooled to its dew point temperature first, before then reheated to the desired indoor temperature. The enthalpy difference of dehumidification can be up to 80% that is needed for cooling the air alone.

There have been some reported efforts to improve the energy efficiency of automotive AC systems. In general, the two main strategies are to optimize the system and to minimize the thermal load. The first strategy includes, among others, optimization of working parameters, better compressor control (e.g. variable speed compressor) and waste heat recovery. The second strategy includes, among others, window materials with less transmissivity to reduce solar irradiation, reduction of fresh air rate intake and better car cabin insulation. Farrington and Rugh (2000) discussed three ways to reduce AC loads: advanced glazing, recirculated air and advanced thermal comfort control system. Advanced glazing can save about 3% of fuel while recirculation of air can reduce thermal load by 80% in humid climates but the air contaminant concentration in the cabin must be watched carefully. In another work, Qi *et al*. (2010) investigated the use of micro-channel heat exchangers to enhance the performance of mobile AC systems. They found that the COP can be increased by up to 8%.

In this paper, three methods are proposed and investigated. They are: 1) a higher indoor temperature setting, 2) a smaller temperature lift between the condenser and the evaporator and 3) to use a dehumidification system. The possible combinations of these methods are also studied. The focus of comparison is on the compressor power requirements as the compressor typically consumes most of the overall power consumption of an AC system. Coefficient of performance (COP) is compared when relevant. Discussions about practical implementations of the methods are also presented.

2. METHODOLOGY

The investigation was carried out numerically. A computer simulation code was written in MATLAB programming language. Two currently most commonly used refrigerants in automotive AC systems, namely R134a and R1234yf, were considered. All thermo-physical properties of the refrigerants were obtained using the REFPROP routine (Lemmon *et al*., 2007) while those of the humid air were computed based on the method proposed by Yo (1994).

It was assumed that the thermal loads in the cabin consisted of loads from solar irradiation, passengers' body heats, heat from the car body and air treatment (cooling and dehumidification). For simplicity, the solar irradiation was assumed constant at 1 kW/m^2 and the exposed car window area was 2 m^2. These are typical for a sedan in afternoon conditions in Singapore. The window glass is assumed to have a transmissivity of 0.75. There were four passengers in the car, each emitting 120 W of heat. The car body had a thermal conductivity of 1.257 W/m^2.K, temperature of 70°C and effective area of 3 m^2. The air flow rate was 0.06 kg/s (Kim *et al*., 2009). The relative humidity in the car cabin was 60%, in accordance to Singapore Standard SS553:2009, Section 7.2, which specifies that indoor temperature should be between 24°C and 26°C and relative humidity should be less than 65%. The outdoor temperature was varied between 30°C and 34°C, while the relative humidity was between 80% and 90%. The benchmark AC system was assumed to operate with a 10°C superheat at the compressor inlet and a 10°C sub-cooling at the expansion device's inlet. The compressor had a total efficiency of 60%. Pressure losses in the heat exchangers and the tubes were negligible. Expansion process in the expansion device is isenthalpic. The evaporating temperature was 5°C lower than the dew point temperature of the indoor air condition, while the condensing temperature was 20°C higher than the outdoor temperature. In the benchmark AC system, hot and humid air flows through the evaporator to reduce its temperature to below the corresponding dew temperature to remove its moisture. The dew temperature is between 12°C (for indoor temperature of 20°C and 60% relative humidity) and 17.6°C (for indoor temperature of 26°C and 60% relative humidity). The air is then heated to the desired indoor temperature before being blown to the cabin. It is assumed that this re-heating is carried out through heat exchange with the ambient and therefore, does not incur any additional energy consumption.

3. RESULTS AND DISCUSSION

3.1 Higher Indoor Temperature

In Singapore, it is common for people to set their AC to operate with 20°C or an even lower indoor temperature. This is although, as mentioned above, SS553:2009 states that the recommended indoor temperature is between 24°C and 26°C. In the recent years, the government has been educating people to set their AC to 24°C instead, to save energy (Ahmad, 2011). The effectiveness of setting the indoor temperature higher is shown in Figures 2 and 3.

