Comparative Study of R134a and R744 Driven Solar Assisted Heat Pump Systems for Different Applications

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Abstract. A solar assisted heat pump (SAHP) system is considered in this study where space cooling, water heating, drying and desalination are carried out using solar energy, ambient energy and the waste heat available from air conditioning system. The integration of different applications with SAHP system leads to many benefits, but the most significant is the energy conservation issue where the prices of fossil fuels are increasing. In recent years, researches have been conducted worldwide to improve the performance of these systems. These systems usually use synthetic refrigerant, such as R134a, which contributes to many atmospheric problems. Currently, embracing natural refrigerants, such as, carbon dioxide in SAHP has become a trend specifically after Kyoto agreement to reduce global warming and improve the performance of SAHP systems. In this paper, comparative study using R134a and R744 in SAHP systems have been considered. The comparison includes the most significant results of previous work relevant to this issue, and the thermo physical properties of the two refrigerants when used in SAHP.

1. Introduction

Heat pump (HP) system is a conventional vapor compression air conditioning system which collects or absorbs the heat from a heat source, usually air conditioning room, and dissipates it to the atmosphere [1-3]. Air-conditioners in tropical countries, such as Malaysia, are used almost in all residential, industrial and office buildings. The amount of waste heat from air conditioners discharged to the environment is considered very large. Exploiting these energy resources instead of throwing it away is considered a viable option to reduce the global warming and other environmental issues. It is also considered an excellent solution for energy conservation issue where the price of oil and other non-renewable energy sources are increasing due to many reasons [2,3]. In recent years, researches have been conducted worldwide in order to modify the performance of heat pump systems and make it more reliable and efficient. The attempts include exploiting the waste heat from condenser to be used for different thermal applications such as drying, water heating, and desalination of seawater. Replacing the synthetic refrigerants, such as R134a, with natural refrigerants e.g. R744 has also been under study. Attempt to reduce the irreversibility of the cycle by replacing the expansion valve with turbine, ejector, and using internal heat exchanger has also been made.

Solar assisted heat pump (SAHP) is a conventional system where solar energy is used as the main or supplementary heat source. Integration of solar energy with conventional heat pump system is considered viable solution to reduce the dependancy on fossil fuel, and improve the performance of the system. SAHP systems usually use conventional synthetic refrigerants such as R134a. Recently, many researchers are moving toward embracing and using carbon dioxide because of environmental
issues such as Ozone depletion and Global warming. Besides that, CO₂ has thermodynamic properties which enable it to be competitive and most promising alternative of conventional refrigerants, which will be discussed in this paper [4]. Using CO₂ in SAHP systems makes the system works under the transcritical thermodynamic cycle not the traditional vapor compression cycle [5-7].

In this paper, the focus is on using carbon dioxide as an alternative of synthetic refrigerants, mainly R134a, in heat pump and solar assisted heat pump systems for space cooling, water heating, drying, and desalination of Seawater. Comparative study between using R744 and R134a have been conducted based on available literature and previous researches.

![Figure 1: Schematic Diagram of Carbon Dioxide Solar Assisted Heat Pump System for Space Cooling, Water heating, Drying, and Desalination](image-url)
2.0 The System
The schematic diagram of a Carbon Dioxide driven solar assisted heat pump system for space cooling, water heating, drying, and desalination of seawater is shown in Figure 1. The system comprises of mainly a R-744 compressor, water tank, room evaporator, evaporator collector, flat plat water collector, expansion valves, and a desalination unit. Air Gap Membrane Desalination (AGM) unit is used to convert seawater into fresh drinking water. Hot air drying unit is used in the system for clothes drying purpose. The system works under supercritical or transcritical cycle where heat rejection process (high pressure side) occurs at the supercritical region (above 73.8 bars), and the evaporation process (low pressure side) occurs at the sub-critical region. Special design is required for the system components because the pressure inside the pipes is 5-10 times higher than those system which work using conventional synthetic refrigerants such as R-134a.

