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Implementation of ZigBee and NB-IoT Networks in Cooling Monitoring Systems for Pelter-based Mini Refrigerators

***Abstract**. Internet of Things (IoT) technology has been applied in many sectors that require real-time or historical information. For example, monitoring the data and getting timely information in research is necessary for the food refrigeration industry. Therefore, a system for measuring a small refrigerator's temperature and relative humidity was developed to study the performance of a wireless communication system, along with a demonstration of its application to connect to the IoT cloud system. This wireless communication system consisted of a wireless sensor network (WSN) and gateway (GW) using ZigBee and Narrowband Internet of Things (NB-IoT). Additionally, this connection to the IoT cloud platform has been used in various cooling types, including air-cooling refrigerators and water-cooling refrigerators. For the experimental results, the ambient temperatures of the refrigerator testings inside and outside the room were 30 and 35 °C, respectively. The beverage cans were set as a cooling load for comparing the temperature and humidity variations over the operating time. It was found that the IoT system could monitor the real-time surroundings both inside and outside the room. The effect of cooling changes from pre-cooling to a steady state has also been discussed. Thus, the IoT system can implement cooling monitoring systems for pelter-based mini refrigerators.*

***Streszczenie.** Technologia Internetu Rzeczy (IoT) została zastosowana w wielu sektorach, które wymagają informacji w czasie rzeczywistym lub historycznych. Na przykład, monitorowanie danych i uzyskiwanie aktualnych informacji w badaniach jest niezbędne dla przemysłu chłodniczego żywności. Dlatego opracowano system pomiaru temperatury i wilgotności względnej w małej lodówce, aby zbadać wydajność bezprzewodowego systemu komunikacji oraz zaprezentować jego zastosowanie w połączeniu z systemem chmury IoT. System komunikacji bezprzewodowej składał się z sieci bezprzewodowych czujników (WSN) i bramy (GW) z wykorzystaniem technologii ZigBee i wąskopasmowego Internetu Rzeczy (NB-IoT). Ponadto, to połączenie z platformą chmury IoT zostało wykorzystane w różnych rodzajach chłodzenia, w tym w lodówkach chłodzonych powietrzem i wodą. W wynikach eksperymentów, temperatura otoczenia testowanych lodówek wewnątrz i na zewnątrz pomieszczenia wynosiła odpowiednio 30 i 35 °C. Puszki z napojami zostały ustawione jako obciążenie chłodzenia, aby porównać zmiany temperatury i wilgotności w czasie pracy. Okazało się, że system IoT mógł monitorować otoczenie w czasie rzeczywistym zarówno wewnątrz, jak i na zewnątrz pomieszczenia. Omówiono także efekt zmiany chłodzenia od stanu wstępnego do stanu stabilnego. System IoT może więc wdrożyć systemy monitorowania chłodzenia dla mini-lodówek na podstawie technologii peltera. (**Implementacja sieci ZigBee i NB-IoT w systemach monitorowania chłodzenia dla mini lodówek opartych na Pelter**)*

Keywords: IoT Implementation; ZigBee and NB-IoT Networks; Monitoring Systems; Mini Refrigerators.
Słowa kluczowe: Implementacja Internetu Rzeczy; Sieci ZigBee i NB-IoT; systemy monitorujące; Minilodówki.

Introduction

Thailand has a tropical environment, making it a popular location for food preservation due to the daily human demand for fresh and sanitary food. Storing perishable foods at low temperatures delays deterioration and metabolic processes, making refrigeration helpful in preserving fruits and vegetables. The majority of refrigeration systems use refrigerant-required vapor compression refrigeration technology. Hydrofluorocarbons are the most widely utilized form of refrigerant in the world today (HFCs). There was a greater reliance on chlorofluorocarbons (CFCs) before the Montreal Protocol was established in 1987, and their usage has been gradually reduced since then [1]. CFCs are chemical molecules that are very stable. However, they can cause damage to ozone depletion when the substance leaks into the atmosphere. After that, the atmospheric ozone concentration drops. The resulting global warming is known as the Greenhouse effect [1-2]. Therefore, the solution is to adopt the thermoelectric concept instead of the traditional cooling system. The operation of the thermoelectric cooling system is based on the Peltier effect [2]. This cooling system has the advantage of being small and easy to transport. Additionally, refrigerants are not CFCs, so portable mini refrigerators are commonly used thermoelectric kits today [3-7]. This principle is thermoelectric cooling (TEC).