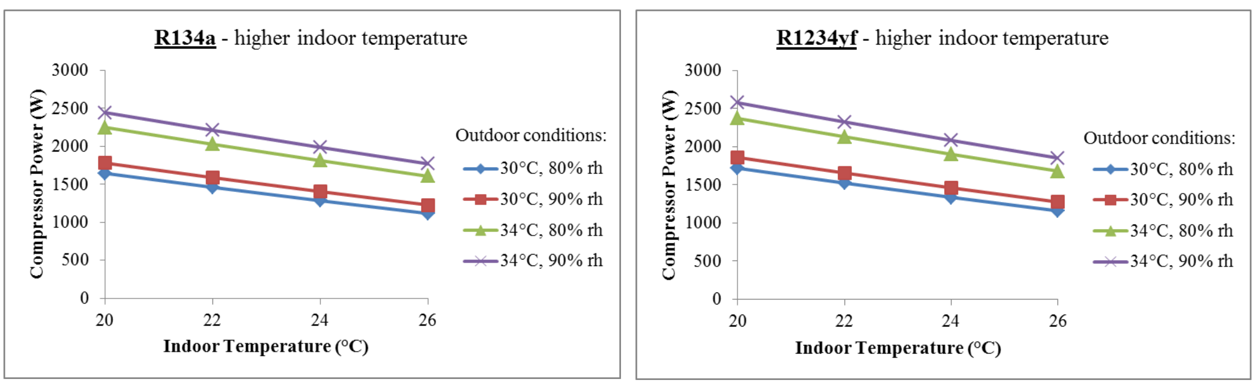


Figure 2: Compressor power requirements at various indoor temperatures

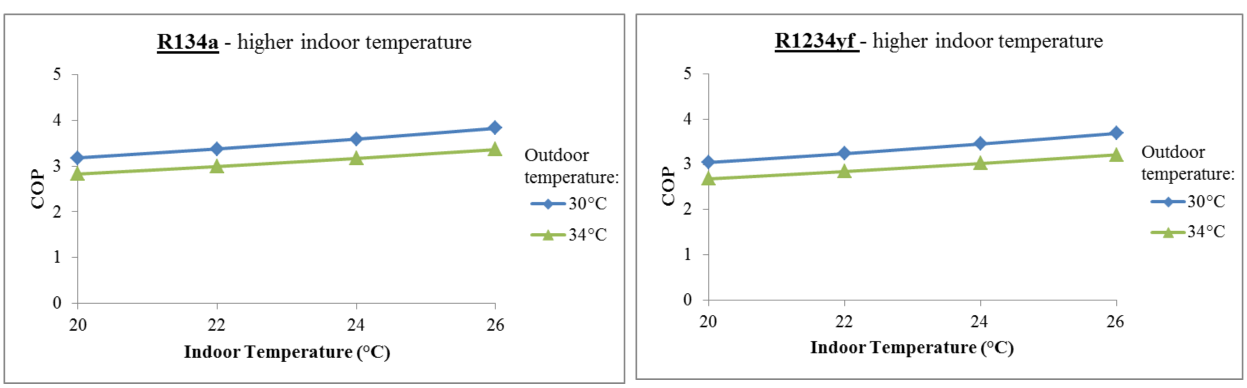


Figure 3: COPs at various indoor temperatures

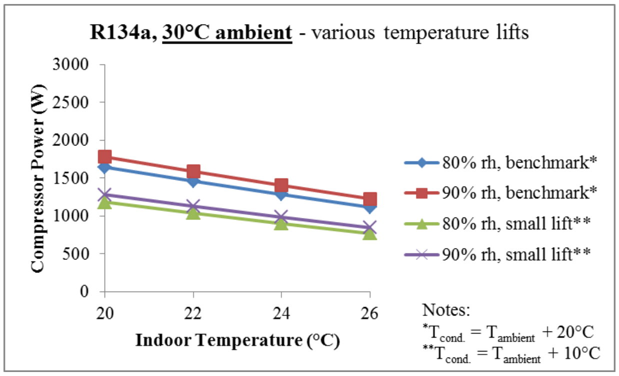
It can be seen that by increasing the indoor set temperature from 20°C to 24°C, the compressor power requirement can be reduced by up to 22%. If the temperature is increased even higher to 26°C, the saving can be more than 30%. However, in practice 26°C is not comfortable for many people. Therefore 24°C is more practical. In terms of COP, an increase of indoor temperature from 20°C to 24°C increases the COP by up to 13%. It is important to remember that the savings are achieved without any additional component or major modification to the system. Therefore, this is one of the simplest ways to reduce energy consumption of AC systems. The energy saving is obtained because with a higher indoor temperature, the corresponding dew point temperature is higher. Therefore, the evaporating temperature is also higher. The condensing temperature, on the other hand, remains unaffected and so, the pressure difference that the compressor has to provide is smaller. This results in smaller compressor power requirements and higher COPs.

3.2 Smaller Temperature Lift

A certain temperature difference is required between the refrigerant in the heat exchanger (evaporator or condenser) and the surrounding air to allow for heat exchange to occur. In the benchmark system, this difference is 5°C between the evaporating and the dew point temperatures at the evaporator; and 20°C between the condensing and the outdoor temperature at the condenser. This results in a temperature lift of around 40°C between the evaporating and the condensing temperatures, which corresponds to about 9 bar of pressure difference that the compressor has to provide in both the R134a and R1234yf systems. If