JST: Engineering and Technology for Sustainable Development
Volume 32, Issue 2, April 2022, 048-056

Experimental Investigation of Energy Efficient Room Air Conditioners for Mini-Stores

Nguyen Viet Dzung, Cung Duc Huy, Nguyen Ba Chien, Ho Huu Phung, Vu Tuan Anh, Trinh Quoc Dung *

School of Heat Engineering and Refrigeration, Hanoi University of Science and Technology, Hanoi, Vietnam
**Email: dung.trinhquoc@hust.edu.vn*

Abstract

An experimental investigation of energy efficiency room air conditioners for the mini-stores was presented and illustrated in the paper. The experiment has been carried out in two well-insulated rooms with two different compressor technologies (fixed-speed and inverter) and essential equipment in a laboratory located at the School of Heat Engineering and Refrigeration (Hanoi University of Science and Technology). The authors conducted the test with three different heat load categories and weather conditions to examine the energy efficiency based on several factors such as room temperature and power consumption of air conditioner from records. Results show the significant effect of various aspects on the efficiency and the behaviour of air-cooled air conditioners including the indoor heat load and the outdoor temperature. The results also suggest a suitable cooling capacity choice that helps improve the energy efficiency of air conditioners besides the technical data such as CSPF (or SEER) and power consumption.

Keywords: Air conditioner, mini-store, CSPF, energy efficiency, power consumption

1. Introduction

According to [1], the average demand for cooling has risen approximately 4% per year since 2000. During the COVID-19 pandemic, the number came down slightly, but it still grew by about 1% in 2020. The trend is expected because of the effect of global warming in recent years. As a result, global energy consumption has increased over time. Air conditioning consumes a large amount of energy, about more than 8% of global electricity based on the report of the Institute of Refrigeration (IIR) in 2020 [2] even though cooling equipment is enhancing its performance remarkably. Moreover, it also has responsibility for 1 Gt of CO_2 emission from 1990 to 2020 [1] which affects enormously the global environment. Because of those, the energy efficiency of air conditioners once again becomes the major issue that is debated in science seminars.

In Vietnam, the Minimum Energy Performance Standards (MEPS), which is announced in 2015 (i.e., TCVN 7830:2015 [3]), have changed the market and consumer behaviour based on the calculation of cooling seasonal performance factor (CSPF) in the national standard TCVN 10273-1:2013 (equivalent to ISO 16358-1:2013) [4]. Therefore, Vietnamese citizens are choosing to buy inverter air conditioners now which are been likely to save more energy than traditional ones or non-inverter air conditioners. Many Vietnamese people who are owners of mini-stores also consider buying it to optimize operating costs for their small retail chains as a survey conducted at the same time as the study. However, many factors impact the real energy efficiency such as indoor heat load and insulation. The technician measured CSPF based on constant test conditions in standards, so it can not reflect exactly the cooling efficiency of an air conditioner.

The paper will give a closer view of the issue. The main goal of the experiment is to investigate factors that affect power consumption and cooling ability for high energy-efficient air conditioners, for instance, inverter air conditioners and compare them to conventional ones. Furthermore, the experiment revealed the operational behaviour of both air conditioners so far.

2. Materials and Methods

2.1. Laboratory Description

The experimental campaign was carried out at School of Heat Engineering and Refrigeration (Hanoi University of Science and Technology). The laboratory includes two well-insulated rooms with dimensions (Length x Width x Height) of 4.9 m x 3.0 m x 3.2 m per one. Each room has a household air-cooled air conditioner that uses a fixed-speed compressor (non-inverter) or variable-speed (inverter) technology with the same nominal cooling capacity of

ISSN 2734-9381
https://doi.org/10.51316/jst.157.etsd.2022.32.2.7
Received: January 18, 2022; accepted: March 28, 2022

18,000 BTU/h (5.3 kW). The technical data of the two air conditioners are shown in Table 1, and they were measured and calculated based on T1 moderate climate conditions. The conditions include indoor dry-bulb temperature of 27 °C and wet-bulb temperature of 19 °C, moreover, the outdoor dry-bulb temperature is 35 °C and wet-bulb temperature is 24 °C. These conditions are also mentioned in National Standard TCVN 10273-1:2013 and TCVN 6576:2013 [5]. Table 2 shows the specification of insulating materials used for the test room.

To simulate different indoor conditions, a humidifier, a heating system, and an additional three-speed ceiling fan which are the same per room are set up, as well as temperature and humidity sensors. In Fig. 1, Fig. 2, and Fig. 3 the test setup for the experimental room was described. A heating system as an artificial load includes a 90 W fan and four resistances: two of them can create 3 kW of heat, and the others create 2 kW of heat load, respectively. The humidification can operate with three distinct levels, and it can adjust the room humidity that is required. The outdoor units are placed on the exterior wall of the building with sensors to rate the effect of outdoor temperature on power consumption. The sensors have the error of ±0.2°C for temperature and ±1% for relative humidity, respectively.

For the measurement of electrical values, circuits were set up and connected with a computer to record instant values of voltage (V), current (A, mA), power input (W), and frequency (Hz) once a minute. Moreover, the authors have installed a mechanical power meter on each line to the air conditioner to examine and record the power consumption per hour.