In order to test a refrigerator's capacity, all parameters mostly used a data collection method that relies on a wired device directly connected to a data logger [8]. However, this technique might leave a gap between the insulated sandwich panels and the door, causing the refrigerator's inside temperature to decrease. The result is an inaccuracy in the assessment procedure for the refrigerator's performance. Therefore, Internet of Things (IoT) technology has been implemented in software and hardware [9-12] to replace conventional data-collecting methods (Wired technology). Many studies decided to record data using a wireless system, which included ZigBee [9], Wi-Fi [10], and Bluetooth [11]. As a result of this method, both the ambient humidity and temperature were difficult to penetrate into the refrigerator. In addition, the refrigerator could maintain the storage temperature according to the value selected.

Based on the literature reviews on temperature measuring systems, IoT devices collect environmental data in cooling systems with temperature sensors connected to various wireless communication systems, including ESP8266 and ESP32 [13]. Multiple access points and a greater need for IP addresses were indicators of the growth of Instant wireless networks. Large IoT-based botnets have repeatedly emerged from IoT devices [14]. Gateways (GW) could reduce IP address connections, and ZigBee also had lower power consumption than Bluetooth [15].

As mentioned above, the wireless sensor might use the GW as a connection point to the server to collect data [16]. When the site was in an agricultural region remote from the digital population, the internet connection system through fiber optical network was restricted [17]. However, low power wide area network (LPWAN) technology enabled the current mobile network to provide IoT services [18]. Therefore, real-time data transmission needed to be developed using LPWAN technology, which comprised NB-IoT and LoRa. However, NB-IoT was the extensively used network regarding technology in Thailand [19-22].

This article aimed to present the development and testing of mini-refrigerator monitoring systems through ZigBee and NB-IoT networks by measuring relative humidity and temperature. At the same time, the refrigeration operated in only the environment to be aware of such information in real-time by using wireless sensors with the Zigbee standard, which on the receiving side has developed firmware. These sensors were connected to a GW and delivered to a server over the NB-IoT network to review real-time and historical data. In addition, the developed system could monitor the temperature and humidity changes inside the TEC refrigerators with different cooling systems. The experimental results have been discussed. This method was expected to be a guideline for a better wireless network design for more extensive cold storage in the food Industry.

IoT System Designed

The system overview of this research consisted of sensor nodes, GW, and IoT cloud platforms. The system architecture was shown in Figure 1. The system worked by launching sensors to measure temperature and humidity data. Next, this data was sent to the internet via the NB-IoT-based GW using the Constrained Application Protocol (CoAP). Moreover, the system could display real-time and historical data.

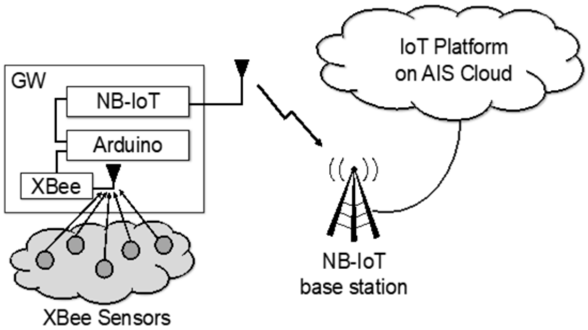

Fig. 1. System architecture

Mini Refrigerator

The mini refrigerators were thermal electric coolers (TEC) with two different cooling systems: fan-cooled and water-cooled [23]. The Peltier plate, fan, and switching power supply were used to measure the temperatures of these systems. The functions of the systems were also the same. They included cooling components that made use of Peltier plate technology. Moreover, fans or water systems were utilized in the cooling function of heat exchangers. A fan-cooled cooling system in the first scenario employed four fans, as illustrated in Figure 2.