a more efficient heat exchanger is employed, the temperature difference between the refrigerant and the air at the heat exchangers can be reduced without significantly increasing the size of the heat exchangers. This approach reduces the system's temperature lift, which corresponds to a reduced pressure difference across the compressor and hence, the compressor power reduces. This method has been tested for buildings (Wyssen *et al.*, 2010).

In this study, the temperature difference between the condensing and the outdoor temperature is reduced to only 10°C. The corresponding temperature lift is, therefore, also reduced by 10°C. The impact to the compressor power consumption and COP are shown in Figures 4-6. The figures show that the smaller temperature lift can reduce the compressor power requirement by more than 30% while the COP can increase by up to 45%. This is because the reduction of the temperature lift to 30°C across the evaporator and condenser reduces the pressure difference to only about 6 bar, as compared to 9 bar in the benchmark system. When this method is combined with a higher indoor temperature setting of 24°C instead of 20°C, the compressor power requirement is reduced by up to 45% while the COP increases by more than 60%.

As mentioned above, a more efficient heat exchanger is necessary for this method. In building applications, where size and weight are less important, bigger heat exchangers can be employed. For illustration, in the case simulated here, the size of the condenser needs to be doubled as the temperature difference is halved. However, for mobile applications, an advanced heat exchanger design that is compact and lightweight, but yet, is able to provide the required heat exchange must be employed. Micro-channel heat exchangers, like that studied by Qi *et al*. (2010), are promising as the heat transfer coefficient is higher than in conventional heat exchangers.



