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EXPERIMENTAL INVESTIGATION ON VARIABLE SPEED OPERATION OF AIR CONDITIONING

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ABSTRACT

Air conditioning installations are typically designed with enough cooling capacity to satisfy the desired minimum temperature under the heaviest load. Since heat loads tend to be less than the maximum designed loads, the system will most often be working under part-load rather than full-load conditions. Operating at these part-load conditions at fixed capacity will be more expensive than if the capacity were able to match the required load. Varying capacity air conditioning systems, which make use of inverter technology, have been developed in order to track the required cooling load more closely. These high quality air conditioners are advertised as consuming around 30 per cent less energy than conventional systems.

This experimental investigation looked into the steady state performance and start-up power requirements of an inverter driven refrigeration unit versus fixed speed operation. A three phase (745 W motor) air conditioning laboratory setup was used in direct-on-line (fixed speed) mode and also with a variable frequency drive (inverter). The results obtained showed that the cooling coefficient of performance increased as the operating frequency was reduced. This means that an improved performance can be achieved at lower operating frequencies. A reduced start-up power was required for the inverter driven system, however the additional power requirements for the inverter resulted in the mains driven system being more efficient at full-load conditions. The improved coefficient of performance at lower frequencies resulted in an improved performance for the inverter driven system when compared to a conventional system at part-load conditions.

INTRODUCTION

The first air-conditioning units for comfort cooling appeared in 1927, and continued to be developed during later years. The home air conditioning market in the US experienced tremendous growth in the 1960's, brought about mainly by the fact that energy was inexpensive. Simple air-conditioning became common in many homes, and this increase in the market demand spurned a growth in technology. By 1990 all areas of refrigeration and air conditioning systems were utilising microprocessor control systems to increase their reliability and efficiency. [1]

Due to the rising of energy prices, the need for rational energy consumption has become a global concern. Energy consumption for air-conditioning in buildings accounts for about 50 per cent of the total energy consumption. It has also been acknowledged by utility companies that 30 per cent of worldwide energy consumption is due to refrigeration and air-conditioning installations, thus these systems have an unarguably major impact on energy demand. For this reason, it has been the aim of many researchers to improve on conventional refrigerating systems, as this would result in a significant energy economy. [2, 3]

The application of inverter technologies to air-conditioning systems for commercial and residential purposes was first implemented in the 1980s, in Japan. Since then, these systems have become increasingly popular owing to their energy saving and better maintaining of comfort when compared to the constant speed air conditioner. In the Japanese market, sales of variable-speed air-conditioners have captured over fifty per cent of the air conditioning market, and are increasing. [4, 5]

Variable-speed capacity control works by means of a closed loop control system. An adjustment signal dependent on the outside and indoor temperatures as well as the set temperature is used to match the required heat load. This signal controls the frequency of the inverter, which changes the speed of the motor and thus of the compressor. As the compressor speed is reduced, the mass flow rate decreases as less refrigerant is discharged out of the compressor, adjusting the cooling capacity to match the load. [2, 6]

At very light loads, the variable-speed system cannot run constantly, since minimum speed constraints will restrict the operation of the machine. If the cooling capacity supplied by the system at minimum speed is still too large for the load, then the air conditioning system will cycle on/off, as in a conventional air conditioner. At high loads, a maximum frequency limit is similarly imposed on the system. [7]

Tassou and Qureshi [8] conducted a series of experiments to investigate the performance of positive displacement refrigeration compressors for this application. They investigated three compressor types; an open-type reciprocating, a semi-hermetic reciprocating and an open-type rotary vane. The majority of air conditioning and refrigeration systems operate using reciprocating compressors. [1] In an open-type system, the compressor is belt-driven from an electric motor. The speed of the compressor is usually considerably less than the speed of the motor. Most early refrigerating systems operated in this way. [1]

Tassou and Qureshi [8] tested the variation of the volumetric efficiency of three compressor types with speed (open-type and semi-hermitic reciprocating compressor and the rotary vane type). They found that the volumetric efficiency of all three compressors decreased with decreasing speed. This indicated that all three compressors had designs for maximum volumetric efficiency at the design speed, which was the maximum speed. The open-type reciprocating compressor showed the least reduction, between 2 and 3 per cent, while the largest reduction was found for the open-type rotary vane compressor. [8]

In the same work, the variation of the isentropic efficiency with speed was also investigated. All three compressors showed an increase in the isentropic efficiency as the speed was reduced. The open-type reciprocating compressor had the highest isentropic efficiency, whilst the isentropic efficiencies of the semi-hermetic and rotary-vane compressor were lower by more than fifteen per cent. [8]

The variation in the cooling capacity per unit displacement with frequency for all three types of compressors showed that the maximum cooling capacity over the speed range was gained at the lower condenser saturation temperature of 30^{o}C for all three compressors. Tassou and Qureshi argue that this is due to the increased enthalpy difference across the evaporator at low condensing pressures. Also, at low condenser pressures, the volumetric efficiency of a compressor increases, resulting in an increase in refrigerant flow rate. This also implies an increased cooling capacity at low pressures. In the open-type reciprocating compressor the cooling capacity per unit displacement for each temperature stayed fairly constant over the entire speed range. This is a result of the fairly constant volumetric efficiency of this compressor with variation in speed. [8]

