Impacts of room temperature on the performance of a portable propane air conditioner

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Abstract
The performance of a portable propane air conditioner system, in which the temperatures of the air passing over the condenser and evaporator are equal, has been experimentally investigated under different room temperatures and refrigerant charge levels. The research has been carried out in a range of room temperatures from 20°C to 35°C and in undercharge, standard charge and overcharge conditions. The results show that, at higher room temperatures, the refrigerant temperature in all parts of the system, the density of the refrigerant at the inlet and outlet of the condenser, mass of the refrigerant in the compressor, the mass flow rate of the refrigerant and the cooling capacity of the system in either the undercharge or full charge condition, the specific cooling capacity of the undercharge system, the useful work of the compressor, and the maximum pressure of the refrigerant increase. The increase in room temperature decreases the density of the refrigerant at the inlet and outlet of the capillary tube, the mass of the refrigerant in the capillary tube, the refrigerant subcooling at the inlet of the capillary tube, the maximum velocity of the refrigerant and the coefficient of performance. In addition, the increase in room temperature at overcharge condition causes an increase in the mass flow rate, cooling capacity and specific cooling capacity to a maximum value followed by their decrease. The most important difference between a portable air-conditioner and a non-portable system is the increase in cooling capacity with an increase in room temperature in full charge condition.

Nomenclature:

A : cross-sectional area of pipe (m^2)
CoP : coefficient of performance
h : enthalpy (kJ/kg)
k : specific heat ratio
$\dot{m}$: mass flow rate (kg s^{-1})
$\dot{Q}$: heat rate (kW)
R : gas constant
SC : specific charge (W/g)
U : velocity (m s^{-1})
$\dot{W}$: power (kW)
w : specific work (kJ/kg)
ρ : density (kg m^{-3})

Subscript:

1 : compressor inlet
2 : condenser inlet
3 : capillary tube inlet
4 : evaporator inlet
comp : compressor
cool : cooling
p : pipe
r : refrigerant

s : isentropic

1. Introduction

The use of hazardous synthetic refrigerants such as R12 and R22 is scheduled to be phased out due to their contribution to global warming and ozone depletion. Hydrocarbon refrigerants have zero effect on the ozone layer and a negligible effect on global warming (Oberthur et al., 1997), and are proposed to replace synthetic refrigerants. There are many recent published studies examining the performance of refrigeration and air conditioning systems using hydrocarbon refrigerants. One of the focus areas of these studies is the assessment of the performance of different systems at different ambient temperatures. Previous studies have not addressed the effect of ambient temperature on portable air-conditioners in which the temperature of the air surrounding the condenser and evaporator are the same. This research aims to narrow the gap in the literature with an empirical approach. It should be noted that in the case of portable air-conditioners, the condenser and evaporator are both located in the room subject to cooling. Therefore, the term "room temperature" refers to the temperature of air entering the condenser and evaporator, and differs from the outside temperature. The room temperature depends on the cooling capacity of the air-conditioner, ambient temperature, size of the room, wall thickness and material type, and many other parameters affecting heat transfer. In this research, the effect of room temperature on the temperature and density of the refrigerant, the degree of subcooling, the maximum velocity of the refrigerant, the mass flow rate of refrigerant, the cooling capacity of the air-conditioner, the specific cooling capacity, the work of the compressor, the coefficient of performance and the maximum pressure of refrigerant have been assessed.

2. Literature review

Previous studies show that a change in ambient temperature has a significant impact on the performance of refrigeration and air conditioning systems. It was found that an increase inthe temperature of the air adjacent to the evaporator, not only increases the refrigerant temperature in the evaporator (Fatouh et al., 2010), but also increases the condensing temperature (Fernando et al.,2004). Corberán et al. (2011),in their research with propane as the refrigerant, found that the lower the source temperature(evaporator temperature), the lower the density of the refrigerant in the evaporator under the same refrigerant charge. The increase in density at higher ambient temperatures is due to the increase in condensing and evaporating pressures (Herbert-Raj et al.,2011, Teng et al., 2012 , Kim et al., 2012, and Kim et al., 2014). Choi et al. (2002), using R22 in their research, showed that the degree of subcooling decreases with the increase in ambient temperature. Nilpueng et al.(2011) reported that increasing ambient temperature and keeping the evaporator temperature constant, increases the pressure difference across the short capillary tube, which in turn increases the velocity of the refrigerant.

The rise in ambient temperature has a significant impact on the refrigerant mass flow rate. Fatouh et al (2010) found that, as the temperature of the air surrounding the evaporator increases, the condenser temperature and the mass flow rate increase. They concluded that the increase inthe mass flow rate is due to the increase in vapor density of the refrigerant. Choi et al. (2002) reported that the mass flow rate of the refrigerant increases with the increasing temperature of water used to cool the condenser. The increase in the mass flow rate is mainly due to the increase in the pressure difference across the capillary tube. Two separate studies by Rodrigez (1995) and Farzad (1990)also concluded that the increase in ambient temperature increases the mass flow rate. The drop of heat source temperature and maintaining the condenser temperature decrease the evaporation pressure, which results in an increase in the pressure difference across the short-tube orifice and leads to an increase in the refrigerant mass flow rate (Nilpueng et al., 2011).

The cooling capacity of non-portable systems is affected by ambient temperature. Farzad (1990), in research using an air conditioner filled with R22, found that at full charge and overcharge conditions, the cooling capacity of his air conditioning system decreased with the increase in ambient temperature which contrasted with the undercharge condition. Rodriguez (1995), in research using R22 refrigerant, found that the cooling capacity of the system is highest when the outdoor temperature is the lowest. Choi et al. (2002), using a 3.5 kW heat pump filled with R22, found a similar result. In their research, the temperature of water entering the evaporator was maintained at a constant temperature of 24°C, while the temperature of the condenser cooling water was raised from 30°C to 42°Cwith an interval of 4°C. Martinez-Galvan et al. (2011), in a research using a 16 kW propane chiller prototype found a decrease in the cooling capacity with the increase in ambient temperature. They maintained the temperature of water entering the evaporator at12°C, and raised the temperature of cooling water entering the condenser from 25°C to 40°C with an interval of 5°C. A similar result was found by Corberán et al. (2011) who used a 16 kW propane chiller prototype and the same temperature range as in the work of Martinez-Galvan et al. (2011). Similar results were also found by (Palmiter et al., 2011).

