Optimal control of boiler system based on IoT and energy consumption simulation

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Abstract: The energy consumption of building heating in China is enormous and reducing heating energy consumption is of great significance to promote energy saving and emission reduction in China. A reasonable boiler heating strategy can effectively reduce heating energy consumption. This paper presents an optimal control method based on the IoT system and an interface that makes Energy Plus in the cloud server work together with the IoT system. The boiler can make corresponding adjustments to the outlet temperature according to weather conditions and other factors to achieve energy-saving. The results show that the intelligent control method proposed in this paper can reduce the boiler outlet temperature by 2-8 ℃ and can reduce energy consumption by about 15%.

1. Introduction

1.1. Research Background

Globally, the building sector accounts for 30% of energy consumption and more than 55% of global electricity consumption. In China, the latest China Building Energy Consumption Report 2019 states that the total building energy consumption in 2017 was 947 million ton of standard coal equivalent, accounting for 21.11% of the total national energy consumption. [1] The total building area in China mainland is 64.3 billion square meters, and the carbon emission of buildings is 2.044 tons of carbon dioxide [2]. At present, building energy consumption has become an important factor limiting the economic development of China. China government has implemented Design Standard for Energy Efficiency of Public Buildings (GB50189-2015) on 2015 February 2 to reduce 20% total energy consumption throughout the year.

In public buildings, heating and cooling energy consumption account for a considerable proportion. On the one hand, the boiler system is usually controlled manually, based on preset times and temperatures. Such temperature control systems cannot dynamically adjust the power and operating status according to the outdoor conditions and other indoor and outdoor interference factors, resulting in significant energy waste. Therefore, it is essential to research indoor environment optimal control
methods based on Intelligent control. On the other hand, most intelligent temperature control systems currently work in the local area networks. They do not make full use of the Internet to achieve remote control, cloud computing and simulation.

IoT presents a new direction and idea for energy consumption collection and intelligent control in public buildings, including smart cities, smart grids, and smart homes [3]. Its advantages are rapid data transmission, various machine controlling types, and lack of spatial distance restriction. With the integration of IoT and intelligent control, we can get the real-time visualization of energy consumption information, building performance evaluation based on actual weather conditions with energy-saving strategies for each area and facility. [4].

1.2. Literature Review

Existing building energy models based on short-term modelling for daily operation and load-shifting plans can be categorized as physical white box models, black box models and grey box models. [5] The physical model method uses the physical characteristics and heat transfer principle to establish a thermodynamic model in the simulation software to simulate the target building's energy consumption. Compared with the white-box models, the black box models are often data-driven models based on using machine learning to mine historical data to predicate building energy consumption.

Researchers often use white-box simulation software to predicate energy consumption. Hong, Taehoon et al. applied energy-saving techniques (ESTs) to educational facilities and analyzed the life cycle cost to reduce energy consumption and CO2 emission in two schools. T. Ramesh [6] et al. simulated ten different residential housing types. He conducted life cycle energy analyses. Kwok, Yu [7] et al. using Design Builder to compare the comfort and energy performance of public and low-cost rental housing in Hong Kong during typical and extreme summers climate.

Researchers also analyzed and compared the impact of different building parameters on building energy consumption by simulations. Yan [8] used DeST to explore the effect of enclosure structure on the year-round energy consumption in a hot summer and cold winter region. This study shows the importance of external wall insulation and window retrofitting in energy efficiency in hot summer and cold winter regions.

Besides, many black-box models have been established. Cao et al. [2] use machine learning to analyze a general hospital in Shanghai, China. It was found that the two ensemble models, Extreme Gradient Boosting (XGBoost) model and Random Forest (RF) model, have better accuracy. Ahmad [9] came with four supervised based machine learning algorithms to forecast future energy requirements.