Tassou and Qureshi also give the variation of input power per unit displacement with frequency at different condenser saturation temperatures. For the open-type reciprocating compressor the power consumption per unit displacement reduces with the reduction in speed, with the highest reduction being at low condenser saturation temperatures. The semi-hermetic reciprocating compressor performed similarly to the open-type compressor at low condenser temperatures; however at high temperatures the compressor shows an increase in the power consumption per unit displacement with the decrease in speed. In the rotary-vane compressor the power consumption per unit displacement increased as the speed was reduced for all condenser temperatures with the reduction in speed for all pressures. [8]

The variation in cooling COP with compressor speed for all three types of compressors was determined, for both fixed and floating head pressure control in [8]. For constant head-pressure-control, i.e. a constant condenser saturation temperature, the COP of the rotary and the semi-hermetic reciprocating compressors decreased with a reduction in the compressor speed. The authors explain that this is caused by the reduction in the volumetric efficiency of these compressors at low speeds and the increase in their specific power consumption. On the other hand, the open-type reciprocating compressor showed an improved COP as the speed was reduced for all condenser temperatures tested. This was deemed to be a result of improved volumetric efficiency and reduced specific power consumption at low speeds. In the case of floating head-pressure-control all three compressors exhibited an increase in the COP when speed reduction was accompanied by a reduction in the condenser temperature. [8]

Since an air conditioner operates at part-load for most of its lifetime, an increase in the COP for low speeds would be a desirable characteristic. The open-type reciprocating compressor showed the most gain in COP at low speeds, increasing to about 118 per cent of the nominal value. The semi-hermetic compressor showed only a 3 per cent rise in the COP over the same speed range, whereas the rotary vane compressor cooling COP decreased slightly from the nominal value. Thus, the open-type reciprocating compressor configuration is the most suitable for variable-speed operation. [8, 9]

Zubair, Bahel and Arshad [5] show the variation of motor efficiency with frequency for three different power sources, a Pulse Width Modulated (PWM) inverter, a six-step inverter and a standard sinusoidal waveform. A similar trend was observed for all three power sources; the motor performs best at frequency values which fall within the range of the rated frequency. At lower frequencies, the motor efficiency decreases. [5] This lower efficiency at low frequency values may be due to the harmonic content of the input waveform. [10]

Tassou and Qureshi [9] performed various start-up tests on a refrigeration system for two modes of operation: direct mains motor driven compressor (MDC) and inverter driven compressor (IMC). They present both electrical (voltage and current) as well as mechanical (pressure, temperature and COP) parameter variation versus time during the start-up transients. Within a vapour-compression cycle, the compressor is the component which has the largest energy requirement. As a result, its transient and steady state energy consumption have a significant impact on overall system efficiency and cost. Their results showed that since a fixed-speed system undergoes many on/off cycles, the transient losses will be significant. The minimum operating speed of variable-speed compressors is usually restricted to between 25 and 30 per cent of the maximum speed, in order to ensure adequate oil return and motor cooling at low speeds. During the period of operation, when the load lies between the maximum and minimum operating speeds, after the initial start-up the system will track the variation in load by regulating the compressor speed without undergoing additional transient losses. [9]

APPARATUS AND SETUP

Experimentation was performed on a Hall Refrigeration Laboratory Unit at the University of Malta. This plant operates on the vapour-compression cycle, and originally used refrigerant R12 as the working fluid, but was retrofitted in 1996 to operate using refrigerant R134a.

The motor is a 1 H.P. three-phase induction motor, manufactured by Small Electric Motors Ltd, England. It has a continuous rating of 400/440 V, 1.6 A, 1420 rpm and was designed to operate at a frequency of 50 Hz. The compressor is an open-type reciprocating compressor. It has a 1 5/8” bore by 1 1/2” stroke, twin cylinder type, which is arranged for a ‘V’ belt drive. It is driven by a 1 H.P. dynamometer which enables a direct measurement of the compressor brake horse power to be made. [11]

The condenser is water cooled, and is of the shell and coil type. It consists of a welded steel shell which also acts as a liquid receiver, and contains a coiled length of copper tubing. The compressor delivers the gas into the shell and outside the coil through which the circulating water passes. The water passing through the coil extracts the heat from the gas; causing it to liquefy and fall to the bottom of the shell. The evaporator is also water cooled and of the shell and coil type. The refrigerant flows though the coil whilst the water flows in the shell around it. It is made of 1/2” diameter copper tubing coiled for 9 times.

The frequency inverter was manufactured by AG Technology Corporation, USA, and is capable of varying frequencies between 0 and 240 Hz. A high pressure cut-out switch was set to break the electric circuit to the dynamometer if the condenser pressure exceeds 14 bar (gauge). A three-phase kilowatt-hour meter, together with a stopwatch, was used to measure to energy consumption of the system. The motor and compressor speeds were measured using an optical tachometer and reflective tape.