Two studies by Choi et al. (2002) and Wu et al. (2012) concluded that the increase in the compressor power is due to the rise in outdoor temperature. Farzad (1990) found that the increment of power at a lower refrigerant charge is higher than that at a higher refrigerant charge.

Many studies reported the decrease of coefficient of performance with the increase in ambient temperature, regardless of the refrigerant charge level (Choi et al., 2002, Martinez-Galvan et al.; 2011; Corberán et al., 2011;Kimet al., 2012; Kim et al., 2014). This result can be explained by the decrease in the cooling capacity and the increase in the compressor work as ambient temperature increases. However, Kim et al. (2014) found that the coefficient of performance increases with the increase in source temperature while maintaining the condenser temperature.

3. Methodology and instrumentation

This study experimentally investigates the effect of ambient temperature on the performance of a portable propane air conditioner. The normal charge of the system is 300 grams of propane. Previous studies show that the impact of ambient temperature could be different at different refrigerant charge levels. Therefore, the experiments were carried out at three refrigerant charge levels of 263.10 grams (-12.3%, undercharge), 302.93 grams (+0.98% overcharge, assumed to be normal charge), and 390 grams (+30%, overcharge). The experiments were performed at six ambient temperatures ranging from20°C to 35°C with an interval of3°C. The air-conditioner was placed in a tent, and air temperature was controlled within ±0.5°C of the desired value using an electrical heater. The air conditioner is supplied by a flexible duct which vents the warm air from the condenser to the outside. The time required to reach a steady state condition in each experiment depended on the room temperature and desired temperature, but was usually in the order of two hours. However, due to unavoidable changes of ambient temperature during the experiments, it was necessary to open/close the tent windows to approach or maintain the desired temperature. The whole process was recorded, and the results were selected for further analysis when the room temperature, with an accuracy of ±0.5°C, was maintained at least for 10 minutes.

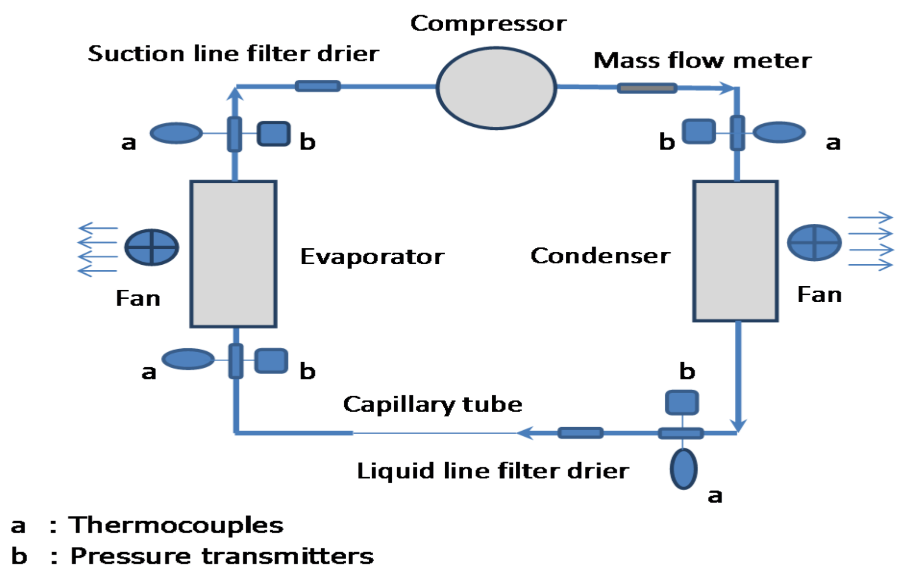

Figure 1: Schematic diagram of the portable air conditioner and instrumentation

A Coriolis mass flow meter was installed at the compressor outlet to measure the mass flow rate of the refrigerant. The Coriolis mass flow meter is able to accurately measure the mass flow rate regardless of the fluid state (gas or liquid). Pressures and temperatures were measured using four J-type thermocouples and four piezoresistive pressure transducers at the compressor, condenser, evaporator and capillary tube inlets. Wind speed over the evaporator and condenser coils was measured using a digital vane anemometer (Lutron LM–8000).A schematic diagram of the instrumentation is shown in Figure 1.The cooling capacity of the air conditioner, heat dissipation of the condenser, and work of compressor were calculated by the energy conservation equation, assuming an adiabatic compressor.

4. The uncertainties of the presented values

Three types of quantities are presented in this paper. The first category includes those that have been measured directly. The direct measured values are room temperature, mass flow rate of refrigerant, charge of the system, and pressures and temperatures at the inlet of all four main components of the air conditioner. The main uncertainty in the experiments is due to the cumulative effect of noise and drift. The maximum uncertainty in measuring the refrigerant temperature is ±1°C(+1.64%), refrigerant pressures is ±25kPa(+14.4%), mass flow rate is ±0.00138 kg/s (+11.94%), charge is ±0.01 gram (+0.003%), and ambient temperature is ±0.5°C(+3.3%).Taking into account the variation of room temperature from 20°C to 35°C in the present work, the relative uncertainty for room temperature was 3.3% ((0.5÷15)×100).

The second type of data is that obtained from the table of properties. The uncertainty of these values (density, enthalpy, and subcooling) caused by the uncertainty of measured values (pressure and temperature).The maximum uncertainty in the density of the refrigerant was calculated by comparing the density at the measured pressure and temperature (P, T) with those obtained at four points of (P+25kPa, T), (P-25 kPa, T), (P,T+1°C), and (P, T-1°C). A similar approach was used to estimate the uncertainty in the enthalpy of the refrigerant and subcooling. The results show maximum uncertainty of 0.6162 kg/m^3 (±16.8%) for the density, 4.9125 kJ/kg (±1.4%) in the refrigerant enthalpy at the evaporator, 3.2395 kJ/kg (±7.1%) in the enthalpy at the compressor, and 1.4°C (±15.24%) in subcooling.

