Investigation the performance of Window-Type Air-Conditioning Units with Different Expansion Devices

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Abstract: In this study, the performance of window-type air-conditioning units with an alternative, ozone-friendly refrigerant was enhanced by incorporating a nozzle instead of a capillary tube as an expansion device. An experimental investigation was carried out on 1.5 RT window-type air-conditioning units with controlled environmental zones. According to operating conditions, an ANSYS-fluent program achieved a suitable nozzle geometry for a lower pressure ratio. The refrigeration cycle model was programmed in Engineering Equation Solver (EES). The experiment showed that using a nozzle of (9mm ID X 2 mm OD X 30 mm L) as an expansion device in an air-conditioning system will decrease the required compressor work by 7.7% from the system with a capillary tube and result in a 21% COP increase from the capillary tube system.

Keywords: Air-conditioner; compressor pressure ratio; nozzle; R22.

Nomenclature

COP: Coefficient Of Performance
h : Enthalpy of refrigerant (kJ/kg)
ID: Inlet diameter (mm)
Q_C: Heat rejected by condenser (kW)
Q_e: Refrigerating effect (kW)
RT : Refrigeration Tons (Ton)
OD: Outlet diameter (mm)
p_r: Compressor Pressure ratio
WC: Compressor work (kW)

1 Introduction

In summer, the use of an air conditioner is very important to cool household buildings, and air conditioners represent a major portion of a household's electric power consumption. R22 is a working refrigerant used in household air conditioners, which has been classified as an ozone-depletion material. In 1987, the Montreal Protocol recommended phasing out the use of HFC refrigerants in favour of ozone-friendly refrigerants and reducing CO_2 emissions[1]. The Kigali Amendment to the Montreal Protocol, which was adopted in 2016, is expected to avoid warming by up to 0.5° Celsius by the end of the century while continuing to protect the ozone layer[2]. With such increased claims for reducing CO_2 emissions and for phasing out HFC refrigerants, many studies have sought to use alternative refrigerants to increase the performance of air conditioners by developing new designs that take into account a reduction in pressure through cooling coils, by reducing the developed pressure ratio by reducing compressor power consumption or by reducing the amount of flashing refrigerant through expansion devices. For instance, Farzad[3] carried out an experimental performance comparison for air conditioning operating with different expansion devices, showing that the cooling capacity for the system with a capillary tube decreases more significantly than with a thermostatic valve. Sadler[4] enhanced the performance of a window type air-conditioning system by reducing the pressure drop over the condenser. She found that tubes with (1/2)" diameters provided the highest seasonal COP. Choi et al.[5] examined the performance of a heat pump with different expansion devices, concluding that system performance with an electronic expansion valve is greater than of a capillary tube. Jongmin et al.[6] compared performances for a heat pump working with different expansion devices, capillary tube and an electronic expansion device with R407C as a refrigerant. The study showed that the system with electronic expansion valve offers more system stability with a higher system performance than a capillary tube.