Pressure tapings were made at the evaporator and condenser inlet and exit points, and the pressure gauges were attached. Four R134a pressure gauges were used; two with a scale for measuring high pressures, and two for low pressures. A filter/dryer and a sight glass were also used to enable proper maintaining and monitoring of the system. An expansion valve was also used.

A refrigerant variable area flow meter and two water variable area flow meters were used. The refrigerant flow meter scale was meant for measuring liquids with a density of 1221kg/m^3, so a density correction was required in the calculations. Two gate valves were also used in order to vary the water flow rates as required.

T-type thermocouples were used together with a Keithley instrument data acquisition system. The thermocouple wires were twisted and attached to the copper pipes at the points of interest using a single drop of solder. The thermocouples were connected to the condenser and evaporator refrigerant inlet and outlet points, and the condenser and evaporator water inlet and outlet points. The parts of the pipes to which the thermocouples were attached were insulated.

Energy balances were carried out to verify the operation of the system. A beaker and a stopwatch were used to check that the water flow meters were giving a good measurement. It was found that they were not giving correct readings, but were still left connected to provide flow indication. Water measurements for the energy balance were thus made using the beaker-stopwatch method, and the flow meters were used solely to aid the maintaining and monitoring of constant flow rates during testing.

It was concluded from the energy balances that the system was performing as expected; the energy absorbed by the refrigerant in the evaporator was almost equal to the energy lost by the water, and the energy lost by the refrigerant in the condenser was almost equal to the energy gained by the water. The slight discrepancy was due to the heat losses to the surroundings. Another important conclusion which was made was that the refrigerant flow meter was indeed giving a correct reading; otherwise the energy balance would not have given such good results.

A check was carried out for correct operation of the motor at reduced frequencies. It was found that the calculated value of rpm from inverter frequency corresponded well with the measured value, though there was a slightly greater discrepancy at lower frequencies than there was at the higher frequencies. This indicated that the motor has a higher slip at low frequencies than at high frequencies.

Table 1: Apparatus uncertainties

Equipment	Uncertainty
High-side pressure gauges	+/- 0.25 bar
Low-side pressure gauges	+/-0.05 bar
Power meter (90000W/rev)	+/- 0.025 revolution
Stopwatch	+/- 0.005 s
Keithley data acquisition system	+/- 0.005 °C
T-Type Thermocouples	+/- 1 °C
Refrigerant flow meter	+/- 5 lbs/hr
Measuring Cylinder	+/- 100 ml
Dynamometer (weight)	+/- 0.0276 lbs
Inverter Frequency	+/- 0.05 Hz
Tachometer	+/- 5 rpm

EXPERIMENTAL PROCEDURE

The aim of the experiments carried out was to investigate the steady-state performance and start-up power requirements of an inverter driven refrigeration system. These experiments were performed to quantify whether the advertised improved part-load efficiency and reduced energy consumption of an inverter air conditioner is indeed justified.

STEADY-STATE EXPERIMENTS

Experiments were carried out to obtain the variation of power requirements, cooling capacity and coefficient of performance, among other parameters, with frequency and outdoor temperature. Since the condenser was water cooled and not air cooled, the condenser exit refrigerant temperature was taken as representative of the outdoor ambient temperature. This is justified as in an air conditioner the refrigerant condenser exit temperature is dependent on the outdoor dry-bulb temperature. The plant performance was then recorded at steady state conditions. After any variation in the settings, the plant was left running for at least an hour before any readings were recorded to ensure steady-state conditions.

The refrigerant temperatures and high-side pressure were varied by varying the flow of water into the condenser and evaporator. By increasing the water flow into the condenser, the refrigerant temperatures at both entry and exit to the condenser decreased, due to increased heat transfer effect. This caused the condenser head-pressure to decrease. For the evaporator, increasing the flow of water meant increasing the superheat given to the refrigerant gas. The evaporator pressure could have been varied by varying the expansion valve setting, however this was kept constant. This was done since the expansion valve also meters the mass flow rate of the refrigerant, and it was desired to see how the performance would vary with a variation in frequency only, and not under other conditions. Therefore an appropriate expansion valve setting was found, one which allowed the achievement of the whole range of set points required.

The frequency input to the motor was varied by changing the inverter setting. The inverter frequency was varied between 20 Hz and 50 Hz, in steps of 10 Hz. At each frequency setting, the condenser exit refrigerant temperature was varied between 25°C and 50°C, in steps of 5°C. In order to have consistent results, the refrigerant exiting the evaporator was always given around 7°C of superheat.

A set of experiments with the system driven directly from the mains were also carried out in order to investigate the efficiency of the inverter. The condenser exit refrigerant temperature was varied between 25°C and 50°C, in steps of 5°C as for the inverter driven system.

After reaching steady-state conditions, the following readings were recorded:

- condenser entry and exit refrigerant pressures
- evaporator entry and exit refrigerant pressures
- condenser entry and exit refrigerant temperatures
- condenser entry and exit water temperatures
- evaporator entry and exit refrigerant temperatures
- evaporator entry and exit water temperatures
- condenser water flow rate
- evaporator water flow rate
- refrigerant flow rate
- time for 1 revolution of the power meter
- motor dynamometer load
- motor and compressor speeds

These readings were used to perform energy balances for the system at each set point, and to calculate the relevant COPs and cooling capacities reported in this work.

