Investigations on the Performance of a Non-Inverter Air Conditioner under Varied Supply Voltage

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Abstract: An experimental investigation on the effect of supply voltage variation on the performance of a non-inverter air conditioning (AC) unit has been carried out. In this test, the supply voltage was varied from 170 to 240 V with 10 V increment and was supplied to an air conditioner with a nominal compressor capacity of 1 hp. The test was conducted under ISO 5151, in which the indoor and outdoor compartments conditions were maintained at constant temperatures as defined by the standard. From the experiment, it was revealed that the operating conditions of the air conditioner are not significantly affected. The suction temperature, discharge temperature, and condensing temperature are almost constant during the test. However, the performance of the air conditioner is significantly affected. In comparison to the standard voltage of 220 V, the power consumption decreased when the supply voltage was set at 170 to 190V. It then increased when the supply voltage was increased from 190 to 240 V. The cooling capacity of the AC unit constantly increases with the increase of voltage from 170 to 220 V. A constant cooling capacity was observed for a voltage range of 220 to 240 V. The energy efficiency ratio (EER) tends to increase with the increase in voltage from 170 to 220 V and then decreases with the increase of voltage from 220 to 240 V. The optimum AC performance is obtained at a supply voltage of 220 V that gives power consumption of 717 W, cooling capacity of 2369 W, and EER of 3.30. In addition to performance evaluation, the results also highlight the environmental aspect of energy consumption. Using appropriate supply voltage on a single AC unit with a compressor capacity of 1 pk has the potential to reduce CO_2 emissions by up to 1.7 tons per year.

Keywords: Energy Efficiency Ratio, Power Consumption, Cooling Capacity, Voltage Variations, Non-inverter AC, ISO 5151.

1. INTRODUCTION

The demand for energy in buildings continues to rise, driven not only by population growth but also by improvements in living standards [1, 2]. At the same time, global warming further intensifies this demand, particularly in the residential and commercial sectors [3, 4]. To ensure reliable energy supply in the future, it is essential to understand how technologies will be adopted and integrated. When combined with the impacts of climate change, the need for cooling is expected to grow significantly [5]. The increase of demand for cooling is highly linked to increases in CO_2 emissions because fossil fuels still dominate the electricity generation. IEA reports that indirect CO_2 emissions from space cooling have nearly tripled since 1990 to over 1 Gt CO_2 in 2022 [6]. Efficiency improvements and cleaner refrigerants should be widely adopted. Otherwise, cooling sector emissions could rise by 210-460 Gt CO_2e over the next 40 years [7]. Due to the increase of population and wealthy, residential cooling emissions per household in India have sharply increased between 2000 and 2022. This emphasizing the urgency of decarbonization strategies [8].

Heating degree-days show a global decline, reflecting reduced demand for heating energy. In contrast, cooling degree-days are increasing, with the strongest growth observed in regions experiencing rapid population expansion. The ongoing demographic shift toward warmer climates further amplifies this trend. Consequently, the increase in cooling demand outpaces the reduction in heating demand, indicating a net rise in global energy needs for thermal comfort [9]. Studies in five representative cities Hong Kong, London, Montreal, Sydney, and Zurich revealed that urban cooling demand is rising over recent decades in the case cities. It was mainly driven by warming climate, more frequent heat extremes, and urbanization. The rise of cooling demand could be anticipated by a combination of policies, behavior change, efficiency improvements, and urban design [10]. A similar study showed that populous region in Iran experienced a higher increase in annual cooling degree days (ACDD) [11].

The rise in cooling demand drives the growth of the air conditioner market. In developing and urbanizing regions, population growth and better living standards make this demand even stronger. As a result, the global AC market keeps expanding. The air conditioning market and sustainable cooling technologies will be a major investment sector, with huge potential if regulations and efficiencies are implemented [12]. This growth brings opportunities but

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also raises challenges, especially in energy use, power system stability, and sustainability.

Room air conditioners require a stable voltage supply to operate efficiently and reliably. Voltage fluctuations can cause compressors and fan motors to draw excessive current, leading to overheating, reduced cooling performance, and shorter equipment lifetime [13]. A study on an investigation on how voltage fluctuations affect torque and vibration in induction motors has been accomplished. It was obvious that the fluctuation affects the motor performance in terms of torque drop and instability. This corresponds to the reduction of performance and increase risk of damage [14]. Another study on a centrifugal compressor showed that voltage drops changed the compressor operation characteristics [15]. It could increase the risk of surge and stress; and it emphasizes that instability or low voltage can degrade the performance of electrical machinery.