Many researchers have used the white-box model to build optimal and intelligent control platforms. Shaikh [10] comprehensively researched intelligent control systems for energy and comfort management in smart energy buildings (SEB's), providing a building research community for better understanding and up-to-date knowledge for energy comfort-related trends and future directions. Wetter [11] researched the implementation of the Building Controls Virtual Test Bed (BCVTB). The BCVTB allows connecting different simulation programs to exchange data during the time integration. Jintaek [12] created a conceptual framework for real-time weather responsive control systems combined with Building Energy Management Systems (BEMS) to make building energy adaptive. For example, they use daylighting responsive controls for electrical lighting and adjust the HVAC operational schedule to weather changes.

2. Methodology

A black box based control model requires a cold start process which takes us a long time for a large amount of data collection. Besides, outliers must be avoided, and data needed to be cleaned. In reality, it is hard to gather data that fits the target building well. It is also unrealistic to establish a new white box model for energy consumption simulation, which involves building structure and integrating thermodynamics and fluid dynamics. For this study, the primary criteria for selecting software were to have the ability to simulate building models and calculate energy consumption and to allow secondary development of external interfaces. This paper chooses the Energy Plus model to let the IoT system
work with through an interface.

2.1. Establishment of Building Internet of Things System

Figure 1 shows the IoT system, which is intermediate between the lower layer hardware and the upper layer software, playing the role of control and information transfer. It connects to various sensors and boiler heating systems downwards and the cloud server for Energy Plus simulation upwards. This paper's IoT system has many functions, such as data acquisition, data management, and Intelligent control.

Data acquisition function. Even though there are many buildings, only one IoT system needs to be built to meet multiple nodes' control and data collection. Each collection node can realize a real-time and accurate collection of each part's energy consumption data inside a large building. The nodes will send the collected energy consumption data and the node number and other information data to the IoT system through ZigBee, UWB, Wi-Fi, Bluetooth.

Data management function. IoT system uses TCP/IP and other means through the gateway to upload data to the IoT cloud server and stored it in the cloud database. So that managers can access the dynamic web page through the web browsers at anytime and anywhere. Managers can view the information stored in the database in real-time and adjust the parameters manually.

The IoT system also integrates features such as system logs and error alarms in addition to the three core functions mentioned above.

![Figure 1 Structure of the IoT System](image)

2.2. The Development of Interface

In addition to the above functions, the IoT system proposed in this paper can achieve intelligent control, but that needs to develop an interface. The IoT system can connect to Energy Plus through an interface. It can simulate and optimize the building's overall energy consumption and then uses a remote configuration to adjust the boiler system to achieve energy saving.

Figure 2 shows the interface used to coordinate the IoT system with Energy Plus in the cloud server. The IoT system collects in real-time the outside temperature and weather conditions, target parameters, operating status of the boiler, disturbance variables such as changes in the number of people in the house, and through the interface, convert them into data that Energy Plus can recognize and use. The model of the building and the envelope parameters should be set up in advance. Then the cloud server runs the Energy Plus simulation, whose results show the real-time load and energy consumption of the existing
system and the correspondence between room temperature and boiler outlet temperature. Finally, the cloud server generates and transmits back to the IoT system the boiler parameters that can be recognized and used to achieve the most comfortable, energy-efficient, and economical operation.

3. Cases Study

3.1. Building Model Settings

In this paper, a typical elementary school building in Beijing is used as the research object to test the proposed optimal control method's performance. The outdoor parameters are adopted from Beijing Typical Meteorological Year data. The geometric model is built using Design Builder and then imported into Energy Plus for calculation. The total building area is 4072.84 m². The model has five floors with 14 thermal zones on each floor. Classrooms which are 10 meters long and six meters wide, with a window-to-wall ratio of 0.3, are arranged on each floor's left and right side. The corridor is 3 m wide. The building is 60 m long and 15 m wide on each floor, as shown in Figure 3.
3.2. **Building Model Enclosure Structure**

The specific parameters and thermal parameters of the enclosure structure are shown in Table 1. The calculation results of the standard building floor's design heat load are as shown in Table 2.