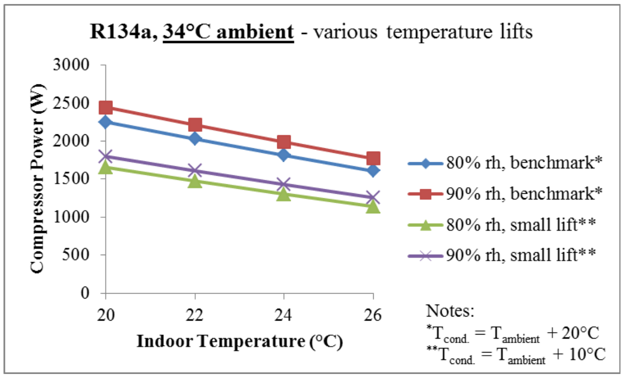


Figure 4: Compressor power requirements (R134a) with various temperature lifts

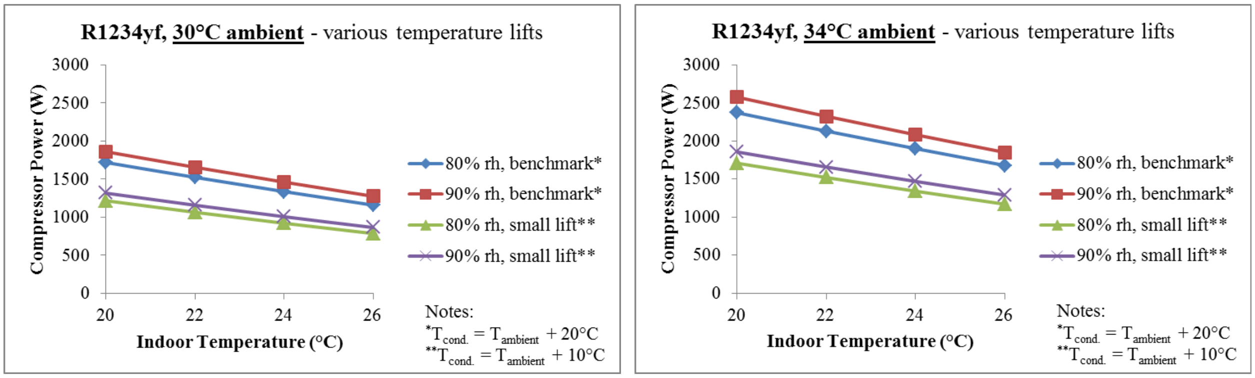


Figure 5: Compressor power requirements (R1234yf) with various temperature lifts

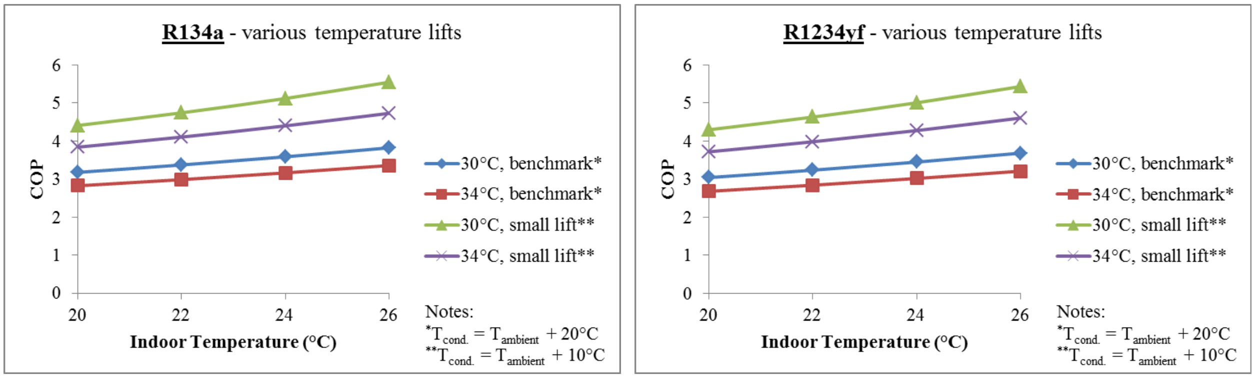


Figure 6: COPs of systems with various temperature lifts

3.3 Dehumidification System

Another method to reduce the energy consumption of AC in the tropics is to separate the dehumidification and cooling of the air, as illustrated by Figure 7. In a normal AC system, fresh air is cooled to its dew point temperature to remove the moisture. This temperature is much lower (about 12°C) than the indoor temperature. The cold and dry air is then reheated to the desired temperature before being blown into the cabin. In the investigated method, dehumidification and cooling are separated. The air is first dehumidified by using a dehumidification system. This process usually increases the air temperature. This hot and dry air is then cooled by letting its heat to be released to the ambient air before being cooled further to the desired temperature by the AC's evaporator. In this study, it was assumed that the air is 5°C hotter than the ambient temperature when it enters the evaporator.