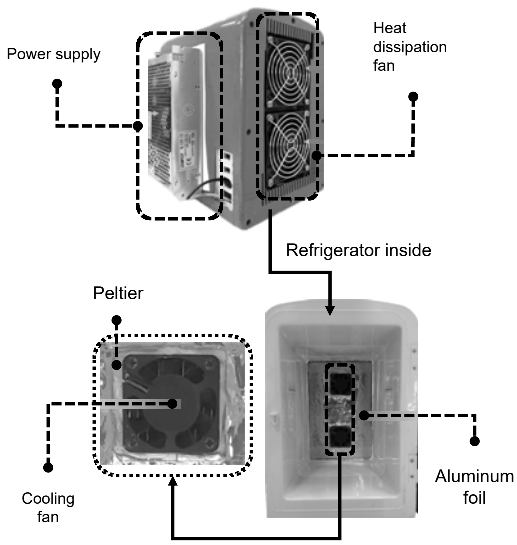

Fig. 2. A fan-cooling type mini-refrigerator

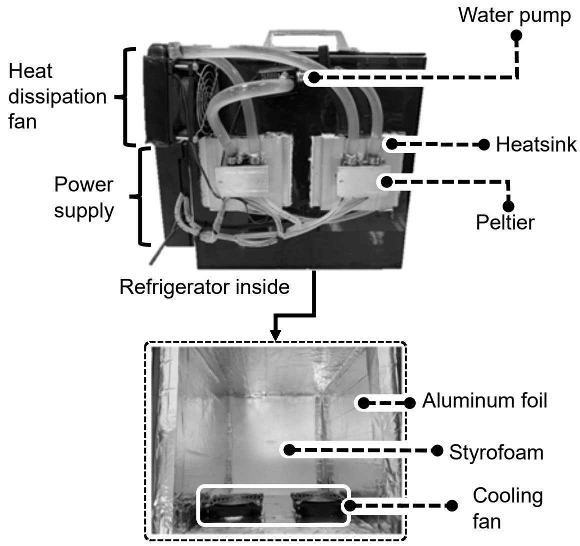

Fig. 3. A water-cooling type mini-refrigerator

In addition, the Peltier plate must be continuously cooled by the heat dissipation fans in order to maintain the Peltier effect [1]. In this article, we have developed another system using a water-cooled refrigerator for comparison with a fan-ventilated system. Figure 3 depicted the second scenario's cooling coil, consisting of a Peltier plate and a cooling fan. The circulating water system was used to remove the heat accumulated at the Peltier plate instead of the fan-cooled cooling system (Figure 2). As a result, the different generator cooling methods inside the refrigerators were experimentally investigated under different surroundings in order to determine the best cooling performance. Furthermore, the beverage cans were set as the cooling loads of the experiment.

ZigBee-based Temperature and relative humidity sensing

This section described the details of the wireless sensor Digi XBee Sensor for measuring refrigerators' internal and external temperature and humidity variations, as shown in Figure 4. This device recorded the environmental data. In addition, the measuring range of this sensor could measure temperature from -18 to 55 °C (accuracy of $\pm$2°C) and relative humidity from 0 - 100% RH, with different accuracy values. The two ranges included, humidity range 0% RH% ~ 59% RH (accuracy of $\pm$5% RH) and humidity range of 60% RH ~ 100% RH (accuracy of $\pm$8% RH). This sensing device supported communication in the 2.4 GHz band, an unlicensed frequency band with a data rate of 250 kbps, and had the advantage of device compatibility. The device could connect to the microcontroller using the application programming interface (API) [24, 25].

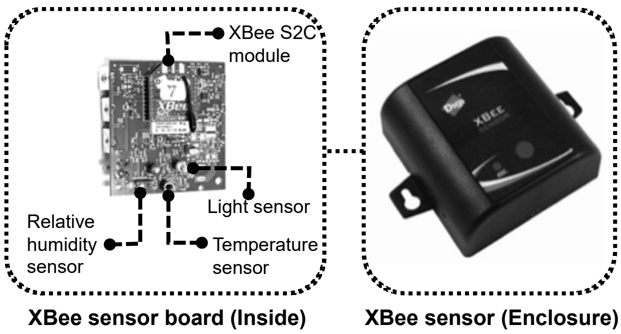

Fig. 4. XBee sensor device

However, it was necessary to validate the accuracy of the data in order to assess the cooling system's performance using the XBee sensor. The XBee sensor device was first calibrated using a standard meter of the UT333 design. The system used the absolute error analysis equation for calibration between the XBee sensor and the standard meter as Equation (1):

$$E_a=|x_m-x_t| \tag{1}$$

where E_a is the absolute error, x_m is the measured value of the XBee sensor, x_t and is the actual value by the standard meter.

The temperatures between 0 and 40 °C were accurately tested. We measure temperature measurements together with relative humidity. The accuracy results reflected the specifics presented in Table 1.

