An Infrared Array Sensor System: Basic Technology for Achieving Human-Centered Smart Buildings

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Azbil has begun selling an infrared array sensor system that consists of sensors developed for air conditioning control and a device that aggregates the data measured by the sensors. This novel product operates without the use of a room temperature sensor installed on a wall or a pillar. It provides comfort and energy efficiency using feedforward air-conditioning control based on a wide range of surface temperature measurements obtained by infrared array sensors. In addition, by detecting human and outputting its results, it is a basic product for achieving smart buildings. It can be applied to air conditioning, lighting control, ventilation control, etc. In this paper we report mainly on the technological aspects of the product.

1. Introduction

In keeping with the azbil Group's corporate philosophy of human-centered automation, Azbil is advancing initiatives aimed at achieving the Sustainable Development Goals adopted at a 2015 UN summit meeting. As a result of one initiative, to provide both comfort and energy conservation, Azbil introduced the Infrared Array Sensor System, a basic product for achieving smart buildings, into the building automation (BA) market in November 2019. The Infrared Array Sensor System provides an easy-to-understand display of the surface temperature of walls, floors, and ceilings, which greatly affect the room temperature in a building. The display can help building managers to better control the air conditioning by, for example, enabling the discovery of hot spots. Also, the system employs a unique human-detection technology, which effectively utilizes the characteristics of infrared array sensors. The technology can be used to start or stop air conditioning and lightning depending on whether people are present, and to control ventilation based on the number of people. The system also incorporates air-conditioning control technology that immediately determines the appropriate air supply temperature and volume using temperatures measured in a wide area, instead of the usual temperature measurement by a single wall- or pillar-mounted sensor. As a result, energy savings can be achieved.

2. System Configuration

Figure 1 shows the system configuration of the Infrared Array Sensor System. Infrared array sensors are installed in a room to measure the surface temperature of the floor, ceiling, and walls. The sensors use Power over Ethernet (PoE), by which both data and power are transmitted by LAN cable, reducing installation work.

An Infrared Sensor Controller (IRSC) is installed in a monitoring room or in a cabinet and is connected via the network to the sensors and to the controllers for air-conditioning and lighting, which are compatible with BACnet communication. The IRSC does the calculations required for detecting people and controlling the air conditioning based on the surface temperatures measured by the infrared array sensors. The IRSC uses BACnet communication to send the processing results to Azbil's savic-net™ FX or savic-net G5, or to another company's BACnet-compatible device to create a BA system with advanced air conditioning and lighting control.