Lazzarin et al.[7] did an experimental comparison of air conditioner performance via electronic expansion valves and thermostatic expansion valves. The study concluded that a system with thermostatic expansion valves show energy savings with respect to thermostatic expansion valves. Kang et al.[8] carried out comprehensive studies on the effects of flash gas generation in multi-air-conditioners using electronic expansion valves, concluding that the refrigerant flow rate decreased rapidly due to the flash gas generation at the electronic expansion valve inlet, thus decreasing the system COP. Chinnaraj et al.[9] did an experimental study on the effects of expansion device type on air conditioner performance, using a capillary tube, thermostatic expansion valve and an electronic expansion valve with three different refrigerants: R22, R290, and R407C. The study concluded that the system with an electronic expansion valve and R290 were the best choices. Shashank et al.[10] studied the effect of capillary tube diameter and coil formation on system performance by using three capillary tubes with different coiled shapes: helical, straight and serpentine. The study concluded that the maximum cooling effect is achieved by using the helical coil and the least by using a straight coil. The system mass flow rate is increased as the capillary tube diameter decreases. Farayibi et al.[11] studied the effect of capillary tube number on the performance of air conditioning systems, concluding that, as the capillary tube number increases from one to three, the COP of the system increases in the order of 5.69±0.04, 6.24±0.04 and 6.71±0.04 when one, two and three capillary lines are used respectively. Jing et al.[12] studied the effect of expansion device type on the performance of a heat pump working with R134a, using three expansion devices: electronic expansion valve, capillary tube and orifice. The study showed that higher system performance can be expected from an electronic expansion valve, and a short tube orifice system would perform better than the capillary tube system. Jusoh et al.[13] performed an experimental study using an ejector as an expansion device in the air conditioner instead of the thermostatic expansion valve. The study concluded that the system with an ejector is better than the thermostatic expansion valve. Aziz et al.[14] investigated the use of a capillary tube and thermostatic expansion valve, the study concludes that thermostatic expansion valve gives better performance than stander refrigeration system with a capillary tube. Al Sayyab[15] performed an experimental exergy-energy analysis comparison for refrigerators working with new alternative refrigerant mixtures for R134a. The experiment revealed that the obtained COP via the new alternative refrigerant mixtures is less than that of R134a. In this context, the most suitable alternative refrigerant to R134a was the mixture of (70%R134a, 10%R290, 20%R600a) with 8% less than COP of R134a. Khalifa et al.[16] carried out an experimental study to optimise air-conditioner performance by using an alternative refrigerant for R22 named R407C, reducing the pressure drop over the condenser. They changed the condenser circuit design, showing that the four-circuit condenser design with a tube diameter of (5/16'') has a lower pressure drop with a 1.2% increase in COP as compared to the base case of one circuit when retrofitted with R407C. Ali [17] studied the effect of capillary tube diameters of 1.4 mm, 1.8 mm and 2.2 mm on refrigerator performance, including new refrigerant mixtures as alternatives to R134a. The experimental work showed that the refrigerator working with a mixture of refrigerants (70%R134a, 10%R290, 20%R600a) and a capillary tube of 1.4 mm demonstrates a 1.3% COP reduction from the base case of R134a and 2.2 mm capillary tube diameter. Al Sayyab[18] carried out an experimental study to check the effect of capillary tube numbers on air conditioning unit performance, using five capillary tubes of the same size: 2.2 mm diameter and 0.6 m length. The experimental work predicted that the air conditioning operating with three capillary tubes provides the highest COP with a 14% increase from the system with two capillary tubes. Mohammed et al.[19] performed a theoretical energy-exergy comparison analysis for the application of an alternative refrigerant to R22 in a small air conditioning unit. The refrigerants under investigation were R290, R600, R600a and R1270. The study concluded that R600a offers an identical performance to R22 and can be used in new units that require compressor modification. Thus, a system with R1270 experiences a lower system performance reduction than R22 by a factor of 4.3% and can be used as a retrofitted alternative refrigerant for units without modification. Ali K.[20] studied the performance of window-type air-conditioning by adding a diffuser at the compressor outlet. The study showed that using a diffuser of 5mm ID, 9mm OD and 12mm L in an air-conditioning system will increase COP by 29% from the base case. Liu et al.[21] studied the effect of expansion devices with a different refrigerant charge on split unit air conditioner performance using R290 as a refrigerant; they adopted three expansion devices: capillary tube, thermostatic expansion valve and electronic expansion valve. The study concluded that the system with a capillary tube has the lowest refrigerant mass flow rate, so the system with the electronic expansion valve has the more significant than with other tested devices.

Any air conditioning unit requires an expansion device that is designed to regulate the mass flow rate and to maintain the pressure ratio over the unit. In a window-type of air conditioner, a capillary tube is the expansion device. The function of the capillary tube is to reduce the condenser pressure and regulate the refrigerant mass flow rate, via the principle of friction force between the capillary tube and the passing liquid refrigerant[11]. Flashing refrigerant vapours are associated with the throttling process, and this vapour ratio will decrease evaporator capacity due to a decrease in the amount of liquid refrigerant. The amount of flashing vapour will increase as the pressure ratio increases (see Fig. 1) (as a result of ambient air temperature increase) due to a decrease in the degree of refrigerant sub-cooling (see Fig. 2).