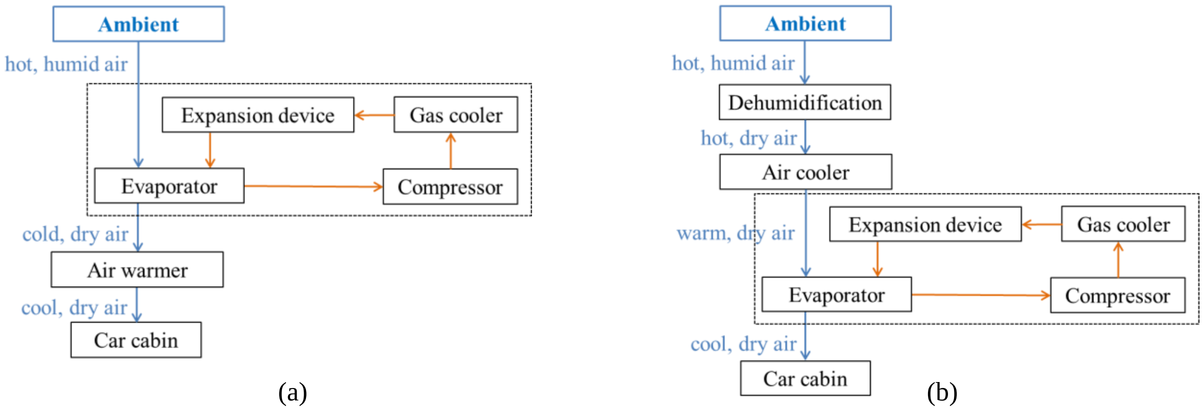


Figure 7: Schematic diagrams of automotive AC systems: (a) without and (b) with a dehumidification system

The effectiveness of the method is shown in Figure 8. The figure shows that by using a dehumidification system with the same indoor temperature setting, the compressor power consumption can be reduced by more than 50%. This large reduction is possible because the enthalpy difference for dehumidification is significantly larger than that for cooling. If the dehumidification system is combined with a higher indoor temperature setting of 24°C, the compressor power requirement can be reduced by up to 60%.

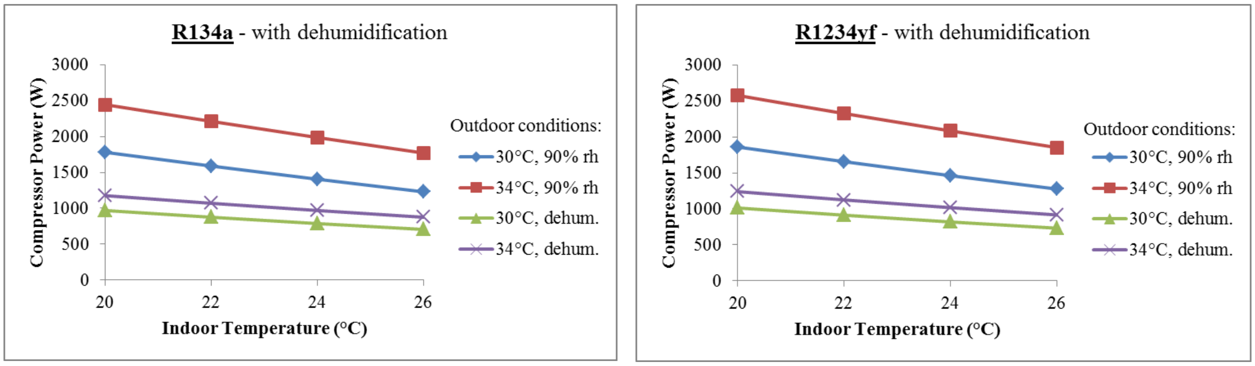


Figure 8: Compressor power requirements with and without dehumidification, evaporating temperature is at the benchmark value of 5°C below dew temperature of the indoor condition