Table 1. The calibration results of XBee sensor device

Number of tests	XBee sensor device		UT333 standard meter		Absolute error	
	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
1	1.7	12.7	0	15	1.7	2.3
2	3.6	15.6	2	18	1.6	2.4
3	5.7	18.5	4	21	1.7	2.5
4	7.8	23.1	6	25	1.8	1.9
5	9.9	25.6	8	28	1.9	2.4
6	11.5	28.5	10	29	1.5	0.5
7	13.4	33.2	12	34	1.4	0.8
8	15.7	37.6	14	38	1.7	0.4
9	17.4	45.2	16	43	1.4	2.2
10	19.7	44.4	18	47	1.7	2.6
11	21.5	47.5	20	50	1.5	2.5
12	22.5	50.3	22	55	0.5	4.7
13	24.3	52.3	24	55.5	0.3	3.2
14	26.5	53.5	26	56	0.5	2.5
15	28.3	53.7	28	56.5	0.3	2.8
16	30.7	54.1	30	57	0.7	2.9
17	32.5	54.1	32	57.5	0.5	3.4
18	34.4	54.7	34	58	0.4	3.3
19	36.7	55.6	36	58.5	0.7	2.9
20	38.8	56.7	38	59	0.8	2.3
21	40.5	58.6	40	59.5	0.5	0.9
Average					1.1	2.35

Table 1 showed the XBee sensor device's calibration and absolute error results. Compared with the standard meter model UT333, the average absolute error was 1.1 and 2.35 for temperature and humidity, respectively. The error value was consistent with the specification of the XBee sensor device. In addition, from this data, we could define the correlation equation between the data from the XBee sensor and the standard meter, which was predicted using the linearity trend as Equation (2, 3):

$$T_x=0.961T_s+1.89 \tag{2}$$
$$H_x=0.981H_s-1.19 \tag{3}$$

where T_x is the temperature value of XBee sensor (°C), T_s is the temperature value of the standard meter (°C), H_x is the relative humidity value of XBee sensor (%RH), and H_s is the temperature value of the standard meter (%RH).

Equations (1) and (2) applied the coefficient of determination (R^2) in order to determine the accuracy of the sensor estimation. The R^2 rate of the accuracy assessment in the case of temperature measurement was 0.999, and the relative humidity was 0.991. the information from Table 1 was shown in Figure 5.

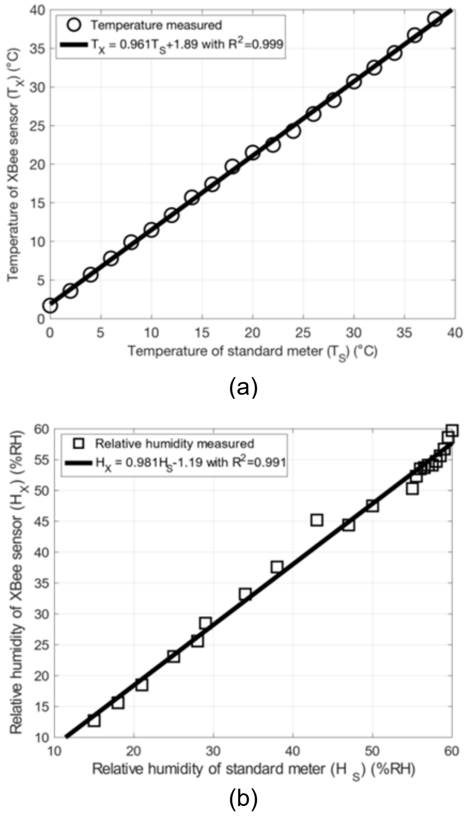

Fig. 5. XBee sensor device calibration: (a) Temperature sensor and (b) Relative humidity sensor

Gateway

The previous sections described sensing devices that had ZigBee communication with ambient sensors. Therefore, measuring devices must have a GW that forwards the data to the server or cloud platform to collect data. The GW used was the Arduino MEGA 2560 microcontroller, a central processing unit for parsing and forwarding to the server via the NB-IoT network, which supported communication in the 900 MHz frequency band [25], as displayed in Figure 6. The coverage area in Thailand was the same frequency as the available cellular network signal.