Table 1. Experimental air conditioners technical data

Parameter	Air conditioners	
	Non-inverter	Inverter
Nominal cooling capacity	5216 W	5170 W
Rated power input	1465 W	1675 W
Maximum air flow	0.22 m^3/s	0.20 m^3/s
Voltage	220 – 240V	220 – 240V
CSPF	3.60	4.65
Refrigerant	R32	R32

Table 2. Specification of insulating materials for the test rooms

Parameter	Structure		
	Wall	Ceiling	Floor
Material	Polystyrene	Polyurethane	Brick
Specific mass, kg/m^3	25	30	1800
Thermal conductivit, W/m.K	0.040	0.023	0.800
Thickness, mm	100	40	220

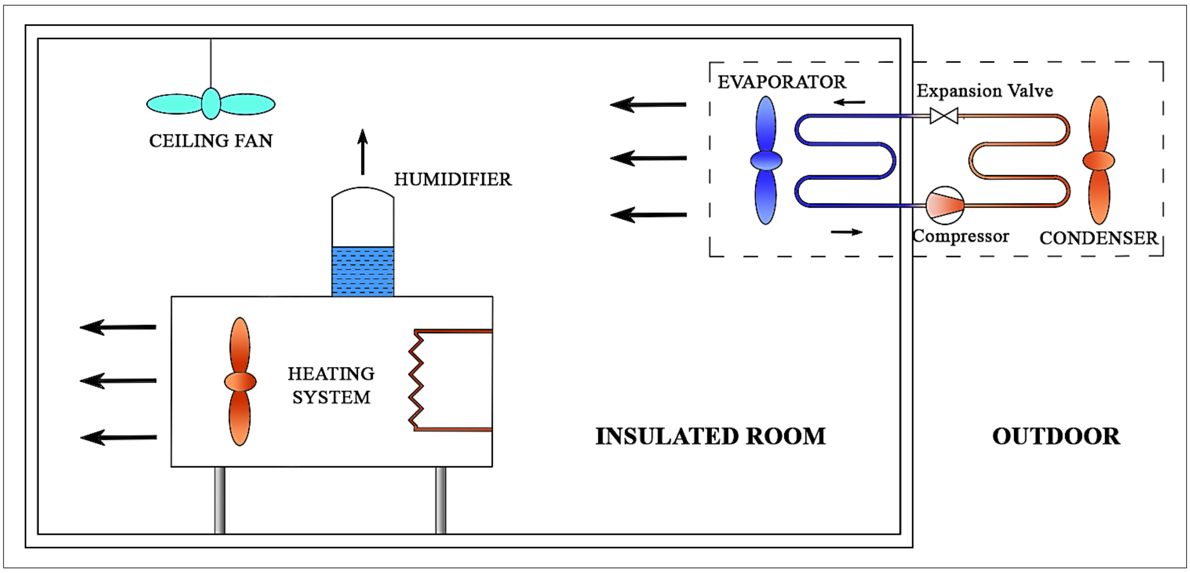

Fig. 1. Schematic diagram of an experimental room

Fig. 2. An insulated room with a non-inverter air conditioner and equipment

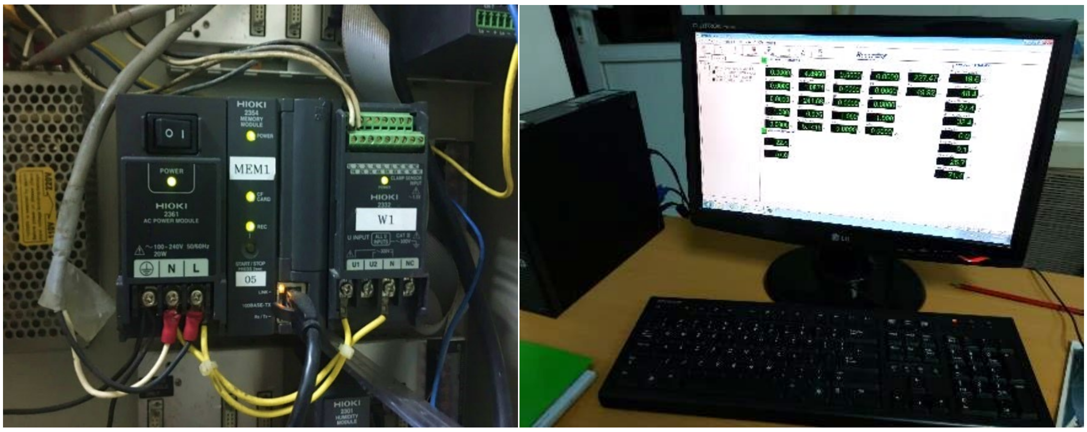

Fig. 3. Electrical circuit with computer gathering and processing the data

2.2. Humid Air Equations and Operating Procedure

To calculate the cooling capacity of air conditioners, the sensors measured the temperature and relative humidity of inlet and outlet air of air conditioners. The data was gathered to compute the enthalpy of air using humid air equations [6-7]. After that, the cooling capacity of the air conditioner could be calculated through equation (6).