A model and analysis on how voltage fluctuation causes increased ohmic losses, vibration, and stress in the motor have also been developed. In this study, the model was used to assess the electrical behavior of three-phase induction motors under voltage fluctuation conditions [16]. It is validated through both small and large signal analyses. By using two equivalent circuits, the model predicted variations in current and torque. It also predicted the increase in additional losses when the motor was operated under periodic sinusoidal voltage fluctuations.

In severe cases, under-voltage may stall the compressor motor, while over-voltage can damage sensitive electronic components [17]. For these reasons, maintaining voltage stability is critical not only for energy efficiency but also for protecting the system. Studies highlight that residential air conditioners are highly sensitive to supply voltage variations, and unstable conditions can significantly affect both performance and power consumption. A study on domestic air conditioners showed that a low voltage drop causes the AC to draw more current but use less power. A larger voltage drop makes reactive power demand rise because the capacitor loses much of its compensation ability [18].

The effects of voltage variation on the performance of refrigeration machines have also been studied. By testing a refrigerator under ISO (International Organization for Standardization) and JIS (Japanese Industrial Standards), it was reported that a variation of supply voltage affected its motor rotational speed and energy consumption [19]. Performance testing experiments on six types of heat pumps have been completed in New Zealand. Tests were conducted under voltage dip/sag, undervoltage, and overvoltage conditions. These tests revealed several types with poor-fair current harmonics and some with high inrush current [20].

Although the qualitative impact of voltage fluctuations on AC performance has been widely studied, quantitative studies on the impact of supply voltage fluctuations on AC performance are still lacking. Therefore, this paper presents experimental results on the quantitative impact of supply voltage changes on AC performance, including power consumption, cooling capacity, and energy efficiency ratio (EER). Besides evaluating technical performance, this study also underlines the environmental impact of energy use. Because electricity production is closely tied to CO_2 emissions, running the air conditioner at its most efficient voltage helps cut down on unnecessary energy consumption and lowers the carbon footprint.

2. MATERIALS AND METHOD

The experiment to evaluate the performance of an air conditioner at varied supply voltage was carried out in a standardized facility in accordance with ISO 5151:2017. The test facility consists of two chambers: indoor chamber and outdoor chamber. The outdoor chamber is a perfectly sealed room where the outdoor unit of the air conditioner is installed. The indoor chamber is the room where the indoor unit of the AC is installed. In this experiment, the outdoor chamber was maintained at 35°C dry-bulb temperature (DBT) and 24°C wet-bulb temperature (WBT). Meanwhile, the indoor chamber was maintained at 27°C DBT and 19°C WBT. The temperature sets refer to the conditions for testing of cooling capacity for moderate climates. Each test were carried out by running the air conditioner for 4 hours after the desired conditions of indoor and outdoor chambers were reached.

To maintain the condition of the outdoor and indoor chamber, the facility is equipped with cooling coil, heating coil, and humidifier. If the chamber temperature exceeds the setpoint, the cooling coil will work to lower the room temperature to the desired setpoint. If the chamber temperature is too low compared to the setpoint, the heater will work to increase the temperature. The humidifier works if the moisture content in the room is too low. If it is too high, the cooling coil will work to lower the moisture content.

The test was conducted by varying the supply voltage from 170 V to 240 V to an air conditioner with a 1 hp compressor. In the first test, the voltage was set at 170 V and the air conditioner was operated and tested to evaluate its performance. The test was then repeated for supply voltage of 180, 190, 200, 210, 220, 230, and 240 V. During the test, 32 parameters were measured, including the dry-bulb temperature, wet-bulb temperature, pressure, air flowrate, voltage, current, and input power. To evaluate the rate of dehumidification, the mass of condensate water from the evaporator was also measured. Suction temperature, discharge temperature, and condensing temperature were also measured to analyze the effect of voltage variation on the operating conditions of the air conditioner.

The uncertainty associated with the measurement of air temperature in this study is estimated to be ±0.2 °C. For the measurement of volumetric airflow rate, the uncertainty is relatively higher, reaching approximately ±5%. In the case of electrical parameters such as voltage, current, and power measurement, the uncertainties are about ±0.5%. The complete summary of the measurement uncertainties considered in this experiment is presented in Table **1**.

