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Evaluation of the Long-Term Utilization of the Internet of Things in a Batch-Type Ceramics Kiln

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Abstract

Batch-type ceramic kilning is an energy-intensive process whose primary expense is fuel consumption. This work demonstrates the incorporation of the Internet of Things (IoT) into an existing ceramic furnace to achieve more precise temperature profile control and lower fuel consumption. A long-term analysis of the kiln owner's continuous utilization and adoption of the technology was performed. A total of 20 kilns in northern Thailand's factories have been selected for implementation. The owner of the facility, who is also the operator of the kiln, can monitor and modify the kiln's settings online using near-real-time information. The sensors, wireless connection devices, a cloud server, and mobile applications that comprise the IoT are tailored to achieve these goals. The kiln has been outfitted with sensors such as a gas flow meter, a gas pressure sensor, and kilning room temperature, wall temperature, and ambient temperature sensors. Using the narrowband-IoT (NB-IoT) network provided by a local communication company, continuous monitoring data, consisting of 8 to 10 hours of kilning time and 2-3 batches per week, have been sent to a cloud server every minute. On a smartphone, online information with alerts can be displayed. The study's outcomes indicate that a kiln operator can consistently control the kiln from batch to batch, resulting in minimal fuel consumption. Compared to before the installation of IoT, data collected over three years indicates a 5.6% improvement in energy efficiency. Total annual petroleum savings amount to $59,787 for the 20 kilns. The straightforward repayment period is 4.7 years. According to a field investigation, IoT technology has an approval rating of nearly 9 out of 10.

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1. Introduction

Currently, the smart industry is the objective of a developing nation, guided by government policy and implemented across all industrial sectors. Goods-producing factories are required to adopt new or improved manufacturing practices, such as those with lower costs, higher production yields, and less environmental impact. The Internet of Things (loT) technology is one of the smart industry's key components. Deployment of the IoT technology in small- and medium-sized businesses (SMEs) could result in a variety of business advantages, such as increased revenues, decreased operation costs, inventory tracking, customer relationship management, automated monitoring, competitiveness enhancement, and the adoption of e-commerce technology (Abazi,2016; Brous,2020). Adopting loT in organizations should concern risk assessment. Important risks include economic resources of the owner and the knowledge of the staff (Parra et al.,2021), noncompliance with privacy regulations, interoperability and integration issues, security risks, and a lack of knowledge and risk awareness (Brous,2020). Hirman et al. (2020) suggested that the technical risks are the signal strength of the wireless communication network, battery installation, and battery life. Malik et al. (2021) reviewed the architecture and applications of the Industrial IoT (IloT). As opposed to the Internet network, devices, sensors, and embedded platforms measure, prepare, and transmit data to cloud storage. The choice of wireless networking, which includes Bluetooth, 3G/4G, WiMAX, Lora, WiFi, and LRWPAN, is crucial for the application at hand due to the variances in standard, application, and limitation between each option. MQTT, XMPP, UDP, TCP, and others are available Internet protocols for data transmission and reception.

This study investigated the incorporation of IoT technology into existing ceramic kilns in northern Thailand. The majority are found in Lampang province, where there are more than 600 shuttle kilns. These kilns provide employment for locals, who generate approximately $300 million annually and produce handmade tableware and furniture that can be exported or sold locally. Most of the kilns are batch-type kilns. In 1993, the technology was transferred from Germany. The kiln was created to produce porcelain products at the lowest possible construction cost. The structure of the kiln consists of a steel frame and a high-density ceramic fiber wall. Figure 1 depicts the outer exterior of the kiln, the front door, and the arrangement of fired green products.

Figure 1. (a) Front door and (b) fired products and support furniture.

Ten-inch-thick ceramic fiber modules are suspended from the steel frame. This wall thickness is sufficient to maintain a maximum temperature of 1,230 ^oC. As a heat source, gun-type burners are located in the bottom left and right corners of the kiln chamber. Liquid petroleum gas (LPG) is used as fuel. Depending on product type and quantity, the fuel cost per kilogram accounts for 25% to 40% of the total cost. Labor expenses account for approximately 70% of the total cost. Because the batch-type kiln is manually operated, it is less energy-efficient than the continuous-type kiln. Using online information for more precise control could result in lower energy consumption and fewer defects. In this investigation, existing batch-type kilns were retrofitted with IoT technology. The aim is to improve energy efficiency.