$$P_h = \varphi \cdot exp\left(12 - \frac{4026.42}{t + 235.5}\right) \qquad (1)$$

with P_h - Pressure of water vapour in moist air, bar

φ - Relative humidity, %

t - Temperature, °C

$$d = 0.621 \cdot \frac{P_h}{P - P_h} \qquad (2)$$

where d - Absolute humidity, kg vapour/kg dry air

P - Atmosphere pressure, bar

$$h_{sensible} = 1.004 \cdot t \qquad (3)$$

$$h_{latent} = d \cdot (2500 + 1.842 \cdot t) \qquad (4)$$

$$h_{air} = h_{sensible} + h_{latent} \qquad (5)$$

with $h_{sensible}$ - Enthalpy of dry air, kJ/kg dry air

h_{latent} - Enthalpy of water vapour in the air, kJ/kg dry air

h_{air} - Enthalpy of moist air, kJ/kg dry air

$$Q_c = V \cdot \rho \cdot (h_{inlet} - h_{outlet}) \qquad (6)$$

where Q_c - Cooling capacity, kW

V - Air Flow, m^3/s

ρ - Specific mass of air, kg/m^3

h_{inlet} - Enthalpy of inlet air, kJ/kg dry air

h_{outlet} - Enthalpy of outlet air, kJ/kg dry air

The experiment begins with two air conditioners starting up for 5 minutes, then heating systems and humidifiers are turned on with the same configuration for each room. The indoor temperature for each room must stabilize at 27±1.5 °C, and the set temperature of the air conditioner must guarantee that indoor temperature. All the data from sensors and circuits transfer to a special program to process into worksheet files. The experiment has run from 10 to 12 continuous hours per day as the mini-store schedules and was conducted for one and a half months until it paused because the COVID-19 struck fourth time in Vietnam in July 2021.

3. Results and Discussion

3.1. Effect of Heat Load on the Room Temperature and Power Consumption

Because mini-stores in Vietnam have different equipment such as freezers, lights, and computers, the indoor heat load is also not equivalent at each store. Therefore, the experiment simulates various heat loads to examine situations. As the explanation about the heating system, the indoor heat load in experiment rooms can vary from 1 to 5 kW, so there would be many cases to test. The experiment tests each configuration for a few days with similar weather conditions to ensure that the data is not random or coincidental. Heat load divides into three groups: low, medium, and high; the low heat load is from 1 to 2 kW, the medium heat load is from 2.5 to 3.5 kW, and finally, the high load is between 4 and 5 kW.

The high heat load cases are examined first. These cases happen in many mini-stores which have freezers to preserve food, for example, fish and meats. Because freezers extract a vast amount of heat from food and transfer it to the environment, they can overload and make the air conditioner tougher to cool space. From Fig. 4 above, the room temperature with the standard, or non-inverter air conditioner did not decrease to the set temperature (27°C) all the operation time, nevertheless, the inverter air conditioner attained the requirement from 9.00 to 14.30 and after 19.00 when the outdoor temperature was not hottest in the day as it described in Fig. 5. However, in Fig.6, the power input of the inverter air conditioner was higher than the non-inverter up to 800 W to cool the room to the set point. As a result, at the end of operating time on that day, the power consumption of the inverter is 8.25 kWh higher than the standard. The experiment also tested in other weather conditions which had lower temperatures with the same configuration, and the results did not change much. In addition, the deviation between the values of two power meters varied from 3.7 to 7.75 kWh per day, and the higher values belong to the inverter. The results are shown in Table 3. In these situations, the inverter does not save energy as its original purpose.

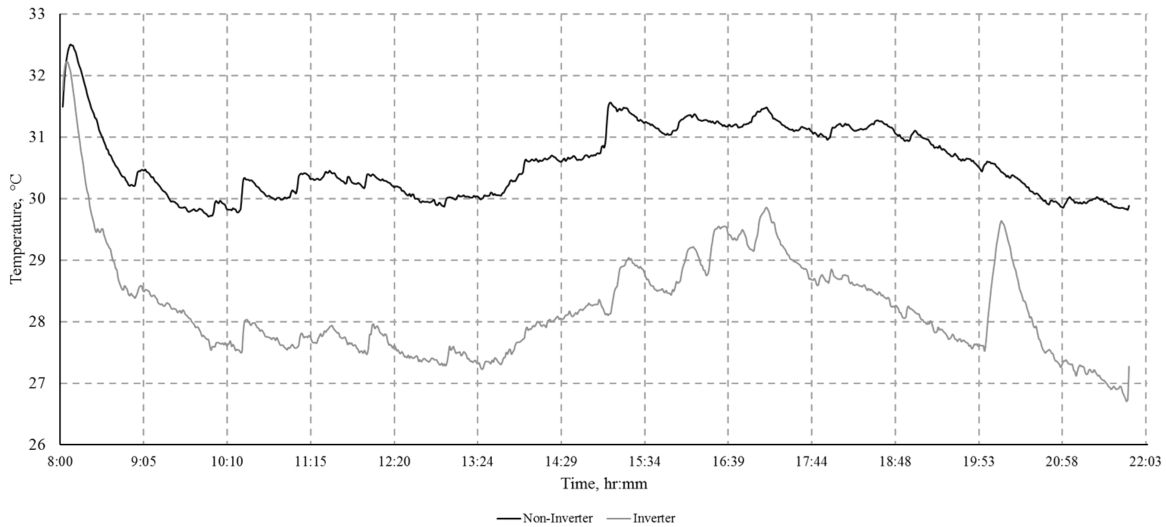

Fig. 4. Variation of the room temperature with 4 kW heat load and air condition operating on 17th June