The third category includes velocity, cooling capacity, useful work of the compressor, specific cooling capacity, and coefficient of performance, all of which were calculated using the above-mentioned quantities and the square root of sum of squares formula. They were calculated using the following formulas:

$$vel = \frac{\dot{m}_r}{\rho\ A_p} \tag{1}$$

$$\dot{Q}_{cool} = \dot{m}_r(h_4 - h_1) + \dot{m}_r(\frac{{vel_4}^2}{2000} - \frac{{vel_1}^2}{2000}) \tag{2}$$

$$\dot{W}_{comp} = \dot{m}_r(h_1 - h_2) + \dot{m}_r(\frac{{vel_1}^2}{2000} - \frac{{vel_2}^2}{2000}) \tag{3}$$

$$CoP = \frac{\dot{Q}_{cool}}{\dot{W}_{comp}} \tag{4}$$

$$SC = \frac{\dot{Q}_{cool}\ .\ 1000}{charge} \tag{5}$$

The maximum uncertainties are estimated to be 7.6516 m/s (±20.61%) for the refrigerant velocity, 0.4477 kW (±12.48%) for the cooling capacity, 0.0736 kW (±13.89%) for the useful work of the compressor, 1.299 (±18.38%)for the coefficient of performance, and 0.0013 W/gram (±12.48%) for the specific cooling capacity.

5. Results and discussions

Some results presented in this article are only indicative since their variations were less than the experimental uncertainties. Some results were also identified as outliers and were removed prior to curve fitting. The maximum standard deviations of the results are presented in the beginning of each section.

5.1. Effect of room temperature on refrigerant temperature

The uncertainty of the experimental data (presented in Figure 2) is determined to be 1.1°C based on 1°C and 0.5°C uncertainties of the refrigerant temperature and room temperature, respectively. The maximum standard deviation of the fitted curve is 0.7 °C.

Figure 2 shows the temperature of the refrigerant at the inlet of all four main parts of the air conditioner versus room temperatures at the three different charges. The results show that the refrigerant temperature increases approximately linearly with the increase in room temperature. In Figure 2, the temperature of the refrigerant at the evaporator inlet ($T_{in\text{-}evap.}$) and compressor inlet ($T_{in\text{-}comp.}$) are almost identical and cannot be clearly discerned from each other. The rise in room temperature shows a minor influence on the $T_{in\text{-}evap.}$ and $T_{in\text{-}comp}$ compared with other components. For example, at the refrigerant charge of 263.10 grams and room temperature of 20°C, $T_{in\text{-}evap}$ and $T_{in\text{-}comp}$ are 3.2°C and 2.8°C, respectively. At35°C, these values increase to $T_{in\text{-}evap}$ of 10.9°C and $T_{in\text{-}comp}$ of 11.0°C, which represent temperature rises of $\Delta T_{in\text{-}evap}$ of 7.7°C and $\Delta T_{in\text{-}comp}$ of 8.2°C, while room temperature rises by 15°C.

The effect of room temperature (T_{room}) on the temperature of the refrigerant at the capillary tube inlet ($T_{in\text{-}cap\text{-}tube}$) is greater than that of $T_{in\text{-}evap.}$ and $T_{in\text{-}comp}$. The maximum effect of T_{room} on $T_{in\text{-}cap\text{-}tube}$ occurs at the charge of 263.10 grams. At this charge, $T_{in\text{-}cap\text{-}tube}$ is 20.2°C at $T_{room.}$ of 20°C and is 41.9°C at $T_{room.}$ of 35°C. This shows a temperature rise of 21.8°C while room temperature increases only 15°C.

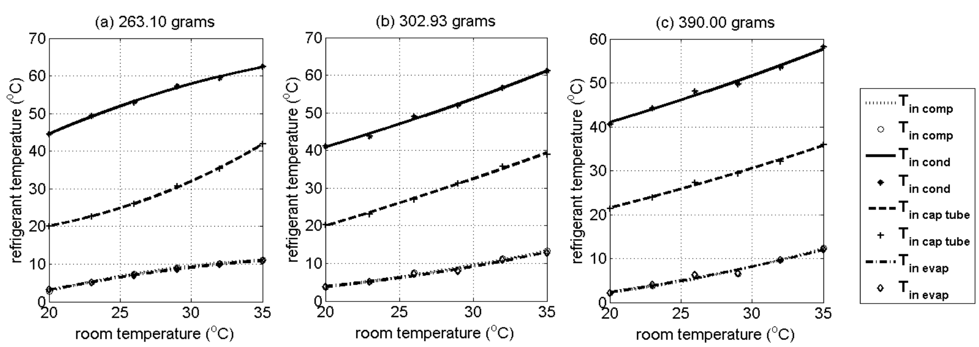

Figure 2: Refrigerant temperature versus room temperature at different charge levels

Room temperature also has a major impact on the refrigerant temperature at the condenser inlet ($T_{in\text{-}cond}$). For example, at 390.00 grams charge, $T_{in\text{-}cond}$ at 20°C and 35°C room temperature is 40.6°C and 58.1°C, respectively. This shows an increase of 17.5°C in refrigerant temperature while room temperature increases by 15°C.The same trend can be observed at302.93 grams charge. The temperature at the condenser inlet increases from 40.8°C to 61.1°C, which represents an increase in 20.3°Cover the same room temperature range. In the case of 263.10 grams charge, the temperature increases from 44.6ºC to 62.3ºC, which represents a 17.7ºC temperature increase.

The experimental results show that the rise in room temperature increases the refrigerant temperature at the inlet of all main components of the air-conditioner. The results were expected and are in agreement with previous studies (e.g. Fatouh et al., 2010, Fernando et al., 2004). Initially the difference between the refrigerant temperature in the evaporator and room temperature increases, it corresponds to a higher cooling capacity. In a steady state operation, the total heat rejected by a condenser is equal to the sum of the heat absorbed by the evaporator and the useful work of the compressor, therefore the heat discharged by the condenser increases according to the energy conservation law. Consequently, the refrigerant temperature in the condenser increases more than room temperature to enable the dissipation of more heat. This increase raises the refrigerant temperature in the evaporator, thus the temperature difference in the evaporator drops, and consequently the cooling capacity decreases in comparison with the initial sharp increase. This analysis is supported by the experimental results indicating that the effect of room temperature on refrigerant temperature is more significant at the inlet and outlet of the condenser as compared to the inlet and outlet of the evaporator. As the refrigerant exists in saturated state in the condenser, the increase in temperature leads to a corresponding increase in pressure. The results also show that a rise in pressure occurs, which is in line with the previous work on non-portable air conditioners (e.g. Hebert-Raj et al., 2011).