2.1 SAHP for Space Cooling, Water Heating
Lorentzen and Petersen [5] experimentally investigated the performance of a CO$_2$ system for automobile air conditioning. A comparison between CO$_2$ and R12 was conducted with equal heat exchanger dimensions. The results showed that CO$_2$ and R12 efficiencies were approximately equal. Based on this study, many projects were initiated in USA and European Union countries. Cecchinato et al. [6] conducted a detailed comparison between heat pump system using CO$_2$ as refrigerant and another one where HFC 134a was used. They found out that Carbon Dioxide showed better results and it is a potential alternative for synthetic refrigerants. In the same year, Sarkar [7] investigated, both theoretically and experimentally, the performance of carbon dioxide HP system for simultaneous cooling and heating. A simulation model of CO$_2$ heat pump dryer also was developed by him. It was concluded that carbon dioxide showed better performance than R134a in HP systems for drying applications, but poorer than R22. The effect of air mass flow rate, ambient temperature, recirculation air ratio, and dryer efficiency were significant on the system performance. The experimental and simulated results of the cooling and heating system showed that the effect of water inlet temperature of the gas cooler is significant on the system performance unlike the effect of mass flow rate.

Carmo et al. [8] designed and built a CO$_2$ heat pump system (Known as Thermal Battery “TB”) for simultaneously heating and cooling. The experimental results showed that thermal battery system could supply water heating with temperature greater than 70 as well as cooling service with temperature less than 10 for commercial and residential building. They also performed optimization study for the system. The results of the optimization relied on the basic operational parameters, such as, water mass flow rate, and the inlet and outlet temperature in the gas cooler. They found out that the COP of the TB system could reach a value more than 4, and it was increasing with increasing mass flow rate in the evaporator. Hawlader and Schaochum [9] designed and experimentally investigated the performance of a solar assisted heat pump system for air conditioning, water heating, and drying using R134a as the refrigerant of the system. The experiments were conducted under the meteorological conditions of Singapore. The average COP of the systems for 24 hours operating was around 4, while the maximum value of it was 6. It is concluded that this system can ensure long term operation, and capable of reducing a lot of buildings thermal costs particularly buildings located in tropical region.

Kokila and Rajakumer [10] theoretically compared the performance of carbon dioxide driven solar assisted heat pump water heating system with conventional (Thermo syphon) solar water heating system. Numerical analysis of the direct expansion SAHP system was introduced as well. Stene [11] compared the performance of CO$_2$ HP water heating system with other systems using conventional refrigerants and concluded that the system achieved 20% higher COP at different evaporating temperature, as shown in Figure 2.
2.1 SAHP Systems for Drying
Drying is an important process which is nowadays widely used in many industries, such as, chemical industry, timber, pharmaceuticals, food, and paper industry. This process usually require great amount of energy that sometime accounts for up to 15% of all industrial energy usage, often with relatively low thermal efficiency in the range of 20-25% [12]. Solar assisted heat pump system for drying has been widely used in industry since many years, and a lot of researches conducted on it. Manuel et al. [13] discussed the shortcomings and the economic issues related to the tumbler dryer technology, and they proposed a solution for the energy conservation in the laundry drying. Hawlader et al. [14-15] investigated the effects of hot air drying, vacuum drying, and freeze drying methods on fruits’ quality. In this study, hot air was replaced by Carbon Dioxide and Nitrogen gases. Guava and Papaya were dried under different conditions. The experimental results showed that using inert gas such as Carbon Dioxide in heat pump drying system lead to a better physical appearance of the product, much better quality, better nutritional value of the product, and faster rehydration process. Sarkar et al. [16] developed a simulation model to study the performance of carbon dioxide heat pump dryer and compare its performance with conventional dryers operating with R-22 and R-134a refrigerants.