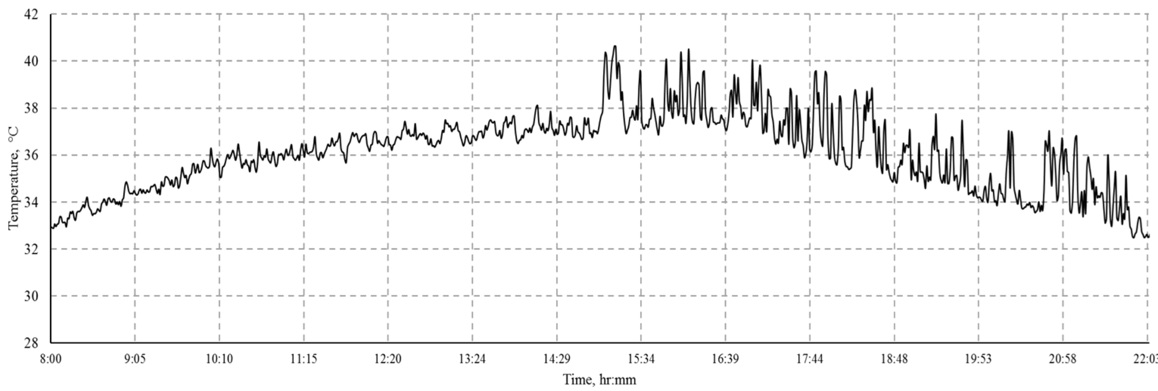

Fig. 5. Outdoor temperature distribution on 17th June 2021

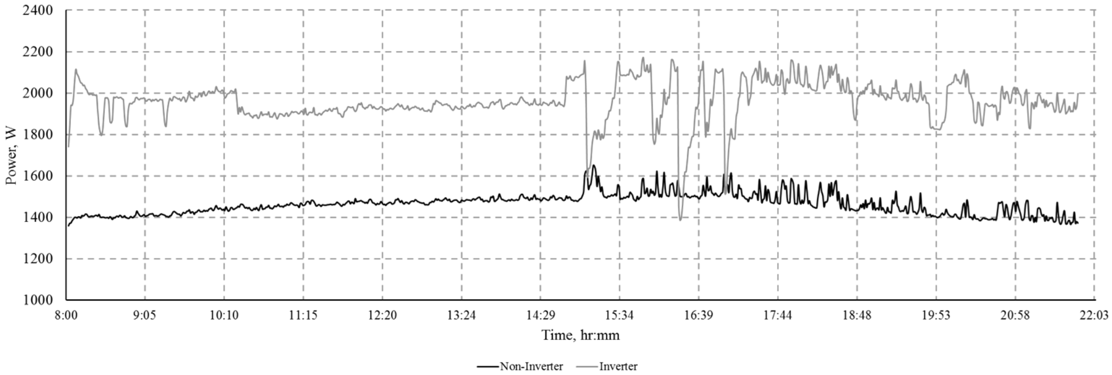

Fig. 6. Power input of the two air conditioners on 17th June 2021

Table 3. The power consumption of two air conditioners when using 4 kW heat load configuration at various outdoor temperature

Date	Power consumption, kWh		Highest Outdoor Temp., °C
	Non-Inverter	Inverter	
June 5th	15.9	19.6	33.7
June 15th	15.45	21.95	38.4
June 16th	16.25	23.05	39.1
June 18th	17.55	25.3	39.8
June 23rd	16.45	23.35	35.8
July 1st	15.75	22.75	38.2

Table 4. The power consumption of two air conditioners when using a 3 kW heat load configuration at various outdoor temperatures.

Date	Power consumption, kWh		Highest Outdoor Temp., °C
	Non-Inverter	Inverter	
June 9th	12.7	11.9	32.5
June 10th	11.25	11.2	34.1
June 11th	11.65	11.35	35.6
June 12th	11.25	10.6	32.6
June 28th	13.7	14.5	37.8
June 29th	14.05	14.85	38.2

Overload is the worst situation that drops off the operating age, especially the compressor as it must work hard to cool the room, and power consumption rockets up compared to normal conditions. Hence, the air conditioner fails more quickly, and the electric bills rise, so the owner must pay more money which is bad for business. To deal with this situation, there are two possible solutions: one, decrease the heat load from indoors and outdoors as much as possible, and two, buy and change to a larger cooling capacity for the store. With the first solution, the store can turn off some unnecessary equipment, but they should ensure those devices that are not affecting business. As for the food mini-stores, they may use curtains to restrict the heat from the direct sunlight through windows which transfer an enormous amount of heat to the store. Furthermore, they can increase the set temperature for freezers if they are lower than the manufacturer's recommendation to preserve the food, this way could save a substantial amount of electricity and drop off the heat that freezers use and release, respectively. The second solution is the easiest way to resolve the issue, however, it costs plenty of money and should consider only when the first solution is ineffective or not possible.

