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Sensor Impact Evaluation at Different Sensor Locations in a Multi-zone Office Building

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January 2022

OAK RIDGE National Laboratory

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Electrification and Energy Infrastructures Division

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EXECUTIVE SUMMARY

FY 2022 Q1 deliverables include the development of an emulator that can evaluate the sensor impacts at different sensor locations (i.e., thermostat locations) in a multizone office building. This report presents the detailed procedure of developing the emulator and using the emulator for preliminary sensor impact analysis.

In designing new multizone buildings or retrofitting existing buildings, the room thermostat locations or subzoning design has been often determined by best practices without considering the effects of this design in terms of energy or thermal comfort. In subzoning design, the total number of thermostats is usually smaller than the total number of rooms. As a result, one thermostat in one room often controls the indoor temperature of several other adjacent rooms. For example, five zones might share one thermostat located in one of the zones. Because the demands for thermal load in different zones could be different for the multizone buildings, this subzoning design can compromise control performance and waste building energy consumption. Furthermore, for multizone buildings, subzoning could introduce thermal discomfort for zones. This issue has not be thoroughly investigated in simulation/field studies, and the US Department of Energy's Oak Ridge National Laboratory explored the impacts of subzoning design through modeling and experimental study.

Oak Ridge National Laboratory's two-story Flexible Research Platform (FRP-2) building was selected as a test building, from which the calibrated simulation model is used for the emulator. The rooftop unit system serves as the building's primary cooling system, and each variable air volume (VAV) box with electric reheat coil serves as the building's main heating system. The control for the rooftop unit and VAV box adopted the practical control sequences from ASHRAE Guideline 36-2018: High-Performance Sequences of Operation. For the FRP-2 building, the two floors each have five office zones. In total, there are 10 zones.

Based on the floor plans, 54 thermostat location combinations were selected for the first floor. Without losing generality, the second floor follows the same thermostat locations. Two types of controls were considered. The first is a thermostat located in one or more zones with several other zones without thermostats. The rooms without thermostats are subzones of the room with thermostat. There are no temperature readings from the subzones, so the temperature readings from the room with a thermostat will control the subzone per the thermostat reading. The second type of control is the same scenario as the first but assumes that there are temperature readings from subzones to calculate the average zone temperature for the room sharing a thermostat. This average temperature will control the cooling/heating for the rooms. The detailed sensor locations are described in Section 2.2.

The 54 thermostat location cases were simulated using the developed emulator via high-performance cloud computing.

The emulator was developed based on the thermostat location designs. The framework is shown in Figure 2. This emulator has four major components: building/HVAC model from EnergyPlus, VAV box model from Python, control modules for the VAV and air handling unit based on ASHRAE Guideline 36-2018, and sensor location designs.

The modeling analysis was conducted with respect to uncertainty analysis focusing on energy consumption and thermal comfort analysis for different sensor locations. The energy consumption factors included site energy, cooling energy, heating energy, and fan energy. The thermal comfort analysis factors included zone air temperature, zone supply air temperature, zone supply air flow rate, and zone VAV reheat coil energy consumption.

The uncertainty analysis was conducted for thermostat locations and showed that the sensor locations and energy consumptions have a nonlinear relationship. Some cases had higher or lower energy consumptions than the baseline case.

The thermal comfort factors show that inappropriate/inadequate thermostat locations strongly affect the zone temperature distributions. Overcooling and overheating are demonstrated in the sensor location simulations in cooling and heating modes, which is consistent with observations in actual building sensor deployments with limited sensor locations.

To summarize, the Q1 milestone for the sensor impact evaluation project includes the following actions being taken:

- Designed sensor locations (54 sensor designs) based on FRP-2 building floorplans
- Further polished the control sequences from ASHRAE Guideline 36 for the VAV and air handling unit
- Developed a preliminary emulator focusing on sensor location impacts for buildings and controls
- Performed cloud simulations for the sensor designs
- Conducted analysis for the sensor locations based on the emulator

The major findings from the study include the following:

- Uncertainty analysis showed that the sensor locations have greater impacts on aggregated energy consumption (e.g., site energy, total cooling energy, total heating energy, fan energy), compared with the baseline.

- Analysis showed that the sensor locations have greater impacts on thermal comfort compared with the baseline. When fewer sensors were used, thermal comfort was decreased. Some zone temperature profiles did not meet the cooling or heating set points. Overcooling, undercooling, overheating, and underheating are all demonstrated, which is consistent with real-world observations.

- If one sensor can be installed per floor, the one sensor would be installed in the room that has the highest cooling load to prevent undercooling in other rooms. However, this would cause overcooling for other rooms, which results in more cooling energy use and thermal discomfort for occupants. Therefore, it appears the case of one sensor per floor should be avoided if possible.

- If two sensors can be installed per floor, one sensor needs to be installed on the southside and share this data with zones where are located in the southside, another sensor needs to be installed in the northside and share this data with zones where are located in northside.

- If three sensors can be installed per floor, one sensor needs to be installed in the core zone, and use this data only for the core zone, and one sensor needs to be installed in southside and share this data with the zones where are located in southside, and one sensor needs to be installed in northside and share this data with the zones where are located in northside.

- If more sensors (higher than three for the 5 zones of FRP) were installed, the zone thermal comfort gets better. The energy consumption slightly decreases compared with fewer sensors.

1. INTRODUCTION

Sensors are critical components for controls in buildings. Sensors collect desired information for input to controls for subsequent control actions. In the past 10 years, the research focus has been on advanced controls, and sensors were not well studied. When sensors work in unhealthy or faulty conditions, the control benefits will be compromised regardless of the promising benefits of the controls [1]. For buildings, multiple components directly influence the sensor placement and deployment, such as sensor errors, sensor locations, sensor types, and sensor costs.

Figure 1 shows the overall research components for this project. Four sensor components are considered in this research, three of which were determined in FY 2021: sensor type, building control type, and sensor accuracy. In this report, we are focusing on the fourth component: sensor location. To achieve the goal of this research, the US Department of Energy's Oak Ridge National Laboratory team developed the physics-based model and surrogate model in FY 2021 and will perform field testing in FY 2022. Using the physics-based model and surrogate model, the Oak Ridge National Laboratory team conducted uncertainty and sensitivity analyses in FY 2021. The goal in FY 2022 is to develop the framework for sensor impacts analysis and verification to support sensor placement and configurations in building designs and analyses. The framework comprises development of a physics-based emulator with sensor errors, sensor locations, and control sequences; large-scale simulations for sensor errors and sensor locations sampling to the controls on the cloud; development of a surrogate model based on cloud simulation results for sensitivity analysis; and sensitivity and uncertainty analyses for the sensors and desired outputs (e.g., energy consumption, thermal comfort). This framework is extendable and scalable to other sensor components, such as sensor types and costs. The ultimate goal of this research is to offer the sensor evaluation tool publicly.

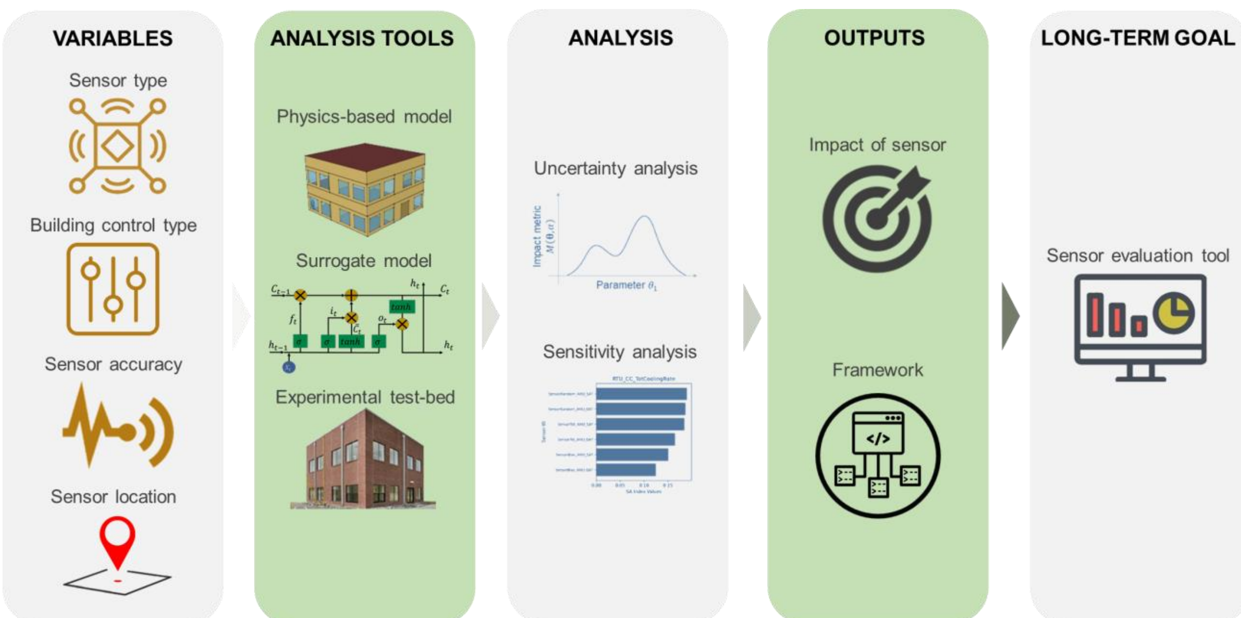

Figure 1. Overall research flow.

To achieve this goal, in FY 2022 Q1, the initial emulator was developed, focusing on the sensor locations. The details of each step are discussed in the following sections.

2. SENSOR LOCATION EVALUATION FRAMEWORK

The framework for sensor impacts and evaluation for sensor location comprises a physics-based emulator with control and sensor modules, cloud simulation, and uncertainty analysis. The overall workflow is illustrated in Figure 2.

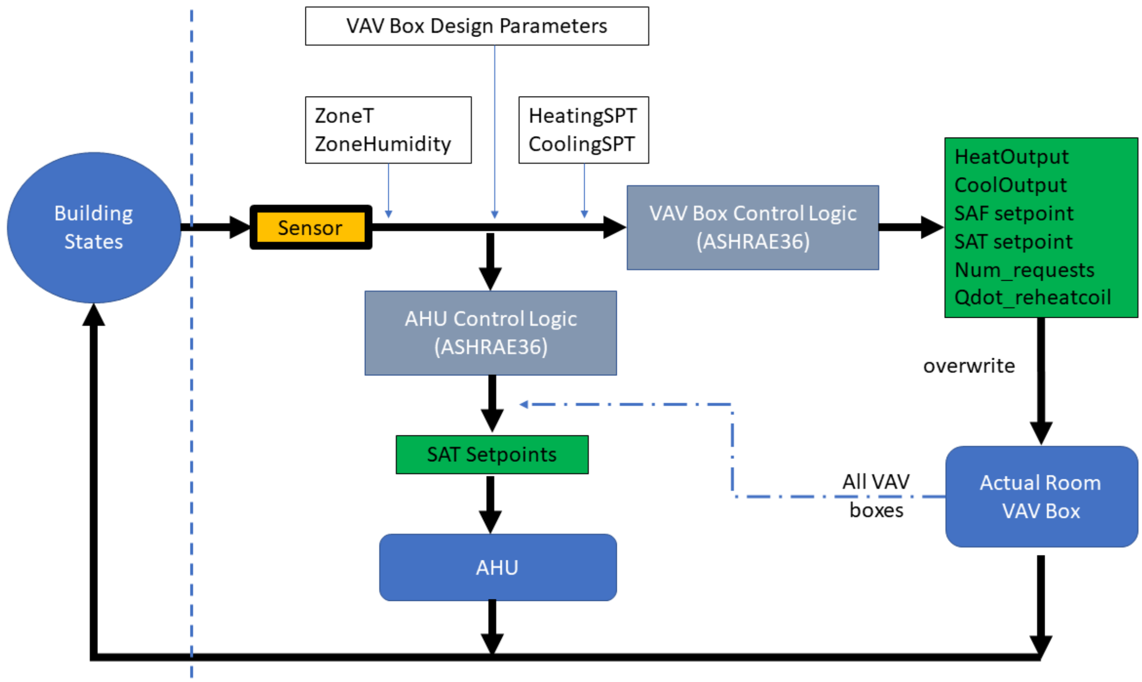

Figure 2. Sensor impact and evaluation framework (sensor location). VAV: variable air volume; SAF: supply air flow; SAT: supply air temperature; AHU: air handling unit.

2.1 SENSOR SETS

Based on extensive literature reviews, 34 sensors were identified. They are typical sensors used to operate rooftop unit (RTU) and variable air volume (VAV) systems in small to medium office buildings. The sensors were prioritized based on the severity of indoor air (IA) temperature impacts, which can significantly affect energy efficiency and occupant thermal comfort.

Based on the HVAC system configuration of Oak Ridge National Laboratory's two-story Flexible Research Platform (FRP-2) building, five sensor types were selected for the following reasons: (1) the IA temperature is the most important variable to be controlled to meet the heating and cooling set point temperatures; (2) the VAV box supply air (SA) temperature and SA flow rate directly affect the IA temperature from the control perspective; (3) RTU system-level operation directly affects the VAV box operations; and (4) RTU outdoor air (OA) temperature and SA temperature are important for determining the system-level energy consumption. The sensor details are listed in Table 1.

Table 1. Selected sensor list

Location	Measurement	Priority	Note
Room	IA temperature	1	IA temperature
VAV box	SA temperature	1	VAV box SA temperature

VAV box	SA flow rate	1	VAV box SA flow rate
RTU	OA temperature	1	OA temperature
RTU	SA temperature	1	SA temperature

2.2 SENSORS LOCATIONS

Figure 3 shows the floorplan of the FRP-2 building. Each floor has six zones, five conditioned zones, and one staircase. The FRP-2 building has 10 sensors for IA temperature in the conditioned zones—1 sensor per conditioned zone.

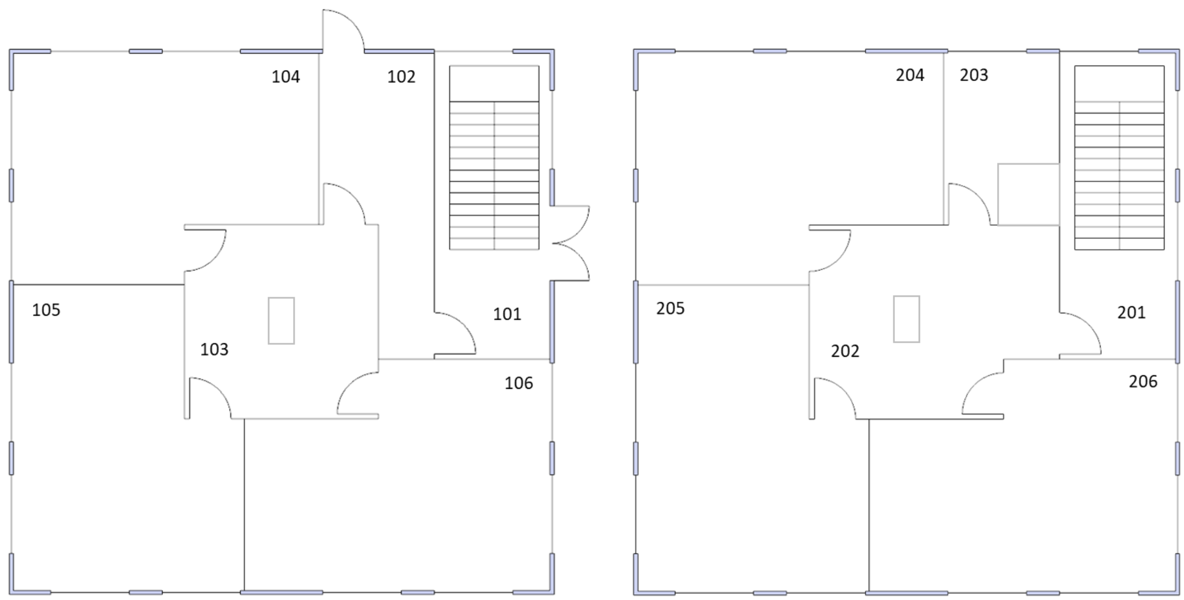

Figure 3. Floorplan of the FRP-2 building.

Table 2 through Table 6 show the sensor location cases based on the number of IA temperature sensors. Even if the IA temperature sensor was installed in each conditioned zone of the FRP-2 building, only a limited number of sensors were assumed to be installed, and the sensor data were assumed to be shared with other zones that do not have an IA temperature sensor.

Without losing generality, the sensor locations were designed for the first floor and repeated for the second floor. In reality, some scenarios use the mean/average values of multiple sensors, so those were incorporated into the sensor location designs. Each floor has five conditioned zones, and there are five cases in the scenario with one sensor. In total, there are 54 cases; 15 cases have 2 sensors, 20 cases have 3 sensors, 13 cases have 4 sensors, and 1 case has 5 sensors. "Mean" indicates the average of two or more sensor data.

The sensor location on the second floor is the same as on the first floor.

Table 2. Sensor location cases (one-sensor scenarios)

<table>
<tr><th>Number of sensors</th><th>Sensor sets</th><th>Sensor locations</th><th>Notes</th><th>Case ID</th></tr>
<tr><td rowspan="5">1</td><td rowspan="5">102/103/104/105/106</td><td>102</td><td>Perimeter zone</td><td>A1</td></tr>
<tr><td>103</td><td>Central zone</td><td>A2</td></tr>
<tr><td>104</td><td>Perimeter zone</td><td>A3</td></tr>
<tr><td>105</td><td>Perimeter zone</td><td>A4</td></tr>
<tr><td>106</td><td>Perimeter zone</td><td>A5</td></tr>
</table>

Table 3. Sensor location cases (two-sensor scenarios)

<table>
<tr><th>Number of sensors</th><th colspan="2">Sensor sets</th><th colspan="2">Sensor locations</th><th>Case ID</th></tr>
<tr><td rowspan="15">2</td><td rowspan="7">102/104</td><td rowspan="7">103/105/106</td><td>102</td><td>103</td><td>A6</td></tr>
<tr><td>102</td><td>105</td><td>A7</td></tr>
<tr><td>102</td><td>106</td><td>A8</td></tr>
<tr><td>104</td><td>103</td><td>A9</td></tr>
<tr><td>104</td><td>105</td><td>A10</td></tr>
<tr><td>104</td><td>106</td><td>A11</td></tr>
<tr><td>Mean (102, 104)</td><td>Mean (103, 105, 106)</td><td>B1</td></tr>
<tr><td rowspan="3">105/106</td><td rowspan="3">102/103/104</td><td>105</td><td>103</td><td>A12</td></tr>
<tr><td>106</td><td>103</td><td>A13</td></tr>
<tr><td>Mean (105, 106)</td><td>Mean (102, 103, 104)</td><td>B2</td></tr>
<tr><td rowspan="3">104/105</td><td rowspan="3">102/103/106</td><td>104</td><td>102</td><td>A14</td></tr>
<tr><td>105</td><td>106</td><td>A15</td></tr>
<tr><td>Mean (104, 105)</td><td>Mean (102, 103, 106)</td><td>B3</td></tr>
<tr><td>102/106</td><td>103/104/105</td><td>Mean (102, 106)</td><td>Mean (103, 104, 105)</td><td>B4</td></tr>
<tr><td>103</td><td>102/104/105/106</td><td>103</td><td>Mean (102, 104, 105, 106)</td><td>B5</td></tr>
</table>

Table 4. Sensor location cases (three-sensor scenarios)

Number of sensors	Sensor sets			Sensor locations			Case ID
3	103	104/105	102/106	103	104	102	A16
				103	104	106	A17
				103	105	102	A18
				103	105	106	A19
				103	Mean (104, 105)	Mean (102, 106)	B6
	103	102/104	105/106	103	102	106	A20
				103	104	105	A21
				103	Mean (102, 104)	Mean (105, 106)	B7
	102	104/105	103/106	102	104	106	A22
				102	105	106	A23
				102	Mean (104, 105)	Mean (103, 106)	B8
	102	103/104	105/106	102	104	105	A24
				102	Mean (103, 104)	Mean (105, 106)	B9
	104	102/106	103/105	104	106	105	A25
				104	Mean (102, 106)	Mean (103, 105)	B10
	104	105/106	102/103	104	Mean (105, 106)	Mean (102, 103)	B11
	105	103/104	102/106	105	Mean (103, 104)	Mean (102, 106)	B12
	105	103/106	102/104	105	Mean (103, 106)	Mean (102, 104)	B13
	106	103/105	102/104	106	Mean (103, 105)	Mean (102, 104)	B14
	106	104/105	102/103	106	Mean (104, 105)	Mean (102, 103)	B15

Table 5. Sensor location cases (four-sensor scenarios)

Number of sensors	Sensor sets				Sensor locations				Case ID
4	103	104	105	102/106	103	104	105	102	A26
					103	104	105	106	A27
					103	104	105	Mean (102, 106)	B16
	103	104	102	105/106	103	104	102	106	A28
					103	104	102	Mean (105, 106)	B17
	102	104	105	103/106	102	104	105	106	A29
					102	104	105	Mean (103, 106)	B18
	102	104	106	103/105	102	104	106	Mean (103, 105)	B19
	104	105	106	102/103	104	105	106	Mean (102, 103)	B20
	103	105	106	102/104	103	105	106	102	A30
					103	105	106	Mean (102, 104)	B21
	102	103	106	104/105	102	103	106	Mean (104, 105)	B22
	102	105	106	103/104	102	105	106	Mean (103, 104)	B23

Table 6. Sensor location cases (five-sensor scenarios)

Number of sensors	Sensor sets					Sensor locations					Case ID
5	102	103	104	105	106	102	103	104	105	106	A31

2.3 ASHRAE GUIDELINE 36 CONTROL LOGIC FOR RTU AND SINGLE-DUCT VAV SYSTEM

The installed HVAC systems in the FRP-2 building are RTUs in which the cooling comes from a direct expansion cooling coil, and the heating comes from the gas heating coil. The FRP-2 building has 10 conditioned zones. Each conditioned zone is served by a VAV box with an electricity reheat coil. The air handling unit (AHU) connects all the zone VAV boxes and the RTU. Control logic from ASHRAE Guideline 36 was developed for the RTU and VAV box.