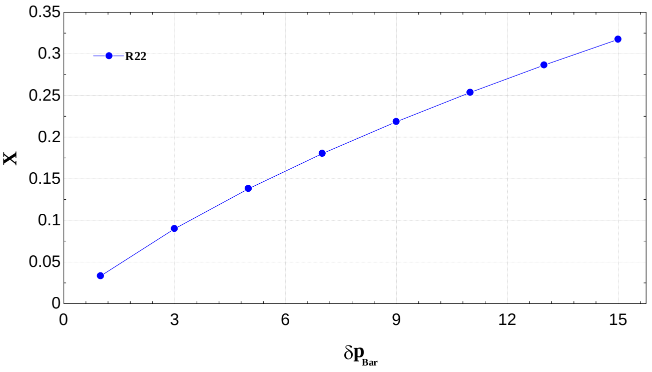

Fig.1. Vapor quality vs. pressure ratio

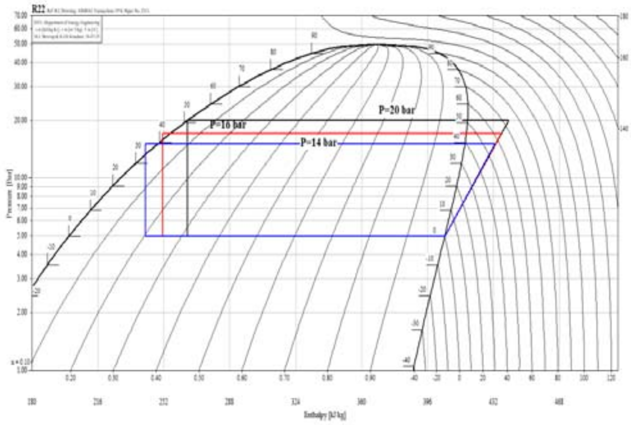

Fig.2. Sub Cool degree vs. pressure ratio

According to this literature review, the effects of changing the capillary tube with non-moving parts expansion device are very limited. The current work is focused on increasing the performance of a window-type air-conditioning unit by using a new expansion device design a subsonic nozzle rather than a capillary tube. A subsonic nozzle is a static device which reduces the pressure of flowing refrigerant by converting some pressure energy into kinetic energy without work consumption[12].

The aim of this study is to:

i. Find a suitable expansion device design to operate with current window-type air-conditioner cycle conditions to address the following issues:

- Reduce flashing refrigerant vapour.
- Increase the refrigerating effect.
- Increase the COP of the refrigeration cycle.

ii. Study the performance of an air conditioner working with nozzle by assessing the effect of ambient air temperature on system performance.

2 The Vapour Compression Refrigeration Cycle

The amount of compressor power of the refrigerant can be found by[23]

$$\dot{w}_{com} = \dot{m}(h_1 - h_2) \quad (1)$$

The condenser heat rejected can be found by

$$Q_{con} = \dot{m}(h_2 - h_3)$$

(2)

The evaporator heat absorbed can be found by

$$Q_{evp.} = \dot{m}(h_1 - h_4)$$

(3)

The coefficient of performance (COP):

To provide an indication of the vapour compression cycle performance, COP is used. This can be found by:

$$COP = \frac{Q_{evp.}}{\dot{w}_{com}} \quad (4)$$

3 Methodology

In this study, all equations related to energy analysis and other properties of studied refrigerants are performed using Engineering Equation Solver Professional (EES) version 8.7, which has built-in thermodynamic property relations, graphical skills, numerical integration, and various other useful mathematical functions.

4 Experimental setup and instrument:

A test rig consisting of a controlled environmental test zone was used to follow the same seasonal air temperature gradient of the climate changes, as shown in Fig. 3.

These consist of:

I. Three metres of an insulated duct of 60 cm*40 cm cross-section area form the controlled zone duct.

II. The supplementary air conditioner of 2 RT: for cooling the outside ambient air temperature to required supply air temperature (flow the low climate conditions). The test conditions are shown in Table A-1.

III. Heating coils formed from six electric heaters of 2000 watts heating capacity associated with a solid-state regulator to regulate the heating watts over the coils.

IV. Two axial fans to blow the air through the duct.

V. Window-type air conditioning unit to be tested with a nozzle. The details for the tested unit component (see table A-4).