START-UP EXPERIMENTS

These experiments were carried out to investigate the start-up power requirements of both a mains driven system and an inverter driven system at 50 Hz. Start-up tests were performed by switching on the setup and letting it run for 6 minutes, then switching off for 5 minutes, and repeating this procedure for a number of times. Readings were taken from the watt-hour meter after certain time periods: every 30 seconds for the first 3 minutes of operation, and every minute for the rest of the on period. An average value of the power consumed within each period was calculated. The condenser and evaporator water flow rates were kept constant, and the water entry temperature was kept constant for both the mains and inverter driven systems so as to be able to compare the results.

Additional calculations and details on the work presented in this paper can be found in Grech [12].

STEADY-STATE RESULTS

As can be seen from Figure 1, the inverter frequency greatly affects the efficiency of the induction motor. The trend seen on this graph is that the motor efficiency remains within the same region when operating between 40 and 50 Hz, but drops drastically at lower frequencies. The induction motor used in this plant was not designed to operate at such low frequencies; therefore its performance deteriorates rapidly.

The energy requirements of the inverter driven system and the direct mains driven system at a frequency of 50 Hz were compared in order to calculate the inverter efficiency. Table 2 shows the power requirements for both systems at each condenser refrigerant exit temperature and the corresponding inverter efficiency. The average inverter efficiency over the range of tested temperatures is 95.2%.

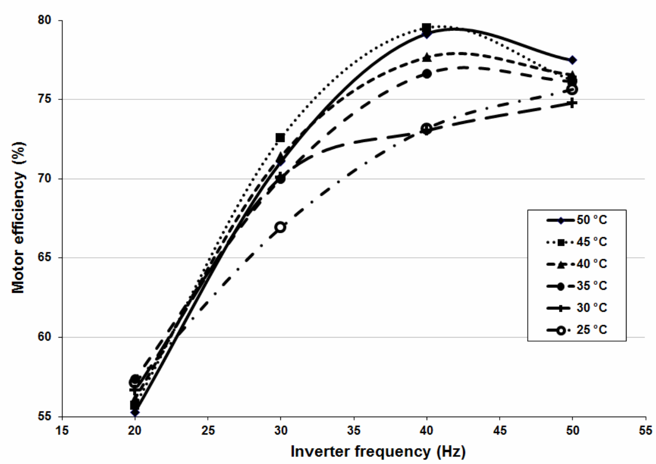

Figure 1: Variation of motor efficiency with inverter frequency at various condenser refrigerant exit temperature.

The analysis of the variation of the compressor discharge superheat with inverter frequency showed that the superheat decreased as the inverter frequency was reduced. This shows that for the same condenser exit refrigerant temperature, the refrigerant exiting the compressor will be at a reduced temperature at low frequencies. This implies that for the same condenser exit refrigerant temperature, the isentropic efficiency of the compressor will increase as the inverter frequency is reduced.

Figure 2 shows the variation of the refrigerant mass flow rate with the condenser exit refrigerant temperature at each tested frequency. The refrigerant mass flow rate increases as the condenser refrigerant exit temperature is reduced. As the condenser exit refrigerant temperature is reduced, the compressor discharge temperature also decreases since it is dependent on the former. The compressor will thus be operating at a reduced pressure ratio. Since the volumetric efficiency of a compressor decreases with an increasing pressure ratio, the volumetric efficiency is reduced as the condenser exit refrigerant temperature is increased. The refrigerant mass flow rate is reduced due to the reduction in the volumetric efficiency, giving the trend observed in Figure 2.

Table 2: Inverter efficiency at each condenser refrigerant exit temperature

Condenser refrigerant exit temperature	Mains driven system		Inverter driven system		Inverter efficiency
	Elect. Power	Mech. Power	Elect. Power	Mech. Power	
25°C	542 W	412 W	583 W	412 W	92.9 %
30°C	574 W	425 W	608 W	425 W	94.4 %
35°C	600 W	447 W	630 W	448 W	95.5 %
40°C	621 W	458 W	641 W	458 W	96.8 %
45°C	643 W	470 W	660 W	470 W	97.4 %
50°C	643 W	493 W	682 W	493 W	94.2 %

For the variation of the cooling capacity with frequency, it can be seen that as the frequency is reduced, the cooling capacity is also reduced. This is due to the reduction in refrigerant mass flow rate at reduced frequencies. There is a great similarity in the trends of refrigerant cooling capacity and the water refrigeration effect, when plotted both against temperature and against frequency. This is implies that a good energy balance was achieved between the refrigerant side and the water side during the operation of the plant.

Graphs showing the variation of cooling capacity per unit displacement of the compressor against frequency were plotted in order to be able to compare with the finding of Tassou and Qureshi [8]. The trend observed in Figure 4 is similar to that reported by Tassou and Qureshi [8], as the cooling capacity per unit displacement remained almost constant as the inverter frequency was changed.