5.2.Influence of room temperature on density of refrigerant

The room temperature has an effect on the density of the refrigerant at different parts of the air conditioner. Density has been estimated using the table of propane properties Refprop 6.01 (NIST 1998) based on the measured pressures and temperatures. The maximum uncertainties of the results in Figure 3 are estimated to be 17.1%. The maximum standard deviation of the fitted curves is 0.0287kg/m^3.

The results show that the density of the refrigerant at the compressor inlet increases as room temperature increases. For example at 263.10 grams charge, the density increases from 10.460 kg/m^3 at 20°C to 12.678 kg/m^3 at 35°C (+21.2%). At 390 grams charge, the density at 20°C is 10.380 kg/m^{3}and increases to 12.455 kg/m^3 at 35°C (+20.0%). The relative increase (20.0%) is more than the relative uncertainty of the experiment (17.1%). The increase in the density at the compressor outlet (inlet of the condenser) is more significant. For instance, the density at the charge of 263.10 grams increases from 21.251 kg/m^3 at 20°C to 31.350 kg/m^3 at 35°C (+47.6%). The density increases by 50.0% and 19.1% at the charges of 302.93 grams and 390.00 grams, respectively, for the same range of temperature.

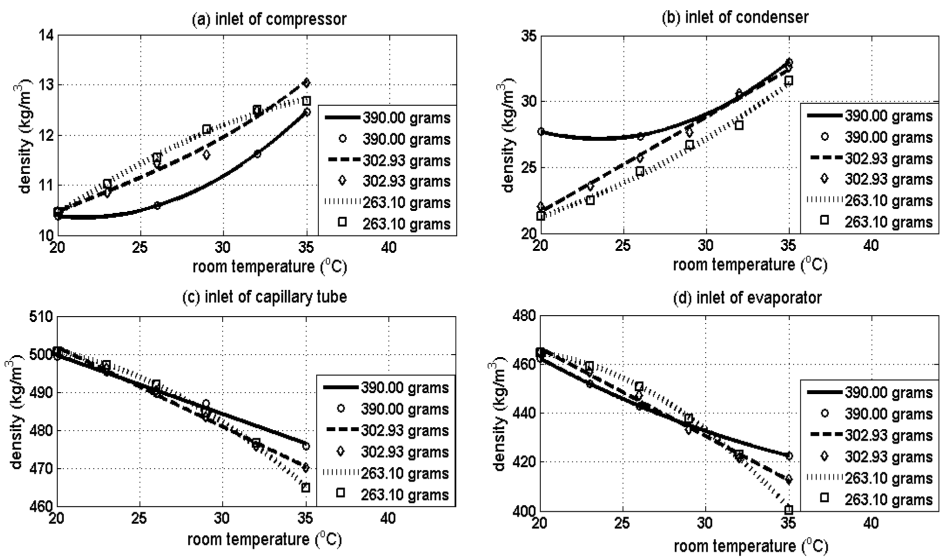

Figure 3: Refrigerant density versus room temperature at different refrigerant charge levels

At the capillary tube and evaporator inlets, the density decreases as room temperature increases. At the inlet of the capillary tube, the density decreases by 7.1%, 6.3%, and 4.7% at the charges of 263.10 grams, 302.93 grams, and 390.00 grams, respectively. At the inlet of the evaporator, as the room temperature increases, the density decreases by 13.7%, 11.5%, and 8.6% at the charges of 263.10 grams, 302.93 grams, and 390 grams, respectively. It should be noted that the relative decrease in the density at the inlets of capillary tube and evaporator is less than the relative uncertainty of the experiment, so inconclusive.

The rise in room temperature increases the density at the inlet of the compressor and condenser. It was shown in Section 5.1 that the temperature and pressure of the refrigerant at the inlet of the compressor and condenser simultaneously increase with the rise in room temperature. The increase in temperature and increase in pressure have opposite impacts on the density, but overall the density increases for superheat propane and decreases for liquid or saturated propane. For instance, at 263.93 grams charge and pressure and temperature of 1.0686 MPa and 44.57°C (the inlet condition of compressor at 20°C room temperature), propane density is 21.26 kg/m^3 which is 48.61% less than the density of 31.60 kg/m^3 at pressure and temperature of 1.5841 MPa and 62.43°C (the inlet condition of the compressor at 35°C room temperature). The density is 500.75 kg/m^3 at the temperature and pressure of 20.16°C and 1.1112 MPa (the inlet of the capillary tube at 20°C room temperature) which is 7.18% higher than the density of 464.81 kg/m^3 in pressure and temperature of 1.6502 MPa and 41.91°C.

The distribution of the refrigerant within the air conditioner could not be directly measured in our experimental setups. In the absence of density distribution, the change of the refrigerant distribution can only be deduced based on the density variation at the inlet and outlet of the components. The results show that the density increases at the inlet and outlet of the compressor as room temperature increases. This indicates that the mass of the refrigerant within the compressor more likely to increase. The density at the inlet and outlet of the capillary tube decreases as room temperature increases. This shows that the mass within the capillary tube probably decreases. However, the refrigerant mass within the capillary tube is small when compared with the mass within other components, and cannot compensate for the increase in the mass in the compressor. The results for the condenser and evaporator are not quite as decisive. At the inlet of the condenser, the density increases; but it decreases at the outlet. At the inlet of the evaporator, the density decreases; but it increases at its outlet. As the value of the density at the outlet of the condenser is greater than that at its inlet, the results show that the mass within the condenser probably decreases. A similar result can be drawn for the evaporator. The value of the density at its inlet is greater than at its outlet, thus the refrigerant mass within the evaporator possibly decreases as room temperature increases. The above results are only suggestive, not conclusive.