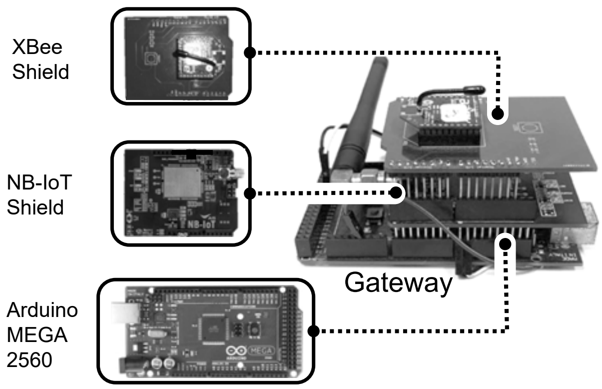

Fig. 6. A GW consists of a microcontroller and connects with XBee shield and an NB-IoT board

IoT monitoring system

To monitor the system, the server was recorded and displayed data by the Magellan user interface (UI) graph history [26], as shown in Figure 7. AIS [26], Thailand's most popular mobile phone provider, provided the IoT cloud system used as a data receiver by the Magellan cloud in this experiment. The connection model used the CoAP procedure. Magellan IoT cloud was used to capture all temperature and humidity data from the cooling system. This platform could automatically receive information that emerges from GW. The information received was temperature and humidity. In addition, the IoT cloud system also recorded data for cooling analysis. The cooling time was determined from both temperatures inside the refrigerators (T_1 and T_2) that keep constant values (Steady state). It also was displayed by selecting "Things." This testing system was named "Project," and selecting "Search Sensor" in this example was chosen to compare the data. It named "Temp1" and "Temp2," which were interested in displaying the measurement data via graphs and could export the data with a comma-separated values (CSV) file to bring the data of interest to analyze the cooling efficiency.

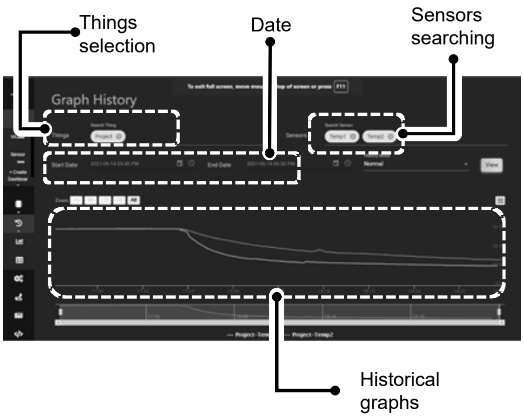

Fig. 7. Graph history example via the Magellan platform

Packet success evolution

Data loss occurred during communication between the sensor and the cloud. Therefore, we intended to know the communication performance before implementing the IoT system. In particular, the performance of the GW through which the sensors were connected to the NB-IoT network. In this test system, we used five XBee sensor nodes to measure the efficiency analysis of the refrigerator in the next step. The test setting information between ZigBee and NB-IoT networks was shown in Table 2. We used the indicator parameters to measure the package success rate [27, 28]. The GW performance was calculated as Equation (4).

$$P_s = \frac{p_r}{p_t} \times 100 \quad (4)$$

Where P_s is packet success rate (%), p_r is the number of packets received, and p_t is the number of packets transmitted.

In addition, in order to better understand the origin of communication problems of IoT systems, we would like to explain in Figure 8, starting to describe 3 cases as follows separately:

Case A, the operation started at the XBee sensor node S_1, reported data to GW and then forwarded it to the cloud accordingly. After that, the cloud responded to GW. The session communication was successful.

Case B, XBee sensor node S_2 reported data to GW as same as case A, but this time GW could not forward the data packet to the cloud normally. Afterward, GW retransmitted the packet, and the cloud received the data. So GW replied and ended the communication.

Table 2. The parameters for communication tests

Parameters	Detail
XBee sensors setting	
Microprocessor	XBee S2C
Communication technology	ZigBee (XBee S2C)
Frequency band	2.4 GHz
No. XBee sensor	5 nodes (i = 1,2,3,4,5)
Communication functionality	Pushing mode (Random) with periods varied (T_{Si} = 1, 5, 10, 15, 20, 25, and 30 s.)
Gateway setting	
Microprocessor	Arduino Uno
Communication technology	ZigBee (XBee S2C) NB-IoT (Devio NB shield)
Frequency band	2.4 GHz and 900 MHz
No. GW	1 device
Communication functionality	Forwarding packet from ZigBee to NB-IoT network using CoAP

Case C, due to the cause in case B, S_3-S_5 gradually transmitted the data sequentially. The performance would cause the memory inside the XBee buffer to overflow, which in this case, resulted in data loss. The performance of the GW was the evaluation of the delay effect. First, the GW sent packet requests, then the status code of the server responded to the GW. Second, the GW varied the data update time to compare periods consisting of T_{Si} = 1, 5, 10, 15, 20, 25, and 30 s. For the GW's efficiency in receiving data from ZigBee and transmitting it to the cloud through NB-IoT, we modified the sensor periods for all five nodes to varied time values.