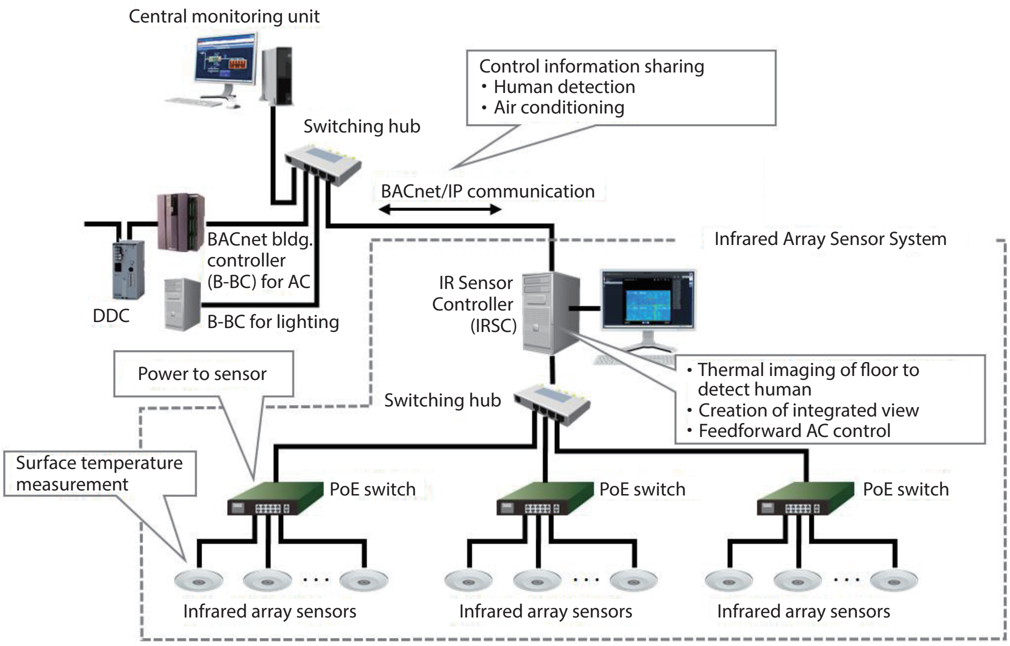

Fig. 1. System configuration

3. Infrared Array Sensors

Objects emit infrared radiation that changes according to the surface temperature. Infrared array sensors detect this radiation and create thermal images. Other companies' infrared array sensors and thermal imaging cameras*1 are often equipped with a mechanical shutter whose purpose is to increase the accuracy of temperature measurement, but the disadvantages of a shutter are the interruption of measurement and a short service life due to the mechanical structure. Azbil's infrared array sensors are specialized for air conditioning use, allowing them to achieve a high temperature measurement accuracy of ±1 °C*2 along with high durability through elimination of the mechanical shutter. In addition, the sensor lineup includes seven models in order to meet the requirements of many kinds of buildings. These models share the same design concept, blending in well with their surroundings. The sensors have been rated highly and received a Good Design Award in 2019.

3.1 Use at Offices

Model TY2000 compact infrared array sensors are designed for offices. Using the three models detailed below, the surface temperature of the floor, walls, and ceiling can be measured.

3.1.1 Model TY2000A1000 Ceiling-Mounted Sensor with Fixed Sensing Angle

The ceiling-mounted model TY2000A1000 sensor (shown in fig. 2) measures the surface temperature of the floor and sends thermal images to the IRSC for analysis so that human can be detected.

Fig. 2. Model TY2000A1000

3.1.2 Model TY2000A2000 Ceiling-Mounted Sensor with Adjustable Sensing Angle

The TY2000A2000 ceiling-mounted sensor (shown in fig. 3), which has an adjustable-angle lens, measures the surface temperature of a wall.

Fig. 3. Model TY2000A2000

3.1.3 Model TY2000A3000 Wall-Mounted Sensor with Adjustable Sensing Angle

The TY2000A3000 wall-mounted sensor (shown in fig. 4), which like the TY2000A2000 has an adjustable-angle lens, measures the surface temperature of the ceiling. The lens can be locked from inside the sensor during installation so that it will not be moved accidentally by workers at the office.

Fig. 4. Model TY2000A3000

*1. Infrared array sensors and thermal imaging cameras work on the same principle, but they are differentiated in this paper because the sensors' resolution is not as high as that of the cameras.

*2. The accuracy depends on the conditions. When the temperature of the measured objects and the ambient temperature of the sensor are between 15 and 35 °C, model TY2000 sensors have a measurement accuracy of ±1 °C.

3.2 Use for High Ceilings

Model TY2001 infrared array sensors are designed for rooms with a high ceiling, such as an exhibition hall. Using the four models detailed below, the surface temperature of the floor, walls, and ceiling can be measured.

3.2.1 Models TY2001C2000 and TY2001B2000 Ceiling-Mounted Sensors with Adjustable Sensing Angle

The TY2001C2000 ceiling-mounted sensor (shown in fig. 5) measures the surface temperature of the floor. The angle of its lens can be adjusted, so the sensor can also be used to measure the surface temperature of a wall. A model with a wider-angle lens (TY2001B2000) is also available, so an appropriate model can be selected depending on the height of the ceiling.