1. AHU: trim and respond (T&R) set point logic

   The first control logic is the T&R set point logic for AHU. T&R logic resets set points of the pressure, temperature, or other variables in the AHU or plant side. T&R logic reduces the set point at a fixed rate until the zone thermal comfort is no longer satisfied, and then it generates the request to reset the set points. The set point is increased in response to a sufficient number of requests. By adjusting the importance of each zone's requests, the critical zones will always be satisfied. If there are not a sufficient number of requests, then the set point decreases at a fixed rate.

   The term *request* refers to a request to reset a static pressure or temperature set point generated by downstream zones or AHUs. These requests are sent upstream to the AHU or plant that supplies the zone or area that generated the request. Figure 4 shows an example of the T&R control provided by ASHRAE Guideline 36.

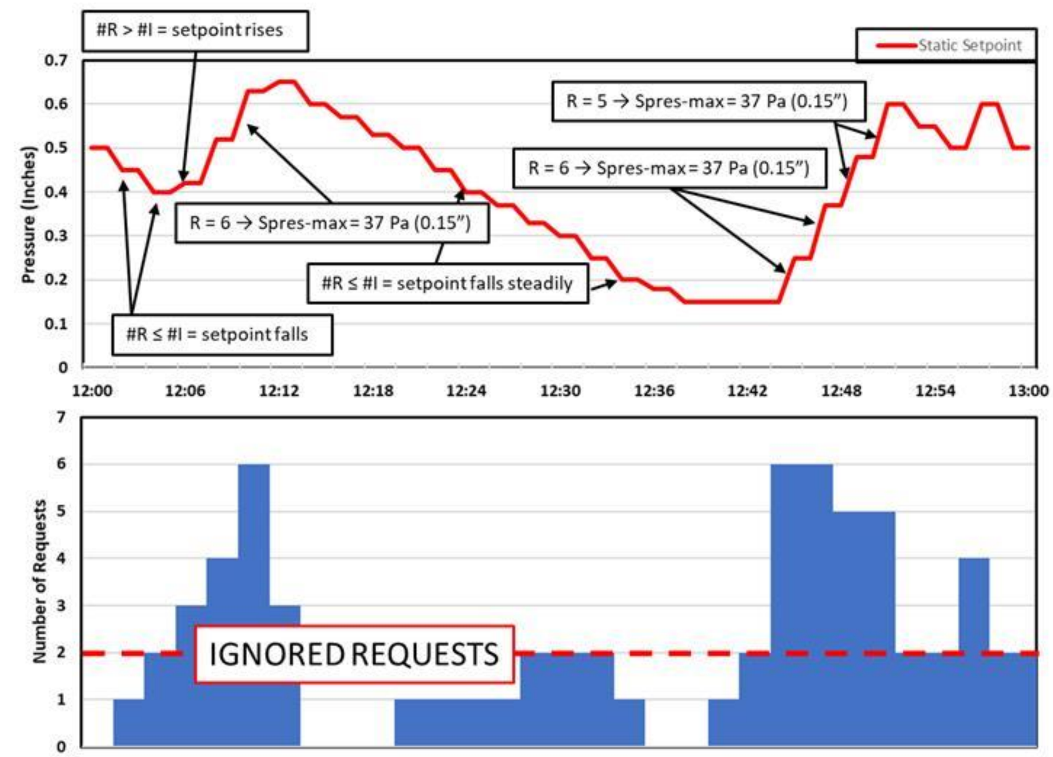

Figure 4. Example of the T&R control logic from ASHRAE Guideline 36 [2,3].

2. VAV box control logic

The VAV box control is the second control logic applied to the emulator. Figure 5 shows the control logic for the VAV box from ASHRAE Guideline 36. The control logic has three sections, which correspond to the heating season, cooling season, and deadband. The control logic uses the heating loop demand concept. Heating loop demand is the ratio (as a percentage) of actual required heating load of VAV box to the design heating capacity of the VAV box. Equation (1) describes how to calculate the heating loop demand.

$$Heating\ loop\ Demand = \frac{Heating\ load\ of\ the\ VAV\ box}{Capacity\ of\ the\ VAV\ box} \times 100. \tag{1}$$

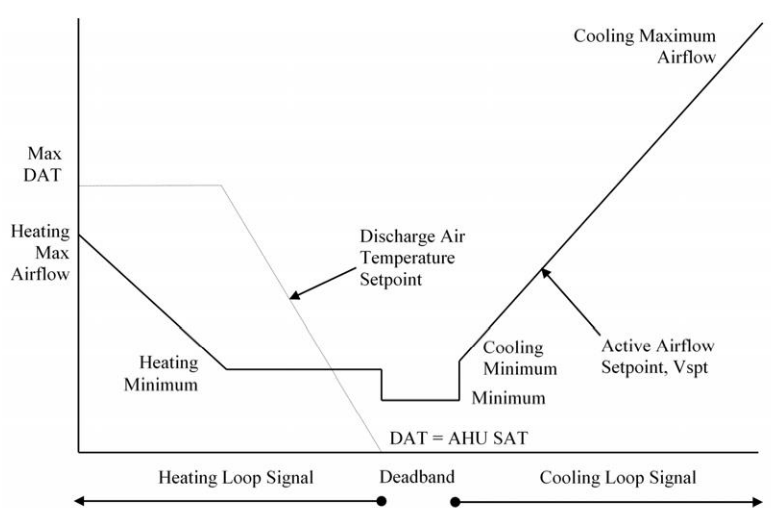

Figure 5. Control logic for VAV box from ASHRAE Guideline 36 [2,3].

3. Applied ASHRAE Guideline 36 control logic

   Figure 6 shows the overall flow of the applied ASHRAE Guideline 36 control logic into the emulator. The gray box in Figure 6 indicates VAV box control logic, and the orange box indicates T&R control logic. Table 7 lists the nomenclature for the ASHRAE Guideline 36 control logic.

   The control logic starts from the VAV box and links with the T&R control logic. Control logic for the VAV box can be divided into three sections:

   a. In the heating season, when the heating loop is less than or equal to 50%, the discharge air (DA) set point temperature of the VAV box is increased from the RTU SA temperature to the maximum DA set point temperature of the VAV box, and the minimum SA flow rate is maintained. When the heating loop is greater than 50%, if the DA temperature of the VAV box is greater than the IA temperature plus 3°C (5°F), then the SA flow rate of the VAV box is increased from the minimum SA flow rate to the maximum SA flow rate while maintaining the maximum DA set point temperature of the VAV box.

   b. In the cooling season, the DA temperature of the VAV box is the same as the RTU SA temperature because no option exists to decrease the SA temperature using the VAV box. Therefore, VAV box control is linked with T&R control in the cooling season, when the VAV box control must be considered the RTU SA temperature. The four cooling SA set point temperature reset requests are as follows:

      - If the IA temperature exceeds the indoor cooling set point temperature by 3°C for 2 min and after the suppression period resulting from an RTU SA set point temperature change via the T&R control, send three requests.

      - Else if the IA temperature exceeds the indoor cooling set point temperature by 2°C for 2 min and after the suppression period resulting from an RTU SA set point temperature change via the T&R control, send two requests.

      - Else if the cooling loop is greater than 95%, send one request until the cooling loop is less than 85%.

- Else if the cooling loop is less than 95%, send no request.

In terms of the SA flow rate in the cooling season, the SA flow rate of the VAV box is increased from the minimum SA flow rate to the maximum SA flow rate as the cooling loop is increased.

c. In the deadband, when neither heating nor cooling are needed, the SA flow rate is set to the minimum SA flow rate, and the DA temperature of the VAV box is set to the RTU SA temperature.

After receiving requests from the VAV box control logic, requests are used for the T&R control to reset the RTU SA set point temperature in the emulator. When the OA temperature was higher than the maximum OA temperature (21℃), the RTU SA temperature was set to the minimum RTU SA set point temperature (12℃). When the OA temperature was lower than the minimum OA temperature (16℃), the RTU SA temperature was set to maximum RTU SA set point temperature (18℃). If the OA temperature was between the minimum and maximum OA temperature when the OA temperature was increased, the RTU SA temperature was increased linearly from the minimum RTU SA set point temperature to the maximum RTU SA set point temperature. For T&R control, following ASHRAE Guideline 36, fewer than two requests were ignored.

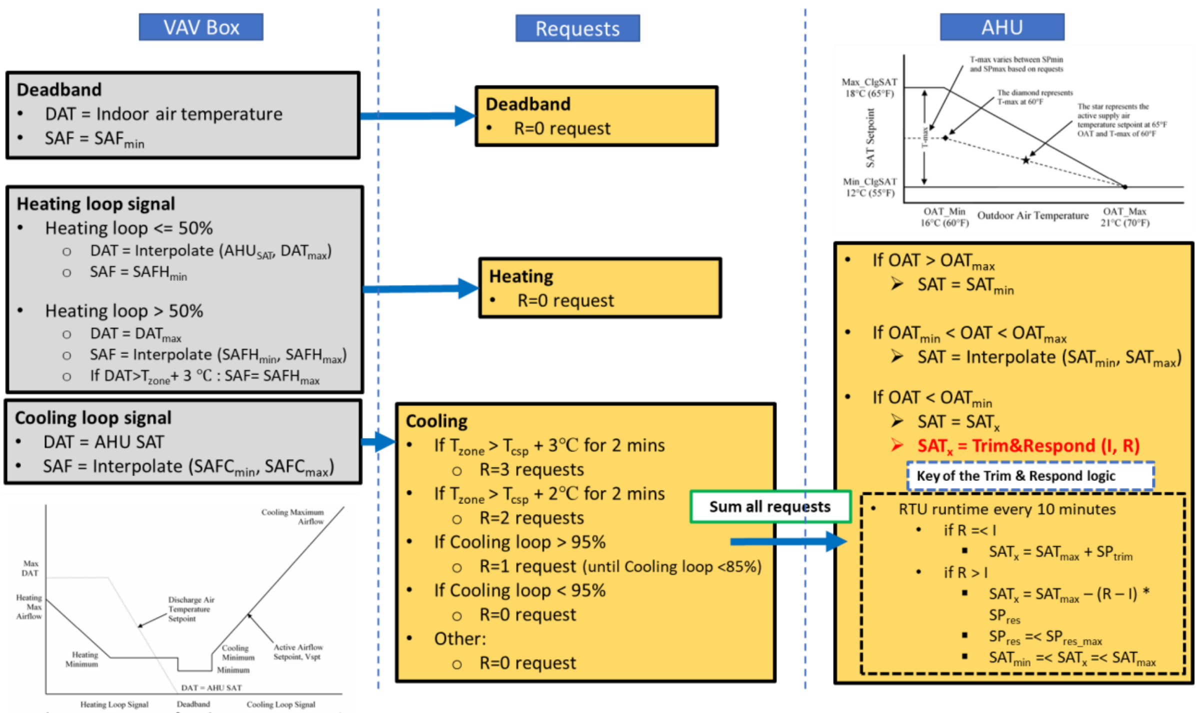

Figure 6. Overall flow of applied ASHRAE Guideline 36 control logic.
Abbreviation definitions are provided in Table 7.

Table 7. Nomenclature for ASHRAE Guideline 36 control logic

Abbreviation	Definition
DAT (°C or °F)	Discharged air temperature (each VAV box)
DAT_{max} (°C or °F)	Maximum discharged air temperature
AHU SAT (°C or °F)	AHU SA temperature
SAT_{max} (°C or °F)	Maximum SA temperature
SAT_{min} (°C or °F)	Minimum SA temperature
SAT_{x} (°C or °F)	Adjusted SA temperature based on the requests
OAT (°C or °F)	OA temperature
OAT_{max} (°C or °F)	Maximum OA temperature
OAT_{min} (°C or °F)	Minimum OA temperature
SAF (m^3/s or CFM)	SA flow (each VAV box)
SAF_{min} (m^3/s or CFM)	Minimum SA flow
$SAFC_{min}$ (m^3/s or CFM)	Minimum SA flow for cooling
$SAFC_{max}$ (m^3/s or CFM)	Maximum SA flow for cooling
$SAFH_{min}$ (m^3/s or CFM)	Minimum SA flow for heating
$SAFH_{max}$ (m^3/s or CFM)	Maximum SA flow for heating
Heating loop (%)	heating load/ capacity of VAV box
Cooling loop (%)	Cooling load/capacity of direct expansion cooling coil
T_{csp} (°C or °F)	Cooling set point temperature
T_{zone} (°C or °F)	IA temperature (each zone)
R	Number of requests from zones/systems
I	Number of ignored requests
SP_{trim}	Trim amount
SP_{res}	Number of responses
SP_{res_max}	Maximum number of responses per time interval

2.4 CLOUD SIMULATION

The sensor location simulation was based on a commercial cloud platform, Microsoft Azure. In total, 54 cases were simulated on the cloud. The inputs were the sensor locations incorporated into the five selected sensors for the FRP-2 building emulator, as shown in **Error! Reference source not found.**. The outputs were the target variables for energy consumption and thermal comfort, such as fan electricity consumption and reheat coil electricity energy in the VAV box.

A basic diagram of the workflow is shown in Figure 7. The workflow is as follows:

1. A Python script was developed to include the sensor locations. In total, 54 simulation input data files (IDF files) were generated. Each IDF file was associated with a Python class of sensor locations through Python EMS. During the simulation, at each time step, the sensor location was injected into the ideal sensor readings from EnergyPlus.

2. After the 54 cases were generated, they were uploaded to the Azure cloud platform.

3. In the Azure cloud platform, a bash script selected the appropriate virtual machine configurations (e.g., memory and hard drive, as shown in Table 8) and a number of virtual machines. The team's subscription included 54 nodes (virtual machines).

4. The Azure cloud provided a job scheduler, which automatically distributed all 54 cases across 54 nodes.

5. The simulation ran automatically until all cases were accomplished.

6. Finally, all the results were selected to set up the data sets (inputs and outputs) to create the black box models.

The configuration for the cloud is described in Table 8.

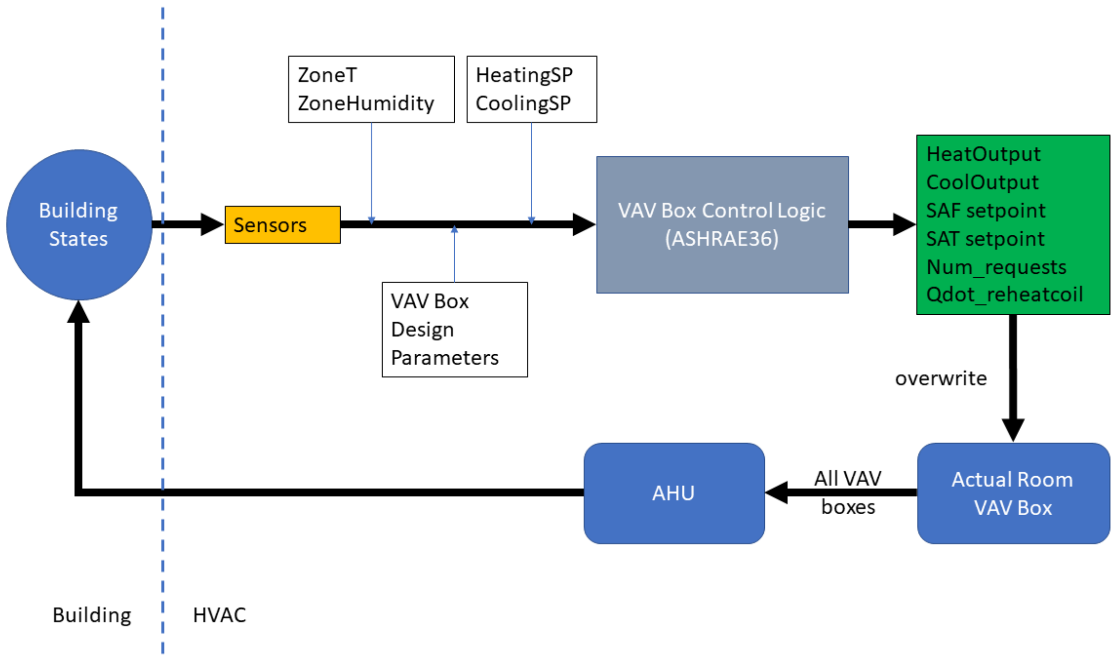

Figure 7. Cloud simulation workflow.

Table 8. Cloud configuration

Machine type	Cores/node	Memory/node	Storage/ node	Total nodes	Time executed
Standard_D16d_v4	16	64 GB	600 GB	54	1 h

3. ANALYSIS OF RESULTS

Based on the sensor locations, energy and thermal comfort analyses were conducted. The energy analysis focused on the aggregated energy: site energy, cooling energy, heating energy, and fan energy. The thermal comfort analysis focused on zone temperature, zone SA temperature, zone SA flow rate, and zone VAV reheat coil energy.

3.1 ENERGY DISTRIBUTION

3.1.1 Energy Without Mean Sensors

Figure 8 shows the energy consumption for the sensor locations without mean sensors. The blue lines are the energy consumptions for different sensor locations. The red star is the baseline (each zone has a sensor).

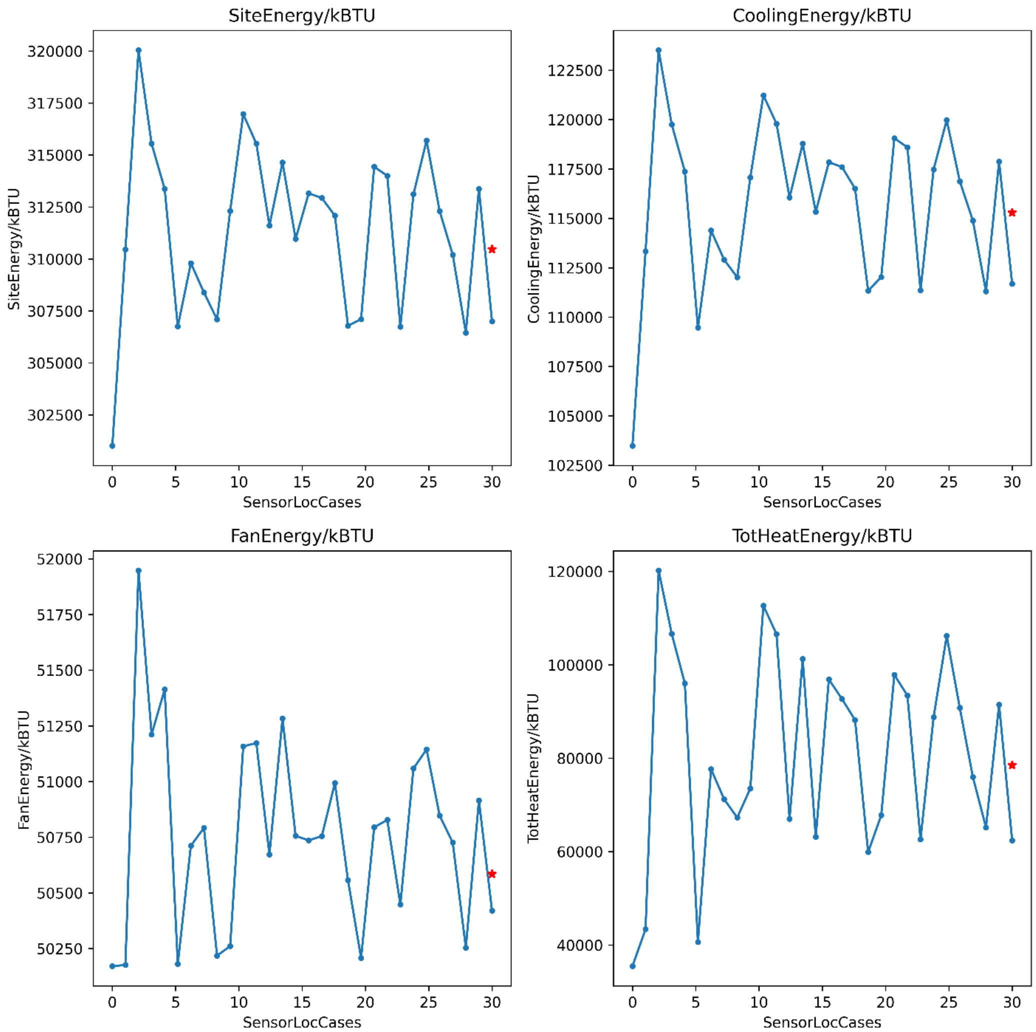

Figure 8. Energy distribution for sensor locations without mean sensors.

In Figure 8, the top left is the site energy. The top right is the cooling energy. The bottom left is the fan energy. The bottom right is the heating energy. As shown, some cases have higher energy consumption than the baseline, whereas some other cases have lower energy consumption than the baseline.

3.1.2 Energy With Mean Sensors

Figure 9 shows the energy consumption for the sensor locations without mean sensors. The blue lines are the energy consumptions for different sensor locations. The red star is the baseline (each zone has a sensor).