2. Kiln Operation

The kilning procedure for ceramics transforms a raw or green body into a finished product by firing at a high temperature. Kaolin is a major component of the raw materials used to manufacture porcelain-like products. Before firing in kilns, the green body is prepared, shaped, dried, painted, and glazed. There are two primary categories of kilns: continuous kilns and batch kilns. Continuous kilns, also referred to as roller or tunnel kilns, are utilized in bulk production. The green body is continuously moved through the kiln's drying, firing, and drying zones. The temperature and air pressure in each zone are automatically regulated. A continuous kiln operates 24 hours per day for more than 300 days annually. Small- and medium-sized enterprises (SMEs) use a batch-type kiln. The green product is initially positioned on furniture supports on top of the kiln car. After placing the kiln car inside the kiln, the front entrance is closed. The procedure for increasing the temperature of the kiln chamber is graphically represented by the temperature profile. In every batch of kilning, the operator must modulate the temperature by adjusting the rate of flue combustion.

The temperature profile is the most essential operating parameter for ceramic kilns. It relates to energy efficiency and the final product quality. Before initiating the killing process, a specific profile is chosen for each kiln, product size, and type. In the gun-type burners, fuel is burned to produce hot gas that LPG circulates in the kiln chamber before exiting through the exhaust stack. The room temperature rises from the ambient temperature to a maximum of 1,230 ^oC along the designated profile. The rising rate is primarily determined by the rate of fuel combustion and the allowed amount of exhaust gas opening. The total kiln time ranges between 8 and 12 hours, which depends on kiln size, load capacity, ware type, ware thickness, and kiln wall age. Before ceramic wares and furniture are removed from the kiln, they can cool to room temperature. Thus, the batch process requires heating and chilling for each cycle, resulting in a 50% to 100% increase in energy consumption per kilogram of final product compared to the continuous kilning process.

There are three essential components for manual ceramic kilning to achieve maximum efficiency. First, the operator must adjust the gas flow rate and air-to-fuel ratio (A/F ratio) to achieve the highest possible flame temperature. The technique adopted is to observe the color of the flame at the burners. The highest LPG flame color is blue, referring to a temperature of 1,800 ^oC, which can be achieved by adjusting the A/F ratio. The flame color must always be blue throughout the kilning process. In large industries, these can be controlled by an automatic loop-back control with an oxygen sensor. Nevertheless, the sensor is costly for SMEs. Observing the flame color while adjusting the A/F ratio is a precise outcome when done manually. Second, the temperature of the room has to correspond to the selected temperature profile with a 5 ^oC tolerance. Adjusting the pressure and flow rate of the fuel every 30 minutes or less is required to maintain the intended temperature. Third, the pressure within the kilning chamber must be either positive or negative, depending on whether oxidation or reduction kilning occurs. The damper opening installed in the stack enables this control. Therefore, controlling the atmosphere in a kiln chamber is a complex process. Experienced operators will use less flue and produce fewer defects. The study proposes assisting the operator by employing precise sensors and near-real-time IoT data.

3. IoT Hardware and Communication

Several factors, including total system cost, sensor selection, metering accuracy, ease of installation, and wired or wireless communication, must be considered when implementing loT technology into an existing ceramics kiln. The majority of the cost of the system is added hardware. The acceptable cost of added IoT should be no more than 25% of the cost of the kiln, or approximately $3,000–4,000 is acceptable.

Sensors, an interface board, a microcontroller, a communication module, and a cloud server comprise the IoT hardware. Figure 2 depicts a single-line diagram of the installed sensor locations. Three to six 48 kg LPG cylinders are connected in parallel. An in-line regulator valve reduces the pressure to the desired 6–14 psi. The gas flow meter, pressure transducer, and type K thermocouple probe measure the flow rate, in-pipe pressure, and temperature, respectively. A thermocouple sensor of type R is used to measure the temperature of the kiln chamber. Sensor specifications are shown in Table 1.