To measure the temperature, fourteen digital thermometers were used with T-type thermocouples attached at the inlet and outlet of the compressor, condenser, evaporator and the test zone-condenser air intake section. In addition, six digital pressure gauges were used to measure refrigerant pressure at the inlet and outlet of the compressor, condenser, and evaporator. ANSYS fluent 12 software was used to design the nozzle expansion device that will be used in the experimental test. The inlet and outlet diameters of the nozzle are constant, at 9 mm and 2 mm respectively[20], with three different lengths at 25 mm, 30 mm, and 35 mm. The inlet boundary conditions of all nozzles are gated from operating the window-type air-conditioning unit of 1.5 RT under the maximum ambient air temperature of 50□. All nozzles operate in the same inlet conditions, so the pressure ratio is the figure by which to select the best nozzle. According to the ANSYS program results, a nozzle length of 30 mm gives the lowest-pressure ratio of 14 (see Fig. 4) which is in the range of the compressor manufacturer recommendation's. Moreover, nozzles (5 mm ID, 9 mm OD, and 30 mm length), manufactured and incorporated into air-conditioning units parallel connected with capillary tubes by individual manual valves, were prepared for the test to study the effects of nozzle use on system performance and for comparison with capillary tube performance. The details of measuring devices are mentioned in Table A-2; moreover, the experimental work error analysis is shown in Table A-3. The test procedure is shown by a flowchart (see Appendix A).