Table 1: Uncertainties of Measurements

Measured quantity	Uncertainty
Air dry-bulb temperature	0.2°C
Air wet-bulb temperature	0.2°C
Air volumetric flowrate	5%
Static pressure	5 Pa for pressure ≤ 100 Pa 5% for pressure ≥ 100 Pa
Electrical current	0.5%
Electrical voltage	0.5%

To calculate the performance of the air conditioner, the mass flow rate and enthalpy of air entering and leaving the evaporator should be determined first. The total cooling capacity can be calculated using

$$q_{e,t} = \dot{m}(h_{a,i} - h_{a,o}) \quad (1)$$

where

$q_{e,t}$: total cooling capacity at the evaporator, kW

$\dot{m}$: mass flow rate of air, kg/s

$h_{a,i}$: enthalpy of air entering the evaporator, kJ/k

$h_{a,o}$: enthalpy of air leaving the evaporator, kJ/kg

The enthalpy of air entering and leaving the evaporator can be determined by using the measurement data of dry-bulb and wet-bulb temperature of air entering and leaving the evaporator. The mass flow rate can be expressed as

$$\dot{m} = \rho Q_{vi} \quad (2)$$

where

ρ : density of dry air, kg/m^3

Q_{vi} : air flowrate, m^3/s

The air density is the reciprocal of specific volume (v_n). So that equation 1 can be written as

$$q_{e,t} = \frac{Q_{vi}}{v_n}(h_{a,i} - h_{a,o}) \quad (3)$$

The relationship between the specific volume of dry air and the specific volume of air-water vapor mixture can be expressed as

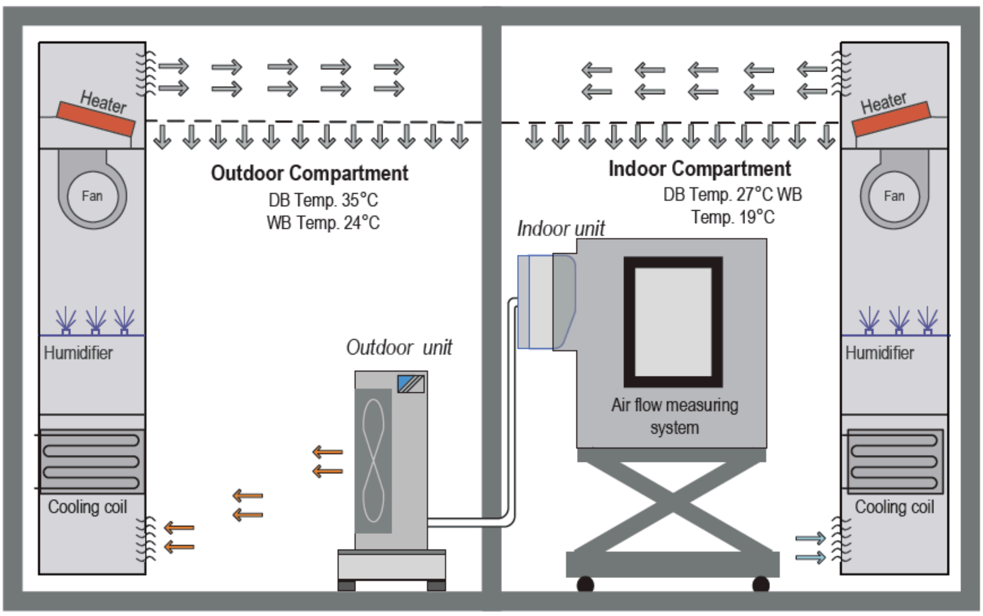

Figure 1: Experimental test rig.

$$v_n = v_n'(1 + W_n) \tag{4}$$

where v_n' is the specific volume of air-water vapor mixture and W_n is the specific humidity of moist air. Combination of equations 3 and 4 results in

$$q_{e,t} = \frac{Q_{vi}}{v_n'(1+W_n)}(h_{a,i} - h_{a,o}) \tag{5}$$

The sensible capacity of the air conditioner can be determined using

$$q_{e,s} = \frac{Q_{vi}}{v_n'(1+W_n)}(c_{pa,i}t_{a,i} - c_{pa,o}t_{a,o}) \tag{6}$$

where

$q_{e,s}$: sensible cooling capacity at the evaporator, kW

$c_{pa,i}$: specific heat of air entering the evaporator, kJ/kg.°C

$c_{pa,o}$: specific heat of air leaving the evaporator, kJ/kg.°C

$t_{a,i}$: temperature of air entering the evaporator, °C

$t_{a,o}$: temperature of air leaving the evaporator, °C

To calculate the latent cooling capacity, the following equation can be used

$$q_{e,l} = \frac{LQ_{vi}}{v_n'(1+W_n)}(W_{a,i} - W_{a,o}) \tag{7}$$

Here, L denotes the latent heat of evaporation of water and $W_{a,i}$ and $W_{a,o}$ denote the specific humidity of air entering and leaving the evaporator, respectively.