The medium heat load cases exist at many other mini-stores such as fashion, cosmetics which have numerous lights and office computers. The heat from these devices is not high compared to the freezers, but they can create a significant heat load if they combine with heat from high outdoor temperatures that transfer into stores through walls. With a 3.5 kW heat load, the power consumption of the inverter air conditioner was still higher than the non-inverter because the indoor heat load simply decreases by 500 W. The power consumption trends from the two machines were the same as the high heat load cases and fluctuated between 0.65 and 2.3 kWh. The trend changed when the heat load was adjusted to 3 kW. In Fig. 7, both room temperature trends fluctuated and had a time cycle. The power inputs which are described in Fig. 8 explain these trends clearly. The standard is only on when the room temperature is higher than the set temperature until it drops off to the requirement. The inverter, meanwhile, works continuously and adjusts the compressor power to ensure the indoor temperature around configuration temperature. The room temperature that has an inverter was more stable than the non-inverter, and this is one of the reasons why more consumers choose inverter over standard. The power consumption of the inverter at the end of that day was lower 0.8 kWh than the non-inverter. In contrast, the results were distinct three weeks later, and the inverter once again consumed more power than the standard 0.8 kWh. Another reason for this is the different outdoor temperatures between days, which Table 4 shows the results. When the temperature rose to 35 °C and above, the deviation of power consumption between two air conditioners increased clearly.

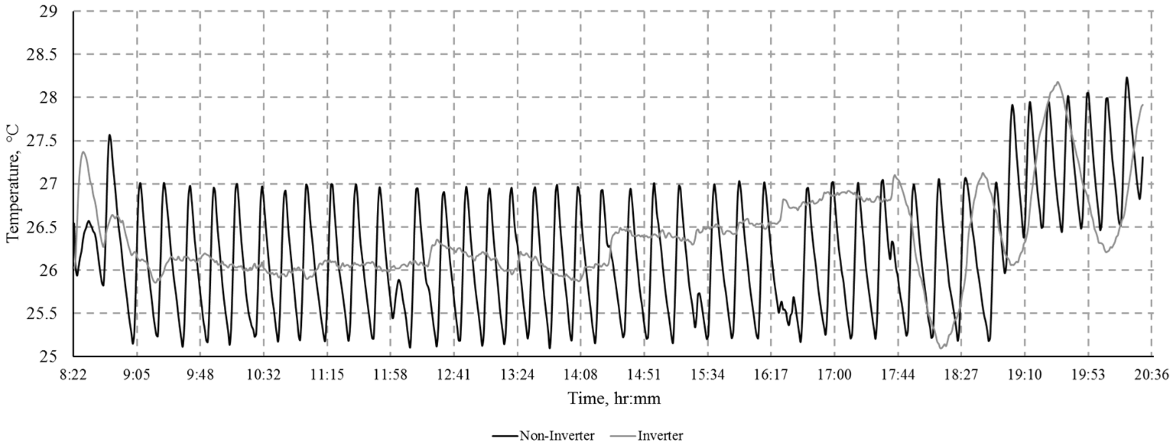

Fig. 7. Room temperature with 3 kW heat load on 9th June 2021

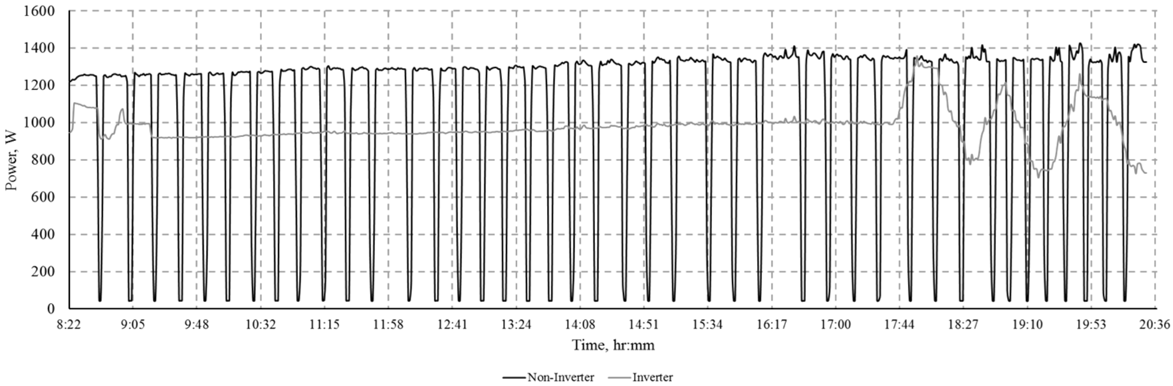

Fig. 8. Power input of two air conditioners on 9th June 2021

As the outdoor temperature increase, more heat transfers through the structure. Due to this, both air conditioners consumed more electricity, but the inverter rose more than the standard. After that, the configuration changed to the 2.5 kW indoor heat load. The results were the same as the lower outdoor temperature case of 3 kW heat load. The power consumption of the inverter was lower than the standard around 1.4 kWh. In conclusion for the medium heat load cases, the outdoor temperature has much impact on the operating efficiency of the air conditioner including cooling ability and power consumption.

The low heat load cases are the final cases that the experiment investigated. Heat load varied from 1 to 2 kW, so air conditioners did not work too hard. The results are illustrated in Fig. 9, Fig. 10, and Table 5. In Fig. 10, the power input of the inverter decreased considerably, and the non-inverter had to turn on and turn off more frequently compared to the 3-kW case. Because of that, the power consumption of the two conditioners dropped off remarkably. In these cases, the power consumption deviation between non-inverter and inverter extended with lower values belong to the inverter. The outdoor temperature impacted slightly the results. To sum up, the inverter saved more energy than the conventional air conditioner in these cases.