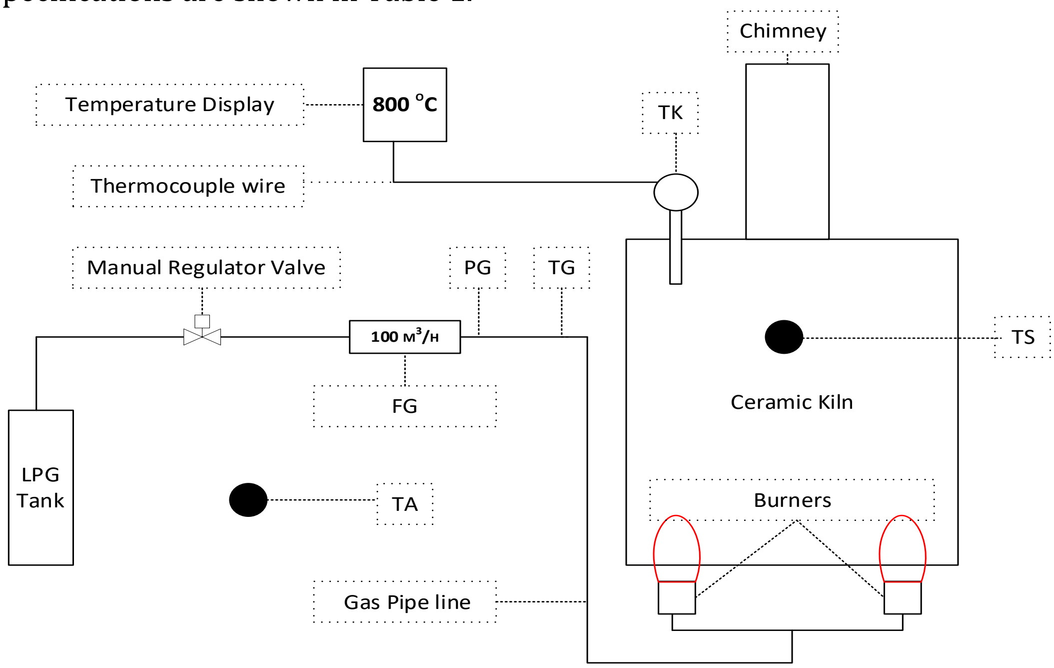

Figure 2. Line diagram of sensors.

Figure 3 demonstrates the connection from sensors to the interface board and microcontroller. The board used Arduino Pro Mini to convert signals from sensors and send them to the IoT box. The box used the Arduino MEGA2560 to acquire data from the interface devices, prepare a data package, and send it to the communication board. The reason to separate the interface board from the microcontroller is the system's stability. All data are prepared in a single package in hexadecimal numbers and then sent to the NB-IoT board. NB-IoT communication is provided by a private service provider, which has the best coverage in the area and is most stable compared to other wired or wireless Internet connections. The NB-IoT board used is a BC95AT chipset. The maximum allowed payload size is 100 bytes with an interval of 15 seconds.