This method has been used to test the performance of AC before it is launched into the market. This method is also used to test the performance of the AC at various outdoor temperature variations with constant WBT [21], constant relative humidity [22], and constant moisture content [23]. In addition, a test on the effect of constant outdoor air temperature at varied relative humidity on the performance of an air conditioning unit also involved this method [24].

3. RESULTS AND DISCUSSION

This section discusses the effect of voltage variation on the operating condition and performance of the air conditioner. The operating conditions include suction line temperature, discharge line temperature, condensing temperature, and supply air temperature. The performance covers the input power, cooling capacity, and energy efficiency ratio.

3.1. Suction Line Temperature

The suction line temperature was recorded at the range of 9.1 to 9.8°C with an average of 9.5°C. Measured at the outlet of evaporator, this parameter represents the temperature of refrigerant at the inlet of the compressor. As can be seen in Figure **2**, the suction line temperature is almost constant for all range of electrical voltage. This means that the air conditioning machine can be operated at the given range of voltage. However, further study should be carried out to find out the lifetime of the machine when it is operated at the given voltage range.

An expression for the effect of electrical supply voltage on the suction temperature can be written as

$$t_s = -0.0064V + 10.83 \tag{8}$$

where t_s is the suction temperature in °C and V is supply voltage in Volt. From equation (1), it is apparent that each change in voltage by 1 V only causes a change of suction temperature by 0.006°C.

3.2. Discharge Line Temperature

The measurement of discharge temperature resulted in an average value of 65.9°C and is plotted in Figure **3**. A range of discharge temperatures of 65.4 to 66.9°C was observed in this experiment. Detailed examination of Figure **3** reveals that a slight decrease in discharge temperature was observed when the voltage was varied from 170 V to 240V. The effect of supply voltage on the discharge temperature (t_d) can be expressed as

$$t_d = -0.0139V + 68.699 \tag{9}$$

Here, each 1 V change in supply voltage causes a change in discharge temperature by 0.014°C. The effect of supply voltage is considered very small. However, the effect of supply voltage on the discharge temperature is more significant than that of suction temperature.

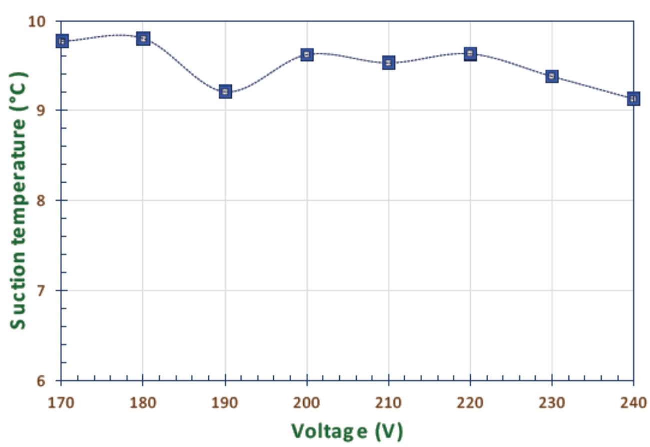

Figure 2: Suction temperature vs supply voltage.

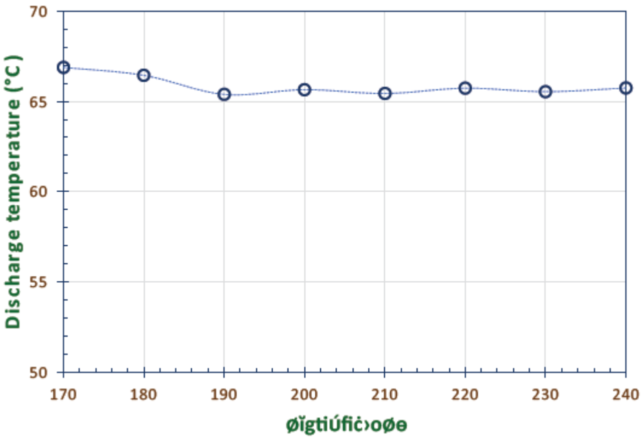

Figure 3: Discharge temperature vs supply voltage.