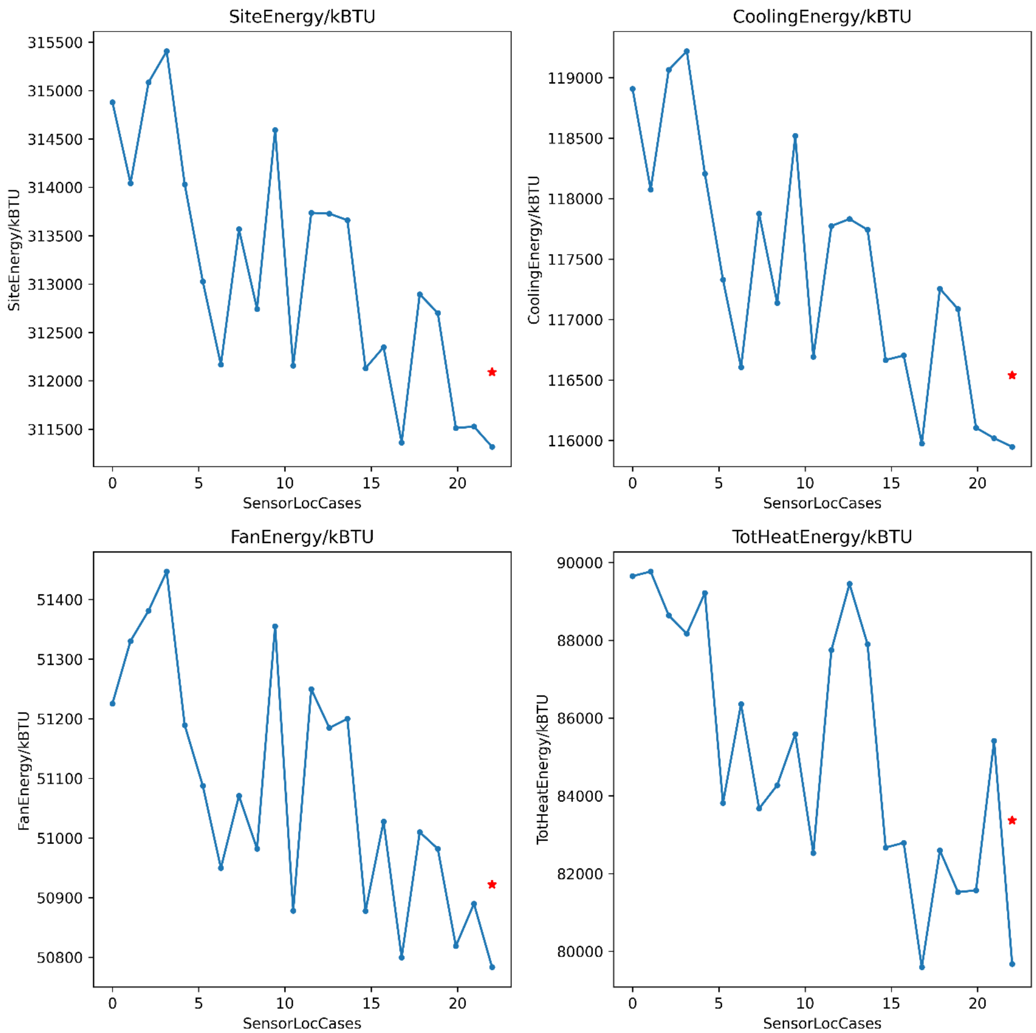

Figure 9. Energy distribution for sensor locations with mean sensors.

In Figure 9, the top left is the site energy. The top right is the cooling energy. The bottom left is the fan energy. The bottom right is the heating energy. As shown, most cases have higher energy consumption than the baseline, and few cases have lower energy consumption than the baseline.

3.2 THERMAL COMFORT ANALYSIS

Sensor location strongly affects the thermal comfort of zones, and especially the zone temperature distributions. This study investigated unmet hours for different sensor location scenarios. The zone temperature profiles are presented in the following plots. Out of the 54 cases, 13 sensor scenarios were selected to see the impact of sensor location on unmet hours.

The limitation of the unmet hour analysis is that unmet hours during the heating season is only counted when indoor air temperature does not meet heating setpoint with 0.36°F (0.2°C) tolerance range and unmet hours during the cooling season is only counted when indoor air temperature does not meet cooling setpoint temperature with 0.36°F (0.2°C) tolerance range. In other words, overheating and overcooling do not count in unmet hours. The low unmet hour seems the indoor condition is comfortable, but it is necessary to check whether overheating and overcooling are occurring.

3.2.1 Sensor 1: 102/103/104/105/106

Figure 10 shows unmet hours during occupied heating based on the one sensor scenarios. For this analysis, we selected five sensor scenarios. X-axis means sensor installation location and y-axis means unmet hours during the heating.

Zones 102 and 104 are located on the north side, these two zones have more heating load than the core zone, and zones are located on the south side. When overriding heating signal of the zones 102 and 104 to other zones, other zones will be overheated because the other three zones have less heating load than zones 102 and 104. That is why unmet hours when one sensor is installed in zones 102 or 104 is less than that of the other three cases. When overriding heating signal of the zones 103, 105, and 106, where are located in core or southside, to other zones, zones 102 and 104 will not be met the heating setpoint temperature. This is because zones 103, 105, and 106 have less heating load than zones where are located on the north side.

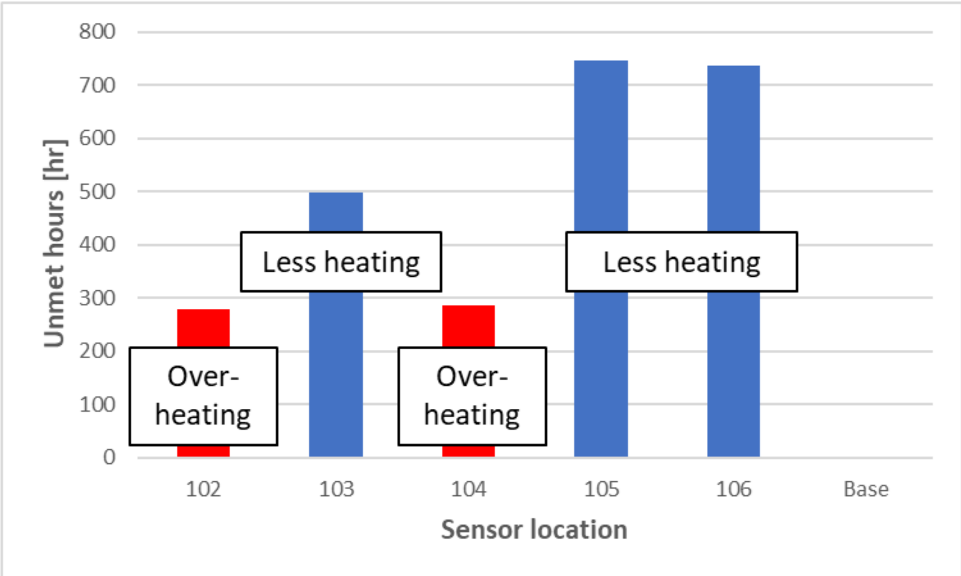

Figure 10. Unmet hours during the occupied heating based on the one sensor scenarios.

Figure 11 shows unmet hours during occupied cooling based on the one sensor scenarios. X-axis means sensor installation location and y-axis means unmet hours during the cooling. The pattern of unmet hours during occupied cooling is opposite when compared with the pattern of unmet hours during occupied heating in Figure 10.

Zones 102, 103, and 104 are located on the core zone or the north side, these three zones have less cooling load than zones are located on the southside. When overriding cooling signal of the zones 102, 103, and 104 to zones 105 and 106, zones 105 and 106 will not be met the cooling setpoint temperature. This is because zones 102, 103, and 104 have less cooling load than zones where are located on the south side. That is why unmet hours when one sensor is installed in zones 102, 103, or 104 are larger than that of the other two cases. When overriding cooling signal of the zones 105 and 106, where are located on southside, to other zones, zones 102, 103, and 104 will be overcooled.

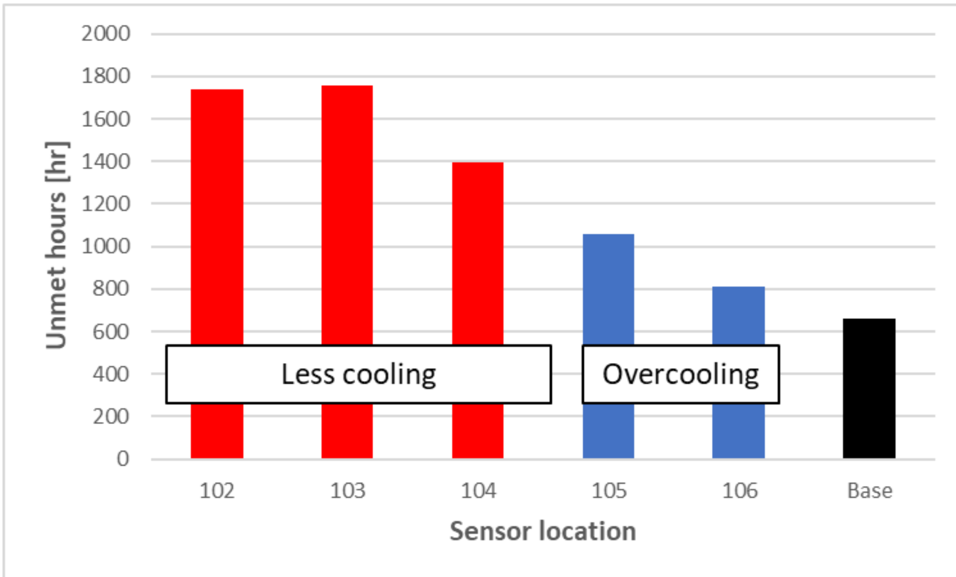

Figure 11. Unmet hours during the occupied cooling based on the one sensor scenarios.

3.2.2 Number of sensors

To understand impact of the number of sensors, five scenarios were selected. Table 9 shows the information of the selected five sensor location scenarios. Red-colored in the Table 9 is the sensor location of the overwritten sensor data. When one sensor is installed, the sensor in zone 106 is used for all the zones. When two sensors are installed, data in zone 102 is covered zones 102 and 104, data in zone 106 is covered zones 103, 105, and 106. When three sensors are installed, data in zone 104 is used for zones 104 and 105, and data in zone 106 is used for zone 103 and 106. When four sensors are installed, only zone 103 does not have its own sensor.

Table 9. Selected five sensor location scenarios.

Number of sensors	Sensor location		Zone 102	Zone 103	Zone 104	Zone 105	Zone 106
1	106	Sensor reading	106	106	106	106	106
2	102, 106		102	106	102	106	106
3	102, 104 ,106		102	106	104	104	106
4	102, 104, 105, 106		102	106	104	105	106
5	102, 103, 104, 105, 106		102	103	104	105	106

Figure 12 shows unmet hours during the occupied heating based on the number of sensors.

As the number of sensors increases, the unmet hour decreases. Since zone 106 has less heating load than other zones, when overriding zone 106 sensor data to other zones unmet hour for heating is increased.

After installing the sensor in zone 102, the unmet hour is decreased. However, zone 102 has less heating load than zone 104 due to zone 104 is more exposed to outdoor conditions than zone 102. Even if zone 102 data is overwritten to zone 104, still that is not enough for zone 104.

After installing the sensor in zone 104, the unmet hour is decreased sharply. Because only zone 103 and 105, where has less heating load than other zones, received the sensor data from other zones.

After installing the sensor in zone 105, the unmet hour is similar to three sensors installed case, however; still, the unmet hour is decreased.

In five sensors installed case (base model), has only 0.8 hour of unmet hours for heating.

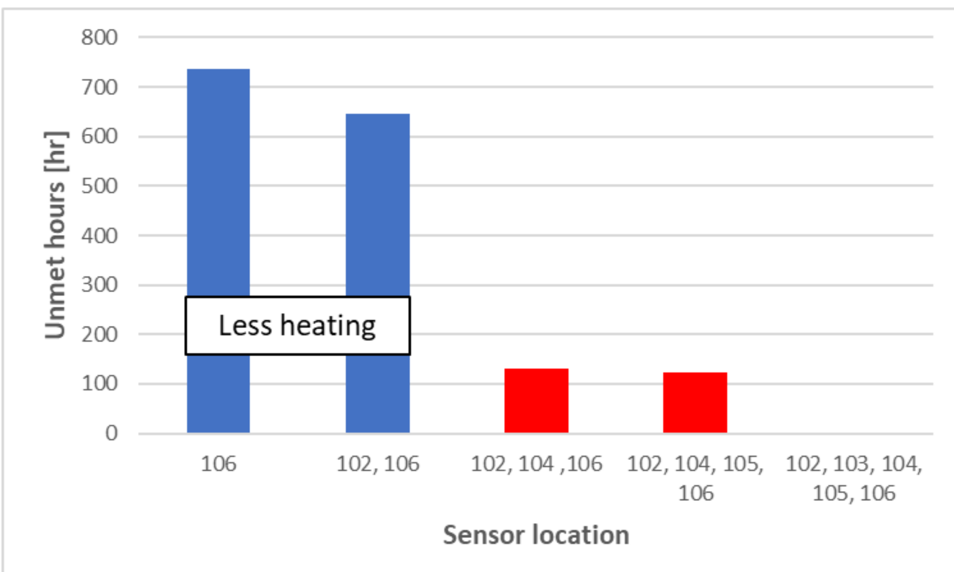

Figure 12. Unmet hours during the occupied heating based on the number of sensors.

Figure 13 shows the unmet hours during the occupied cooling based on the number of sensors.

Since zone 106 has more cooling load than other zones. When the overriding the cooling signal of zone 106, at least, zone 102, 103, 104 will be overcooled.

After installing the sensor in zone 102, the unmet hour is increased. Zone 102 has less cooling load than zone 106. zone 104 was under the overcooling because zone 104 received the cooling signal of zone 106, however; after installing the sensor in zone 102 and overriding 102 sensor data to 104. Unmet hours during cooling is increased because the cooling load of zone 102 is smaller than that of zone 104. The cooling signal in zone 102 is not enough for zone 104.

After installing the sensor in zone 104, the unmet hour is increased due to zone 105 receiving the sensor data in zone 104 where less cooling is needed.

After installing the sensor in zone 105, the unmet hour is decreased sharply, only zone 103 receive 106 sensor data. Zone 103 will be overcooled due to zone 106 has more cooling load than zone 103.

In five sensor installed case (base model), unmet hours in increased than 4 sensor installed case due to zone 103 was under the overcooling because zone 103 received zone 106 sensor data.

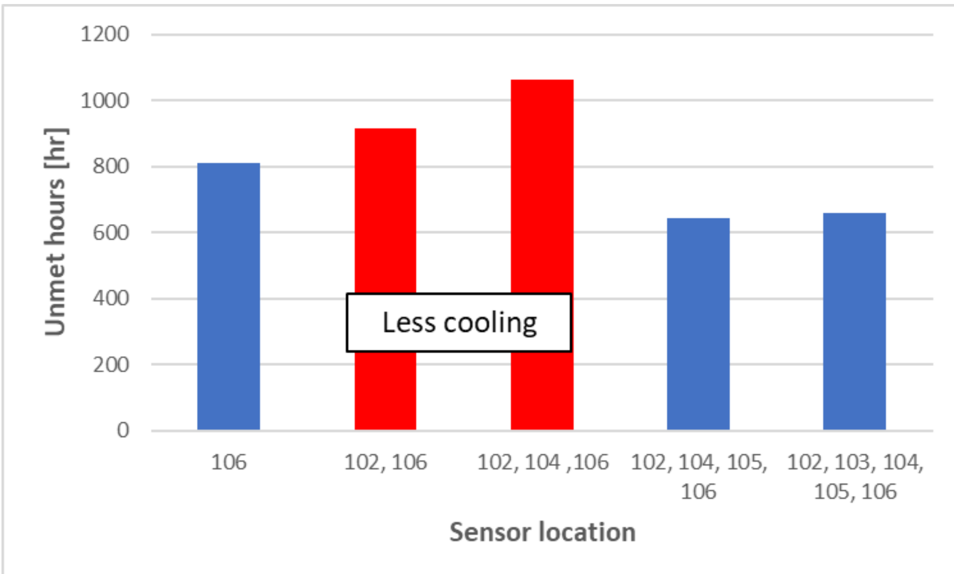

Figure 13. Unmet hours during the occupied cooling based on the number of sensors.

3.2.3 Impact of the sensor in zone 103

In this section, we analyze the impact of the sensor locations with mean values. In order to detailed analysis, we selected three sensor location scenarios related to the sensor in zone 103.

Table 10 shows the information of the selected three sensor location scenarios. Red-colored in the Table 10 is the sensor location of the overwritten sensor data. The first scenario is the zone 103 sensor, the mean value of zones 102 and 104 (Northside), and the mean value of zones 105 and 106 (Southside). The second scenario is the mean value of zones 102 and 104 and the mean value of zones 103, 105, and 106. The third scenario is the mean value of zones 102, 103, and 104 and the mean value of zones 105 and 106. The only difference between the three scenarios is how to use the sensor data in zone 103. In three cases, we can see the impact of the sensor location with the mean value.

Table 10. Selected three sensor location scenarios.

Number of sensors	Sensor location		Zone 102	Zone 103	Zone 104	Zone 105	Zone 106
3	103, (102, 104), (105, 106)	Sensor reading	(102, 104)	103	(102, 104)	(105, 106)	(105, 106)
2	(102, 104), (103, 105, 106)		(102, 104)	(103, 105, 106)	(102, 104)	(103, 105, 106)	(103, 105, 106)
2	(102, 103, 104), (105, 106)		(102, 103, 104)	(102, 103, 104)	(102, 103, 104)	(105, 106)	(105, 106)

Figure 14 shows unmet hours during the occupied heating based on the selected three scenarios with the mean value.

When sensor data in zone 103 is used independently, it shows the lowest unmet hour.

When the sensor data of zones 102, 103, and 104 are averaged, sufficient heating will not be provided to zones 102 and 104, which has a relatively large heating load than zone 103, and zone 103 will be overheated.

When the sensor data of zones 103, 105, and 106 are averaged, sufficient heating will not be provided to zones 105 and 106, which has a relatively large heating load than zone 103, and zone 103 will be overheated.

However, since the heating load in zones 105 and 106 are relatively lower than that of zones 102 and 104, the increasing ratio of the unmet hours when combined with zone 103 is smaller than that of 102 and 104.

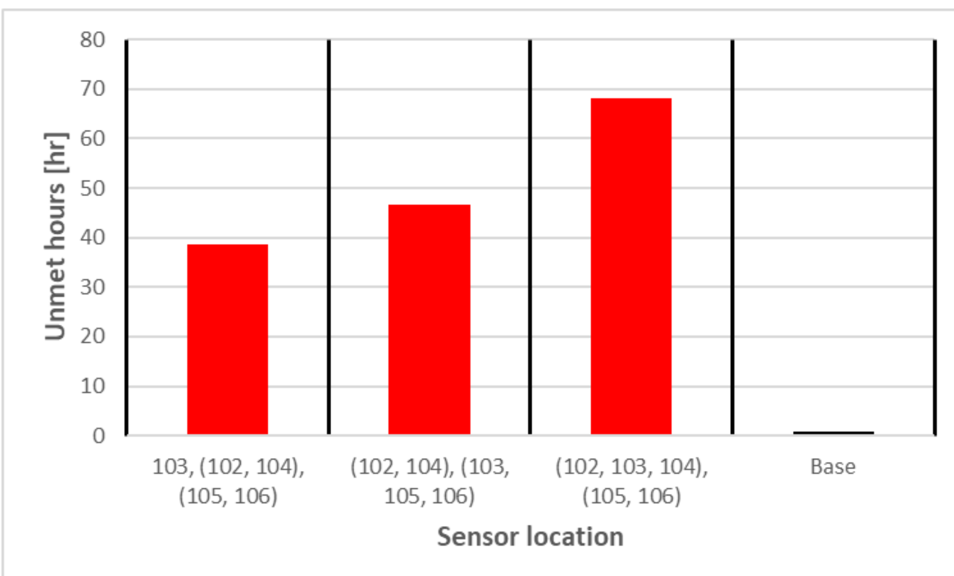

Figure 14. Unmet hours during the occupied heating based on the three scenarios with the mean value.

Figure 15 shows unmet hours during the occupied cooling based on the selected three scenarios with the mean value. When 103 data is used independently, it shows the lowest unmet hour like Figure 14.

When the sensor data of zones 102, 103, and 104 are averaged, sufficient cooling will not be provided to zones 102 and 104, which has a relatively large cooling load than zone 103, and zone 103 will be overcooled.

When the sensor data of zones 103, 105, and 106 are averaged, sufficient cooling will not be provided to zones 105 and 106, which has a relatively large cooling load than zone 103, and zone 103 will be overcooled.

However, since the cooling load in zones 105 and 106 are relatively higher than that of zones 102 and 104, the increasing ratio of the unmet hours when combined with zone 103 is bigger than that of 102 and 104.