Table 5. The power consumption in 2 kW heat load cases of two air conditioners on days with outdoor temperature

Date	Power consumption, kWh		Highest Outdoor Temp., °C
	Non-Inverter	Inverter	
June 13th	8.15	6.5	34.1

June 14th	8.25	6.8	36.8
June 21st	12	10.6	39.3
June 22nd	10.85	10.05	39.6
June 25th	8.3	7	35.7
June 26th	8.4	7.2	37.6

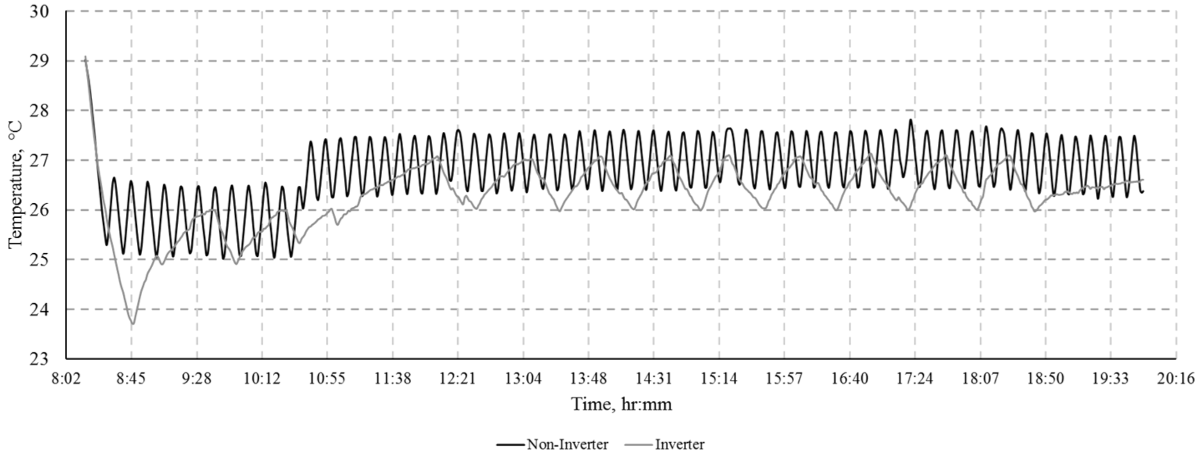

Fig. 9. Room temperature with 2 kW heat load on 26th June 2021

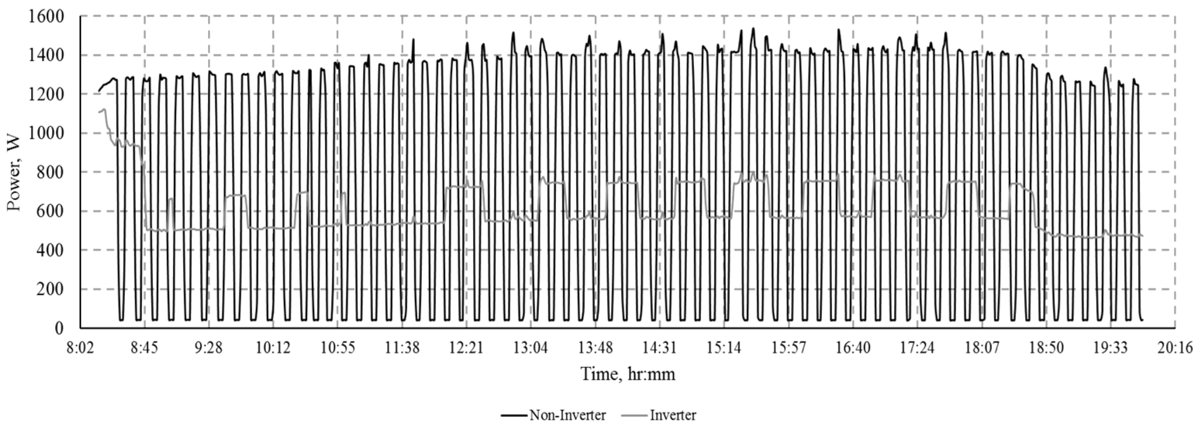

Fig. 10. Power input of two air conditioners on 26th June 2021

3.2. Cooling Capacity of Non-Inverter and Inverter Air Conditioners

In the prior discussion, at high heat load cases, the inverter air conditioner had shown cooling ability to bring the room temperature to reach the set temperature while the conventional did not do that. Nevertheless, the calculation of cooling capacity depicted different results which have illustrated in Fig. 11 and Fig. 13. The conventional air conditioner had greater capacity than the inverter approximately 1 kW. As mentioned, the calculation is based on the data from the sensors, which measured the temperature and relative humidity of inlet and outlet air of air conditioners. Accordingly, the results reflected the real ability of each air conditioner.