3.3. Condensing Temperature

A range of condensing temperatures of 41.8 to 43.3°C with an average of 42.4°C was noted from the measurement of condensing temperature. The profile of condensing temperature is presented in Figure **4**. The condensing temperature data implies the more significant effect of supply voltage on condensing temperature than that of suction and discharge temperature. From this experiment, it is apparent that each change in supply voltage by 1V causes the change in condensing temperature by 0.019°C. Based on the experimental data, the effect of supply voltage on the condensing temperature (t_c) can be expressed as

$$t_c = -0.0187V + 46.23 \qquad (10)$$

This correlation should be verified using a wider range of voltage variation, so that the influence of supply voltage can be analyzed more thoroughly.

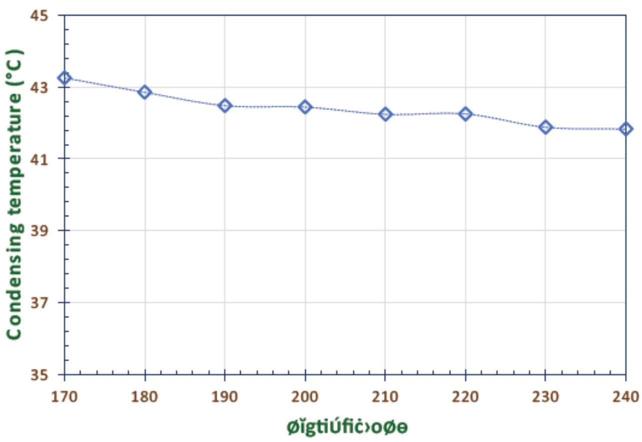

Figure 4: Condensing temperature vs supply voltage.

3.4. Supply Air Temperature

This parameter expresses the temperature of air after being cooled by evaporator and measured at evaporator outlet. The experimental data showed a range of supply temperature of 11.9 to 12.3°C with an average of 12.1°C. Figure **5** summarizes the experimental data for supply temperature. A quick look at this figure shows that there is almost no effect of supply voltage on the supply air temperature. This is supported by the linear approximation which shows that each 1V change in supply voltage only causes the change of supply air temperature by 0.0035°C. Equation (4) can be used to express the effect of supply voltage on supply air temperature (t_{sa}).

$$t_{sa} = -0.0035V + 12.78 \qquad (11)$$

3.5. Power

The effect of voltage variation on the input power of the air conditioner is depicted in Figure **6**. At the lowest voltage, the power was recorded at 729 W. The input power drops to 715, 705, and 707 W when the voltage was increased to 180, 190, and 200 V, respectively. At the voltage of 210, 220, and 230 V, the input power increased again to 709, 717, and 724 V, respectively. Finally, at the voltage of 240 V, the power reached 738 W.

The fluctuation of the input power due to the variation of voltage is mainly caused by the inherent behavior of the compressor motor. When the supplied voltage is below the rated voltage, the motor draws the higher current in order to maintain the cooling capacity. In this experiment, the current was measured at 4.31 A when the unit was operated at 170 V. At normal voltage of 220 V, the current drops to 3.29 A. Again, the current drops to 3.10 A when the supply voltage is set at 240 V.

The correlation between the input power (P_i) and supply voltage (V) can be best approximated by 2nd order polynomial

$$P_i = 0.0215V^2 - 8.657V + 1576.2 \qquad (12)$$

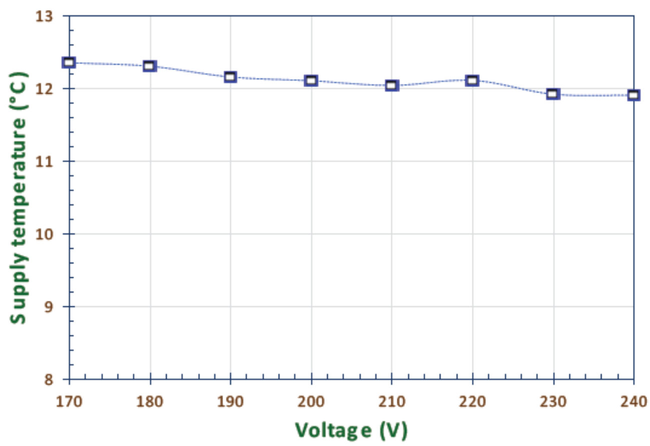

Figure 5: Supply air temperature vs supply voltage.