Fig. 5. Model TY2001B2000

3.2.2 Model TY2001C4000 and TY2001B4000 Sensors with Ball Head

The model TY2001C4000 sensor is mounted on a ball head (shown in fig. 6) for measuring the surface temperature of a wall or ceiling. If a TY2001C2000 or TY2001B2000 (discussed in 3.2.1) cannot be installed on the ceiling, model TY2001C4000 sensors can be installed on a catwalk, etc., to measure the temperature of the floor. Model TY2001B4000, with a wider-angle lens, is also available.

In addition, model TY2001 sensors are designed with safety in mind because they are installed in high locations (up to 18 m high). There is a hole in the back of the sensor for attachment of a fall-prevention wire.

Fig. 6. Model TY2001B4000

4. Infrared Ray Sensor Controller (Model BH-311J0W0000)

The IRSC obtains thermal images from the infrared array sensors and combines them to create a thermal image of the entire floor. The IRSC calculates the average surface temperature, the estimated number of people, etc., in specified rectangular areas in the thermal image of the floor, shows them on a screen (see fig. 7), and provides them for external devices a BACnet point. By specifying the rectangular areas based on the system of variable air volume (VAV) and lighting, control of the air conditioning and lighting for each desired area on the floor can be achieved.

Some similar products of other companies have the sensors process various types of data about measured surface temperature and output the results to external devices only. This creates problems because data processing across multiple sensors is difficult. On the other hand, the IRSC first creates a thermal image of the whole floor from the individual thermal images acquired from the infrared array sensors before data processing. This allows it to process the data without a problem if information from individual thermal images overlaps.

The IRSC's two main functions are described below: its integrated view function in section 5 and feedforward air-conditioning control in section 6.

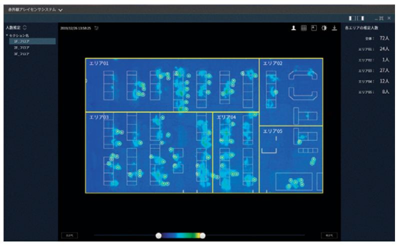

Fig. 7. IRSC screen

5. Integrated View Function

This function shows thermal images, area information, and human detection results on the floor layout of the building (fig. 8), which allows users to intuitively grasp the temperature of room surfaces, occupant movement, occupant density, etc. We call this display the integrated view. The IRSC can create an integrated view of an area as large as 2,000 m^2. The integrated view can be divided by floor, allowing separate floor management for as many as 10 floors.

The paragraphs below describe the main sub-functions of the integrated view.

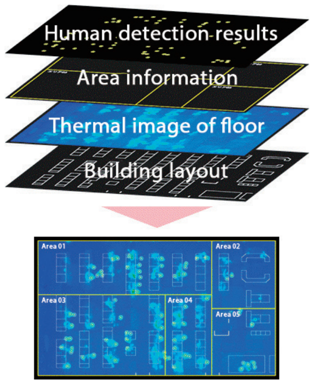

Fig. 8. Integrated view

5.1 Thermal Image Composition Function

This paragraph gives an explanation of how a thermal image of the whole floor is composed for display in the integrated view. In general, for a floor measuring dozens of meters on a side as shown in figure 9, a high-resolution thermal imaging camera directly above cannot take an image of the whole floor with the people on it because a typical office ceiling is about 3 meters high, which is not high enough. Alternatively, installing a thermal imaging camera in a corner as shown in figure 10 may be considered. In this case, the camera takes images of the floor from an oblique angle and processes them by correcting trapezoidal distortion, etc. However, it is likely that occupants will be hidden behind PC monitors or that, depending on the floor material, infrared rays will be reflected if the angle of incidence exceeds 50°, preventing accurate temperature measurement.

In light of the above, using sensors with a 100° angle-of-view lens for imaging from directly above is desirable. Our system solves the aforementioned problems by the installation of low-resolution infrared array sensors on the ceiling as shown in figure 11 and combining the images. As a result, the system can show a thermal image of the whole floor in real time as if it were taken with a high-resolution thermal imaging camera from a great height (fig. 12).

The engineering work required for installation is simple, since the information required for creating a composite thermal image is only the sensor type and the installation location.