5.3.Effect of room temperature on subcooling

Figure 4 shows that the refrigerant subcooling at the outlet of the condenser decreases with the increase in room temperature for all the charges measured. From Figure 4, the maximum impact was observed at the lowest charge of 263.10 grams. At this charge, the degree of subcooling decreased from 11.0°C to 6.5°C (-4.5°C), while at the highest charge of 390.00 grams, the subcooling decreased from12.3°C at 20°C to 10.9°C at 35°C room temperature (-1.4°C). These results are in agreement with the previous work of Choi et al. (2002). As discussed in section 5.1, the increase of refrigerant temperature in the condenser is more than the increase of room temperature, which results in a higher heat transfer rate in the condenser. However, as it will be shown in Section 5.5, the mass flow rate increases more than that of the heat transfer, pointing to a less severe decrease of specific enthalpy, thus less subcooling. For instance, at a refrigerant charge of 263.93 grams and room temperature of 20°C, the heat rejected by the condenser is 3.4663 kW which increases to 4.3175 kW at the room temperature of 35°C, representing an increase of 24.56%. At the same time, the mass flow rate increases from 0.0088 kg/s at 20°C room temperature to 0.0123 kg/s at 35°C room temperature which shows an increase of 40.07%. The comparison between the increase of heat rejected by the condenser (24.56%) and the rise of the mass flow rate (40.07%) shows that the change of the specific enthalpy in the condenser actually decreases leading to the reduction of subcooling.

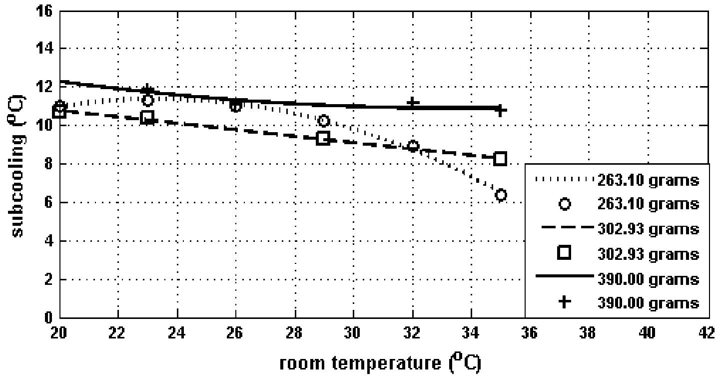

Figure 4: Degree of subcooling versus room temperature at different charge levels

5.4. Influence of room temperature on maximum velocity

The maximum uncertainty of the results presented in this section is expected to be 20.88% based on 20.61% uncertainty of the velocity and 3.3% uncertainty associated with the room temperature. The fitted curve has a maximum standard deviation of 2.4m/s.

The effect of room temperature on the maximum velocity at low and moderate charge (263.10 grams and 302.93 grams charge) is less than the maximum uncertainty of the experiment. At the charge of 263.10 grams, the velocity increases from 25.8 m/s at 20°C to 29.7 m/s at 35°C room temperature (+15.2%). These values become 34.6 m/s and 32.1 m/s(-7.3%) respectively at the charge of 302.93 grams. However, at the highest charge of 390.00 grams, the maximum velocity decreases from 50.6 m/s at 20°C to 36.3 m/s at 35°C room temperature (-28.3%).

The results for the maximum velocity of the refrigerant within the air-conditioner at undercharge and standard charge are not conclusive. The results at the overcharge condition show that the maximum velocity decreases by the increase in room temperature. This result can be explained based on the increase in density. Velocity increases if the rate of increase in mass flow rate surpasses that of density (see eq. 1). For example, in 302.93 grams refrigerant charge, the mass flow rate increases from 0.011775 kg/s at 20°C to 0.01360694 at 35°C (15.56% increase), and the density at the inlet of the compressor increases from 10.470 kg/m^{3}at 20°C to 13.048 kg/m^{3}at 35°C (24.62% increase). As the rate of the increase in the mass flow rate is smaller than that of the density, the velocity decreases. On the contrary, in the case of 263.10 grams refrigerant charge, the velocity increases with the increase of room temperature. In that case, the mass flow rate increases from 0.00875 kg/m^{3}at 20°C to 0.01226 kg/m^{3}at 35°C (40.07% increase), while the density increases only 20.0%, from 10.380 kg/m^3 at 20°C to 12.455 kg/m^{3}at 35°C.It should be noted that the maximum velocity occurs at the outlet of the evaporator where the density is at a minimum. This result shows that the outlet diameter of the evaporator can be increased to reduce the maximum velocity. In contrast, a previous work (Nilpueng et al., 2011) shows that the refrigerant velocity slightly increases as room temperature increases.

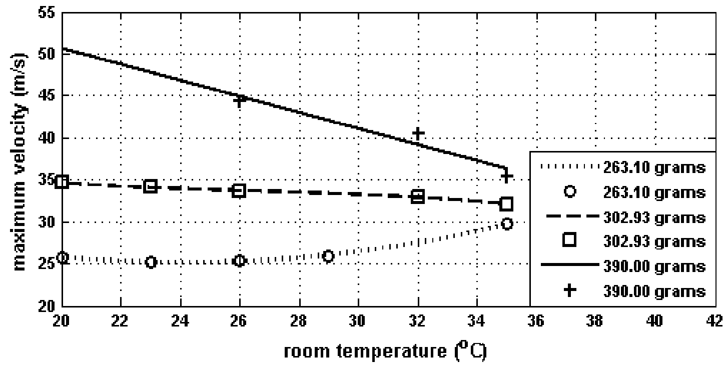

Figure 5: Maximum velocity versus room temperature at different charge levels

5.5. Influence of room temperature on mass flow rate

The presented results are expected to have a maximum uncertainty of 12.40% based on 11.94% uncertainty of mass flow rate and 3.33% uncertainty of room temperature. The maximum standard deviation of the fitted curves is 0.8392×10^{-3} kg/s.

Figure 6 shows the effect of room temperature on the mass flow rate of the refrigerant. The mass flow rate increases with the increase in room temperature except at 390.00 gram charge. For instance, at the charge of 263.10 grams, the mass flow rate increases from 0.0084kg/s at 20°C to 0.0121 kg/s at 35°C room temperature (+44.0%). The same pattern can be observed at the charges of 302.93 grams (+15.7%). The only exception occurs at the charge of 390.00 grams where the mass flow rate shows a peak at around 27.2°C room temperature. In this charge and at the room temperature of 20°C, the mass flow rate is 0.0145 kg/s, and increases as the temperature increases until it reaches a value of 0.0158 (+9.0%) at room temperature of 27.2°C. With further increases in room temperature, the mass flow rate decreases and reaches a value of 0.0143 kg/s at a room temperature of 35°C, representing a 9.5% decrease with respect to the peak value.