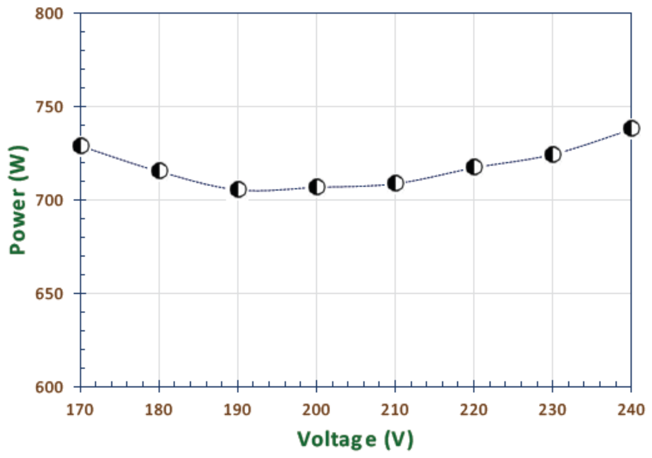

Figure 6: Input power vs supply voltage.

The relationship between power and voltage is approximated using two linear equations from 170 V to 190 V and from 190 V to 240 V as follows:

From 170 V to 190 V:

$$P = -1.2\,V + 927.9 \qquad (13)$$

and from 190 V to 240 V:

$$P = 0.64\,V + 579.3 \qquad (14)$$

From eq. (13), it is obvious that the power required to operate the AC decreases by 1.2 W per 1 V increase in supply voltage from 170 V to 190 V. On the other hand, eq. (14) indicates that the required power increases by 0.64 W every 1 V increase in supply voltage. In percentage, every 1V increase in supply voltage results in 0.09% increase in power.

3.6 Cooling Capacity

Cooling capacity is affected by voltage variation, as can be seen in Figure **7**. At the lowest supply voltage, the capacity of the air conditioner is 2214 W. The capacity increases to 2280 W, 2337 W, and 2369 W at the voltage of 180 V, 200 V, and 220 V, respectively. At the supply voltage higher than 220 V, the cooling capacity tends to be constant.

For the range of voltage of 170 V to 220 V, the relationship between the cooling capacity and the supply voltage can be expressed using a linear equation as follows:

$$q = 2.93\,V + 1727.7 \qquad (15)$$

where q is the cooling capacity in Watt. It indicates an increase of cooling capacity by 2.93 Watt for every increase of 1 V of supply voltage. This equation is valid for V = 170V to 220 V. For 220 ≤ V ≤ 240 V, the cooling capacity is constant.

The low cooling capacity at low input voltage could be caused by the decrease of compressor ability to compress and circulate refrigerant. The mass flow rate of refrigerant could be reduced due to the decrease in supply voltage. It results in a lower cooling capacity.

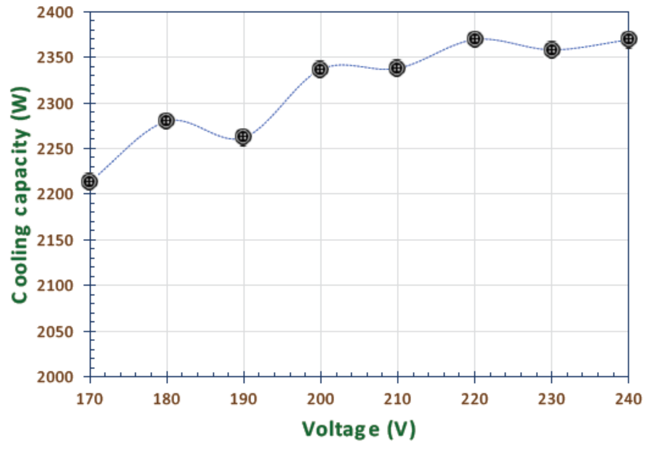

Figure 7: Cooling capacity vs supply voltage.

3.7. Energy Efficiency Ratio (EER)

This parameter represents the ratio of cooling capacity and input power. In air conditioning applications, usually EER has a value of more than one. This means that the air conditioner could produce thermal energy in terms of cooling more than the input power in terms of electrical energy.