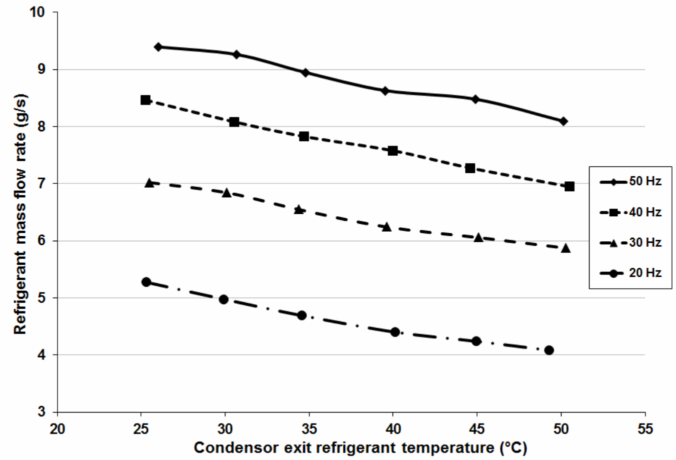

Figure 2: Variation of refrigerant mass flow rate with condenser exit refrigerant temperature.

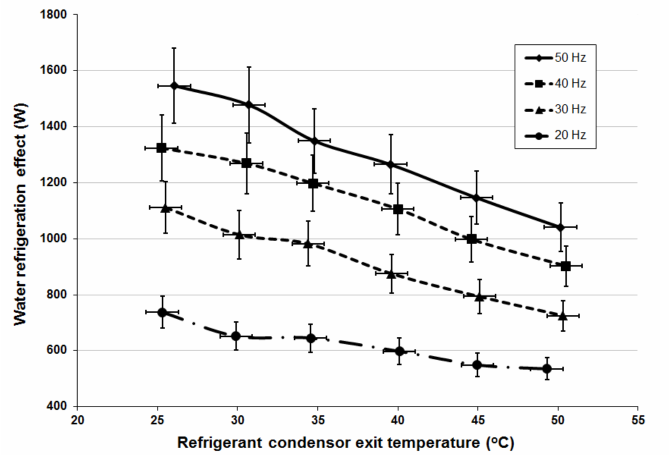

Figure 3: Variation of water refrigeration effect with refrigerant condenser exit temperature.

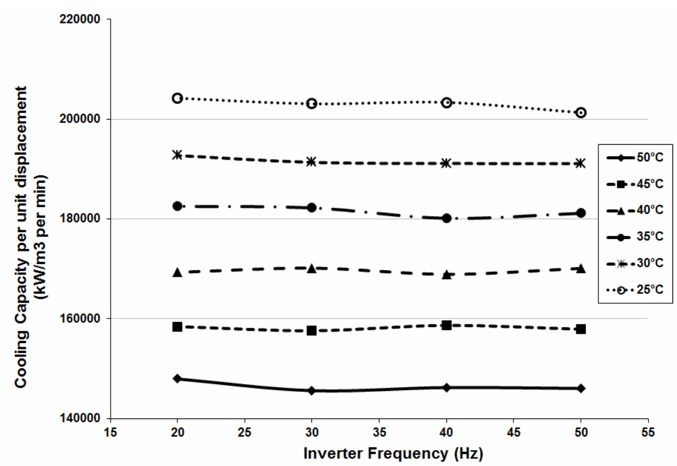

Figure 4: Cooling capacity per unit displacement (using refrigerant liquid volume flow rate) with inverter frequency

The electrical power input variations with temperature and frequency were also analysed and are shown in Figure 5. A reduction in the condenser exit refrigerant temperature implies a reduction in the condensing pressure of the system. As the condensing pressure is reduced, the overall compressor pressure ratio will also reduce and the compressor will require a reduced amount of input power, as seen in Figure 5. The electrical power input also reduces drastically as the inverter frequency is reduced. This can be attributed to three factors; the lower mass flow rate of the refrigerant, the lower pressure ratio and the improved isentropic efficiency of the compressor.

As explained previously, by reducing the inverter frequency the refrigerant mass flow rate is also reduced. This implies that for a constant condensing pressure, the power required to compress with the same pressure ratio will be less at reduced inverter frequency due to the reduced mass of refrigerant required to be compressed.

For a constant condensing temperature, the evaporating temperature increases with a reduction in frequency. This causes the evaporating pressure to increase, hence reducing the overall pressure ratio required in the compressor, thus reducing the power requirement.

The isentropic efficiency of the compressor increases with a reduction in the inverter frequency, as explained previously. Therefore for the same condenser exit refrigerant temperature (or compression ratio), the isentropic efficiency of the compressor will increase as the frequency is reduced; resulting in a reduced power requirement.