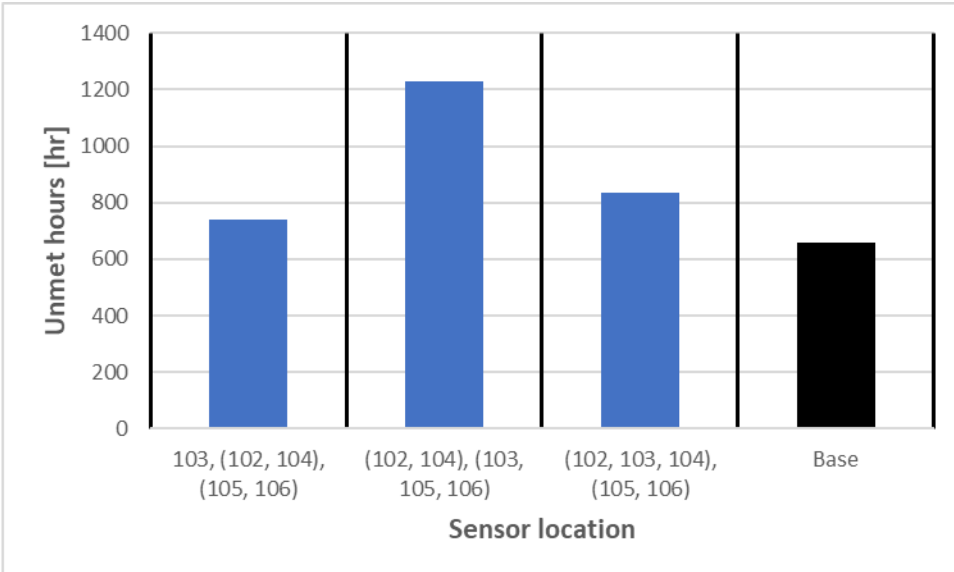

Figure 15. Unmet hours during the occupied cooling based on the three scenarios with the mean value.

3.2.4 Thermal comfort vs. energy consumption

To understand the relationship between thermal comfort and energy consumption based on the sensor locations, we are considered the heating, reheating, cooling, and fan energy for energy consumption and unmet hours based ASHRAE 55-2004 for indoor thermal comfort. EnergyPlus simulation program provides three types of unmet hours, which are unmet hours during the occupied heating, unmet hours during the occupied cooling, and unmet hours based on simple ASHRAE 55-2004. Both unmet hours during the occupied heating and cooling is only considered the heating or cooling setpoint temperature. When indoor air temperature does not meet cooling or heating setpoint temperature (with 0.36°F (0.2°C) of tolerance range), then it is counted as an unmet hour.

Unless the unmet hours during occupied cooling and heating, unmet hours based on the simple ASHRAE 55-2004 is considered how many hours that the space is not comfortable for each zone under the criteria of assuming winter clothes, summer clothes or both summer and winter clothes [U.S.DOE, 2021]. Figure 16 shows the summer and winter comfort range.

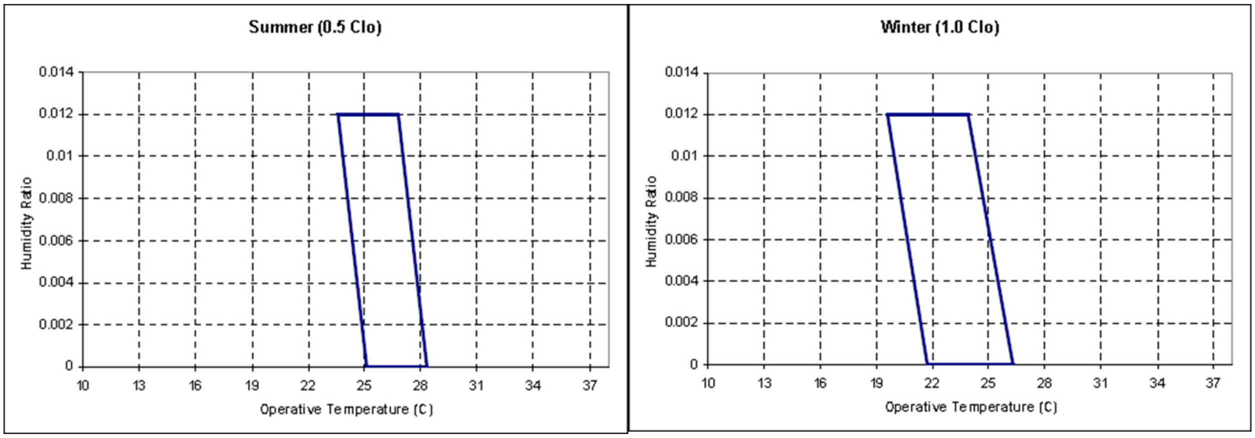

Figure 16. Summer and winter comfort range [U.S.DOE, 2021].

Energy consumption is determined by several factors, including outdoor conditions, internal heat gain, building geometry, and HVAC system operation. In order to figure out how the change in thermal comfort by the sensor location is related to energy consumption, the simplest scenario, the scenario in which one sensor is installed, was analyzed. Figure 17 shows relationship between energy consumption and indoor thermal comfort in one sensor scenarios. Energy consumption is calculated by sum of heating energy, reheating energy, cooling energy, and fan energy consumption. When unmet hour is high, that means cooling or heating is not sufficient, that time energy consumption is lower than others. Based on Figure 17, we can understand higher unmet hours means not enough cooling and heating in the building, it affects low energy consumption, low unmet hours means enough cooling and heating or over-cooling and heating, it affects high energy consumption.

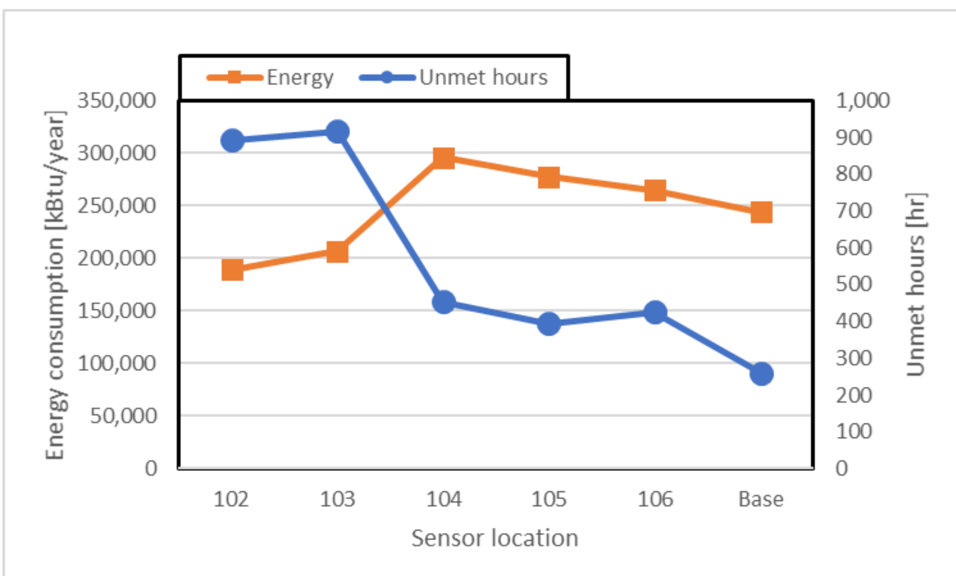

Figure 17. Energy consumption vs. thermal comfort (one sensor scenario)

3.3 ZONE THERMAL ANALYSIS

Two sensor location cases (case A1 and case B1) are demonstrated in this section, regarding the zone thermal analysis, including zone temperature, zone supply air temperature, zone supply air flowrate, VAV box reheat coil energy consumption. The other case results are listed in the section of **Error! Reference source not found.**

3.3.1 Case A1: Sensor 102

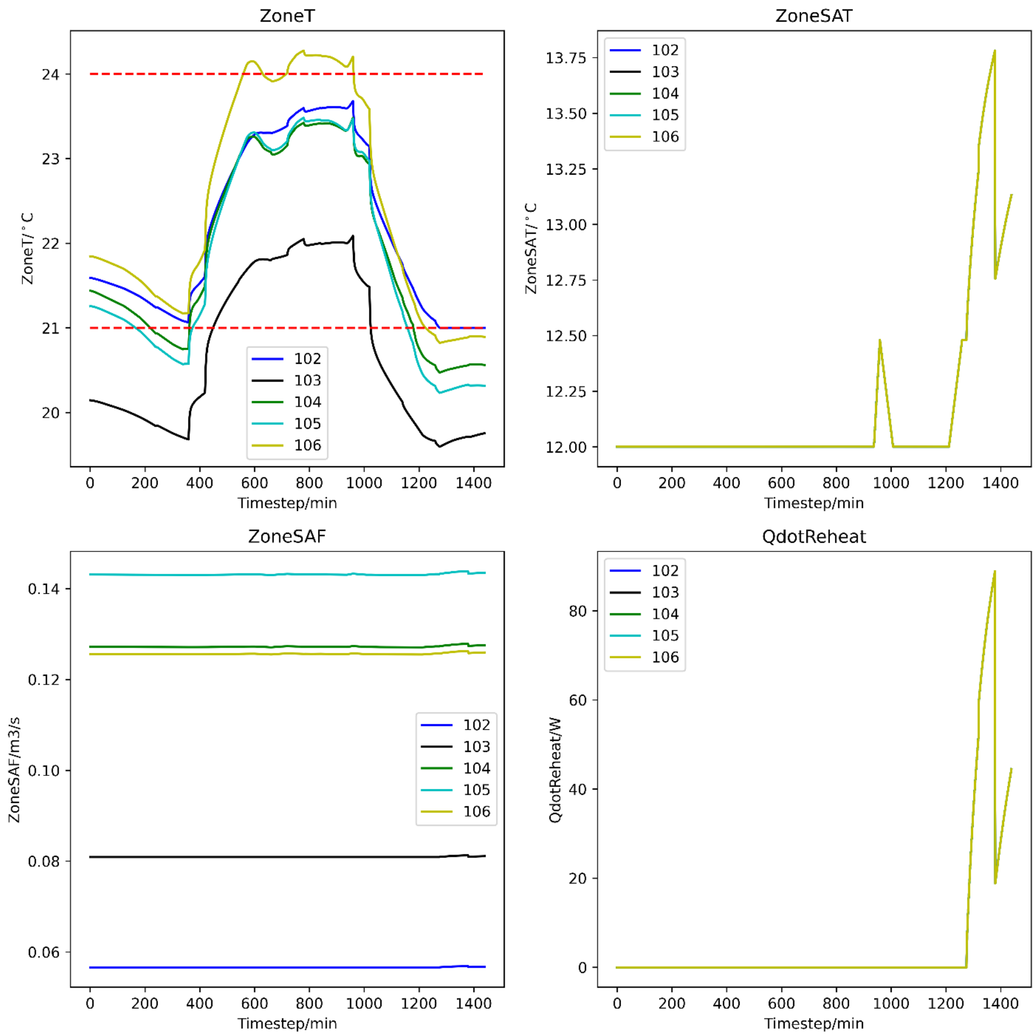

Figure 18. Zone profiles on the first floor in the summer

Figure 18 shows the zone profiles for the first floor in the summer. The zone 106 temperature is higher than the cooling set point. The other zones have a little overcooling, but they are above the heating set points. The SA flow rates are almost constant. The SA temperature for all zones is almost the same. The reheat coil energy consumption is mostly zero.

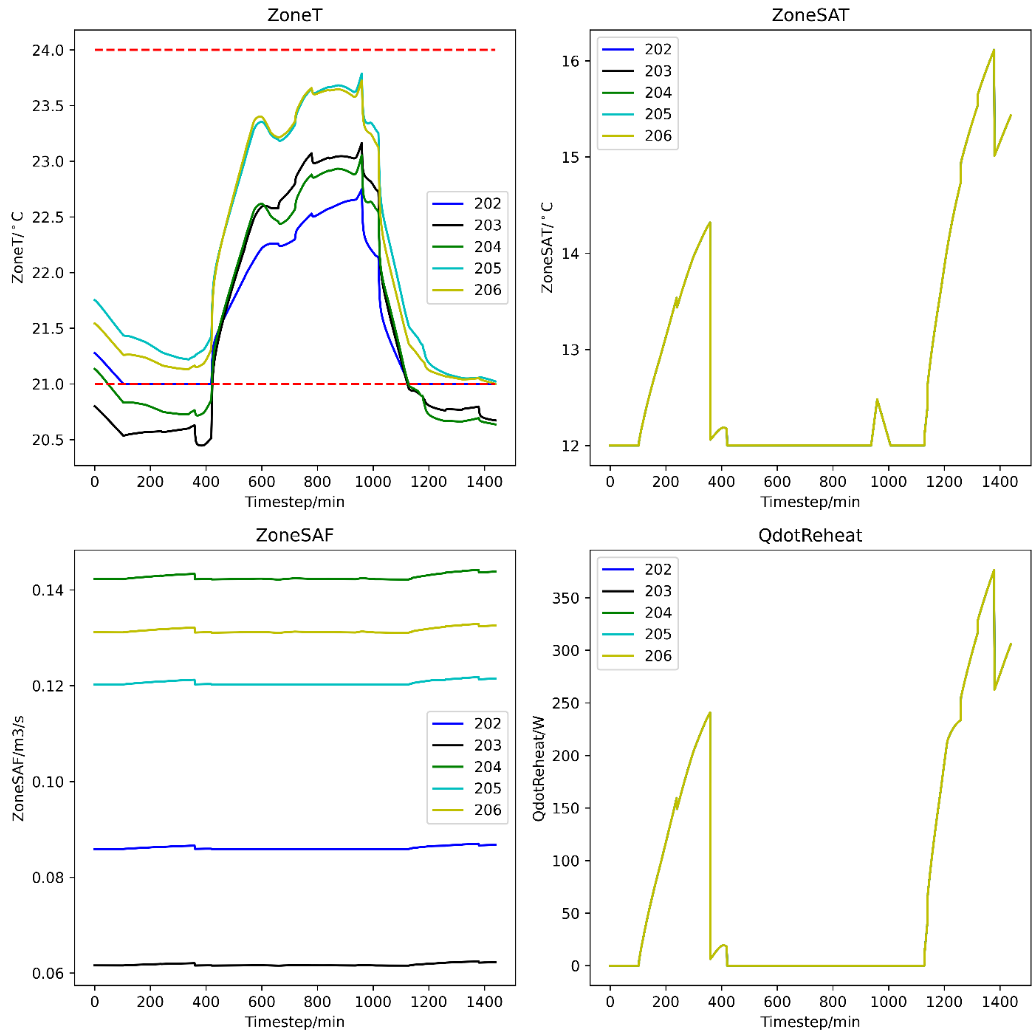

Figure 19. Zone profiles on the second floor in the summer

Figure 19 shows the zone profiles for the second floor in the summer. All five zones have zone temperatures between the heating and cooling set points during the daytime. Zones 205 and 206 have higher zone temperatures than the other zones. The zone SA flow rate is almost constant. The zone SA temperature and reheat coil energy are following each other.

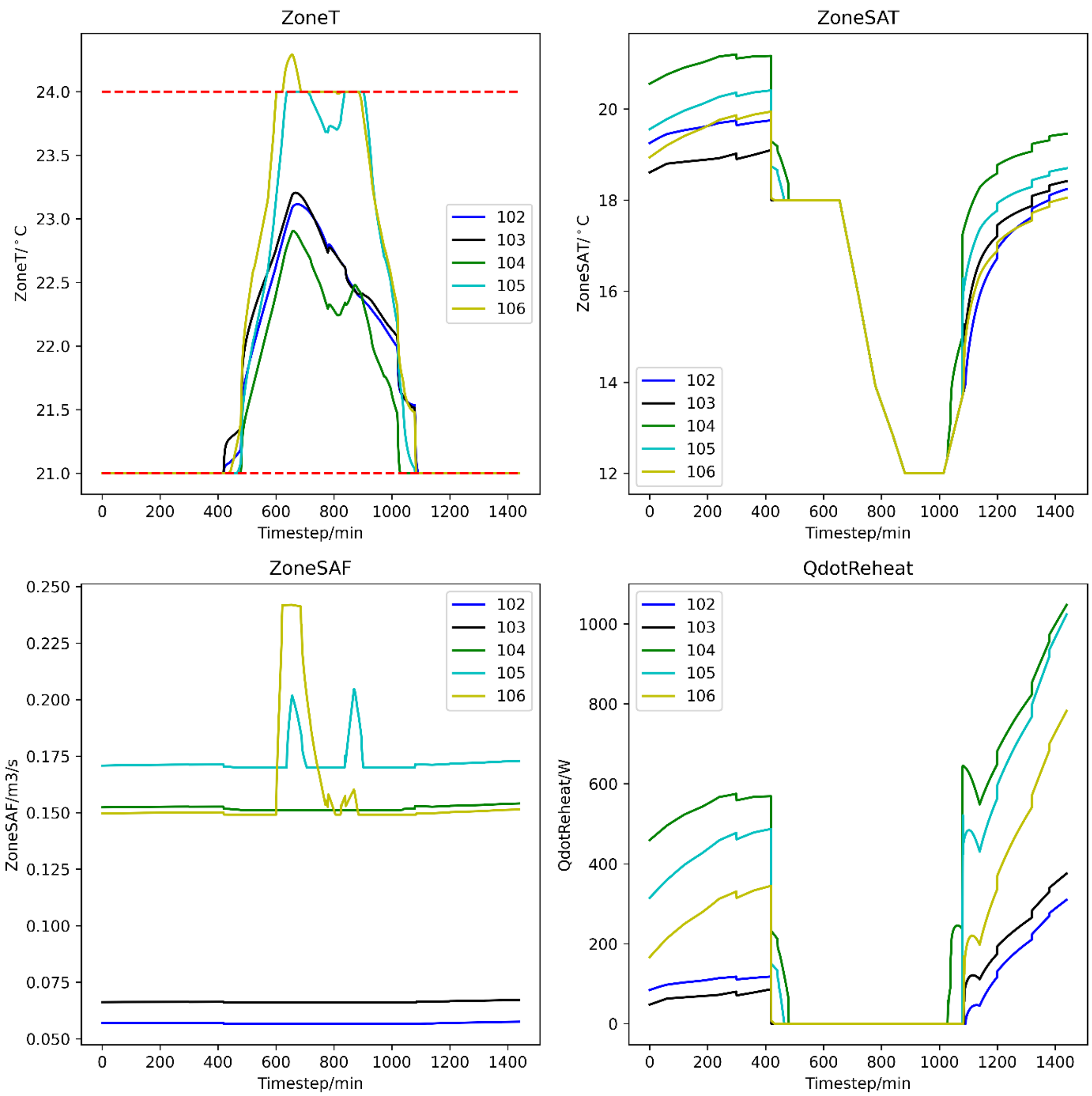

Figure 20. Zone Profile at 1st Floor at winter (A1)

Figure 20 shows the zone profiles for the first floor in the winter. All zones have zone temperatures between the heating and cooling set points during the daytime except zone 106. The zone 106 SA flow rate is increasing due to the higher heating load demand.

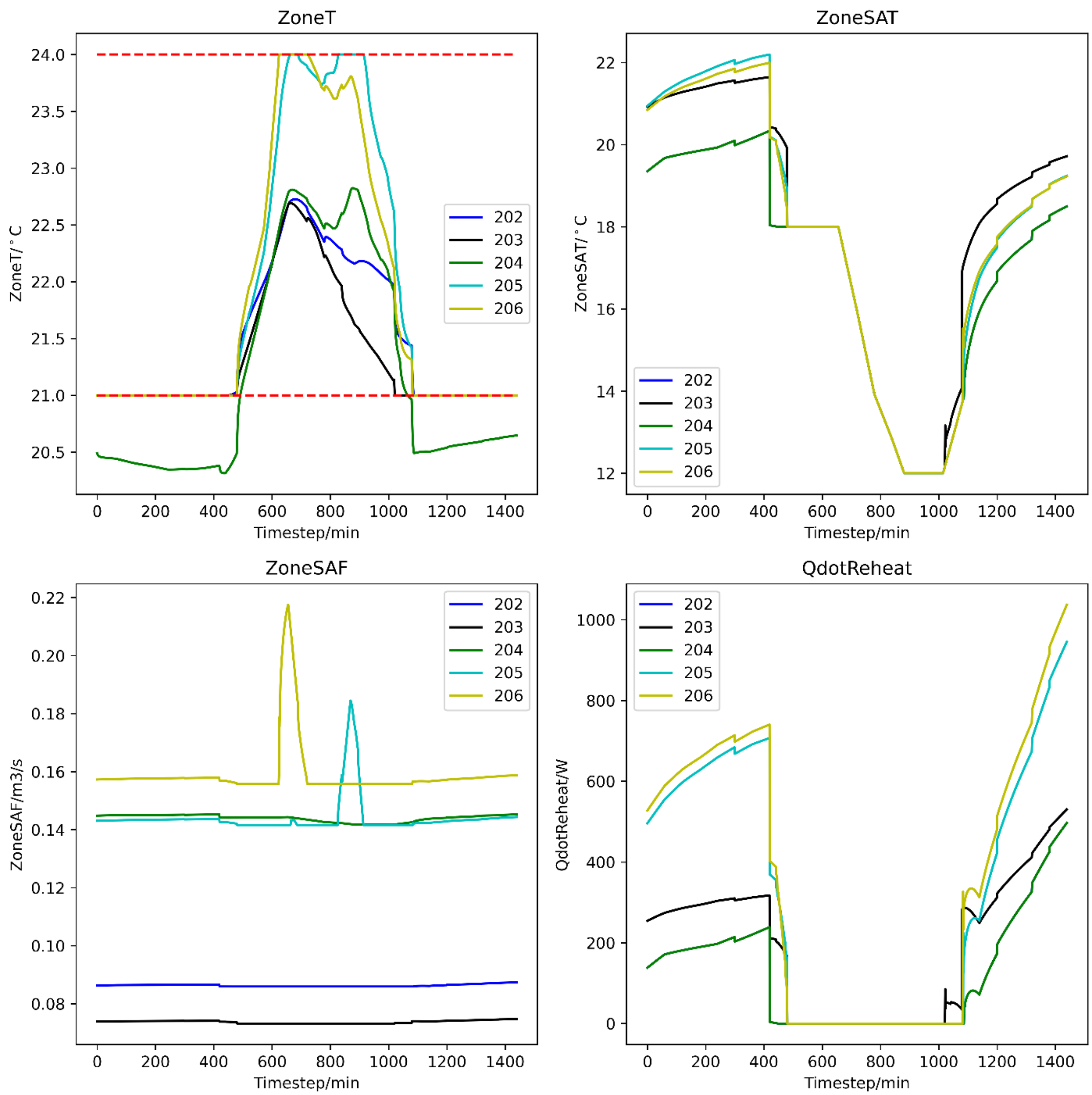

Figure 21. Zone Profile at 2nd Floor at winter (A1)

Figure 21 shows the zone profiles for the second floor in the winter. All zones have zone temperatures between the heating and cooling set points during the daytime.