The increase in mass flow rate due to the increase in room temperature is in agreement with previous studies by Farzad (1990), Rodrigez (1995), Choi et al. (2002), and Fatouh et al. (2010). The mass flow rate increases with T_{room} due to the increase in the density of the refrigerant (see Section 5.2). However, at the highest charge, some decrease can be seen. This could be ascribed to a possible increase in internal leaks of the compressor. In Section 5.1, it was shown that the rise of room temperature increases the refrigerant temperature and hence, the viscosity of oil in the mixture with the refrigerant decreases. The poor viscosity of oil increases the internal leakage (Evans, 2013). However, it should be noted that the decrease in the mass flow rate at the highest charge is less than the uncertainty of the experiment and the results are not conclusive.

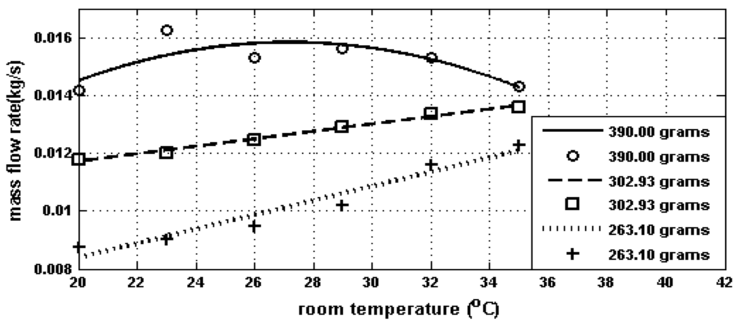

Figure 6: Mass flow rate versus room temperature at different charge levels

5.6. Effect of room temperature on cooling capacity

The cooling capacity of the air-conditioner has been calculated using the experimental data. Some typical results are presented in Figure 7. The uncertainty of the results presented in this section is 12.48% based on 12.03% uncertainty in the calculated cooling capacity and 3.33% uncertainty of room temperature. The maximum standard deviation is 0.0304 kW.

The results show that the cooling capacity of the portable propane air-conditioner increases as room temperature increases, with the exception of the overcharged condition. According to the Figure 7, in the case of 12.3% undercharge (263.10 grams), the cooling capacity increases from 2.860 kW at 20°C room temperature to 3.518 kW at 35°C room temperature (+23%). The increase is only 2.7% (0.107 kW) in the case of 302.93 grams charge (0.98% overcharge)over the same room temperature range. In the case of 30% overcharge (390.00 grams), the cooling capacity initially increases from 4.743 kW at 20°C to 4.977 kW at 27°C (+4.9%), and then decreases to 4.248 kW at a room temperature of 35°C. In this case, the cooling capacity at 35°C is 10.45% and 14.65% less than those at 20°C and 27°C, respectively. Taking into account the uncertainty of the experiment (12.48%), the change of cooling capacity at 20°C to 27°C(+4.9%) is not conclusive. The cooling capacity decreases from 27°C to 35°C (-14.65%) and the results are conclusive.

Equation 2 shows that the cooling capacity of an air conditioner is a function of the mass flow rate. A comparison between the experimental the results of cooling capacity and mass flow rate (Figures 6 &7) shows that their changes are extremely similar.

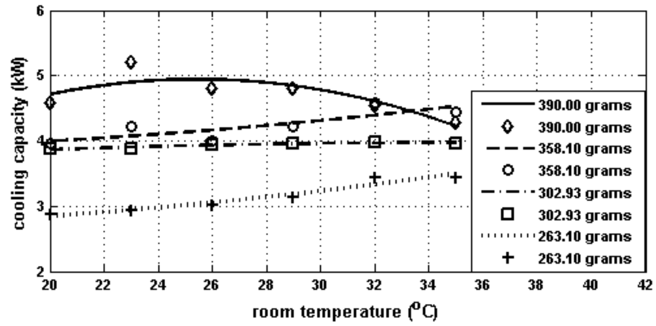

Figure 7: Cooling capacity versus room temperature at different refrigerant charge levels

The results obtained are not fully consistent with previous studies. Farzad (1990) commented that, in an undercharged condition, the cooling capacity increases with room temperature, but it decreases under full and overcharged conditions. The results presented by other researchers are partially different from those obtained by Farzad. Choi et al. (2002) found that the cooling capacity decreases as condenser temperature increases, but the rate of decrease is higher at undercharged conditions. Rodriguez (1995), Martinez-Galvan et al. (2011), and Corberán et al. (2011) obtained similar results. It should be noted that, in the previous studies, the increase in ambient temperature refers to the increase in air temperature surrounding the condenser, while the air temperature around the evaporator remains unchanged. In this work, the contrary is found. The increase in refrigerant temperature in the evaporator is less than that of the room temperature (see Section 5.1), thus the temperature difference increases, resulting in an increase in the cooling capacity.

5.7. Effect of room temperature on specific cooling capacity

The uncertainty of the specific cooling capacity is 12.48% based on the uncertainty of the cooling capacity and the uncertainty of mass measurement. The maximum standard deviation of fitted curves is 0.7441 W/g.

Figure 8 shows that, at the undercharge condition, the specific charge increase from 10.83 W/g at T_{room}= 20°C to13.30 W/g at T_{room}= 35°C (+20.8%). At the standard charge, the change of specific charge is less than the maximum uncertainty of the experiment. It increases from 12.76 W/g at T_{room}= 20°Cto 13.11 W/g at T_{room}= 35°C(+2.74%).Therefore, there is no conclusive result. At the overcharged condition, the specific charge first increases from 12.13 W/g at 20°C to 12.68 W/g at 25.4°C (+4.56%), and then decreases to 10.78 W/g (-14.96%) at 35°C. In the absence of previous studies, the only conclusive result that can be obtained is the reduction of the specific cooling capacity at overcharged condition and at higher room temperature. The specific cooling capacity is defined as cooling capacity per mass of refrigerant (eq. 5). Thus, for a certain mass of refrigerant in the system, its change with room temperature is expected to be similar to that of the cooling capacity, which is confirmed by the current experimental results.