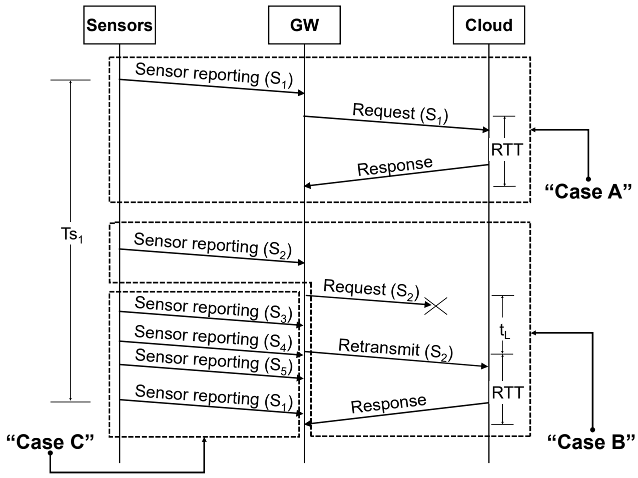

Fig. 8. System timing diagram

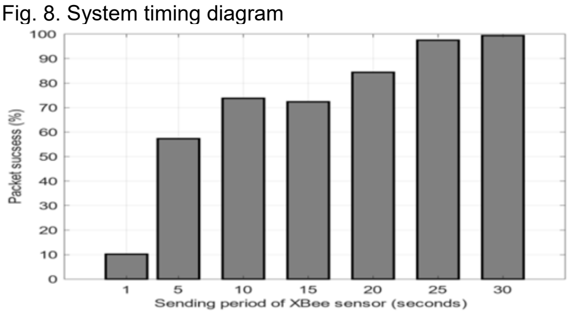

Fig. 9. Packet success rate of GW between ZigBee sensor and cloud

The PDR results were shown in Figure 9. It was noted that GW efficiency showed the optimum point is to have a PDR of 100% when a period was equal to 30 s. So, the packet arrivals at the same time caused packet loss. The

XBee's period must be optimized to minimize packet loss by determining the period every 1 minute, with the slightest chance of packet loss. However, regarding the Cooling efficiency in this paper, we compare the parameters between the two systems in terms of COP with five measurement data points and environments, which were discussed in the next section.

Experimental Setup

The cooling system consisted of a fan-cooled and a water-cooled system, regarding the ZigBee measurement system and GW wireless data measurement systems. This test aimed to observe the temperature and humidity behaviors of both cooling and no-cooling loads. Furthermore, there were two environmental data with different ambient temperature values. The initial conditions of the experiments included the temperature of 30 ^{o}C and the laboratory at 35 ^{o}C for the indoor and outdoor test cases, respectively.

Figure 10 showed a cooling measuring device by installing sensors in 5 test points (S_1-S_5). The sensor positions (S_1 and S_2) were employed to measure the inside condition of the mini refrigerator. At the same time, S_3 and S_4 were installed near the cooler's heat sink to measure the heat-rejected conditions. Finally, S_5 was mounted on a table to measure the outside temperature and humidity to verify all measurements. Thus, the experiments were divided into 4 cases: 1) the refrigerator without cooling loads inside the room, 2) the refrigerator with cooling loads inside the room, 3) the refrigerator without cooling loads outside the room, and 4) the refrigerator with cooling loads outside the room. All experiments had repeatable experiments at least three times to diminish the chance of spurious effects.