3.3.2 Case B1: <u>Mean (102, 104) and Mean(103, 105, 106)</u>

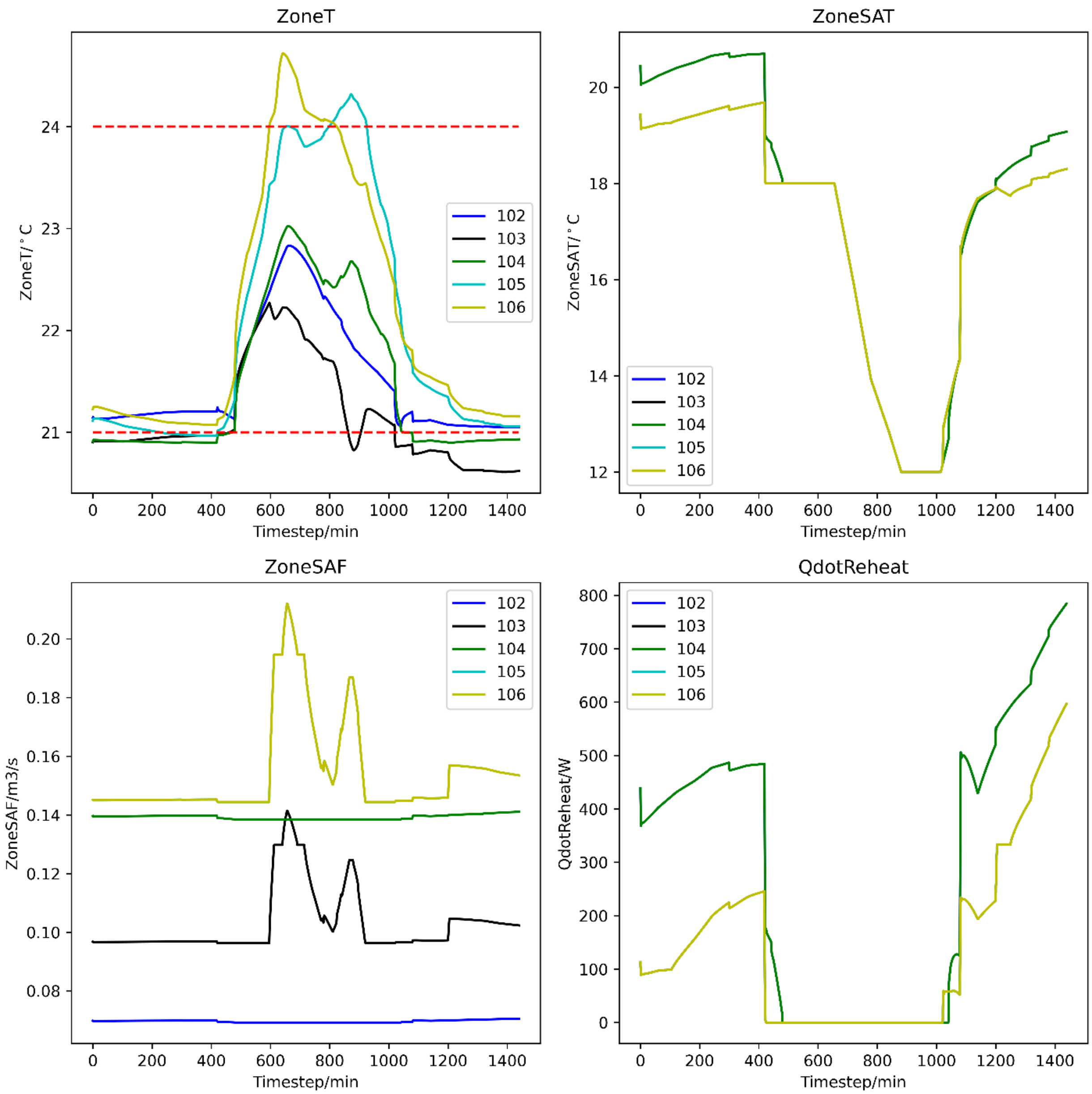

Figure 22. Zone Profile at 1st Floor at Summer

Figure 22 demonstrates the zone profiles for the 1st floor at summer. It is shown that three zones have indoor air temperature between heating and cooling setpoints during the daytime. Zone 103 temperature are a little bit of overcooling. The temperatures of zones 105 and 106 are higher than the cooling setpoints. The zone supply air flow rate is almost constant. The zone supply air temperature and reheat coil energy are following with each other.

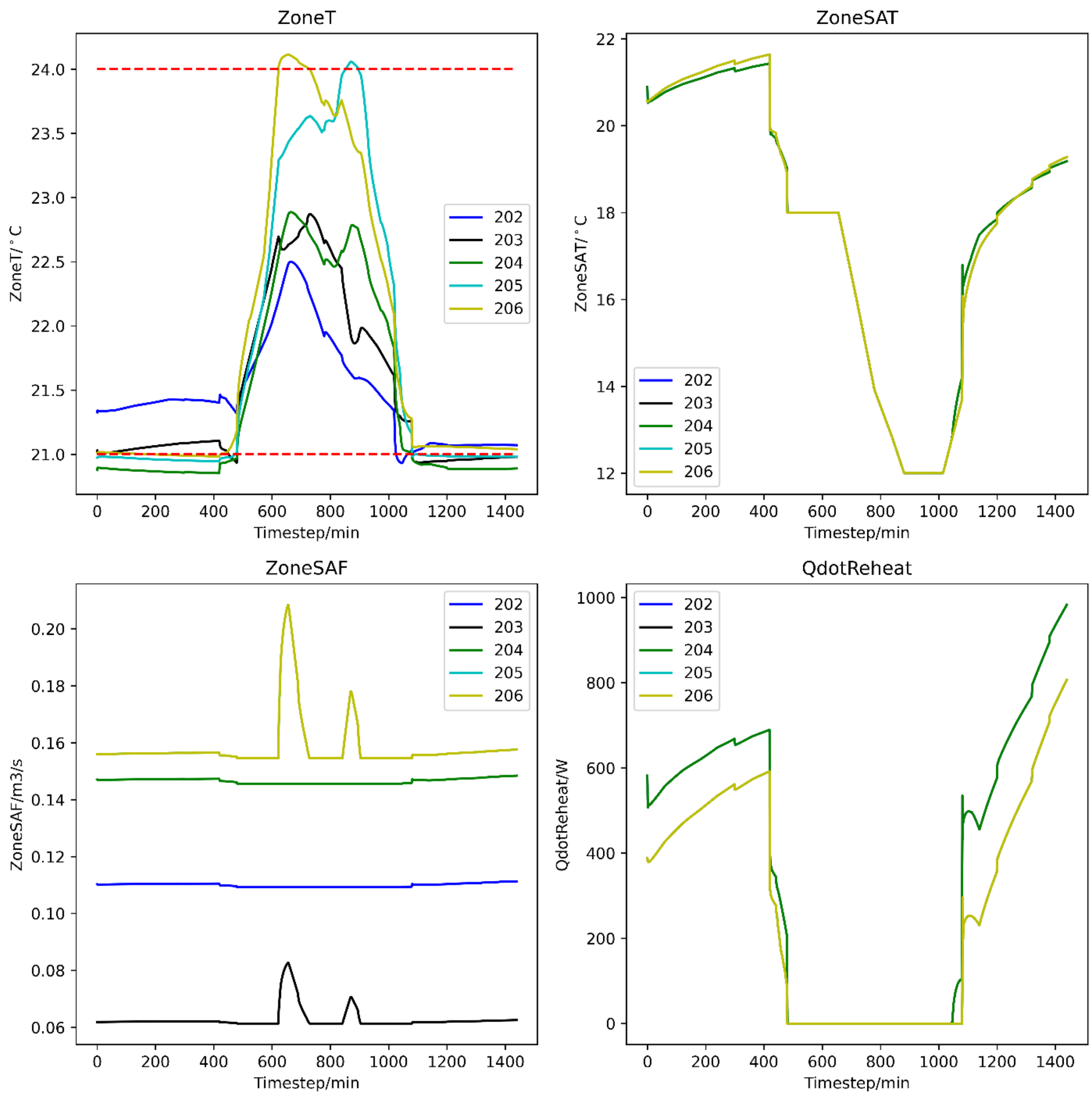

Figure 23. Zone Profile at 2nd Floor at Summer

Figure 23 demonstrates the zone profiles for the 2nd floor at summer. It is shown that three zones have zone temperature between heating/cooling setpoints during the daytime. Zones 205 and 206 temperature are a little bit of overcooling. The zone supply air flow rate is almost constant. The zone supply air temperature and reheat coil energy are following with each other.

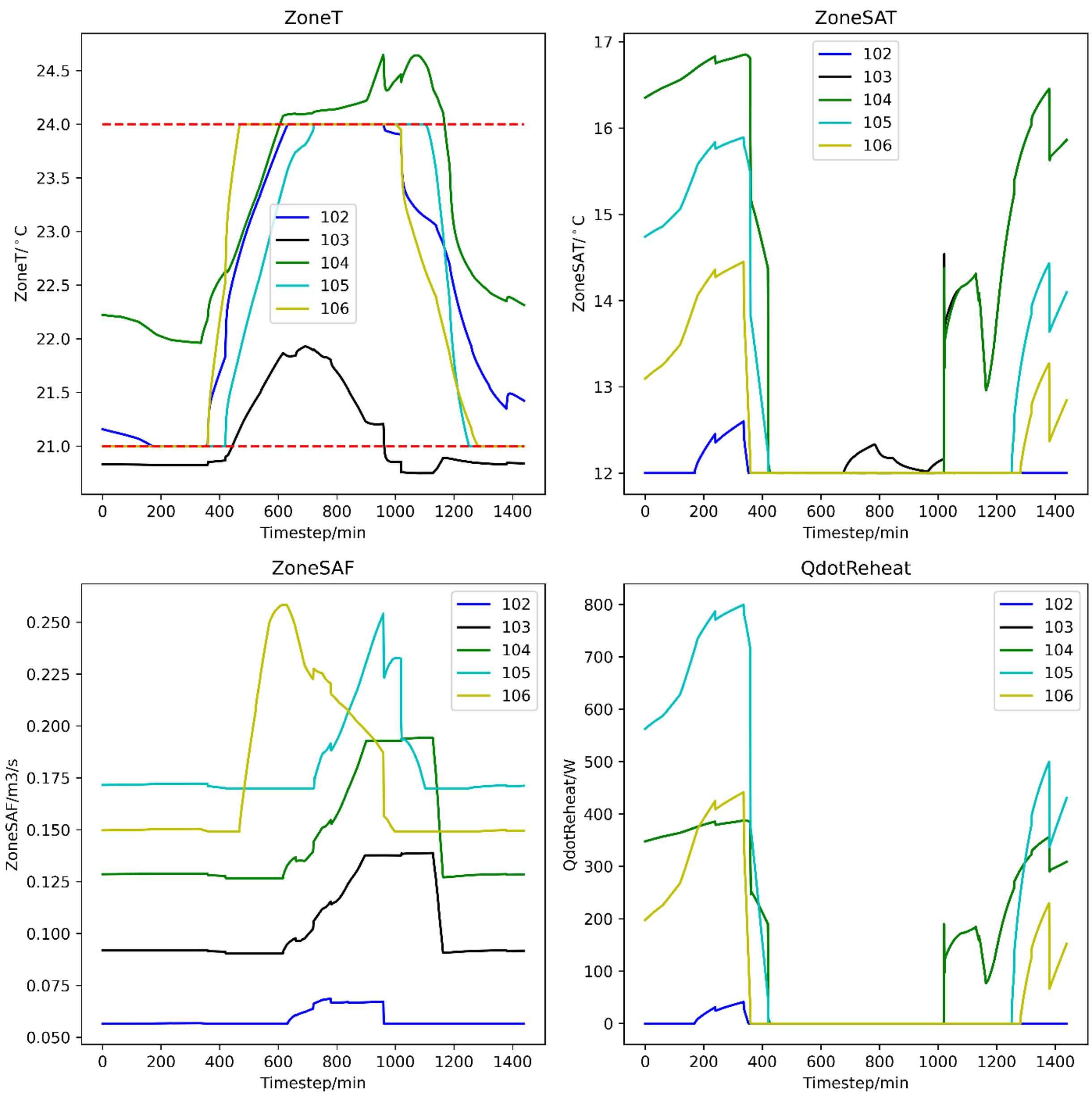

Figure 24. Zone Profile at 1st Floor at winter (B1)

Figure 24 demonstrates the zone profiles for the 1st floor at winter. It is shown that four zones have zone temperature between heating/cooling setpoints during the daytime. Zone 104 temperature are a little bit of undercooling. The zone 104 supply air flow rate stays at peak. Zone 104 supply air temperature keeps increasing. The zone supply air temperature and reheat coil energy are following with each other.

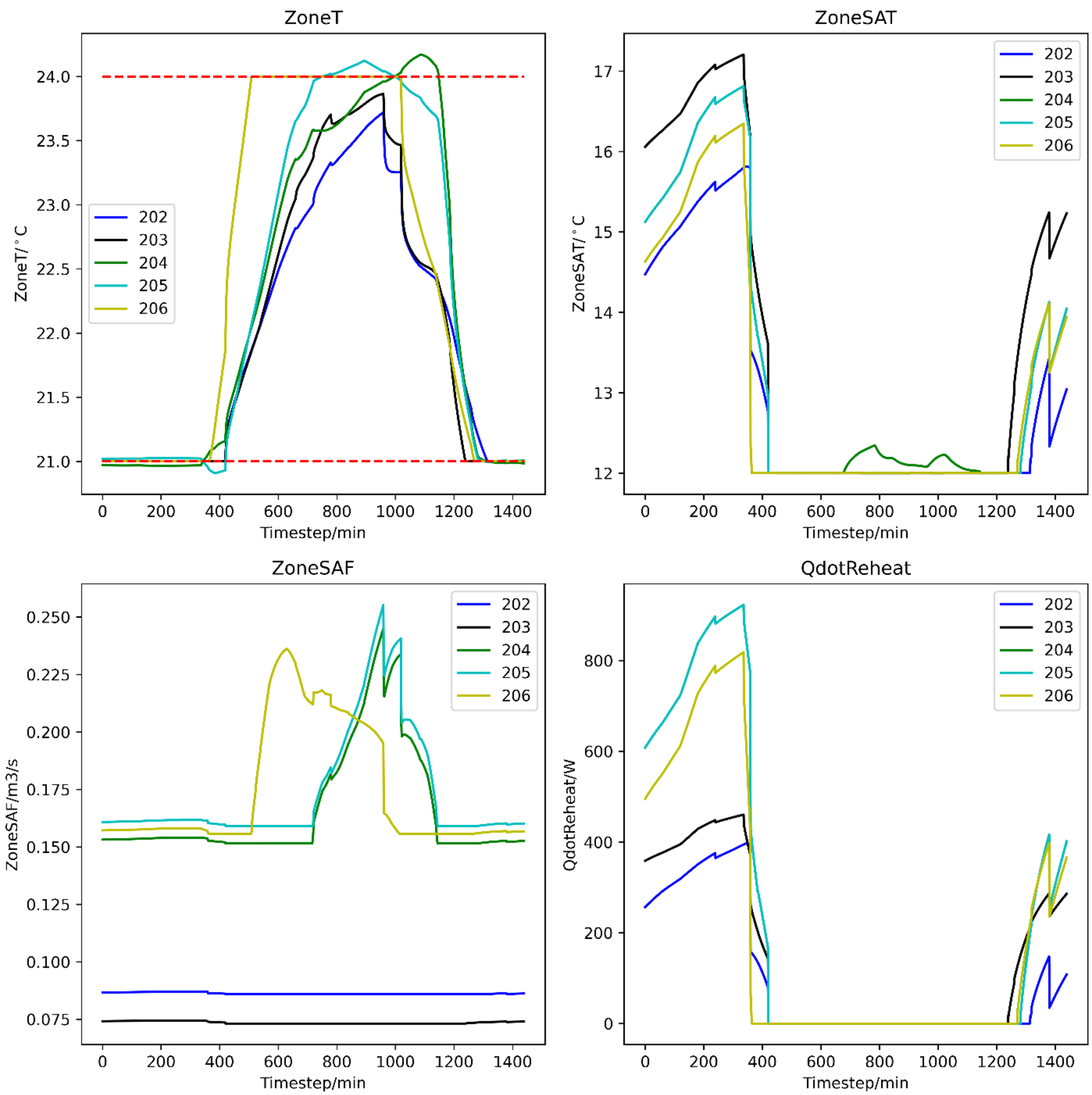

Figure 25. Zone Profile at 2nd Floor at winter (B1)

Figure 25 demonstrates the zone profiles for the 2nd floor at winter. It is shown that three zones have zone temperature between heating/cooling setpoints during the daytime. Zones 205 and 206 temperature are a little bit of undercooling. The zone supply air flow rate is responding with heating load demands. The zone supply air temperature and reheat coil energy are following each other.

4. CONCLUSIONS

This study investigated the preliminary emulator for energy consumption and thermal comfort with respect to sensor locations. The sensor locations were studied under two scenarios: scenarios without mean sensors, and scenarios with mean sensors. The sensor locations were examined with user inputs based on the FRP-2 building. The cloud simulations were conducted based on the sensor location samplings (a total of 54 simulation cases).

The energy consumption factors included site energy, cooling energy, heating energy, and fan energy. The thermal comfort analysis factor included unmet hours.

The uncertainty analysis was conducted with respect to sensor locations. The uncertainty analysis showed that the sensor locations and energy consumptions have a nonlinear relationship. Some cases had higher or lower energy consumptions than other cases.

The thermal comfort factors indicate that inappropriate/inadequate sensor locations significantly affect zone temperature distributions. Overcooling and overheating are demonstrated in the sensor location simulations in cooling and heating modes, which is consistent with observations in actual building sensor deployments with limited sensor locations.

Here are the key findings of thermal comfort analysis.

Through the thermal comfort analysis based on the FRP-2 building, five sensors are installed on each floor. If there is the limitation of the number of sensors, our suggestions are as follows:

- If one sensor can be installed per floor, the one sensor would be installed in the room that has the highest cooling load to prevent undercooling in other rooms. However, this would cause overcooling for other rooms, which results in more cooling energy use and thermal discomfort for occupants. Therefore, it appears the case of one sensor per floor should be avoided if possible.

- If two sensors can be installed per floor, one sensor needs to be installed on the southside and share this data with zones where are located in the southside, another sensor needs to be installed in the northside and share this data with zones where are located in northside.

- If three sensors can be installed per floor, one sensor needs to be installed in the core zone, and use this data only for the core zone, and one sensor needs to be installed in southside and share this data with the zones where are located in southside, and one sensor needs to be installed in northside and share this data with the zones where are located in northside.

- If more sensors (higher than three for the 5 zones of FRP) were installed, the zone thermal comfort gets better. The energy consumption slightly decreases compared with fewer sensors.

Indoor thermal comfort and energy consumption are inversely correlated. The large number of unmet hours can be explained that the zone does not have enough cooling and heating, it consumes low cooling and heating energy than the base model. The small number of unmet hours can be explained by the zone having enough cooling and heating, or the zone is under overcooling and overheating. In the case of overcooling and overheating, cooling and heating energy consumption is higher than the base model. Even if the building has low unmet hours, the indoor conditions should be further investigated whether the zone is overcooled or overheated or not.

For the rest of FY 2022, the immediate task is to demonstrate the sensor impacts with different sensor types and control types. Finally, a comparative analysis will be conducted based on the field test results and emulator results.

5. REFERENCES

[1] Bae, Y., et al. "Sensor impacts on building and HVAC controls: A critical review for building energy performance." *Advances in Applied Energy* 4: 100068, 2021. https://doi.org/10.1016/j.adapen.2021.100068.

[2] ASHRAE. *ASHRAE Guideline 36-2018: High-Performance Sequences of Operation*. 2021.

[3] Taylor, S. "Resetting setpoints using trim & respond logic." *ASHRAE Journal* 11: 52–7, 2015.

[4] U.S.DOE. EnergyPlus version 9.5.0 documentation: EnergyPlus input/output reference. 2021.