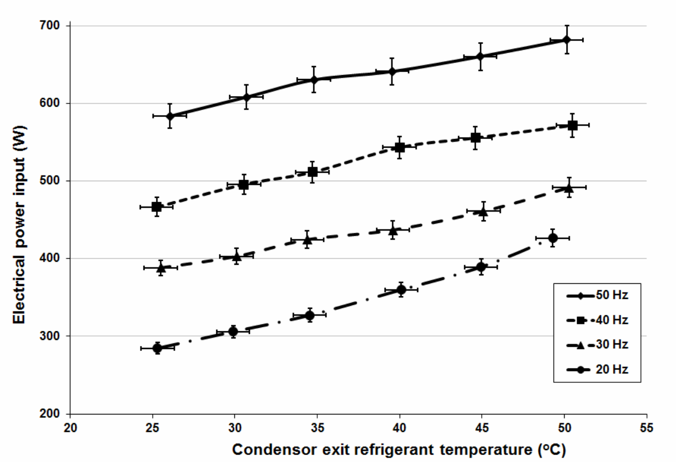

Figure 5: Variation of electrical power input with condenser exit refrigerant temperature.

The variation of input power per unit displacement of the compressor against frequency were plotted in order to be able to compare to that reported by Tassou and Qureshi [8] for an open-type compressor. In Figure 6 the trend is similar as the mechanical input power per unit displacement decreased as the inverter frequency was reduced.

COOLING COEFFICIENT OF PERFORMANCE

The variation in cooling COP calculated using various methods was plotted against temperature and frequency. The Carnot cooling COP shows an increase in its value at lower condenser exit refrigerant temperatures as shown in Figure 7. This result compares well with that previously reported by Tassou and Qureshi [8]. As previously explained, at lower condenser exit refrigerant temperatures the cooling effect produced increases whilst the power required decreases, leading to an increased value of cooling COP. The variation of mechanical cooling COP shown in Figure 8 shows a similar trend, implying that in order to achieve a given cooling effect, less power is required when operating at low frequencies. These graphs compare well with those for an open-type compressor given in [8].

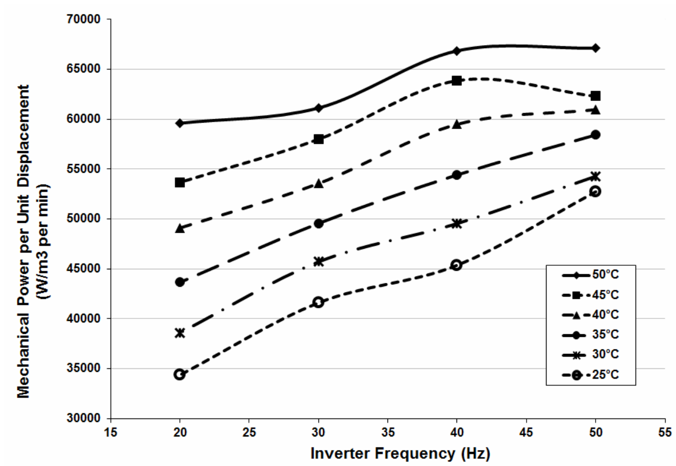

Figure 6: Variation of mechanical power input per unit displacement (using refrigerant liquid volume flow rate) with inverter frequency.

For the electrical cooling COP however, given in Figure 9, a different trend is observed. It can be seen that the cooling COP increases as the frequency is reduced from 50 Hz to 40 Hz but then decreases as the frequency continues to decrease, unlike the previous COP trends. This is a result of the decreased motor efficiency at low frequencies, as shown previously in Figure 1. Therefore, the actual performance of the tested system deteriorates at low frequencies.

It can be observed that the COP values for the Carnot efficiency are greater than the COP calculated for the refrigerant enthalpies, which is to be expected since the Carnot COP is the ideal and maximum possible value of COP. The refrigerant COP has a lower value since the actual refrigeration cycle used involved superheating and subcooling of the working fluid, along with throttling losses, unlike in the ideal Carnot cycle. The mechanical COP is further reduced due to energy losses in the transmission of power from the motor to the compressor, and compressor losses. The electrical power input also includes inverter and motor energy losses thus reducing the electrical COP further.

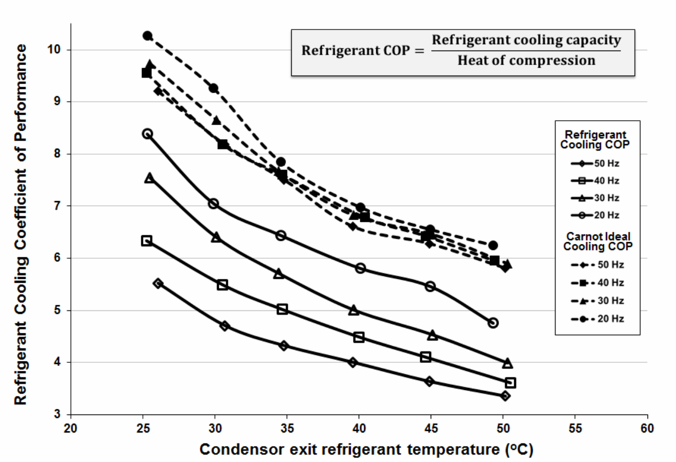

Figure 7: Variation of refrigerant cooling COP with condenser exit refrigerant temperature.