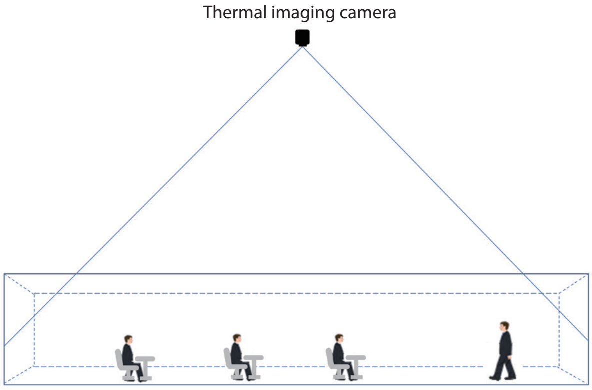

Fig. 9. High-resolution thermal imaging camera directly above

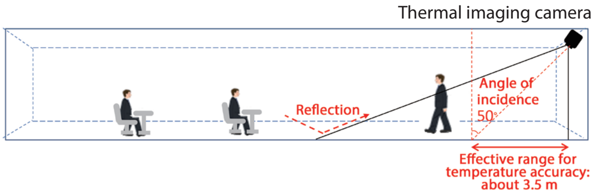

Fig. 10. High-resolution thermal imaging camera at an oblique angle

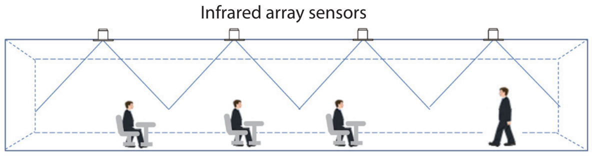

Fig. 11. Multiple low-resolution sensors directly above

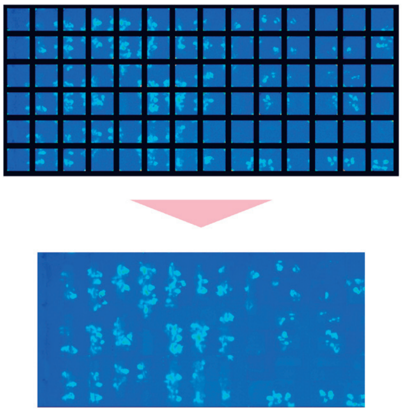

Fig. 12. Composite image of temperature data

5.2 Human Detection Function

This function uses the composite floor thermal image as input and identifies heat-generating objects that meet certain conditions as human. For example, people differ in temperature from the floor, are of a certain size, and are in motion (as contrasted with objects completely at rest), etc. Our system continually measures the temperature of the occupants and of the floor in the office so that people at rest can be detected based on information like temperature difference between the person and the floor. In contrast, pyroelectric sensors, which are widely used for human detection, can detect changes in infrared radiation only, not people at rest. Also, one IRSC unit can detect people in an area up to 2,000 m^2 in real time.

On the integrated view, heat-generating objects detected as human are shown with a circle (fig. 8). Other companies' human detection sensors are likely to count people twice at a boundary between the ranges of two sensors (fig. 13 [a]) since both will detect the person (fig. 13 [b]). By contrast, our system reduces double counts by creating a composite image that takes overlapping into account and by detection of people after completing the image (fig. 13 [c]). Additionally, many of the human detection sensors of other companies output the location of a person in units of a few meters, but our system can output the location in units of several tens of centimeters.