APPENDIX A. Zone Profiles for All Sensor Location Scenarios

A.1 SENSOR LOCATIONS WITHOUT MEAN SENSORS

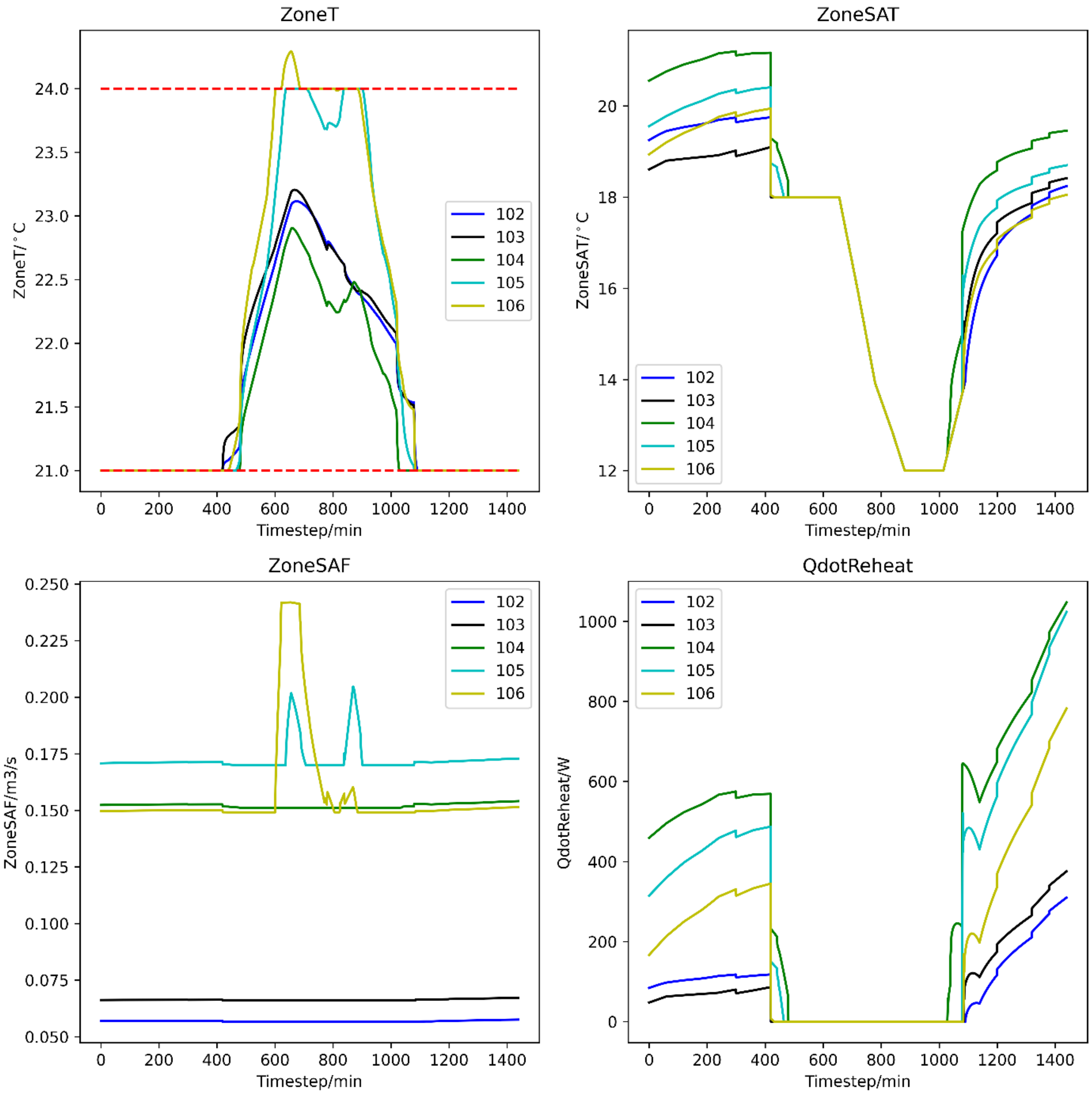

Figure A.1. Zone profiles on the first floor in the winter (A1).

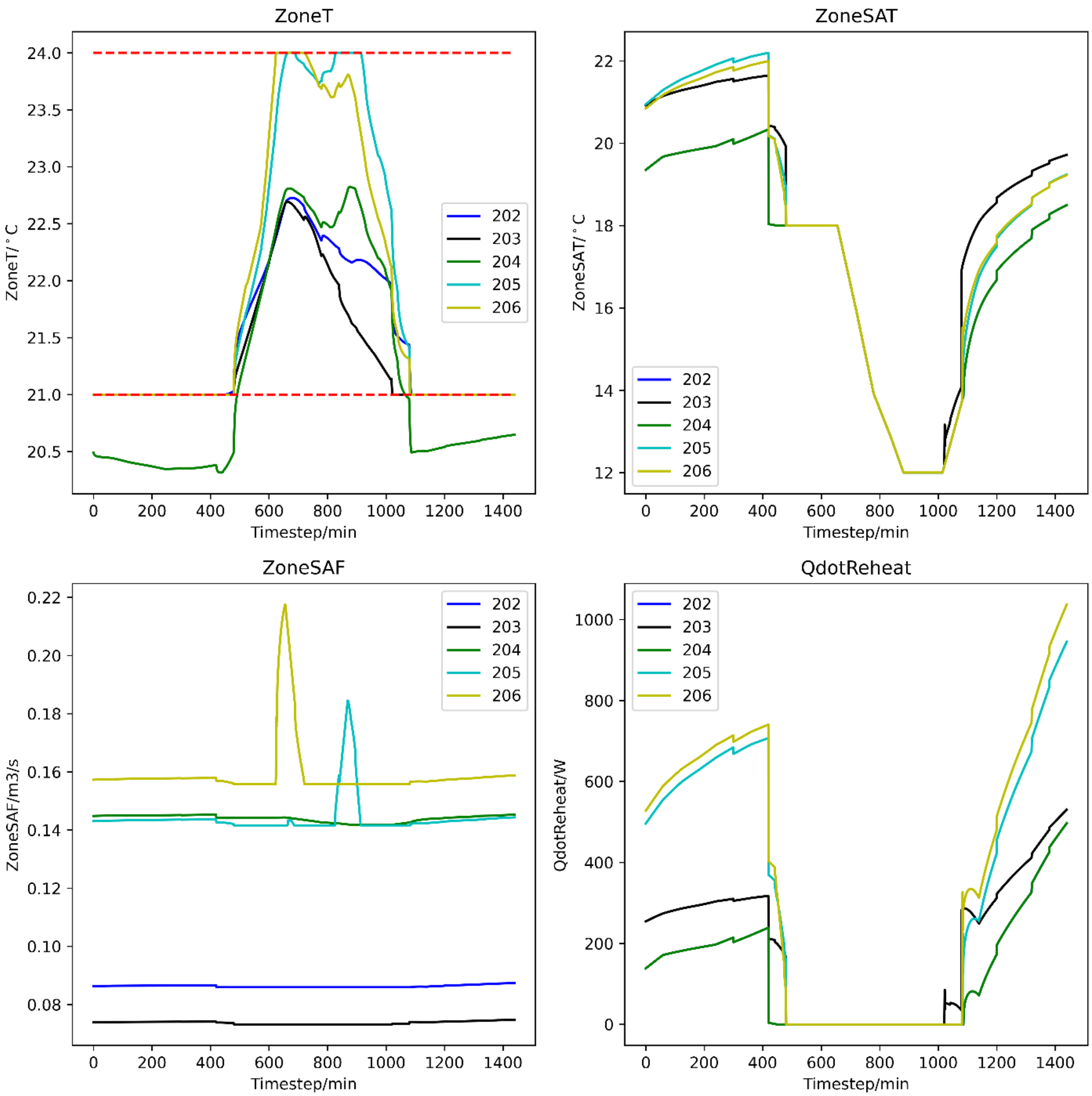

Figure A.2. Zone profiles on the second floor in the winter (A1).

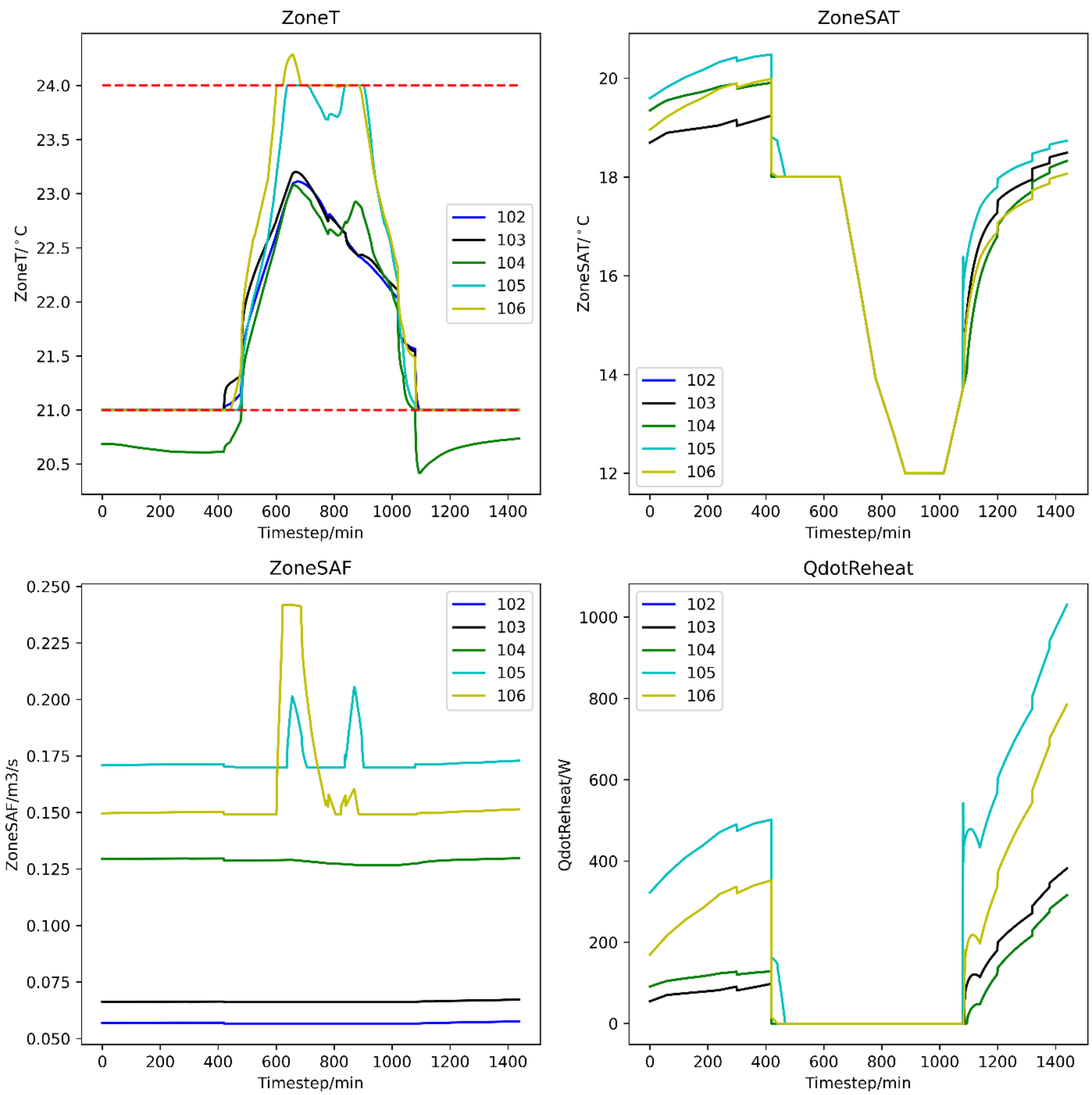

Figure A.3. Zone profiles on the first floor in the winter (A2).

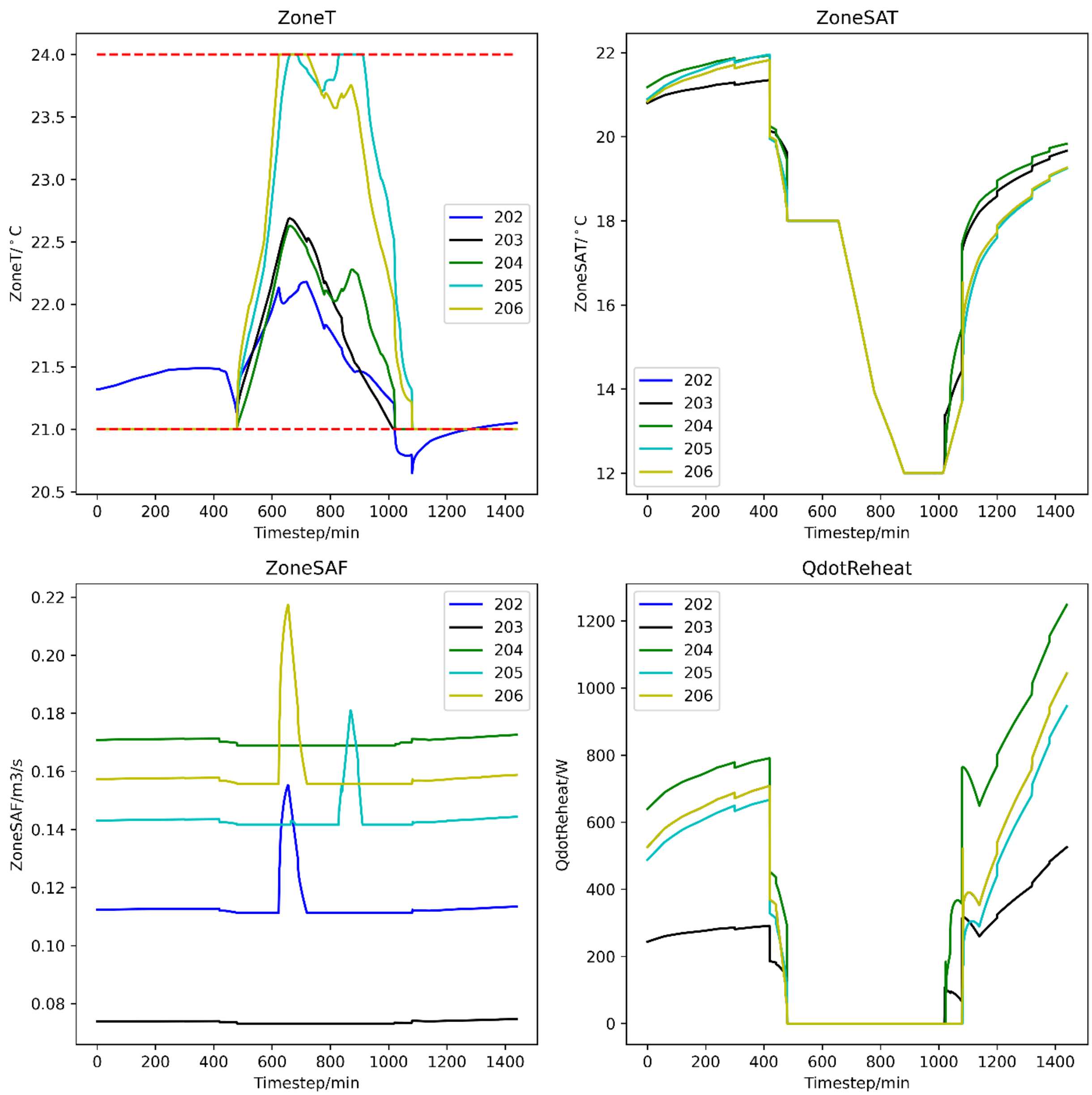

Figure A.4. Zone profiles on the second floor in the winter (A2).

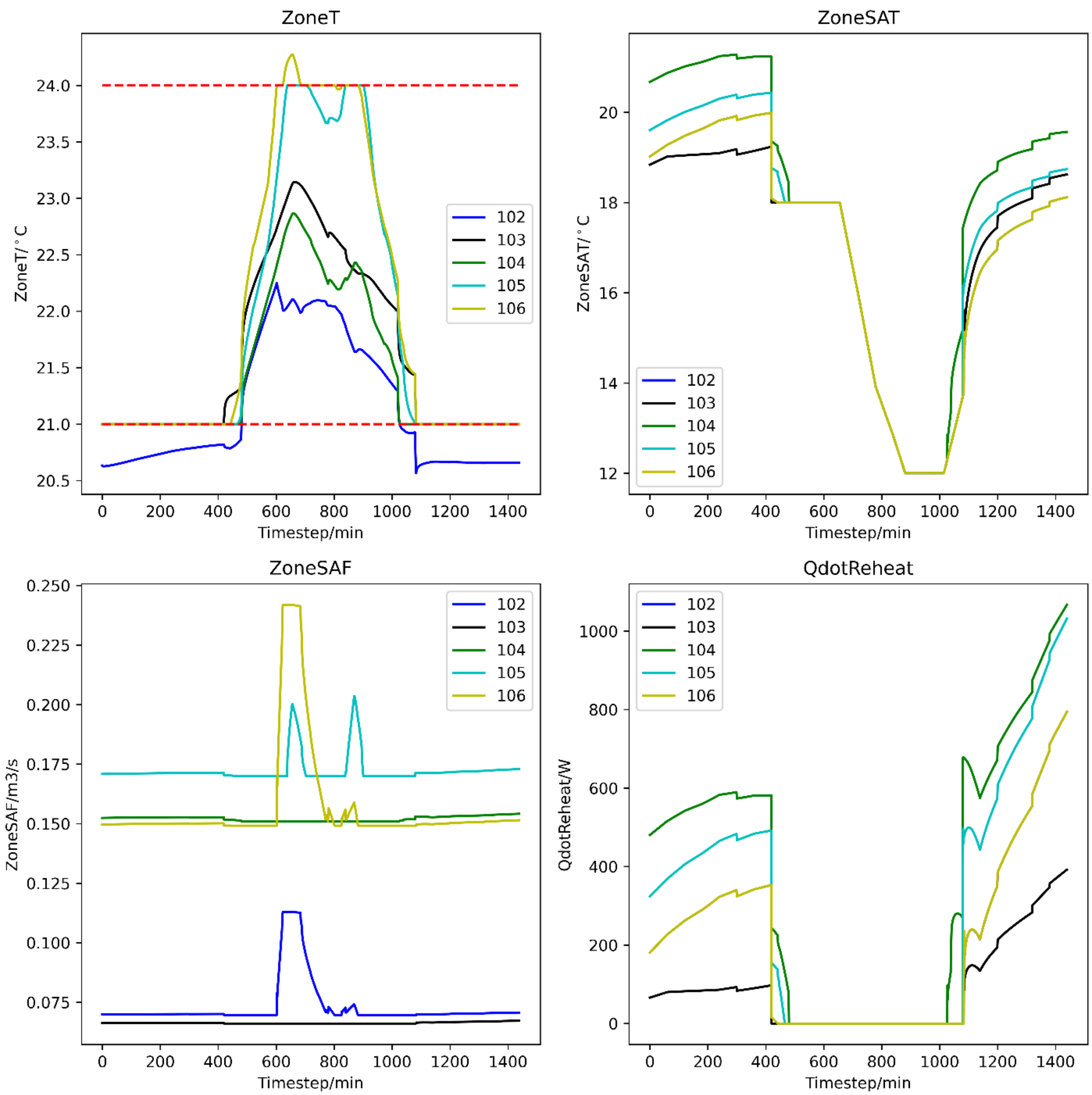

Figure A.5. Zone profiles on the first floor in the winter (A3).

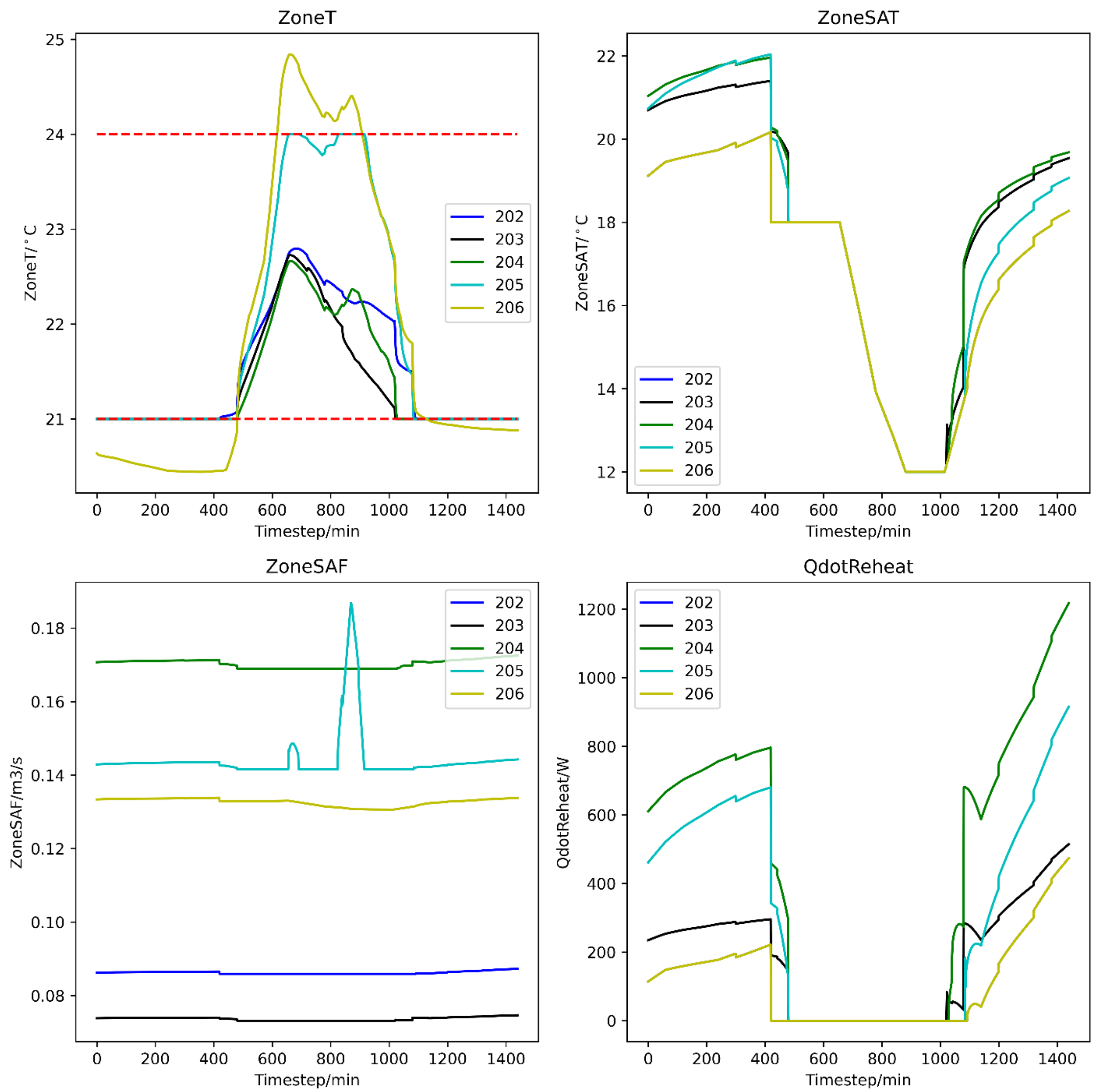

Figure A.6. Zone profiles on the second floor in the winter (A3).