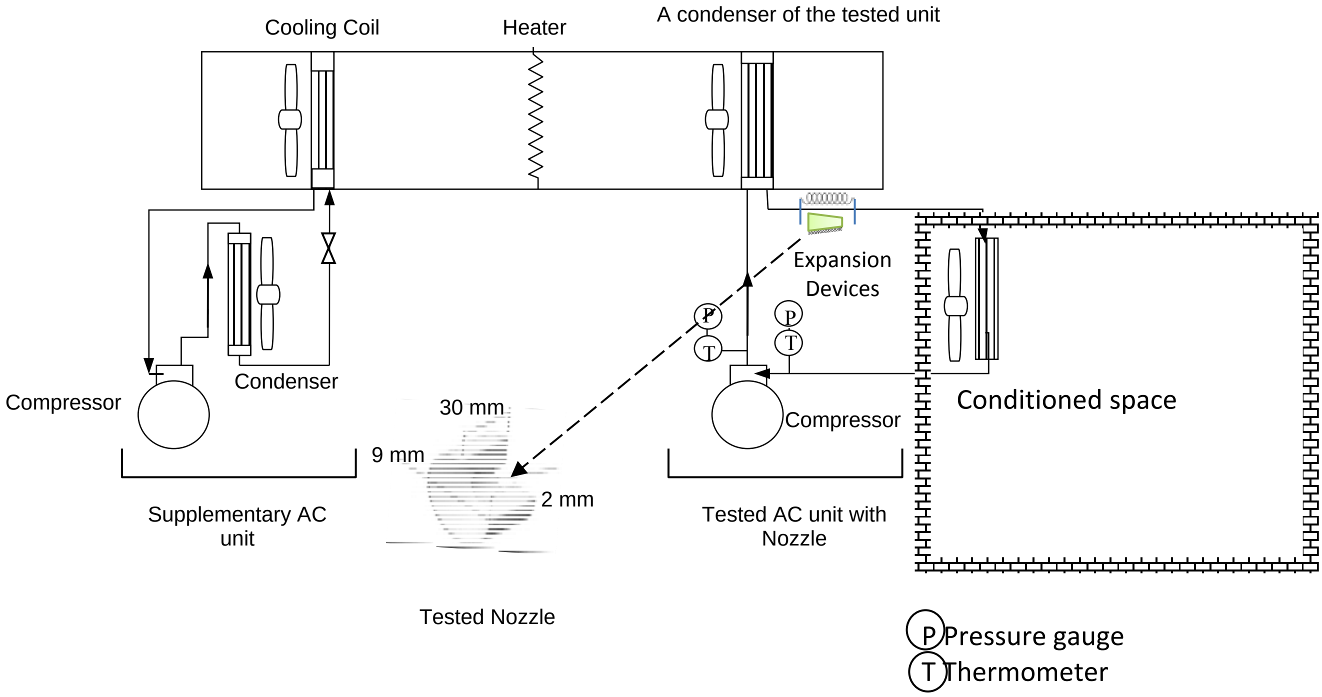

Fig. 3. Test Rig layout

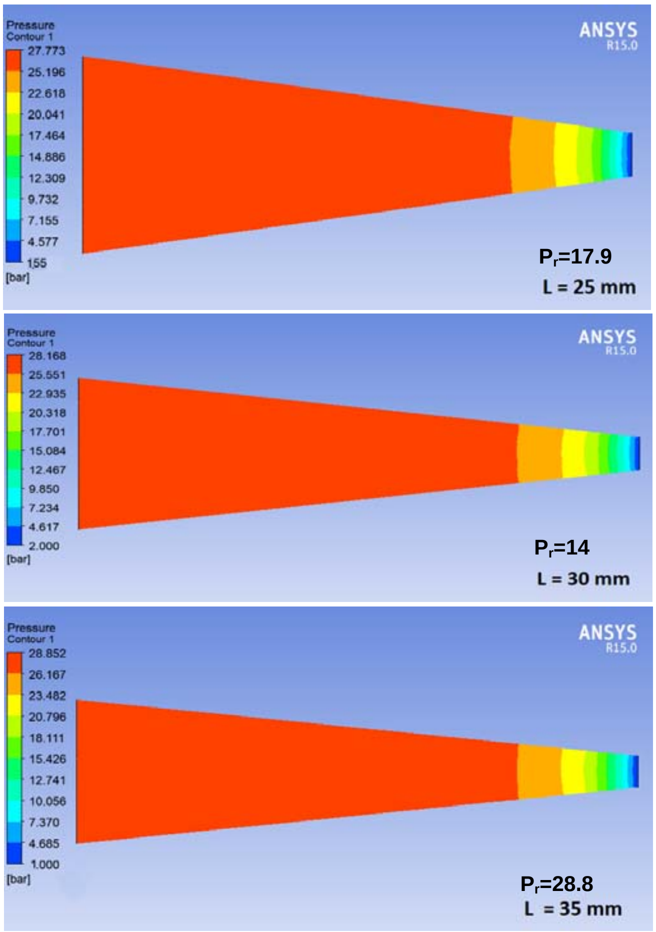

Fig. 4. ANSYS-fluent results of selective nozzles

5 Results and Ddiscussion

5.1. Compressor Work

According to Fig. 5, for all case studies, the compressor work is directly proportional to ambient air temperature; as the ambient air temperature increases, the compressor tends to increase the temperature difference between the refrigerant and ambient air by increasing the condensing pressure: a higher pressure ratio means more work.

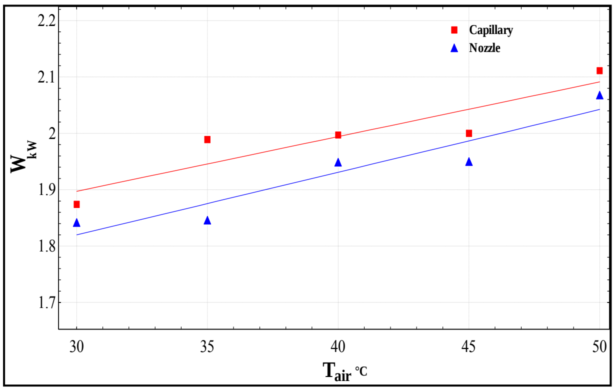

Fig.5.Compressor work vs. ambient air temperature

Also, from Fig. 5, we can see that the air conditioner operating with a capillary tube has more compressor work than other cases, because the capillary tube reduces the pressure by friction. This generates more flashing gas when compared with a nozzle's greater obstruction; this, in turn, requires more work.

5.2 Condenser Heat Rejection

According to Fig.6, for all case studies, the condenser heat rejection is inversely proportional to ambient air temperature. There are two reasons for this phenomenon: the first one is that, as the ambient air temperature increases, there will be a decrease in the air to the refrigerant temperature difference required to achieve heat exchange, and this will decrease the heat transfer coefficient of refrigerant to air side. The second reason is, to achieve the required heat rejection, the compressor tends to increase the condensing temperature by increasing the pressure ratio, and this leads to a decrease in the required pumped refrigerant mass flow rate by the compressor (see Fig. 7), which is associated with decreasing in the latent heat of condensation . For these reasons, the condenser heat rejection will decrease.

According to Fig. 6, at any ambient temperature, the system operating with a nozzle has a higher heat rejection that the other tested cases, due to a higher mass flow rate producing a higher heat transfer coefficient (i.e. more turbulence) than a capillary tube.