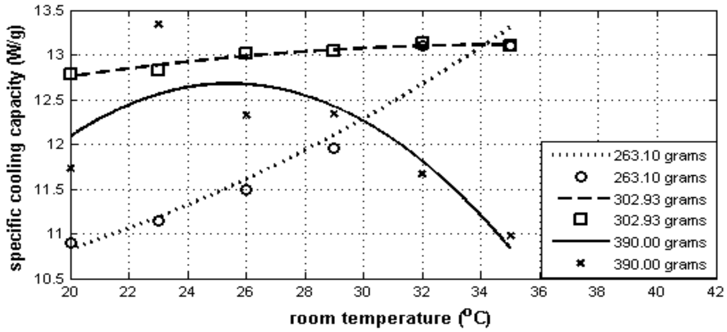

Figure 8: Specific charge versus room temperature at different refrigerant charge levels

5.8. Effect of room temperature on useful work of compressor

Figure 9 indicates the useful work of the compressor versus room temperature. The maximum uncertainty of the results is expected to be 14.28% and the maximum standard deviation is 0.0203 kW. The Figure shows that the useful work of the compressor increases with the increase in room temperature in all the cases. However, the impact of room temperature on the work is greater at lower charges. The useful work of the compressor at 263.10 grams charge is 0.4928 kW at 20°C and 0.8358 kW at 35°C, representing an increase of 69.9%. At 302.93 grams and 390 grams charges, the rate of the increase in the useful work of the compressor over the full room temperature range decreases to +46.17% and +32.31%, respectively. It should be noted that the useful work of the compressor decreases by 3.7% at the highest charge as room temperature increases from 31.2°C to 35°C.As the value of the decrease is less than the relative uncertainty of the experiment, the result is not conclusive. There are two reasons for the increased of the work of the compressor. The first is the increase of mass flow rate, discussed in Section 5.5, the second is the increase in the specific work of the compressor, defined as follows:

$$w_s = \frac{kRT_1}{k-1}\left[\left(\frac{P_2}{P_1}\right)^{(k-1)/k} - 1\right] \qquad (6)$$

The above formula shows that the specific work of a compressor increases by the increase in pressure ratio or inlet temperature. The increase of inlet temperature with room temperature was discussed in Section 5.1. In addition, the pressure ratio increases with the rise of room temperature. For example, at 263.93 grams charge, P_2 increases from 1.0686 MPa at 20°C room temperature to 1.6502 MPa at 35°C room temperature (48.23% increase), but P_1 increases only 22.60% from 0.4854 MPa at 20°C room temperature to 0.5951 MPa at 35°C room temperature. This shows that the pressure ratio increases from 2.20 at 20°C to 2.77 at 35°C.

The results are in agreement with the previous work by Farzad (1990). The work of the compressor is expected to increases as the room temperature increases, mainly due to the increase in mass flow rate which was discussed in Section 5.5.

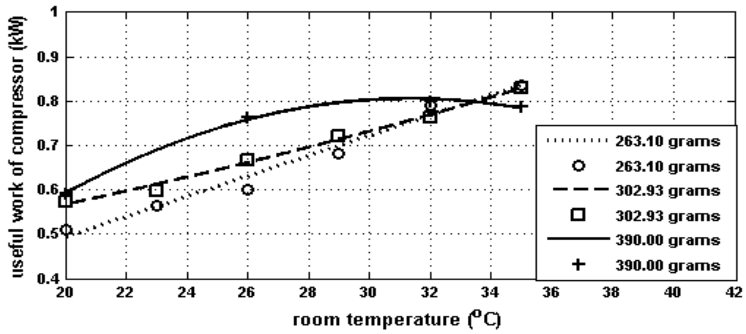

Figure 9: Work of compressor versus room temperature at different refrigerant charge levels

5.9. Effect of room temperature on coefficient of performance

Figure 10 shows the coefficient of performance of the portable air conditioner (used in this work) versus room temperature. The maximum uncertainty of the results is expected to be 18.68%, and the fitted curve has a maximum standard deviation of 0.4784. The coefficient of performance of the air-conditioner is calculated based on the cooling capacity and the useful work of the compressor which were calculated in previous sections (see Sections 5.6 and5.8).

The results show that the coefficient of performance of the air-conditioner decreases with the increase in room temperature. For example, at 12.30% undercharge condition (263.10 grams charge), CoP decreases from 5.83 at room temperature of 20°C to 4.26 at room temperature of 35°C (-26.9%). The effect of room temperature on CoP is slightly stronger as the charge increases. At 302.93 grams charge, the CoP decreases from 6.78 at 20°C to 4.92 at 35°C (-27.4%). The CoP decreases from 7.83 to 5.49 (-29.9%) at the charge of 390.00 gram as room temperature increases from 20°C to 35°C , respectively.

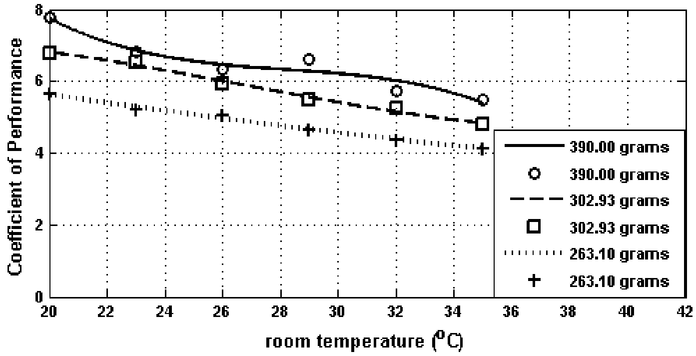

Figure 10: Coefficient of Performance versus room temperature at different refrigerant charge levels

The results are similar to the previous results for non-portable air-conditioners. Choi et al. (2002) found that the CoP decreases with an increase in room temperature at all charge levels. They found that the decrease of the CoP is due to the increase in power consumption and the decrease in cooling capacity due to the rise of room temperature. Recent studies also show similar results (e.g. Martinez-Galvan et al., 2011; Corberán et al., 2011). However, it should be noted that in this portable air-conditioner, the cooling capacity increases with the increase in room temperature (Figure 7), therefore the decrease of the CoP is less severe than that of non-portable air conditioners.