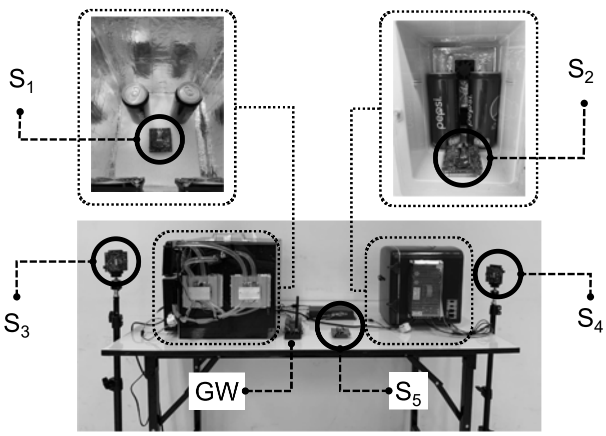

Fig. 10. Testing system installation consists of two types of mini-refrigerator, five XBee sensor devices, a Gateway, and loads (two soft drink cans)

The cooling performance of TEC was represented by the Coefficient Of Performance (COP). The COP indicated the efficiency with which a TEC transferred heat with the amount of electricity required. Evaluating the COP needed the cooling capacity, which comprises heat transfer rate from the air, water, and heat transfer flow through the cooler walls [1-3]. The experimental COP calculation of the refrigerator was based on Equation (5).

$$COP=\frac{Q_c}{P_{Tec}} \tag{5}$$

where Q_c is the cooling capacity or the total heat transfer rate (W), P_{Tec} is the power supplied to the thermoelectric (W)

The Q_c may also be predicted using the COP equations, which are written as Equation (6):

$$Q_c=\alpha I T_c+0.5I^2R+k(T_h-T_c) \tag{6}$$

where R is the thermoelectric resistance, k is the thermoelectric conductance (W/C), α is seebeck coefficient, T_c is cooling temperature of TEC section (K), T_h is hot temperature of TEC section (K), and I is the current (A).

Experimental results and discussion

For the experimental results, the temperature and humidity variation over the operating time of the mini-refrigerators without loads inside the room were shown in Figure 11.

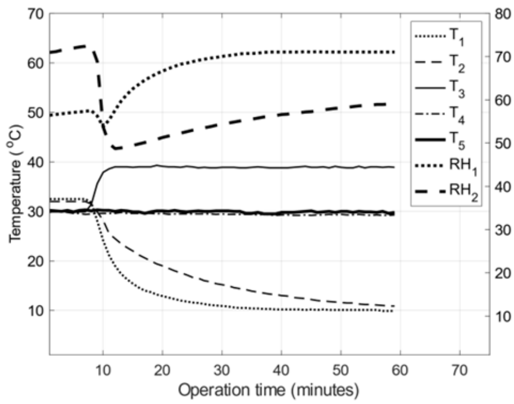

Fig. 11. Cooling data recording of mini-refrigerators without cooling loads inside the room (case_1)

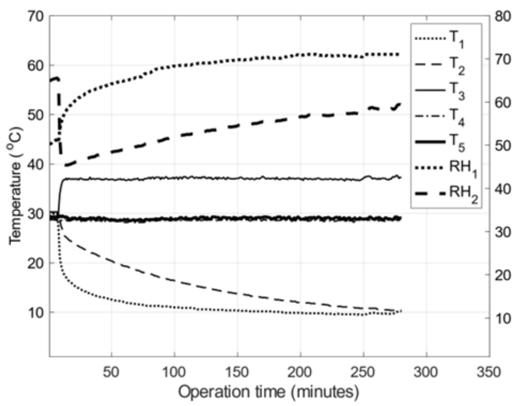

Fig. 12. Cooling data recording of mini-refrigerators with cooling loads inside the room (case_2)

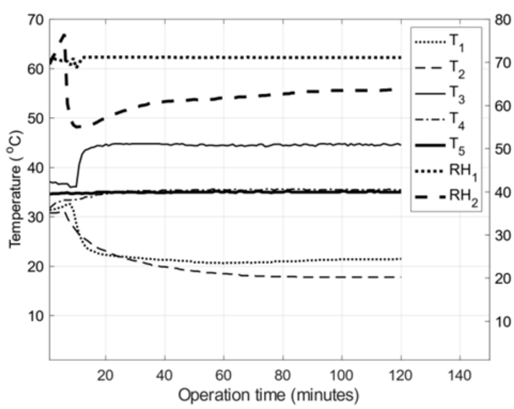

Fig. 13. Cooling data recording of mini-refrigerators without cooling loads outside the room (case_3)