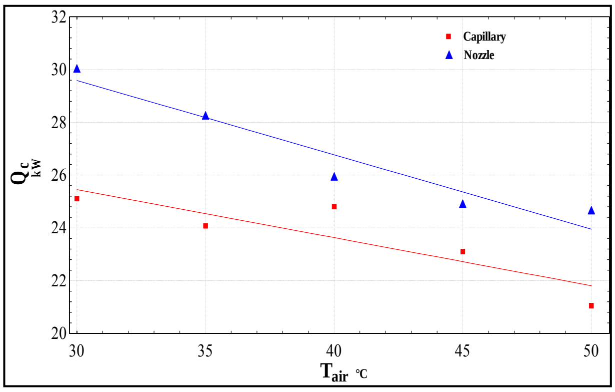

Fig.6. Condenser heat rejection vs. ambient air temperature

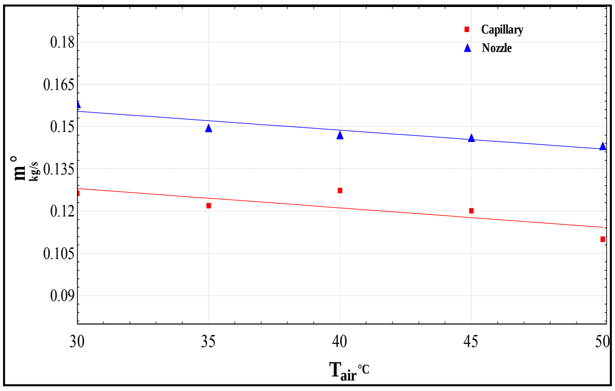

Fig.7. Refrigerant mass flow rate vs. ambient air temperature

5.3 Refrigerating effect

According to Fig. 8, for all case studies, the refrigeration capacity is inversely proportional to ambient air temperature. Due to a reduction in condenser heat rejection associated with ambient air increase, a decrease in the degree of sub cool increases the amount of flashing gas.

Also, per Fig. 8, the system operating with a nozzle has a higher refrigerant capacity due to higher refrigerant mass flow rate, more condenser heat rejection, more subcooling and less flashing gas.

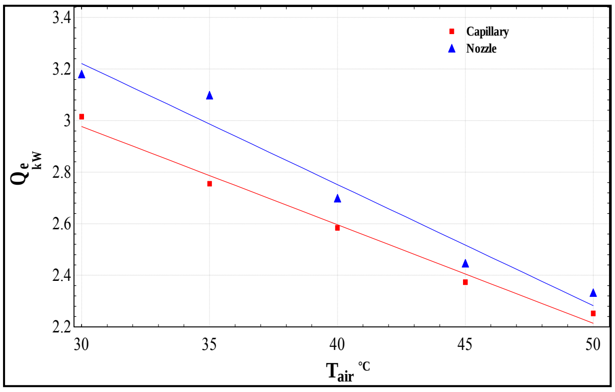

Fig.8. Refrigerating effect vs. ambient air temperature

5.4. Coefficient of performance

According to Fig. 9 for all case studies, COP is inversely proportional to ambient temperature: as the ambient air temperature increases, the compressor work will increase. According to Fig. 5, on the other hand, the refrigeration capacity will decrease as the ambient air temperature increases (see Fig.8), so the COP is the ratio of refrigeration capacity to compressor work.

In addition, Fig. 9 shows that the system with a nozzle provides more COP than that with a capillary tube due to lower compressor work and higher refrigeration capacity.

In the end, the system with a nozzle shows a 21% increase over the system with a capillary tube.