| Table 1 Enclosure Structure Information |
|-----------------------------------------|
| **Structure** | **Material** | **Conductivity [W/(m*K)]** | **Thickness (mm)** |
| Exterior wall | Cement mortar | 0.93 | 20 |
| Autoclaved Aerated Concrete Block | 0.14 | 240 |
| Cement mortar | 0.93 | 20 |
| Interior wall | Cement mortar | 0.93 | 20 |
| Autoclaved Aerated Concrete Block | 0.14 | 200 |
| Cement mortar | 0.93 | 20 |
| Gypsum board | 0.40 | 10 |
| Floor | Reinforced concrete | 1.74 | 100 |
| Cement mortar | 0.93 | 30 |
| Polystyrene board | 0.046 | 20 |
| Roof | Gypsum board | 0.40 | 20 |
| Reinforced concrete | 1.74 | 100 |

| Table 2 Heating Load |
|----------------------|
| **Zone** | **Calculated Design Load [W]** | **Load per Area [W/m²]** |
| FLOOR1: CORRIDOR | 5995.22 | 46 |
| FLOOR1: ZONE1 | 2889.62 | 67.39 |
| FLOOR1: ZONE3 | 2390.75 | 54.59 |
| FLOOR1: ZONE4 | 2374.63 | 53.98 |
| FLOOR1: ZONE5 | 2364.5 | 53.98 |
| FLOOR1: ZONE6 | 2396.71 | 54.6 |
| FLOOR1: ZONE7 | 2910.49 | 67.73 |
| FLOOR1: ZONE8 | 2880.04 | 67.51 |
| FLOOR1: ZONE9 | 2383.71 | 54.71 |
| FLOOR1: ZONE10 | 2367.72 | 54.1 |
| FLOOR1: ZONE11 | 2357.64 | 54.1 |
| FLOOR1: ZONE12 | 2389.7 | 54.72 |
| FLOOR1: ZONE13 | 2900.85 | 67.86 |

3.3. **Occupancy Rate**

The occupant density is 0.4 people/m². For the campus building schedule, the occupancy rate is set to 0 for 00:00-7:00 and 18:00-24:00 and 1.0 for 8:00-18:00 during the working day. The metabolic rate per person (W/person) is 108. Students sit and study in the room. Ignore the heat consumed by the external work of the human body. The thermal resistance of the garment is 0.5 clo for summer conditions and 1.1 clo for winter conditions. The lighting is turned on when the illumination level is below 250 lx. The indoor lighting is controlled by continuous dimming according to the indoor illumination level. This paper also considers the effect of holidays and sets the heating system not to turn on Saturday and Sunday. There is also a winter holiday from February 1 to February 28, when the students are not in school, and the heating system is also not turned on.

3.4. **Boiler System and Scenario Settings**

Design Standard for Energy Efficiency of Public Buildings (GB50189-2015) divides cities into severe cold regions, cold regions, hot summer and cold winter regions, hot summer and warm winter regions, and temperate regions. Beijing is a cold region. The heating supplement should be considered in winter.
Compared with coal-fired boilers, gas boilers are more efficient and have fewer pollutant emissions. This paper chooses to build a self-built gas boiler heating system with a radiative heat transfer heater at the end of the system. The annual heating season is defined from October 1 to March 31. According to GB 50189-2015, the set temperature of heating in winter is 20 ºC.

Energy Plus simulates the impact on building energy consumption under two different control strategies and reflects the meaning of intelligent control. Tested Scenario and Baseline Scenario are set up in this paper. Tested Scenario is Scenario A, which simulates the scenario that IoT collects external data in real-time and uses the simulation of Energy Plus to precisely control the output water temperature so that the output heat always matches the actual demand heat load. Baseline Scenario is Scenario B, which simulates a conventional boiler operation pattern, where the temperature and flow rate of the water output is fixed after the boiler is turned on and the outside condition does not affect the operation of the boiler. Two scenarios have the same external envelope, the same personnel presence rate, and the boiler heating system's specific parameters are in Table 3.

| Table 3 Boiler System Settings |
|--------------------------------|
| **Radiator heating, Boiler HW, Nat Vent** | **Scenario A** | **Scenario B** |
| Design outlet temperature | Automatic control | 80 ºC |
| Return temperature difference | 10 ºC | 10 ºC |
| Flow type | Constant flow | Constant flow |
| Fluid type | Water | Water |
| Fuel type | Natural gas | Natural gas |
| Sizing factor | 1.00 | 1.00 |
| Loop supply pump | Constant flow | Constant flow |
| Availability | 7:00-18:00 | 7:00-18:00 |
| Targets of temperature | 20 ºC | None |

4. Testing Results

The typical classroom models under the above different boiler operation forms are established in the Design Builder. Its envelope structure parameters, meteorological parameters, hourly parameters are set according to Chapter 3. Finally, we calculate the boiler outlet temperature, water flow rate, heating season total gas consumption and gas cost.