It is important to note that the results in Figure 8 are obtained with an assumption that the evaporating temperature is still 5°C below the corresponding dew point temperature. However, with a dehumidification system, the evaporating temperature can potentially be increased to a level that is closer to the indoor temperature. This will make power saving even more dramatic. For example, if we assume that the evaporating temperature is 5°C below the indoor temperature and the refrigerant enters the compressor at the indoor temperature, the compressor power requirements are shown in Figure 9 where the power saving is now more than 60% at the same indoor temperature. It is useful to note that the effectiveness of the dehumidification system is highly dependent on the air flow rate. For example, when the air flow rate of the data in Figure 9 is halved, the power saving at the same indoor temperature condition is only 54%, instead of 60%. On the other hand, when the air flow rate is doubled, the power saving is as high as 68%.

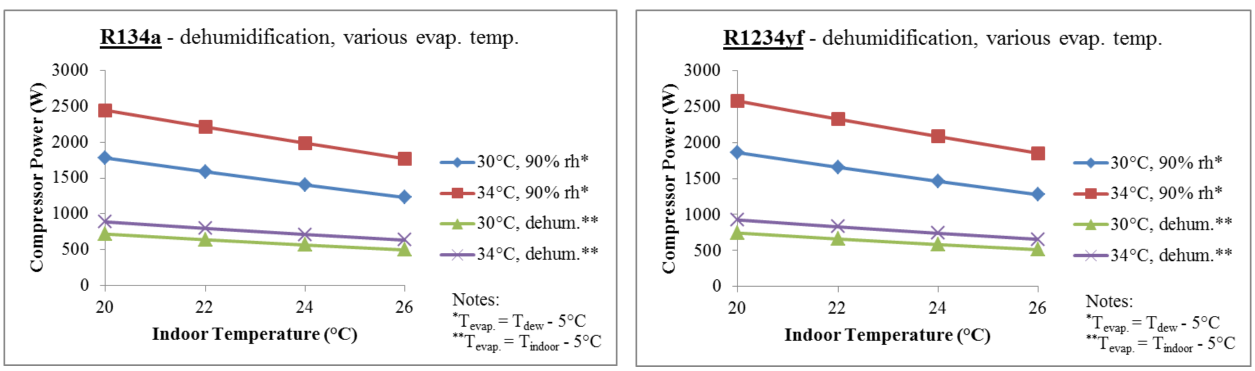


Figure 9: Compressor power requirements with and without dehumidification, at various evaporating temperatures

This method has been used in buildings (Mei and Dai, 2008, La *et al.*, 2010). However, as far as to the authors' knowledge, no mobile application has been reported before. A desiccant based dehumidification system requires regular regeneration. The energy required for regeneration must be supplied from waste energy to make the energy balance positive. In cars, this energy can be from the waste heat of the engine or from the condenser. A design challenge in mobile applications is to design the device small and lightweight. Another practical challenge that needs consideration is the need to rearrange the car components to accommodate the required space of the dehumidification system, to allow for the change of air flow route and to provide the required heat for regeneration.

3.4 Combined Methods

After discussing about the possible methods to reduce energy consumption of automotive AC systems separately, we will now combine various methods. The results are shown in Figure 10. At the same indoor temperature setting, combining dehumidification system and a smaller temperature lift can save up to 65% of compressor power. When the indoor temperature is increased from 20°C to 24°C, a dehumidification system is used and the temperature lift is smaller by 10°C as compared to the benchmark system, the compressor power requirement is reduced by up to 70%.