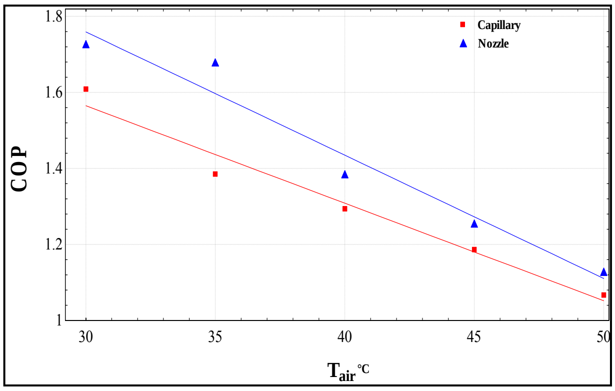

Fig.9. COP vs. ambient air temperature

6 Comparison with Other Studies

According to this literature review, studies of Chio et al.[5] and Chinnaraj et al.[9] are taken for compression with the current study. The study by Chio et al.[5] study examined the effect of refrigerant charge with two expansion devices: electronic expansion valve and capillary tube. Chinnaraj et al.[9] examined the effect of expansion device type (the electronic expansion valve and capillary tube) on the performance of window-type air conditioners working with R407C. The three studies are similar in the base expansion device (capillary tube) but use different refrigerating capacities. The study by Chio et al. shows that the use of an electronic expansion valve will increase the COP by 0.8% from the system with a capillary tube. On the other hand, Chinnaraj et al.[9] shows that the use of an electronic expansion valve will increase the COP by 10% from the system with a capillary tube. The summary of this comparison is shown in Table 2.

Table 2 Comparison with Other Studies

Study of	Decreasing in Wc	Increasing in RC	Increasing in COP
Choi et al. [5]	17.4%	0.6%	0.8%
Chinnaraj et al. [9]	0.27%	11.4%	10%
Current study	7.7%	12.4%	21%

7 Conclusions

Our conclusions are: 1. The system operating with a nozzle results in a 7.7% reduction in compressor work over that of a capillary tube.

2. The system with a nozzle and R22 has more condenser heat rejection from a base case due to the increase in refrigerant mass flow rate as well as the heat transfer coefficient.

3. The air-conditioning system with a nozzle has the highest COP, with a 21% increase.

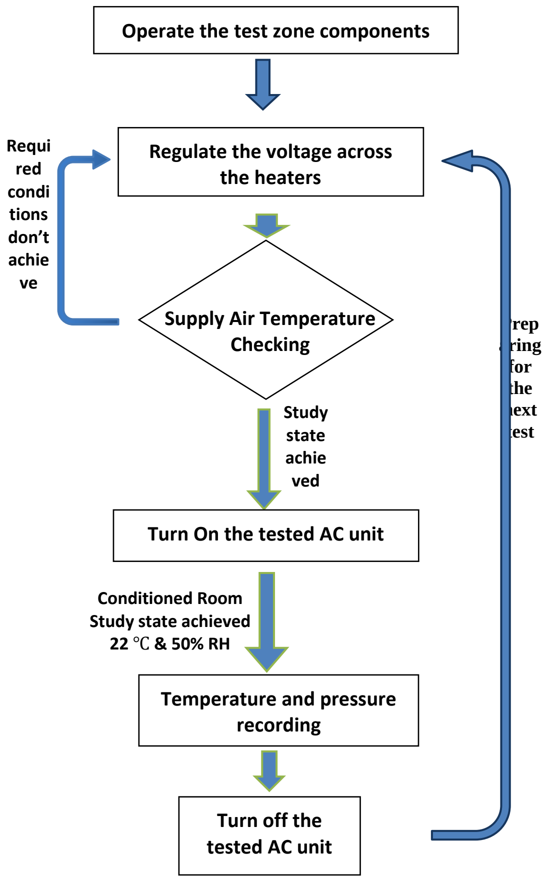

Fig.A.1 Test Procedure

Appendix A

Table (A-2)

Device	Uncertainty
TC41-Thermocouple Thermometers	± 1°C
Omega Digital Pressure Gauges DPG2001B	±0.25%
Fluke 376 FC Clamp Meter	2%±5 digits
Elitech Electronic Refrigerant Charging	+0.05% g
Sold state voltage regulator	+-20 kOhm

Table (A-3)

Independent variables		Variable Errors
COP	Capillary tube	1.308±0.033
	Nozzle	1.434±0.054
Qc	Capillary tube	23.63±0.016
	Nozzle	26.768±0.0231
Qe	Capillary tube	2.595±0.0738
	Nozzle	2.751±0.115
Wc	Capillary tube	1.994±0.0056
	Nozzle	1.931±0.0069

Table (A-4)

Component	Descriptions
Evaporator	Air cold evaporator of 41 Cm *38 Cm (L*W)
Condenser	Air cold condenser of 60 Cm *40 Cm (L*W)
Compressor	Reciprocating compressor of
Fan	Axial fan
Expansion device	Two Capillary tubes of 60 cm length with 2.2 diameter for each one

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