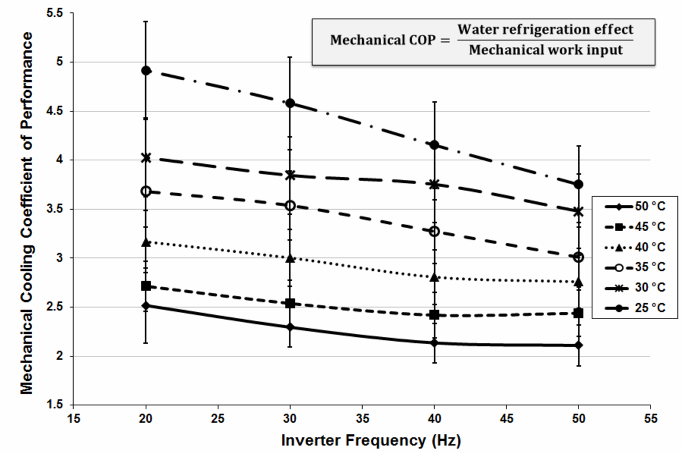

Figure 8: Variation of mechanical cooling COP with inverter frequency.

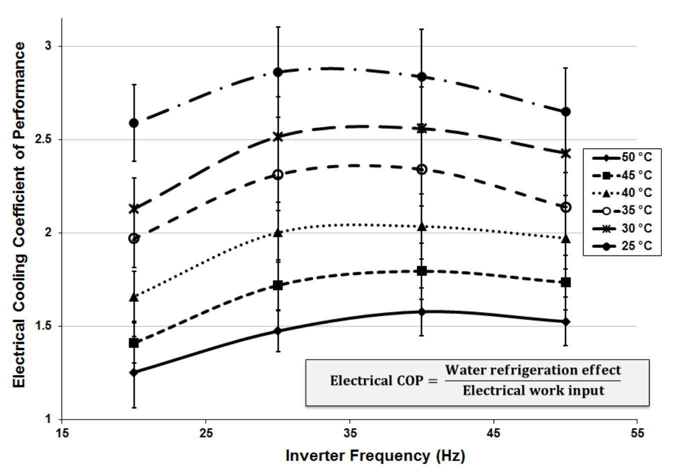

Figure 9: Variation of electrical cooling COP with inverter frequency.

Figure 10 shows the matching capability of a conventional and an inverter driven air conditioning to an appropriately sized house or room. This figure shows the improved load matching capability of the inverter driven unit by the reduction of the operating frequency. For the refrigeration unit tested, the full-load conditions were at a refrigerant condenser exit temperature of 50°C and a frequency of 50Hz. This resulted in a refrigerating effect of 1040W. The conventional air conditioner will only match the house load at this designed point, and will have to cycle on/off if the load is less than 1040W. The inverter driven system matches the load over a range of outdoor temperatures (from 50°C to 40°C), eliminating the need for on/off cycling in this operating range, though it will still have to cycle on/off below 40°C.

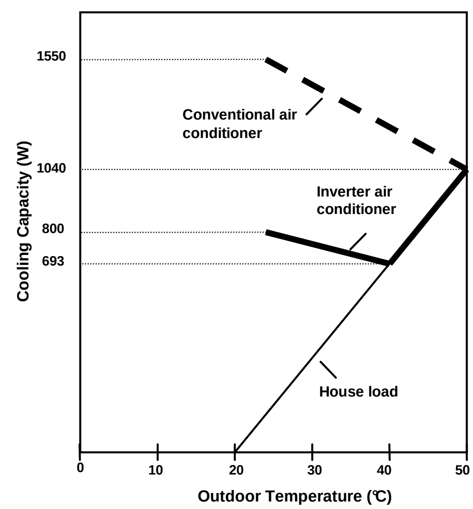

Figure 10: Range of matching capabilities for the refrigeration unit**.**

START-UP RESULTS

The results for the start-up experiments are shown in Figures 11 and 12. In a mains driven system, during the first few seconds after switching on, there is a large power consumption. This is attributed to the large starting current required by the motor to start-up. The inverter driven system allows for a softer start as it takes some time to reach its maximum speed (50Hz), therefore less starting power is required. This experiment could only be performed at a frequency of 50Hz, since the frequency of the mains is constant.

At 50Hz, the inverter driven system required more power overall to operate, due to the additional power requirement of the inverter. The experiment showed that the power consumption for the inverter driven system after around a minute is greater than the mains driven system. Therefore, the inverter's soft start capability did not result in much energy savings, since the direct mains system became more efficient after 60 seconds of operation. Thus, it can be concluded that for a conventional system and an inverter driven system both operating at full-load conditions, the conventional air conditioner is more efficient since the start-up savings obtained by the inverter are not enough to make up for the additional power requirement of the inverter.

CONCLUSION

From the experiments performed, it was found that the mechanical cooling coefficient of performance increased as the operating frequency was reduced. This means that an improved performance can be achieved at lower operating frequencies. However when operating at full-load, and therefore both inverter air conditioner and conventional air conditioner having an operating frequency of 50 Hz, the conventional air conditioner was more efficient. This occurred since the inverter start-up did not result in significant energy savings when compared to the additional power required by the inverter. The inverter air conditioner had a lower electrical COP than the conventional air conditioner due to this additional power requirement. Therefore, at full-load conditions the conventional air conditioner had a superior performance to the inverter air conditioner.