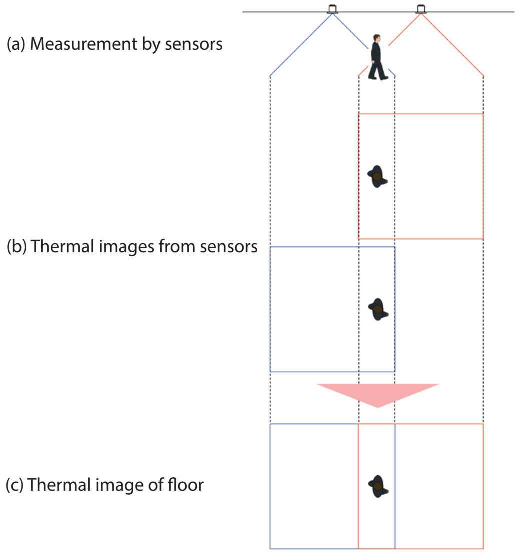

Fig. 13. Reducing double counts by combining thermal images

5.3 Other Functions

The IRSC can store the data used for the abovementioned functions at 10-minute intervals for up to one year. In addition, the IRSC has a function that operates in conjunction with alarm information output from external equipment. This function stores the floor surface temperatures measured at 10-second intervals for 10 minutes before and after an alarm is detected. This data can be seen on the integrated view.

In the thermal analysis of room environment, only a temperature representing a specific area was available in the past, but now with this product the surface temperature of the whole floor can be used. For example, with analysis that is now possible, a PC or PC monitor that was left on can be located and switched off to save energy. In addition, the stored data that is linked with alarm information can be used to help the building manager, etc., to understand the situation when the alarm was triggered.

6. Feedforward Air-Conditioning Control

In this section, we first describe the general concept of feedforward air-conditioning control and its advantages, and then explain how the concepts underlying our product were implemented and report the results of product operation verification.

6.1 The Room Model and the Importance of Surface Temperature

The temperature in a room can be predicted given information on the air supply from the air conditioning and the surface temperature of the ceiling, floor, walls, people, and office automation equipment (fig. 14). We call the formula used to calculate the predicted room temperature "the room model." Note that "air supply" refers to both air supply temperature and air supply volume.

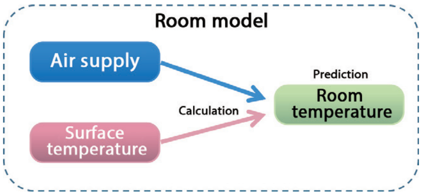

Fig. 14. The concept of the room model

Surface temperature is a key factor for determining the room temperature. Many of the air-conditioning heat loads (heat flows, internal heat generation, solar radiation heat, and heat storage) are reflected in surface temperatures. If there is no air supply, the room temperature can be determined by the surface temperatures only. The room and surface temperatures are in equilibrium and equal (fig. 15).

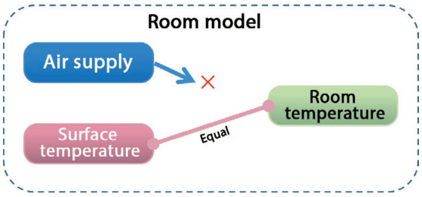

Fig. 15. Room model (no air supply)

Usually, the surface temperature is not measured, so the room temperature cannot be calculated because only the air supply data is available (fig. 16).

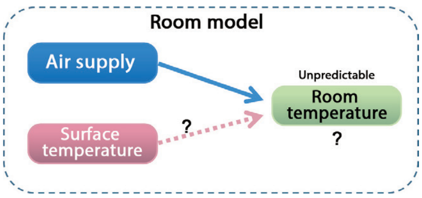

Fig. 16. Room model (if surface temperature is unknown)

If the air supply is constant, the room temperature varies depending on the day. For example, if the air supply is 16 °C, the room temperature may be 26 °C one day but 28 °C another day. This difference is caused by the difference in surface temperatures. This explains why it takes time to lower the room temperature after a holiday when the air conditioning was stopped. The surface temperatures are higher than usual due to heat stored throughout the entire building.

6.2 Feedback Control

This section discusses the conventional control method for bringing the room temperature to the desired set-point temperature. Since the surface temperatures are unknown, sensors are used to measure the room air temperature (fig. 17). Based on the air temperature measurement, the air supply is changed, the variation in the temperature in the room is monitored, and the air supply is adjusted accordingly. It is obvious that the room temperature can be brought close to the set point in this way. This method of automatically and repeatedly adjusting the air supply using information from target of control is called feedback control.