It should be noted that the CoP is the ratio of cooling capacity to useful work of compressor (see eq. 4). Therefore, the decrease in CoP with the rise of room temperature reflects the fact that the increase in the cooling capacity is less than the increase of useful work of the compressor (see Sections 5.6& 5.8). For example, at 263.93 grams charge, the cooling capacity increases 23% from 2.860 kW at 20°C room temperature to 3.518 kW at 35°C room temperature while the useful work of the compressor increases 69.9% from 0.4928 kW at 20°C to 0.8358 kW at 35°C.

5.10. Effect of room temperature on maximum pressure of air conditioner

The maximum uncertainty of the results presented in this section is 5.5% based on 25 kPa (4.4%)and 0.5°C (3.3%)uncertainties associated with pressure and temperature readings, respectively.

Figure 11 shows a significant increase in the maximum pressure versus room temperature. The maximum pressure is reached at the compressor outlet. According to Figure 11, at the charge of 263.10 grams, the maximum pressure increases from 1.067MPa at 20°C to 1.574MPa at 35°C (+47.47%). The maximum pressure increases by 50.75% and 23.98% at the charges of 302.93 grams and 390 grams, respectively, over the same room temperature range.

The results of the present work are similar to the results of previous studies. The maximum pressure occurs at the outlet of the compressor and increases due to the increases in refrigerant temperature at the compressor outlet as room temperature increases (as discussed in Section 5.1).

The process is usually assumed to be adiabatic or isentropic in a compressor. The relationship between pressure and temperature for an adiabatic process is

$$P_2 = P_1 \left({}^{T_2}/_{T_1}\right)^{k/_{k-1}} \tag{7}$$

The above formula shows that the outlet pressure of the compressor increases as T_2/T_1 ratio or P_1 increases. It was shown (Section 5.1) that at a room temperature of 20°C and refrigerant charge of 263.93 grams, the inlet pressure is 0.4854 MPa and the inlet and outlet temperatures are 275.93K and 317.72K respectively. At the room temperature of 35°C, the inlet pressure is 0.5951 MPa and the inlet and outlet temperatures are 284.19K and 335.58K respectively. This shows not only the inlet pressure increases, but that also the temperature ratio increases from 1.15 at 20°C to 1.18 at 35°C room temperature.

All the previous work found that the pressure of refrigerant increases with an increase inroom temperature (Hebert-Raj et al., 2011; Teng et al., 2012; Kim et al., 2012; Kim et al., 2014).

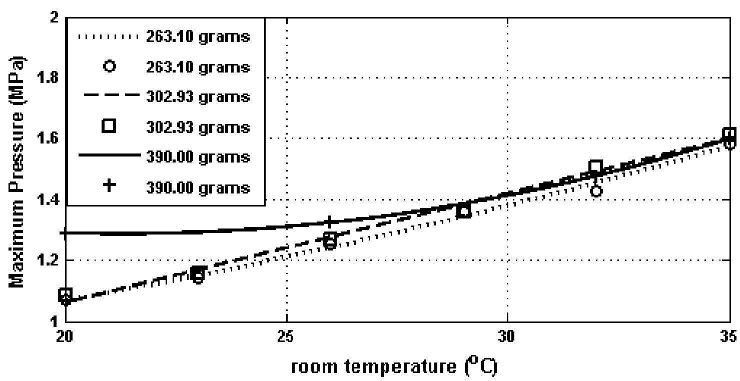

Figure 11: Maximum pressure versus room temperature at different refrigerant charge levels

5.11 Summary and further discussion

The results show many similarities and some difference between the performance of portable propane air conditioners and non-portable air-conditioners and refrigeration systems. The refrigerant temperatures increase as room temperature increases. The increase in refrigerant temperature at the inlet and outlet of the condenser is higher than the increase in room temperature, whereas the increase in the refrigerant temperature at the inlet and outlet of the evaporator is less than the increase in room temperature. This is the key point to the discussion of portable air-conditioners' performance. As the refrigerant in the evaporator and condenser is in a saturated state, the increase in temperature leads to an increase in pressure. Therefore, the pressure ratio and pressure difference increase at both sides of the capillary tube and compressor, leading to an increase in the mass flow rate and useful work of the compressor. The increase in the difference between the refrigerant temperature at the condenser and room temperature leads to a better discharge of heat from the condenser. However, as the mass flow rate increases, the degree of subcooling decreases slightly. A greater difference between the refrigerant temperature at the evaporator and room temperature increases the cooling capacity of the air-conditioner. However, the coefficient of performance decreases. The main difference between the performance of portable air-conditioners and others is related to cooling capacity. The effect of room temperature rises is significant for the increase in the specific cooling capacity at lower charge, but is insignificant at the standard charge. At overcharge condition, the specific cooling capacity increases at lower room temperatures, but decreases at higher room temperatures.

6. Conclusion

The performance of a portable propane air-conditioner at different room temperatures shows many similarities and a few significant differences with those of non-portable air-conditioner and refrigeration systems. Similar to non-portable systems, as room temperature increases, the refrigerant temperature in all parts of the system, the refrigerant mass flow rate, work of the compressor, and maximum pressure of the system increases, and the level of refrigerant subcooling and coefficient of performance of the system decreases. The results also suggest that, as room temperature increases, the refrigerant accumulates more in the compressor and less in other parts of the system.

The main differences between portable and non-portable systems are the change of the maximum velocity of the refrigerant and cooling capacity with the increase in room temperature. Unlike non-portable systems, the maximum velocity of the refrigerant at the overcharge condition decreases with the increase in room temperature. The results in undercharge condition are not conclusive, but they suggest an increase in maximum velocity with temperature, similar to non-portable systems.

Similar to non-portable systems, the results obtained show that the cooling capacity of an undercharge system increases with an increase in room temperature. Unlike a non-portable system, the results indicate a slight increase in cooling capacity for a full charge portable air-conditioner. In addition, the cooling capacity of an overcharge and portable air-conditioner initially increases and then decreases with the increase in room temperature.

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