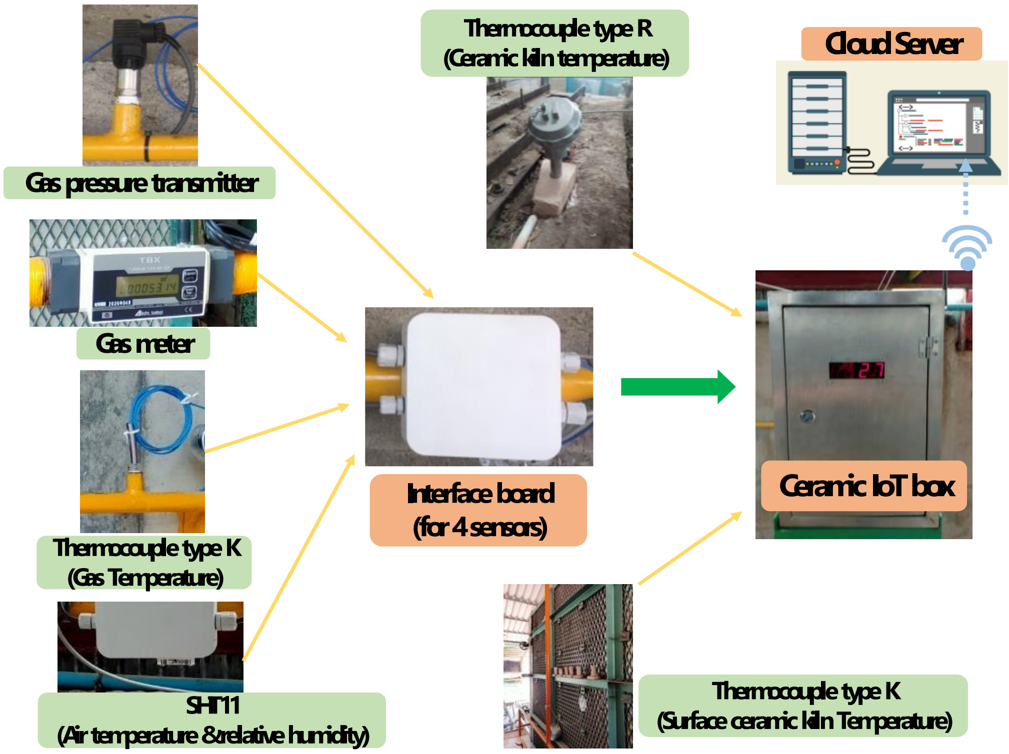

Figure 3. Sensors, interface board, and IoT box.

The renting server is a 2 CPU with 4 GB of RAM provided by the private service company, and the rent rate is $20 a month. The cloud server employs Node-RED, InfluxDB, mySql, and Grafana. Node-RED is an interpretation application developed by IBM. Data are stored in the InfluxDB database. Grafana is used as graphics monitoring software, and a dedicated user account is created for every factory proprietor. The hardware architecture is shown in Figure 4.

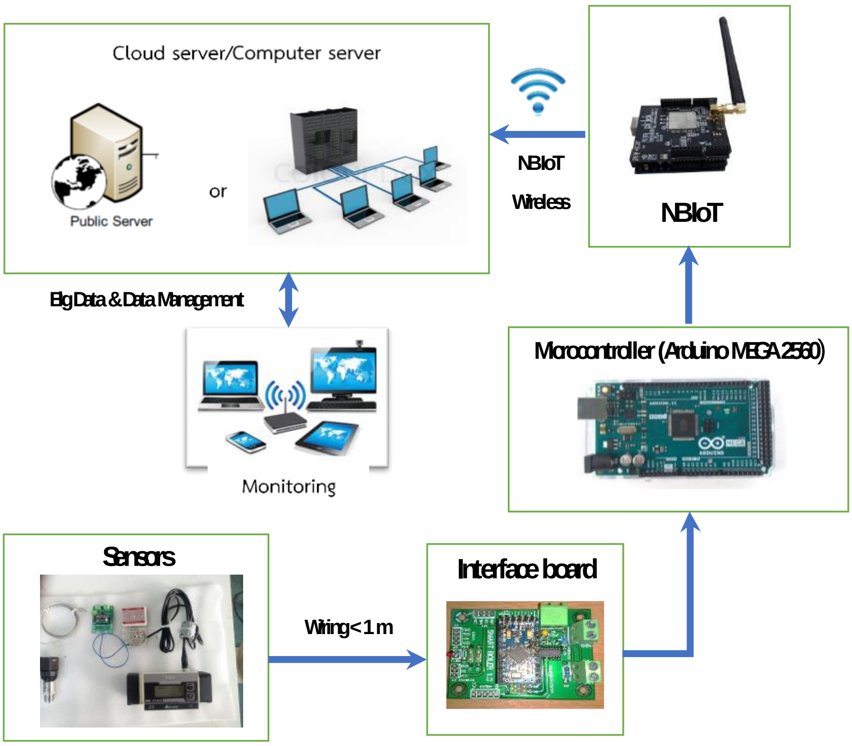

Figure 4. IoT components.

The investigation installed the same devices in the designated 20 kilns. With an average of 2-3 kilning batches per kiln per week, approximately 3000 data sets are collected for the testing period of three years. Currently, basic data analysis is used to analyze the collected data.