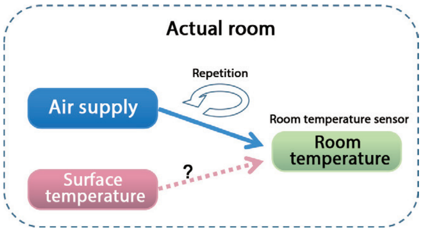

Fig. 17. Feedback control

6.3 Feedforward Control

Our system does not use room sensors, but instead uses infrared array sensors to measure surface temperatures. With a room model that uses surface temperatures, our product can predict the room temperature given the air supply characteristics (fig. 18). Eventually, it is possible to determine the air supply needed to bring the room to the set temperature without using data from the actual room. Specifically, it may be possible to obtain the inverse function of the room model formula, or if the inverse function cannot be obtained, a solution close to the room temperature can be selected by inserting an air supply pattern into the room model formula. The method of calculating the air supply using a room model formula but not the controlled target is called feedforward control.

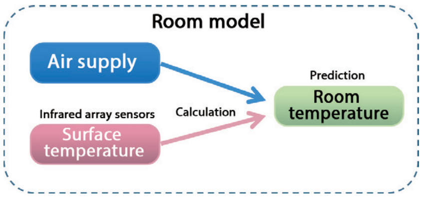

Fig. 18. Feedforward control

6.4 Advantages

Feedforward air-conditioning control has three advantages. First, the air supply temperature and volume can be determined immediately without using information from the controlled target. As a result, waste is avoided and energy is saved. The second advantage is a quick response to changes in heat-generating objects in the room. For example, if a person starts a PC, the heat of the PC is measured immediately by infrared array sensors, but it would take time for that heat to be transmitted to room temperature sensors on the wall or ceiling. Lastly, the predicted room temperature will be closer to the temperature around workers because the infrared array sensors measure a wide range of surface temperatures. Room temperature sensors on the wall or ceiling, on the other hand, can be affected by heat-generating objects nearby, such as a copying machine. As a result, the measured temperature might be different from the temperature around workers, which can negatively affect temperature control.

6.5 An Optimization Problem

There are many combinations of air supply temperature and volume that can bring the room temperature to the desired set point. Selecting the most energy-efficient combination can be seen as an optimization problem. Furthermore, if we define comfort as the state when the room temperature is equal to the set point, and discomfort as the state when there is a deviation between the two, optimizing comfort and saving energy can be treated as a multi-objective optimization problem.[(1)] This allows control based on various viewpoints, such as avoiding the use of a large amount of energy to achieve a slight improvement in comfort.

6.6 Implementation in the Product

Up until now, we have discussed the general concepts of the room model and optimization. This section describes concretely how these concepts were implemented in the product.

There are various ways to express a room model mathematically. Our product uses a lumped-parameter system model, which assumes that surface temperature heat and air supply is mixed instantaneously in VAV zone units.

For optimization, it is known that lowering the air supply volume saves energy. Our system uses an algorithm to find the combination of air supply temperature and volume with the smallest volume that will bring the room temperature to the set point.

6.7 Verification Test

Twenty infrared array sensors were installed in a laboratory (15 × 8 × 3 m). In the test, we used the product to lower the room temperature from around 30 °C to 26 °C and checked whether the optimal air supply temperature was selected to minimize the air supply volume.

Figure 19 shows variations in the average surface temperature of the floor, ceiling, and walls measured by the infrared array sensors. The figure also shows changes in the room temperature measured by a room temperature sensor installed on the wall for reference, although it would not have measured the temperature around workers. The figure shows that the air conditioning brought the surface temperatures and room temperature close to 26 °C. Figures 20 and 21 show the requested air volume and the air supply temperature respectively. The feedforward control selects the air supply temperature (15 °C [the coldest setting] in this case) that minimizes the air supply volume at the start of air-conditioning operation so that energy can be saved. Soon after the test started, a large air volume was requested due to the high surface temperatures. However, when the surface temperatures dropped, the volume decreased first while the air supply temperature was kept the same. If the surface temperatures had decreased further and the requested air supply volume had reached the minimum volume of 1,200 m^3/h, the temperature of the air supply would have been raised to keep the quantity of heat in the air supply balanced.