To explain the reason, the authors considered another factor: latent heat. Human depends on perspiration to cool the body temperature, so high humidity hampers this process and causes the body to feel uncomfortable. When the air conditioner cools the room, dehumidification also occurs. Therefore, perspiration vapours swiftly. In Fig. 12 and Fig. 14, the extracted sensible enthalpy from both air conditioners was the same, but the extracted latent enthalpy from the non-inverter was larger than the inverter. Manufacturers design the standard air conditioner to cool space rapidly, so both sensible and latent heat must remove as speedy as possible. The inverter controls temperature and humidity stricter than the non-inverter air conditioner to maintain comfort. On account of this, customers who use conventional ones often feel drier than the inverters. The medium heat load and low heat load cases also have the same results: the non-inverter still performed better cooling ability, but the main reason why the inverter had lower cooling capacity in these cases was the adjustment of power input to be equal to heat load in the room. In summary, the conventional air conditioner must operate more to extract heat from the room.

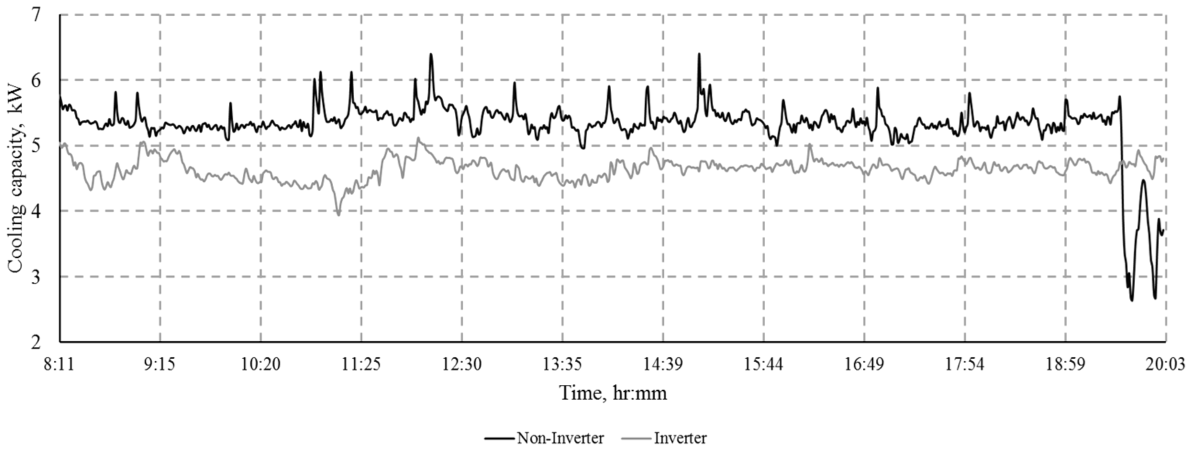

Fig. 11. Calculated cooling capacity with 4 kW heat load on 16th June 2021

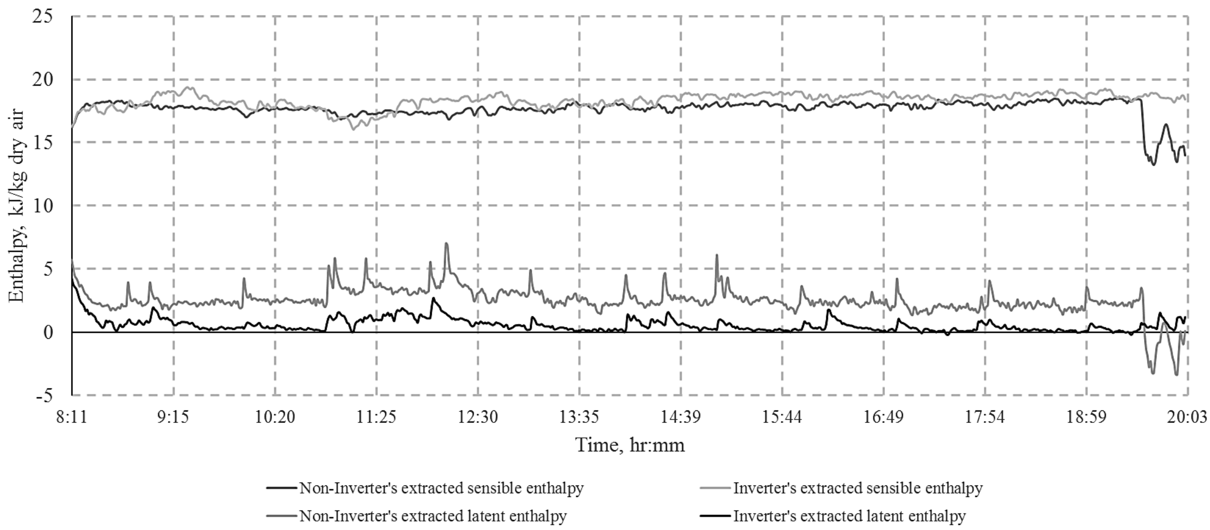

Fig. 12. Extracted sensible and latent enthalpy from the air of two air conditioners on 16th June 2021