Table 1. Sensors used in this study

No.	Sensor/Meter	Output signal	code /Unit	Function
1	Gas flow meter (Turbine type)	Pulse	FG* / m³	Measure LPG flow rate in cubic meter per hour. Sensor rate is 4-30 cubic meters. The maximum operating pressure and temperature are 15 psi and 60°C, respectively.
2	Pressure sensor and transmitter	Analog (4–20mA)	PG* / bar	Measure fuel pressure in the gas pipeline. The pressure indicates fuel pressure before entering into gun-type burners. The measurement range is 0–14.5 psi.
3	Thermocouple Type K	mV	TG* / °C TS* / °C	Measures fuel temperature in gas pipe line (TG) and kiln room surface temperature (TS).
4	Thermocouple Type R	mV	TK* / °C	Measure kiln room is thermocouple Type R. The measure range is 1,600°C.
5	Temperature and relative humidity sensor (SHT11)	Digital	TA* / °C and %RH	Measure ambient air conditions.

* Sensor position is referred to Figure 2.

4. Near-Real-Time Information and Dashboard

Node-RED is used on the server to convert the uploaded data to a format that can be saved directly into the database. It is an interpreted graphic with drag-in function components. The user mostly utilizes Node-RED with a minimum of Java scripting. The database used is InfluxDB, which is non-SQL. It records time-series data efficiently. Node-RED can be set up to monitor crucial data, e.g., a drop of flue pressure in the pipe. Node-RED also takes care of notifications to the operator by comparing the uploaded data with the required values, such as room temperature and the temperature profile. The generated alert is conveyed and immediately sent to the operator via social media applications. Some daily routine processes can be programmed to be done in Node-RED, such as daily data analysis of every batch.

Grafana can visualize the recorded data. Figure 5 depicts a sample of a plotted screen. InfluxDB time-series information can be easily plotted in Grafana.

Figure 5. Plot of data of one kilning batch.

Using the same URL, the graph can also be displayed on a mobile device, making it very convenient for kiln operators to observe the recent data. The information can be used to enhance the next batch's kilning process. Node-RED performs daily data analysis regarding energy consumption. Simple JAVA scripts, calculation routines, and a schedule are constructed. As an example, the specific energy consumption (SEC), calculated by dividing the weight of the fuel by the weight of the final product, is scheduled to be computed daily at 4:00 a.m.

5. Results

The implemented sensors and IoT systems have been utilized by factories for over three years. No significant maintenance is necessary. The stability of data uploads to the NB-IoT network remains constant.

After three years of monitoring the kiln's utilization after installing the IoT into the existing ceramic kiln, it was determined that the operator had successfully acclimated to the new technology. The majority of them make use of the acquired online information. There is no significant maintenance required. The NB-IoT network has very reliable data transfer consistency. Before implementing the IoT system, energy audits were conducted to collect baseline data. Based on the accumulated data, the oxygen concentration in the exhaust gas varied between 4.9% and 7.5%. Nonetheless, the oxidation process requires a minimal oxygen level in the kiln chamber throughout the entire production time. The optimal oxygen content is 1-3 percent. The authors have given instructions on how to manually control combustion air to kiln operators. As discussed in the preceding section, operators of kilns are aware of how to alter the combustion air to maximize flame temperature and minimize heat loss in the exhaust gas. The exhaust gas oxygen content has been reduced to between 1.9% and 3.0%, as depicted in Figure 6.