Figure **8** shows the effect of supply voltage on the EER of the air conditioner. A range of EER from 3.04 to 3.31 was observed from this experiment. Detailed inspection of Figure **8** reveals that the EER decreases with the decrease of supply voltage, and reaches its minimum at the lowest voltage, 170 V. The increase of supply voltage to 180 V, 200 V, and 220 V causes the increase of EER to 3.19, 3.30, and 3.30, respectively. Further increase in supply voltage to 230 V and 240 V provides the EER of 3.26 and 3.21, respectively. A maximum EER was obtained at a range of voltage 200 V to 220 V.

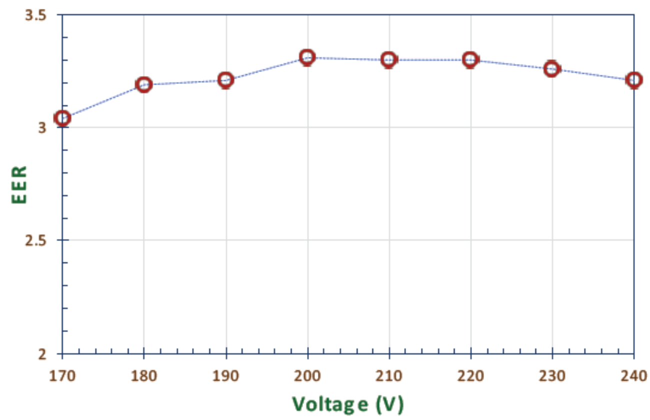

Figure 8: Energy efficiency ratio vs supply voltage.

By using a linear approximation, for the voltage range of 170 V to 110 V, the energy efficiency ratio increases by 0.12% for every 1 V increase in supply voltage. Conversely, for the supply voltage range of 220 V to 240 V, there is a decrease in EER of 0.05% for every 1 V increase in supply voltage.

3.8. CO_2 Emission

In addition to performance evaluation, the results also highlight the environmental aspect of energy consumption. Since electricity generation is commonly associated with CO_2 emissions, optimizing AC operation at the most efficient voltage directly contributes to carbon footprint reduction. For instance, operation at 220 V not only minimizes excess energy use but also reduces indirect CO_2 emissions compared to off-optimum voltages.

At the optimal voltage, the air conditioner EER is recorded at 3.30. At the lowest test voltage, the EER drops to 3.04. This indicates a potential 8% reduction in energy efficiency. If the AC consumes 717 W of power under optimal conditions, then under inappropriate voltage supply, the power consumption could be up to 8% higher to produce the same cooling capacity. In other words, CO_2 emissions could also increase by the same percentage.

Assuming the grid emission factor of 0.82 kg CO_2/kWh, operating the AC unit at the optimum voltage of 220 V results in an annual indirect emission of about 1.7 tons CO_2 (based on 8 hours daily use). Under inappropriate voltage supply, the power consumption could rise by up to 8%, which increases annual emissions to nearly 1.9 tons CO_2. If a building has 100 units of AC, the emissions could reach 20 tons CO_2 annually.

4. CONCLUSION

An experimental investigation on the effect of voltage variation on the performance of a non-inverter air conditioner has been carried out in a standardized test room. The operating conditions such as suction temperature, discharge temperature, and condensing temperature are not significantly affected by the voltage. However, the performance of the air conditioner is significantly affected.

The power consumption to operate the AC decreases when the voltage is varied from 170 V to 190 V, but then increases when the voltage is increased from 190 V to 240 V. The cooling capacity of the AC increases constantly from 170 to 220 V supply voltage. At 220 to 240 V voltage, the cooling capacity is relatively constant. The energy efficiency ratio (EER) of the AC tends to increase when the voltage is increased from 170 V to 220 V. However, it then decreases when the voltage is increased again from 220 V to 240 V.

Taking energy efficiency as the primary consideration, optimum AC operation is obtained at a voltage of 220 V. At this voltage, the AC power consumption was recorded at 717 W, cooling capacity 2369 W, and EER 3.30. From an environmental perspective, the use of appropriate supply voltage on an AC unit with a compressor capacity of 1 pk has the potential to reduce CO2 emissions by up to 1.7 tons per year per AC unit.

CONFLICTS OF INTEREST

The authors have no conflicts of interest to declare.

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