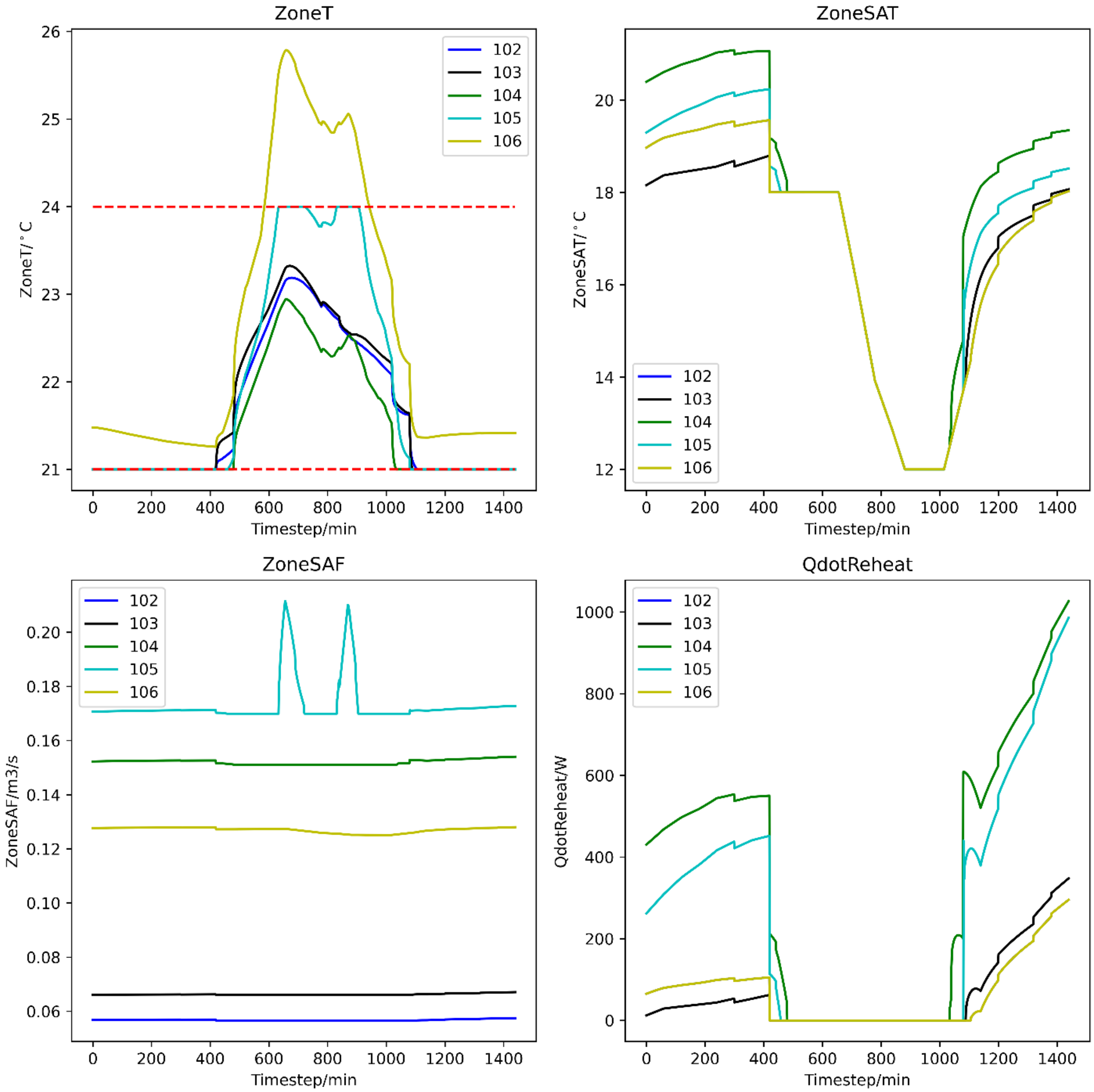

Figure A.7. Zone profiles on the first floor in the winter (A4).

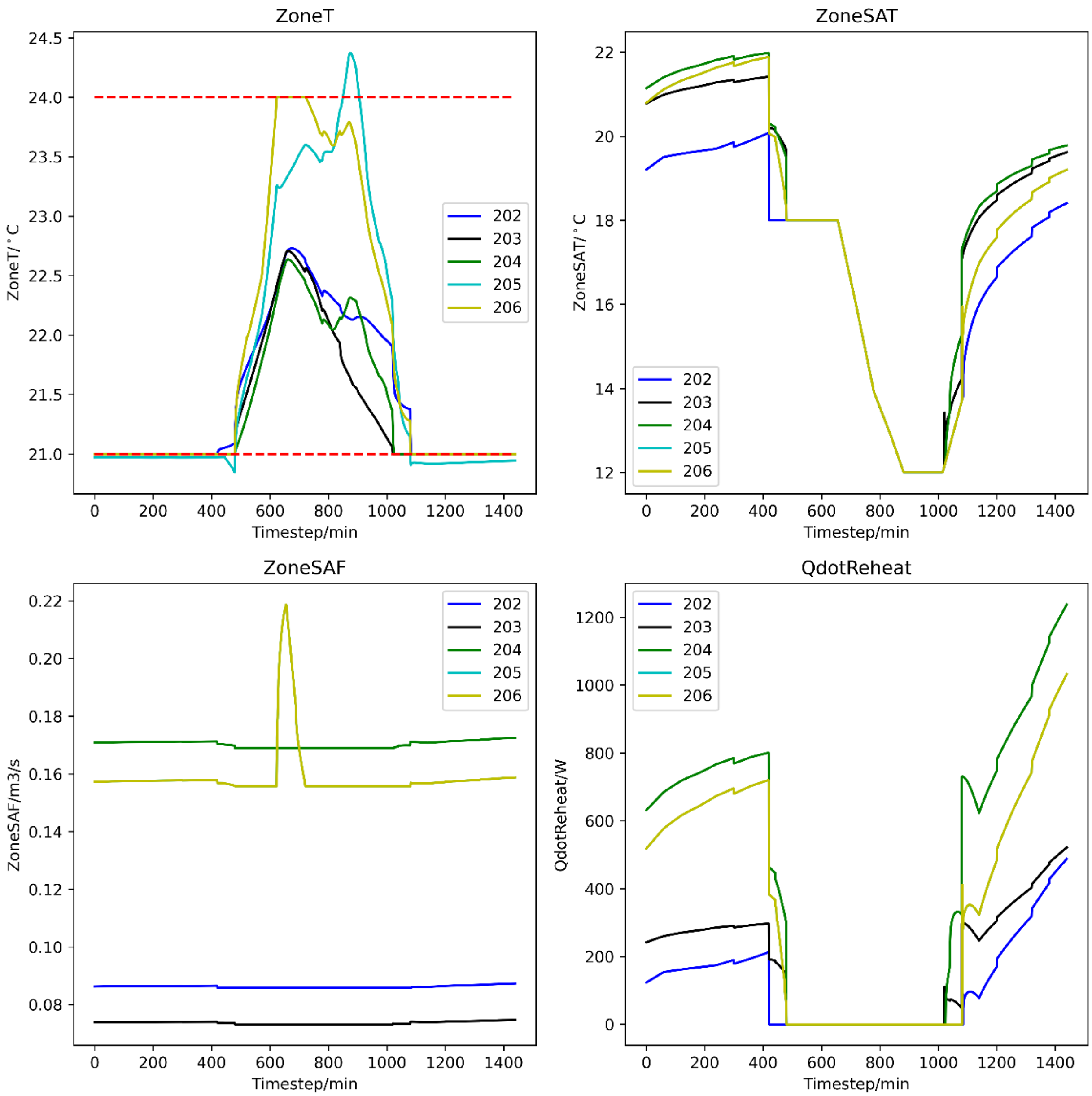

Figure A.8. Zone profiles on the second floor in the winter (A4).

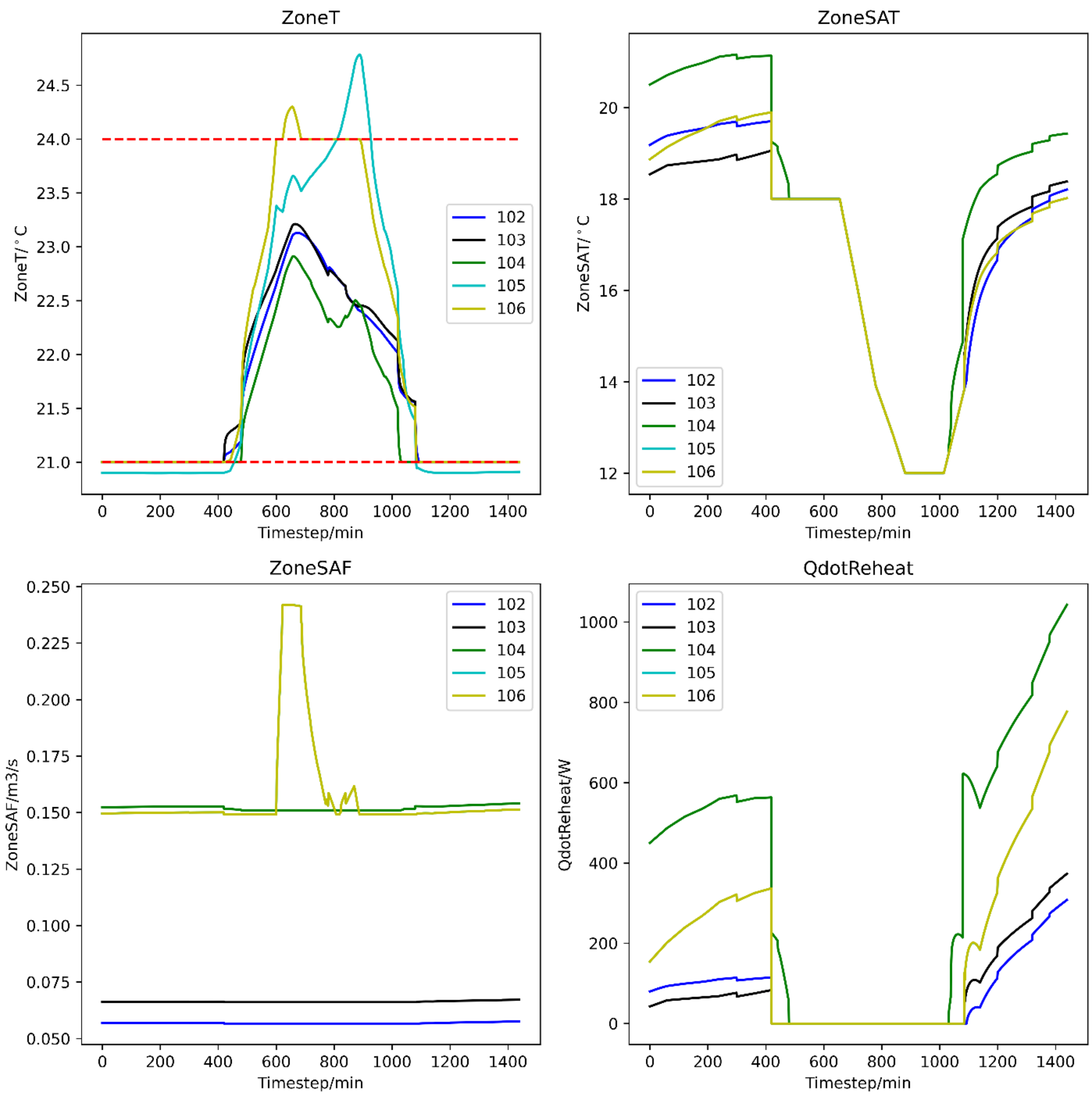

Figure A.9. Zone profiles on the first floor in the winter (A5).

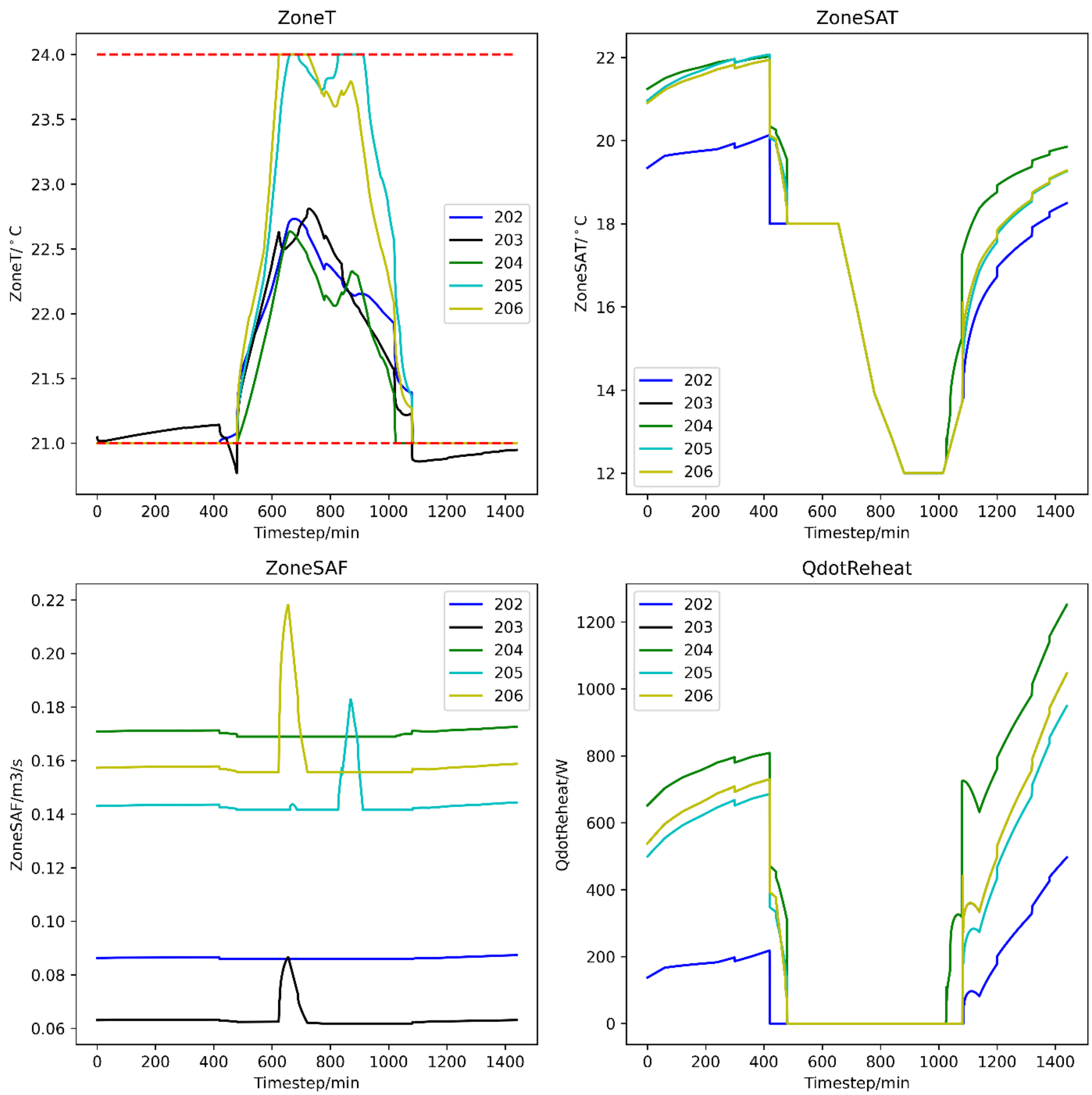

Figure A.10. Zone profiles on the second floor in the winter (A5).

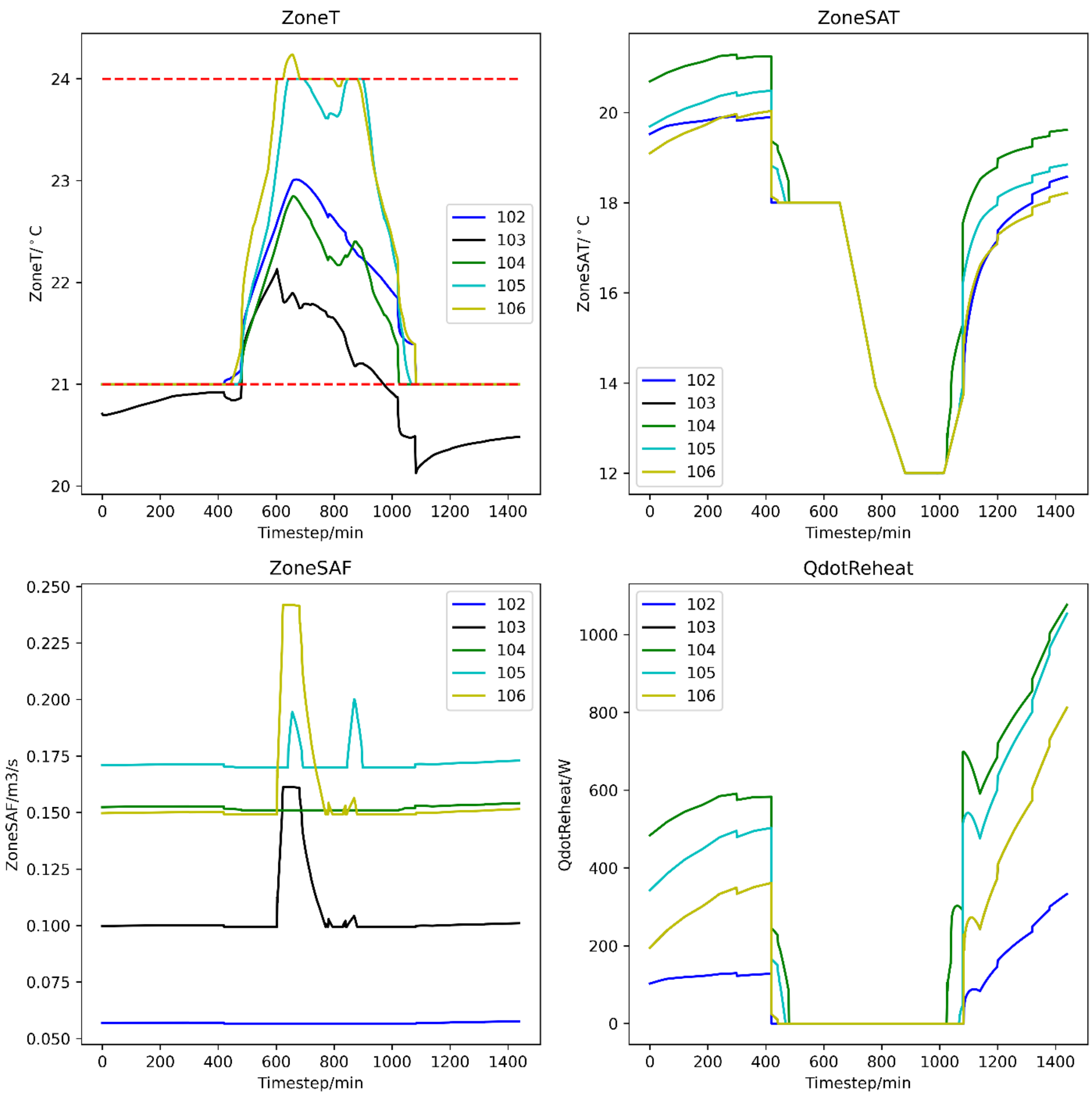

Figure A.11. Zone profiles on the first floor in the winter (A6).