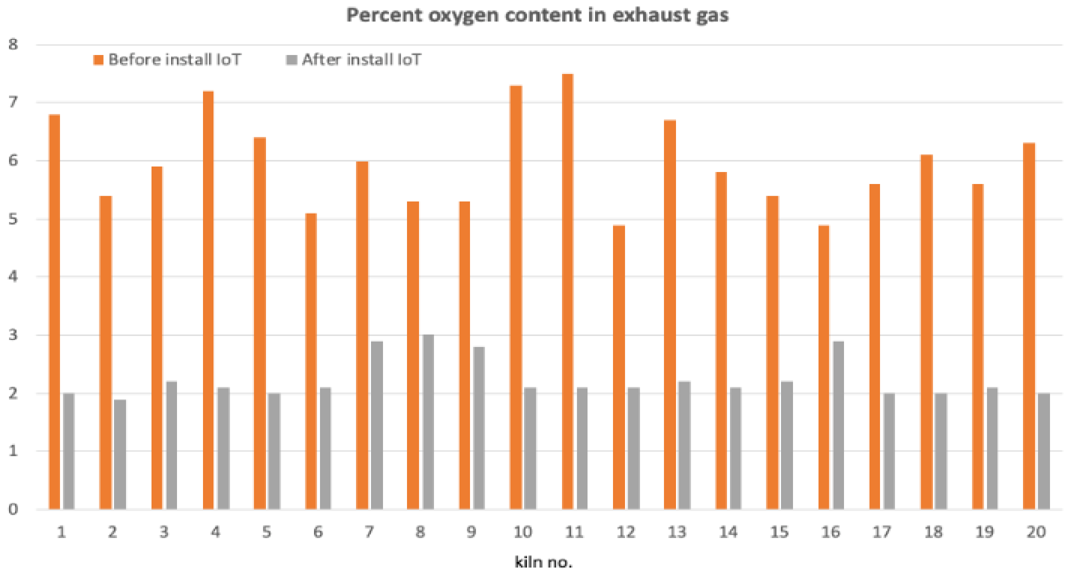

Figure 6. Oxygen content in the exhaust gas in the kiln stack. Lower value means less heat loss.

The improvement in energy efficiency is determined by comparing the SEC, which is calculated by dividing the weight of the fuel by the weight of the final product. Table II examines the SEC of every kiln before and after the IoT system was implemented. Comparing SEC before and after IoT system implementation constitutes energy savings. The kiln with the greatest savings is number 11, which is 8.60%. The annual savings for 20 kilns is approximately 38.1 tons of LPG, or $20,189 a year. The average savings per kiln is $1,009 compared to the additional cost of the IoT system, which is about $2,800 per kiln. The simple payback period is 2.8 years.

6. Conclusion

The study incorporates affordable IoT devices into existing small-scale ceramic kilns to enhance fuel efficiency. Sensors are chosen to improve fuel usage efficiency; meanwhile, the measured data are uploaded to a cloud server, making it accessible to the kiln operator through a mobile device. This near-real-time data enables more accurate control over the kiln room conditions, controlled by a temperature profile graph. Alerts can be sent to a mobile social app for quicker response times. The results indicate that the average energy efficiency improvement is 5.6%. The implementation of IoT technology in the ceramic kilning process offers several other benefits, as well.

In recent years, IoT systems have become more affordable, broadly available, and simple to install. The sensors and IoT devices used are very robust and dependable in terms of maintenance. The lifespan evaluation of a system may extend beyond ten years. The cloud recorded data can be analyzed to investigate each batch's history. This data can be used to refine operations for future orders, resulting in fewer defects and increased yields. When a large number of kilns are connected to the IoT, big data analytics can be applied. It is possible to combine data packages with external data sources. The outcomes will benefit both kiln owners and energy policymakers.

Enhancing the control of the temperature-time profile results in improved product quality, such as color uniformity and batch-to-batch consistency. This reduces the number of defective products.

Table 2. Estimation of fuel saving per year

Kiln no.	Specific energy consumption (kg LPG/kg product)			Capacity (kg. product /batch)	Batches per year	Annual saving (kg.LPG /year)
	Before	After	Saving (%)			
1	0.322	0.296	8.07	510	200	2652
2	0.352	0.332	5.68	450	175	1575
3	0.446	0.420	5.83	570	208	3083
4	0.328	0.301	8.23	440	255	3029
5	0.431	0.399	7.42	370	160	1894
6	0.311	0.297	4.50	270	230	869
7	0.280	0.268	4.29	650	210	1638
8	0.291	0.280	3.78	550	280	1694
9	0.337	0.323	4.15	400	220	1232
10	0.395	0.367	7.09	350	190	1862
11	0.221	0.202	8.60	850	231	3731
12	0.377	0.365	3.18	320	220	845
13	0.375	0.352	6.13	410	185	1745
14	0.271	0.260	4.06	530	202	1178
15	0.279	0.265	5.02	460	265	1707
16	0.296	0.292	1.35	660	270	713
17	0.355	0.337	5.07	430	200	1548
18	0.289	0.271	6.23	440	180	1426
19	0.613	0.579	5.55	330	210	2356
20	0.476	0.441	7.35	400	240	3360

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