2.2 SAHP Systems for Desalination
The most abundant substance in the world is water and about 97% of the water is seawater while the rest is fresh water. According to some reports [17], about one billion people are not able to drink fresh water across the world. Billions of Dollars are currently spent worldwide on different desalination technologies for producing fresh water from brackish and seawater that could meet the demand of drinking water. Bahar and Hawlader [18] reported that about 60 Million RM have been spent on Seawater desalination project in Sarawak- Malaysia. According to Hawlader et al. [19] and Carter [20], integration of renewable energy in the conversion of seawater into fresh water by using thermal distillation process, such as air gap membrane distillation shows significant potential. Tjandra [21] conducted a study on solar assisted heat pump desalination system. The system consisted of a solar assisted heat pump working on R-134a, and a single effect desalination unit. Byrne et al. [22] investigated the performance of heat pump system for simultaneous cooling and desalination. Air Gap MD type was integrated with heat pump system.

**Figure 2:** Calculated COP as a function of Evaporation Temperature $t_0$ [°C]
(Source of Data: Stene, J [11])
3. Thermo physical properties of Carbon Dioxide (R-744)
Pressure drop and heat transfer process in solar assisted heat pump systems are strongly affected by the transport properties of the refrigerant, such as, thermal conductivity and viscosity. Thermal conductivity of the refrigerant influences the heat transfer coefficient in both single and two-phase flow. Viscosity affects the liquid flow behavior, two-phase heat transfer, and pressure drop in the system. It is reported that thermal conductivities of CO$_2$ in both saturated liquid and vapor are 20 and 60% higher than liquid and vapor thermal conductivity of R134a respectively. On the other hand R134a has liquid viscosity 40% lower than carbon dioxide. In the supercritical region, the high pressure and temperature are not coupled, so that they can be regulated independently to obtain the optimal operating conditions, as shown in Figure 3.

![Figure 3: Pressure- Temperature Phase Diagram of Carbon Dioxide][23]

3.1 Heat Transfer Coefficient of R-744 compared to HFC R-134a
Mastrullo et al. [24] experimentally compared the heat transfer coefficients (HTC) of carbon dioxide and R134a during flow boiling in a 6mm diameter horizontal and circular tube at similar operating conditions. A comparison was performed to accurately evaluate the effect of the thermodynamic and transport properties, such as, vapor quality, the refrigerant mass flow flux, saturation temperature, and heat flux on the heat transfer coefficients. However, it is concluded that the HTC of the Carbon Dioxide is always higher than R134a at same operating conditions. Therefore, HTC of the R134a is dependent on mass flux and independent on saturation temperature whereas HTC of R744 is dependent upon saturation temperature and independent of mass flux.

4. Comparison between R-744 and R-134a Compressors
The pressure in CO$_2$ heat pump system is usually 5-10 time higher than other refrigerants which requires proper design for the system component especially compressor and gas cooler. For instance, suction and discharge pressures for R134a compressor at 0 °C and 80 °C are 3 and 27 bars, while suction and discharge pressures for CO$_2$ compressor at 0 °C and 80 °C are 35 and above 120 bars, respectively. The wall of Carbon Dioxide compressor is thicker, but the compressor itself is much
smaller compared to conventional compressor of HFC refrigerants because of the high volumetric capacity of CO₂, as shown in Figure 4 [25].

![R134a Compressor vs. CO₂ Compressor](image)

**Figure 4**: Pictures of R-134a and Carbon Dioxide Compressors [25]

According to Kruse et al. [26] CO₂ compressors consume energy 18-37% less than compressors for conventional refrigerants (Mainly R-134a). Figure 5 shows comparison between CO₂ and R-134a Compressors without fans, motors and lights.

![Comparison of Power Consumption](image)

**Figure 5**: Comparison of Power Consumption from R-744 and R134 Compressors (Source: Kruse et al. [26])
5. Conclusions
Using carbon dioxide in Solar assisted heat pump system for different applications could lead to a significant improvement in the thermal performance of the system and reduce the global warming issue. Comparative study between using R134a and R744 in SAHP system have been presented in this paper. Drying and desalination technolgoies consume large amount of energy which usually contribute to more than 50% of these technolgoies costs. This energy usually obtained from electricity. Integration of drying and desalination technologies with solar assisted heat pump system could reduce the dependency on fossil fuel to operate them which will reduce the cost and make them envirementally friendly applications.

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