4.1. Daily Results Analysis

Taking the outdoor dry-bulb temperature in Beijing on January 24, 2020, as the data reference. The lowest temperature of the day was -10 ºC, and the highest was -2.9 ºC. During the test, the outlet water temperature and outlet water flow rate were recorded every 1 hour. The water flow rate of Scenario A and B are both 4.768 kg/s. Scenario A's temperature fluctuates around 75-79 ºC. The temperature of Scenario B is fixed at 80 ºC. As shown in Figure 4. This result proves that our control system is effective and lays the foundation for the following analysis.
4.2. Monthly Results Analysis

Figure 5 shows little difference between the two control strategies in October and March, and the total energy consumption is also low. This is because the temperature in October and March is still relatively appropriate in Beijing, and the room can still maintain a relatively appropriate temperature without the heating system. Gas consumption began to increase significantly from November and reached the maximum value in January. The difference between Heating Energy between the two scenarios reached 14%.
4.3. Total Results Analysis

The outlet temperature difference between the two scenarios is put in Figure 6. Most of the time, the outlet temperature of Scenario B is significantly higher than that of Scenario A. The difference can be as high as 10 degrees Celsius but fluctuates between 2 and 4°C most of the time. This is enough to show that intelligent control can reduce the outlet temperature to adapt to external factors and indoor interference, reducing the overall system energy consumption when the outlet flow rate is constant. We can also see that the outlet water temperature of Scenario A is higher than Scenario B on some days. This means that the outdoor temperature is relatively low these days. The IoT system instructs to slightly raise the water temperature to meet the indoor temperature requirements. On the contrary, Scenario B has a low heating effect and does not make the room reach 20°C, which we set as a temperature target.

Figure 7 shows the total gas consumption in the whole heating season. Scenario A can save nearly 15% of the total gas consumption. It shows that intelligent control based on the Internet of Things platform has a noticeable effect on building energy saving.

If converted into the natural gas price for calculation. According to the current price of natural gas in Beijing, which is 0.36 yuan per kWh. Scenario B will cost 21,609.09 RMB. In contrast, scenario A will cost 18,355.8348 RMB. This means that in only one heating season in a primary school, the intelligent control system can save us 9000KWh natural gas consumption, equivalent to saving 3,254 yuan. If this control strategy can be extended to more than 970 primary schools in Beijing, 3.1 million RMB can be saved in one heating season.

If converted into carbon dioxide emissions for calculation, Scenario A emits 9580.725997Kg of carbon dioxide. As a comparison, Scenario B emits 11278.74448 Kg of carbon dioxide.
5. Conclusion

In this paper, by developing an interface between building IoT system and Energy Plus, an optimal control method for boiler system is studied. Taking the thermodynamic model and the boiler system of a primary school in Beijing as a case study, the intelligent control method's effect is verified and evaluated.

The results show that the boiler system with intelligent control based on an IoT system has a pronounced energy-saving effect when the building parameters and internal loads are the same, which is an ideal model for building energy saving. Compared with the current method of fixing the setting value of outlet temperature, the boiler's dynamic control can appropriately increase the outlet temperature in icy conditions. It also can reduce the outlet temperature by 2-8°C in most scenes. This saves 15% of the total gas consumption, total gas cost, and carbon dioxide emission.

Therefore, it is a resultant method of energy-saving and environmental protection. The promotion and application of this boiler heating system and intelligent control scheme to other school buildings in Beijing is of great significance for energy saving and emission reduction.

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