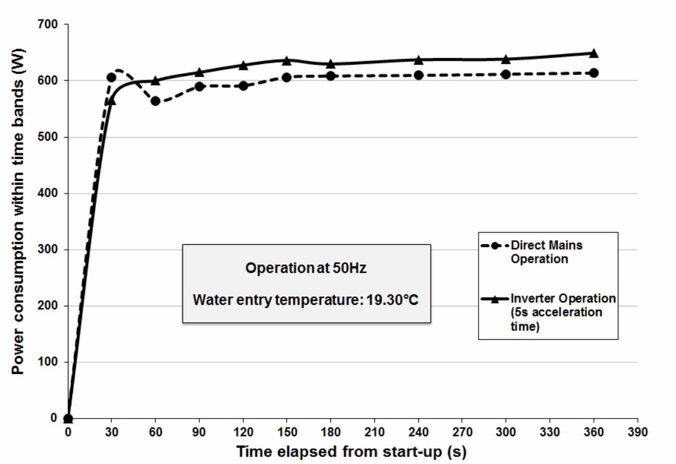

Figure 11: Variation of power consumption during start-up with time.

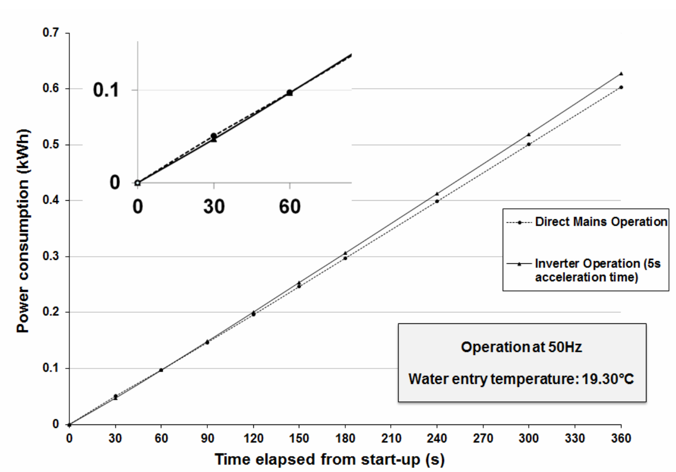

Figure 12: Variation of power consumption during start-up with time.

Under part-load conditions, the conventional system operates at maximum speed and cycles on/off frequently. This results in a reduced efficiency due to start-up losses and produces a greater cooling capacity at a lower COP than is required. The inverter driven system can operate at a lower frequency, depending on the outdoor conditions and the indoor required temperature, in order to match the load and obtain the highest possible COP at those conditions. The experimental investigation showed that the power required by the inverter system at part load was significantly lower than if the system was cycling on/off in the fixed-speed mode. The inverter air conditioner did not only operate with a reduced power requirement when compared to the conventional air conditioner, but also achieved an improved performance due to the increased cooling COP at low frequencies. The experienced performance deterioration due to the reduced motor efficiency at low frequency incurred during the experiments showed that there is a lower limit to the lowest frequency the inverter system can be expected to operate with. It was observed that as the lowest frequencies were approached, the electrical cooling COP of the inverter air conditioner started to decrease, while the mechanical cooling COP kept increasing.

A conventional air conditioning system undergoes many on/off cycles, with each cycle requiring a high start-up energy. Due to the softer start of the inverter, the power required to start up such a system is reduced. Additionally, since an inverter system cycles on/off less frequently than a conventional system, it encounters less start-up losses. Therefore, for an inverter air conditioner, the start-up power required during its period of operation is reduced both due to the softer start of the motor and the reduced number of start-ups. However, it was experimentally determined that due to the additional power requirement of the inverter, this softer start did not result in overall energy savings, since the tested mains driven system became more efficient than the inverter driven system after around 60 seconds of operation.

From this experimental investigation, it is possible to conclude that an inverter driven system can offer energy savings over a conventional air conditioner when operating at part-load conditions. The maximum steady state mechanical COP improvement obtained when operating at a reduced frequency of 20 Hz and a refrigerant condenser exit temperature of 25°C was 31.2 per cent. Even though the inverter air conditioner will still have to cycle on and off at these conditions, the improved part-load performance will still result in significant energy savings.

The inverter driven system requires a greater power input than the conventional system to operate at the same speed (50 Hz), due to the additional power requirements (losses) of the inverter. However the inverter system will be operating at reduced speeds during most of the on-time. At these reduced speeds, the overall power required will be less than if the system were operating at fixed maximum speed under part-load conditions. The inverter system will also be operating for longer periods of time than the conventional system, but the power requirement during most of its on-time will be very low. These factors allow the inverter air conditioner to achieve energy savings when compared to conventional air conditioning systems. The amount of gains or possibly losses is heavily dependent on the operating regime of the air conditioner according to the outside temperature and cooling load requirements.

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