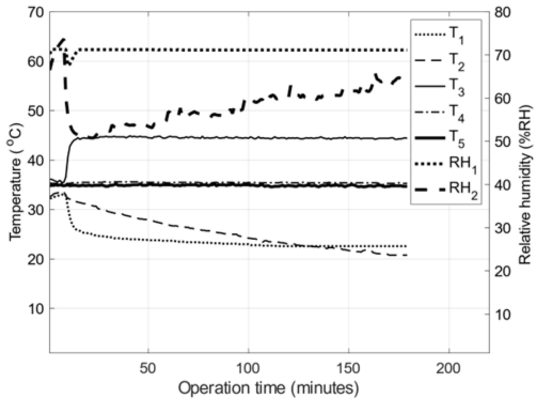

Fig. 14. Cooling data recording of mini-refrigerators with cooling loads outside the room (case_4)

It was found that the IoT system could sense the cooling data until the steady-state condition. Thus, the operating time of case_1 was 60 min. The IoT system was also able to figure out how temperature and humidity behaved thermo- dynamically inside the refrigerators. In other words, the humidity-temperature formula is inversely proportional. If the temperature rises, relative humidity falls, and the air dries out; if it falls, the air becomes moist and relative humidity rises. The result was similar to the previous works [2, 3, and 8]. For the cooling loads (case_2), the temperature and humidity variation over the operating time was similar to that of case_1, as shown in Figure 12. The operating time was 250 min, which was longer than case_1 due to the cooling loads. Both ambient temperatures (T_5) of case_1 and case_2 were approximately 30 ^oC. It was indicated that the IoT system had the stability of communication networks.

For the cooling test outside the room, both ambient temperatures were approximately 35 ^oC. The heat dissipated temperature (T_5) was about 45 ^oC, higher than case_1 and case_2 due to the higher ambient temperature.

Moreover, the temperature measurement results in both cases of load and no load were different by about 10 ^oC , as displayed in Figure 13 and Figure 14. The operating times were 120 min and 180 min for case_3 and case_4, respectively. The IoT system provided the natural phenomena detection for the humidity measurement inside the refrigerator with a fan cooling system outside the room. It was noted that the humidity profile (RH_2) of case_4 had more fluctuation than that of case_2 because of uncontrolled ambient temperature for the fan-cooled system.

From the results mentioned, the temperature and humidity profiles could be clarified to show the cooling performance of the various TEC refrigerators. All parameters were employed to calculate the COP. The COPs of mini refrigerators for all case studies were presented in Table 3.

The TEC with water cooling system offered higher COP than that of TEC with fan cooling system because the water had higher thermal properties than air. Nevertheless, in the case of testing inside the room, both COP of different cooling systems were almost the same due to the controlled ambient temperature inside the room. The best COP appeared at the mini refrigerator with a water cooling system of about 1.35. This COP was somewhat lower than the TEC from the previous work [2, 3] due to the larger capacity and different testing conditions. On the other hand, it was higher than the COP of Mainil et al. [8] proposed, about 0.85, because of the different heat removal methods.

However, the recommendation of the TEC cooling system was the fan cooling system because the water cooling system offered higher management costs than the fan cooling system. Furthermore, the maximum COP for the water cooling system was higher than that of the fan cooling system, by approximately 8%. In contrast, the water cooling system had a more complicated installation than the portable thermoelectric cooler.

Table 3. COPs of mini refrigerators for all case studies

TEC	Condition	COP
Fan	No loads, Inside	1.23
Fan	No loads, outside	1.12
Fan	Cooling loads, Inside	1.01
Fan	Cooling loads, outside	0.85
Water	No loads, Inside	1.35
Water	No loads, outside	1.28
Water	Cooling loads, Inside	1.10
Water	Cooling loads, outside	1.05

Conclusion

The investigation of the implementation of ZigBee and NB-IoT networks in cooling monitoring systems for Pelter-based mini refrigerators with variation surroundings and cooling load has been presented. ZigBee and NB-IoT networks provided good stability of communications networks for real-time or historical data. In the refrigeration test section, the experiment showed that the IoT system could measure the efficiency of small refrigerators. Their installations in the surrounding environment differed by the effect of cooling changed from a pre-cooling state to a steady state. In addition, the IoT system could monitor the temperature and humidity behavior of the cooling process. This information was used to calculate the COP. A comparison between different cooling systems from TEC showed that the highest COP occurred in the mini refrigerator with a water cooling system (COP of 1.35). However, the fan cooling system was suitable for portable mini refrigerators due to more accessibility to installation. Finally, this study has proved that this wireless cooling measurement system will develop in real-world applications.

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