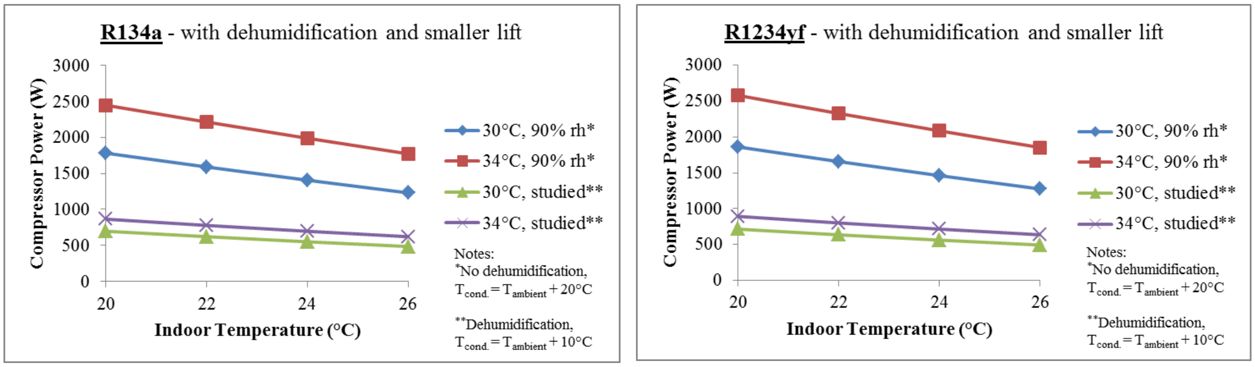


Figure 10: Compressor power requirements with dehumidification and a smaller temperature lift

4. CONCLUSIONS

Car air conditioning (AC) consumes a large amount of energy, up to 30% of the fuel in internal combustion engine cars, and up to 40% of the driving range in battery electric vehicles. In this study, three methods and the possible combinations have been proposed and investigated to reduce car AC energy consumption in the tropics. They are:

- To use a higher indoor temperature setting
- To use a dehumidification system to dehumidify the air before cooling the air at the evaporator
- To use a smaller temperature lift between the condenser and the evaporator

The basic working principle of each method was discussed. The effectiveness of each method and the possible combinations were compared. The focus was on the compressor power requirements. Coefficient of performance (COP) was compared when relevant. Discussions about practical implementations of the methods were also presented. The results are summarized in Table 1.

Table 1: Summary of the effectiveness of the methods

No.	Method	Power Saving Potential	COP Increase Potential	Remarks
1	Higher indoor temperature (from 20°C to 24°C)	22%	13%	No additional component is necessary
2	Smaller temperature lift (from 20°C to 10°C difference at the condenser)	30%	45%	More advanced heat exchangers are required
3	Smaller temperature lift and higher indoor temperature (from 20°C to 24°C)	45%	60%	Same as remark (2)
4	Dehumidification system	50%	-	A dehumidification system is needed, external waste energy is used for regeneration, rearrangement of car components maybe necessary, effectiveness depends on operational air flow rate
5	Dehumidification and higher indoor temperature (from 20°C to 24°C)	60%	13%	Same as remark (4)
6	Dehumidification and smaller temperature lift	65%	45%	Same as remarks (2) plus (4)
7	Dehumidification, smaller temperature lift and higher indoor temperature (from 20°C to 24°C)	70%	60%	Same as remarks (2) plus (4)

From the results, the following conclusions were drawn:

- By setting the indoor temperature at 24°C instead of 20°C, about 22% saving of the compressor power consumption and 13% increase in COP can be obtained. This is the simplest energy saving measure. It requires no additional component to the existing AC systems. It only requires the passengers to set the desired indoor temperature higher.
- The reduction of the lift between the evaporating and condensing temperatures can save up to 30% of compressor power and increase COP by about 45%. However, an advanced heat exchanger design that is compact and lightweight is necessary, particularly in automotive applications.
- The employment of a dehumidification system is very effective in the tropics due to the high humidity of the ambient air. The energy saving can be as high as 50%. An important note is that the regeneration process must be powered by waste energy to make the energy balance positive. The implementation may be costly due to the need of a dehumidification system and rearrangement of components may be necessary for the installation of the system.
- Finally, the combination of all the methods can potentially cut up to 70% of the power consumption of automotive AC systems in the tropics.

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