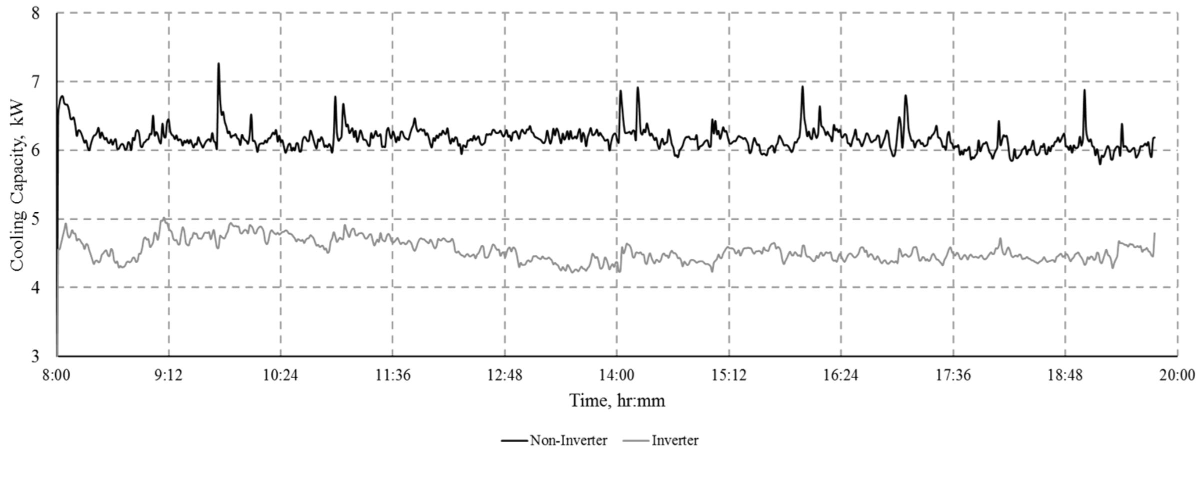

Fig. 13. Calculated cooling capacity with 4 kW heat load on 1st July 2021

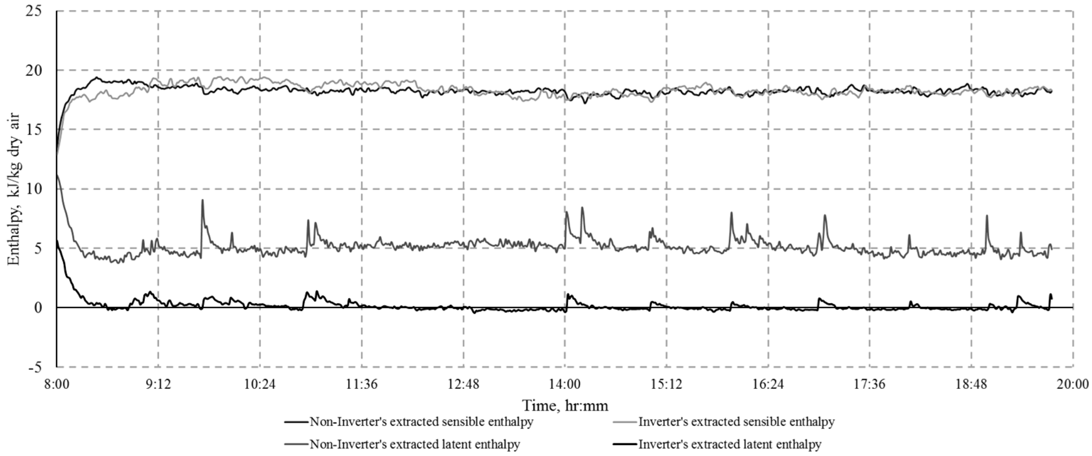

Fig. 14. Extracted sensible and latent enthalpy from the air of two air conditioners on 1st July 2021

4. Conclusion

The investigation of high energy-efficient air conditioners at the mini-stores has been implemented in this work. The authors also studied the impact of heat load on cooling ability and power consumption and compared inverter and non-inverter air conditioners. The results show that the heat load has a significant influence on those factors. The greater indoor heat load makes air conditioners harder to cool the space and increases the power consumption. Furthermore, the inverter cannot save and even consume more energy compared to the non-inverter type if it has medium and high heat load combined with high outdoor temperature. Thus, decreasing heat load is crucial to have better energy efficiency. Additionally, a suitable cooling capacity choice is essential to avoid unnecessary full load conditions for a prolonged period that would decline the working durability of air conditioners. It should be the final solution if the first method is heavily ineffective or not possible.

References

[1] C. Delmastro *et al.*, Cooling, International Energy Agency (IEA), Paris, France, Nov. 2021. [Online] Available: https://www.iea.org/reports/cooling.

[2] Dupont JL et al., The role of refrigeration in the global economy, 38th Informatorily Note Refrigeration Technologies, International Institute of Refrigeration (IIR), Paris, France, rep. 30027313, 2019. [Online] Available: https://iifiir.org/fr/fridoc/le-role-du-froid-dans-l-economie-mondiale-2019-142028.

[3] Non-ducted Air Conditioners - Energy Efficiency, TCVN 7830:2015, 2015.

[4] Air-cooled Air Conditioners and Air-to-air Heat Pumps – Testing and Calculating Methods for Seasonal Performance Factors – Part 1: Cooling Seasonal Performance Factor, TCVN 10273-1:2013, 2013.

[5] Non-ducted Air Conditioners and Heat Pumps – Testing and Rating Performance, TCVN 6576:2013, 2013.

[6] L. N. Anh, Moist air, in Engineering Thermodynamics, 1st ed, Hanoi, Vietnam: Vietnam Education Publishing House, 2017, ch. 4, sec 4.3, p. 109.

[7] T. V. Phu, Moist air & smoke, in Drying Engineering, 3rd ed, Hanoi, Vietnam: Vietnam Education Publishing House, 2011, ch. 2, sec 2.1, p. 15.