From the above testing, we confirmed that the air conditioning using this product lowered the air supply volume as planned. As to energy savings, the system reduced the power consumption for conveying air by at least 30 % as compared to feedback control (fig. 22), although the effect varied depend on the verification conditions.

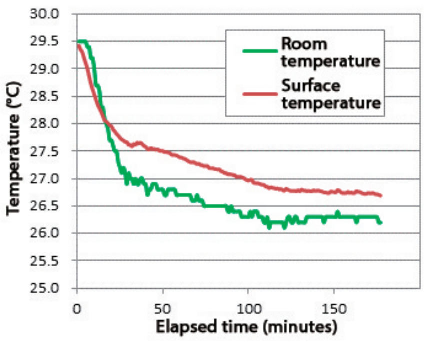

Fig. 19. Average of surface and room temperatures

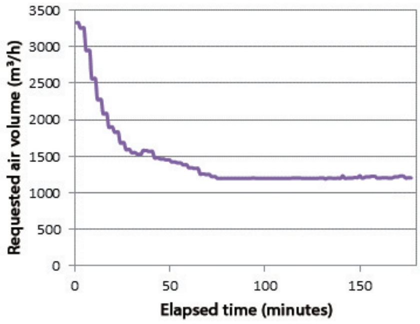

Fig. 20. Requested airflow

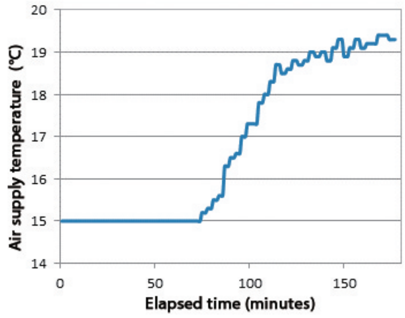

Fig. 21. Air supply temperature

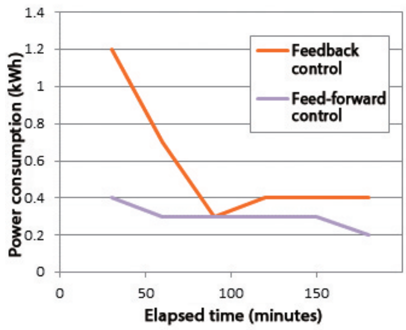

Fig. 22. Power consumption

7. Future Enhancements

Since the air conditioning control of this product was designed for offices, the room model using a lumped-parameter system cannot be applied to some buildings. Specifically, the model cannot be applied if there is a large difference between the average room temperature and the temperature in the desired place (for example, 1 meter above the floor). Therefore, this model cannot be used for a large space like an exhibition hall, although there is no problem for use in offices. This limitation can be resolved by selecting a different model, one which predicts the temperature distribution in a large space. At present, we believe that the room model using a lumped-parameter system requires the smallest amount of calculation. In contrast, a room model using computational fluid dynamics (CFD) that can handle spatial distribution requires the largest amount of calculation. If a complicated model is used, the method for determining the air supply is also complicated, making it unsuitable for real-time air conditioning control.(2) Also, CFD room models often do not match the actual situation.

Therefore, we will develop an intermediate room model requiring a small amount of calculation and having the capability to estimate the spatial temperature distribution. This model will be provided as a selectable option. Before use for control at a particular site, the model will be completed by onsite adjustment or learning. Additionally, since this model will be able to predict the temperature distribution in space, we would also like to develop a three-dimensional integrated view.

8. Conclusions

In this paper, we introduced our newly available Infrared Array Sensor System. The Infrared Array Sensor System is an innovative industry-leading product which also can be upgraded for higher system functionality by using more highly accurate sensors. In the future, based on the azbil Group's corporate philosophy of human-centered automation, we intend to develop a basic product that will help to achieve smart buildings and will provide an unparalleled experience for its users.

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