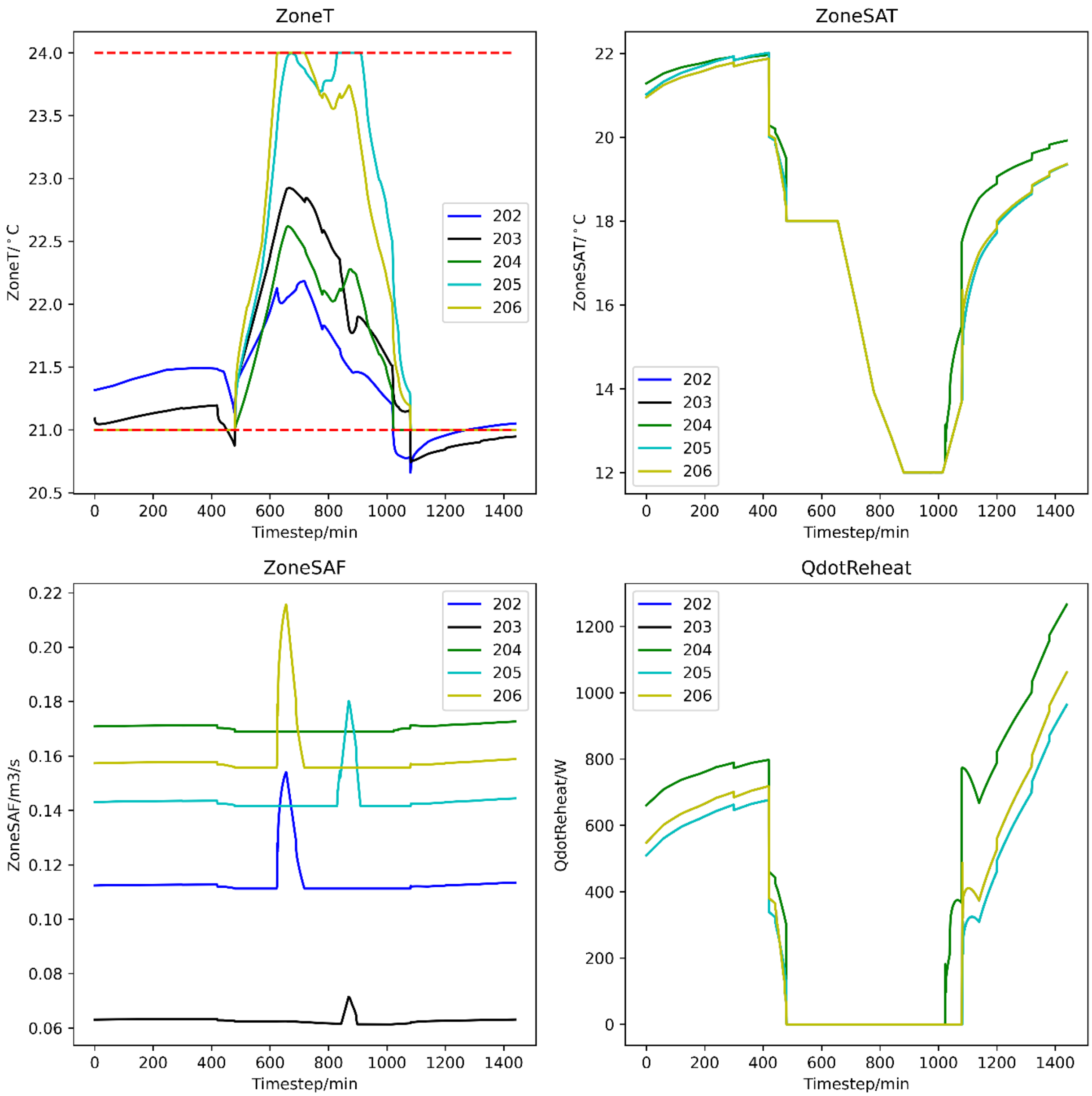

Figure A.12. Zone profiles on the second floor in the winter (A6).

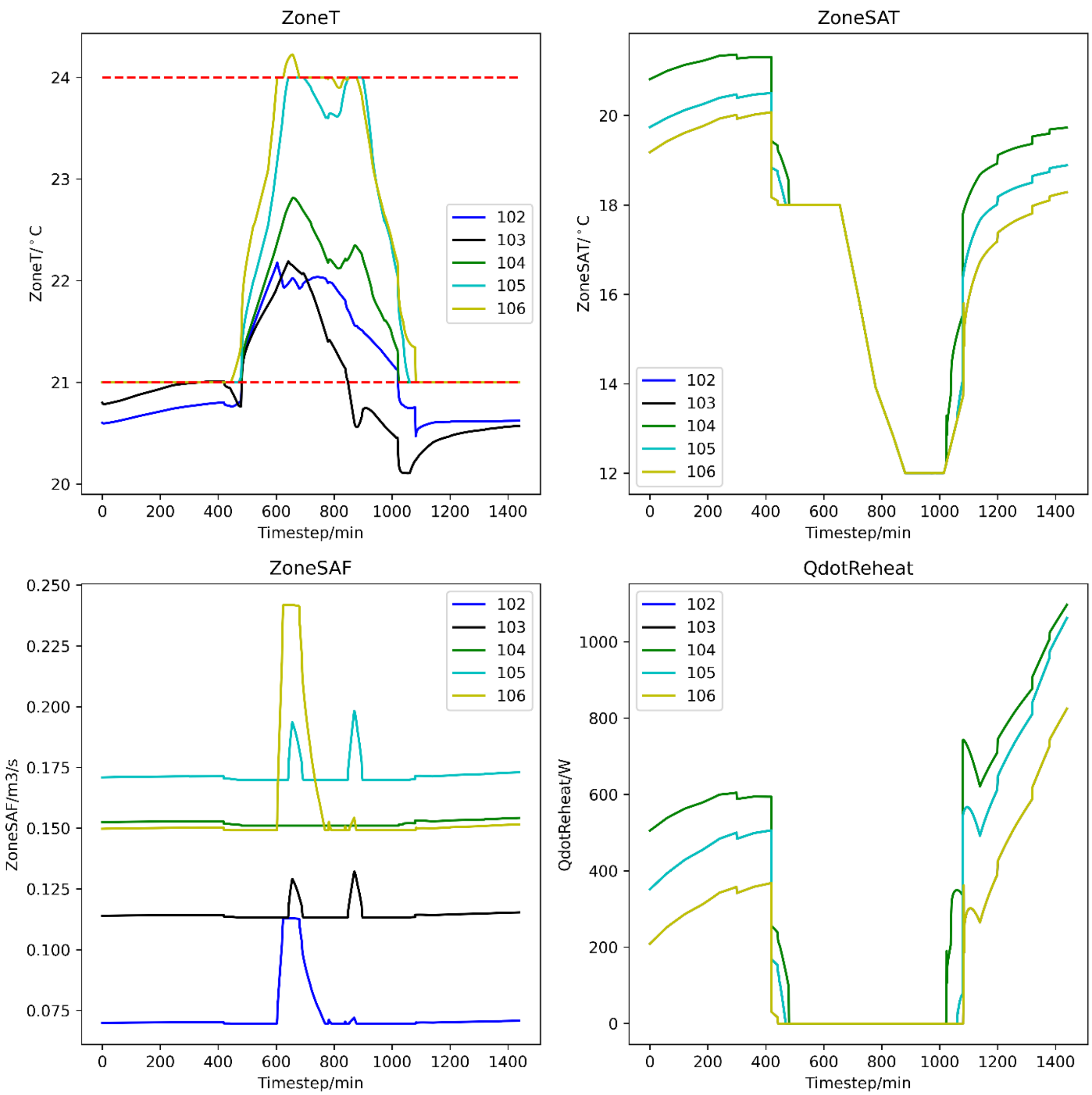

Figure A.13. Zone profiles on the first floor in the winter (A7).

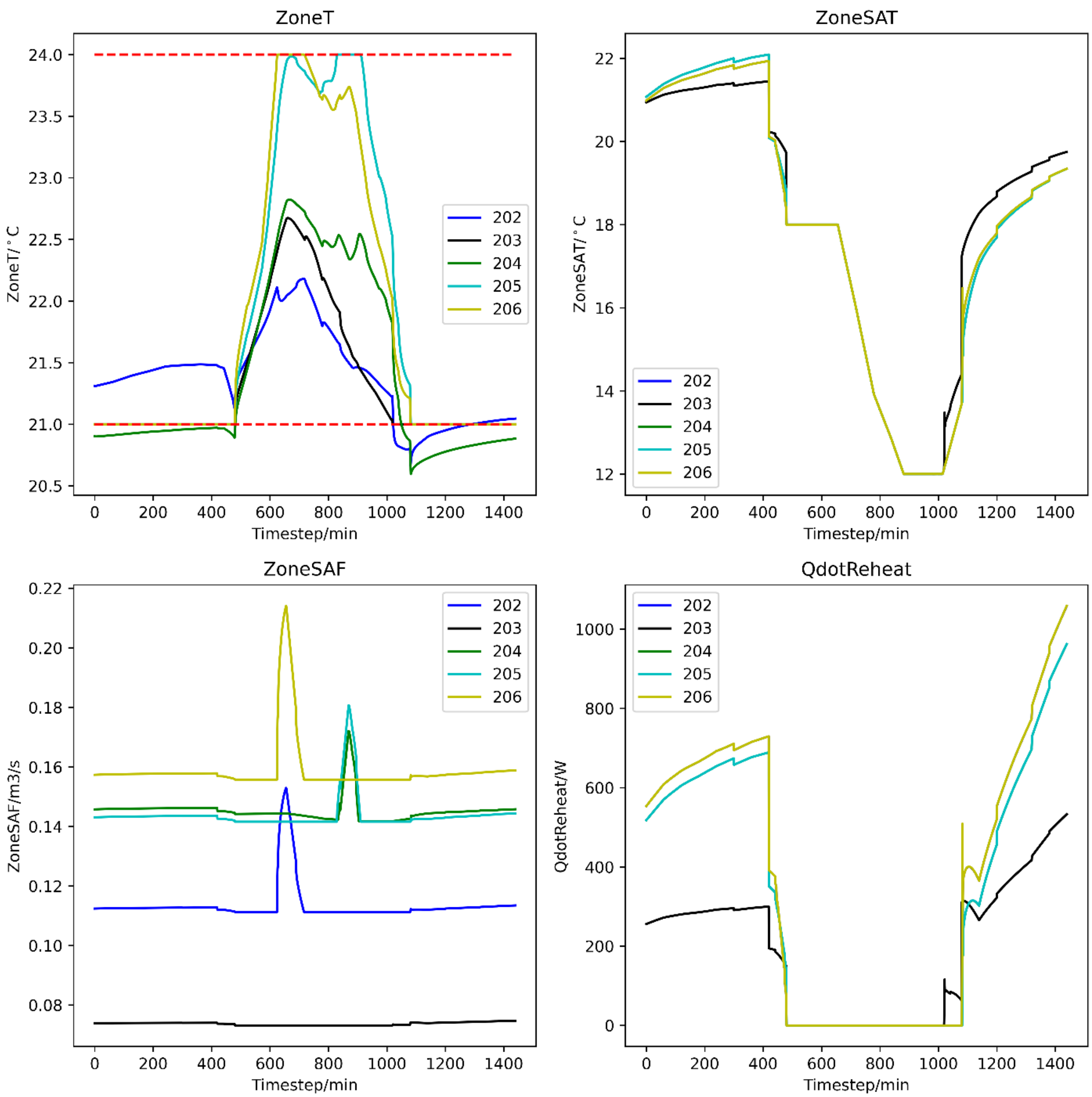

Figure A.14. Zone profiles on the second floor in the winter (A7).

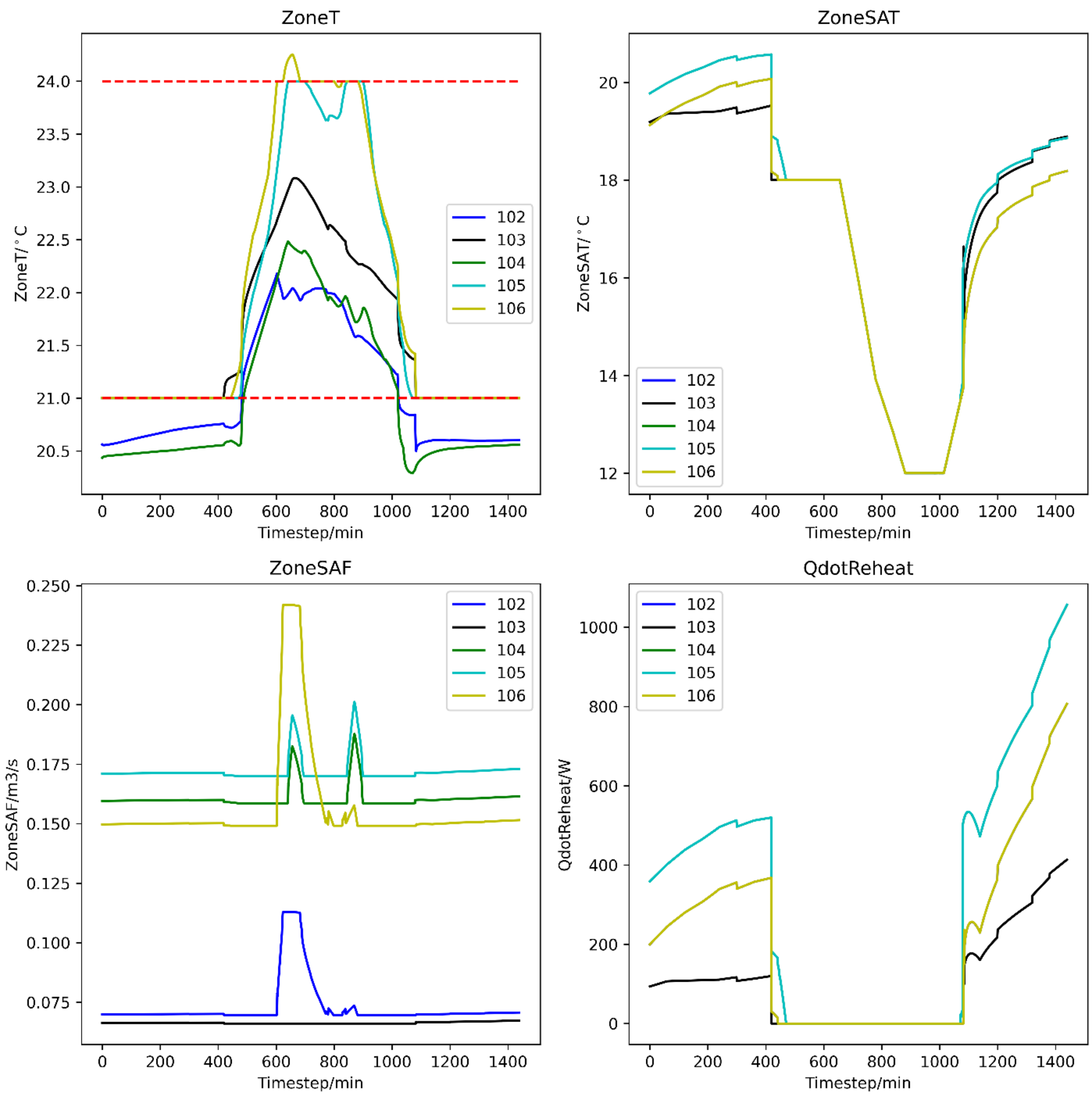

Figure A.15. Zone profiles on the first floor in the winter (A8).

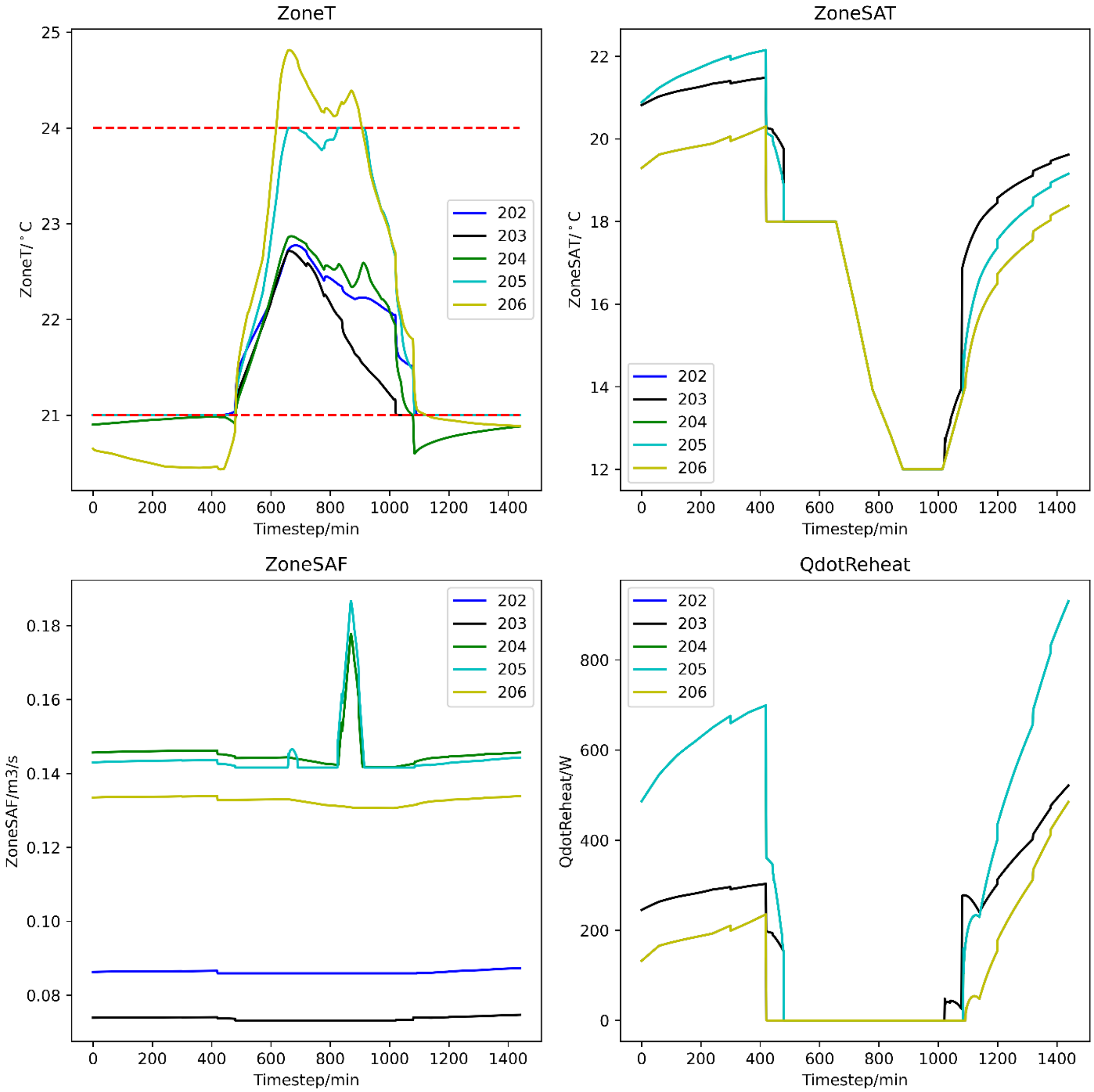

Figure A.16. Zone profiles on the second floor in the winter (A8).

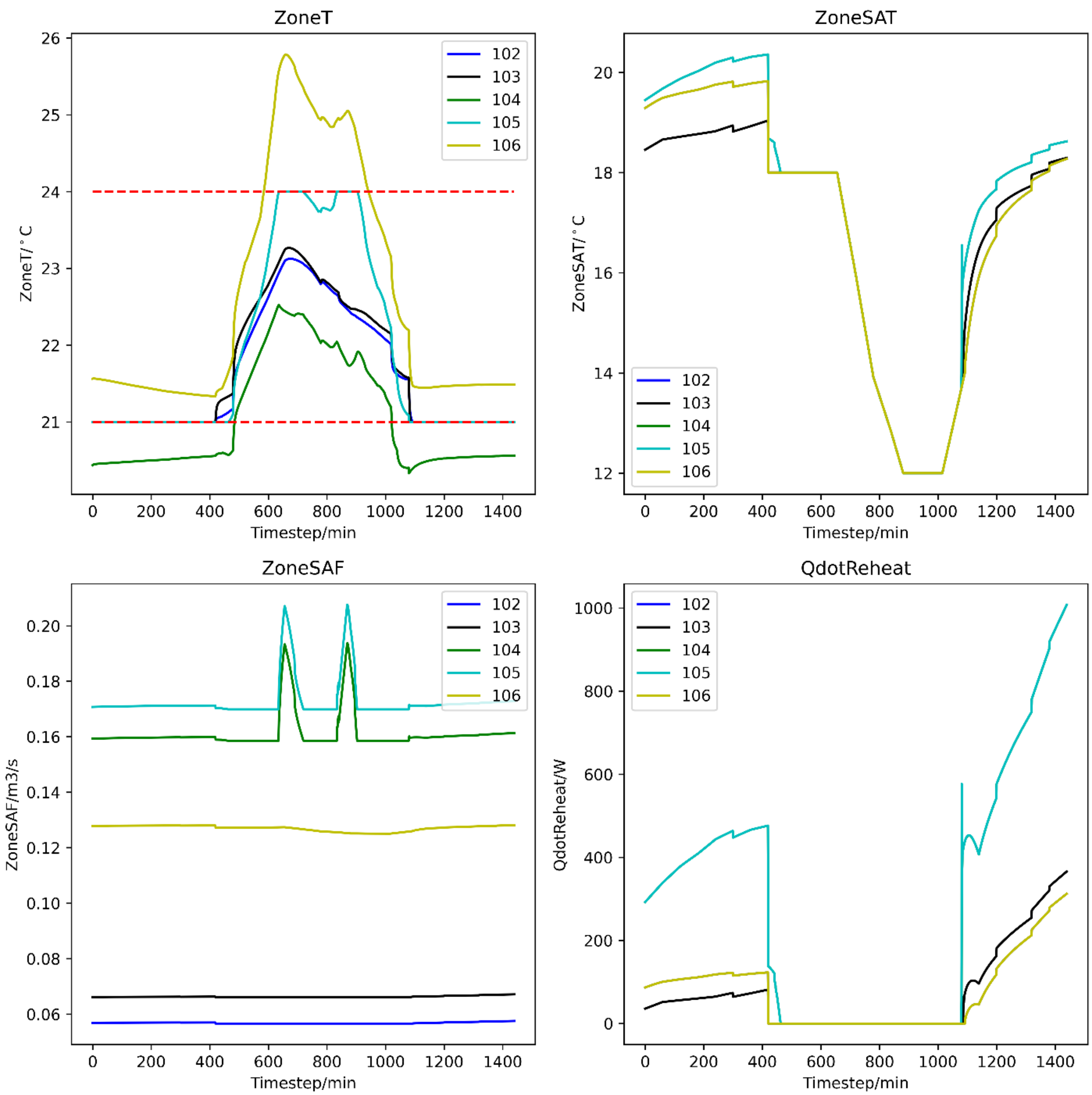

Figure A.17. Zone profiles on the first floor in the winter (A9)

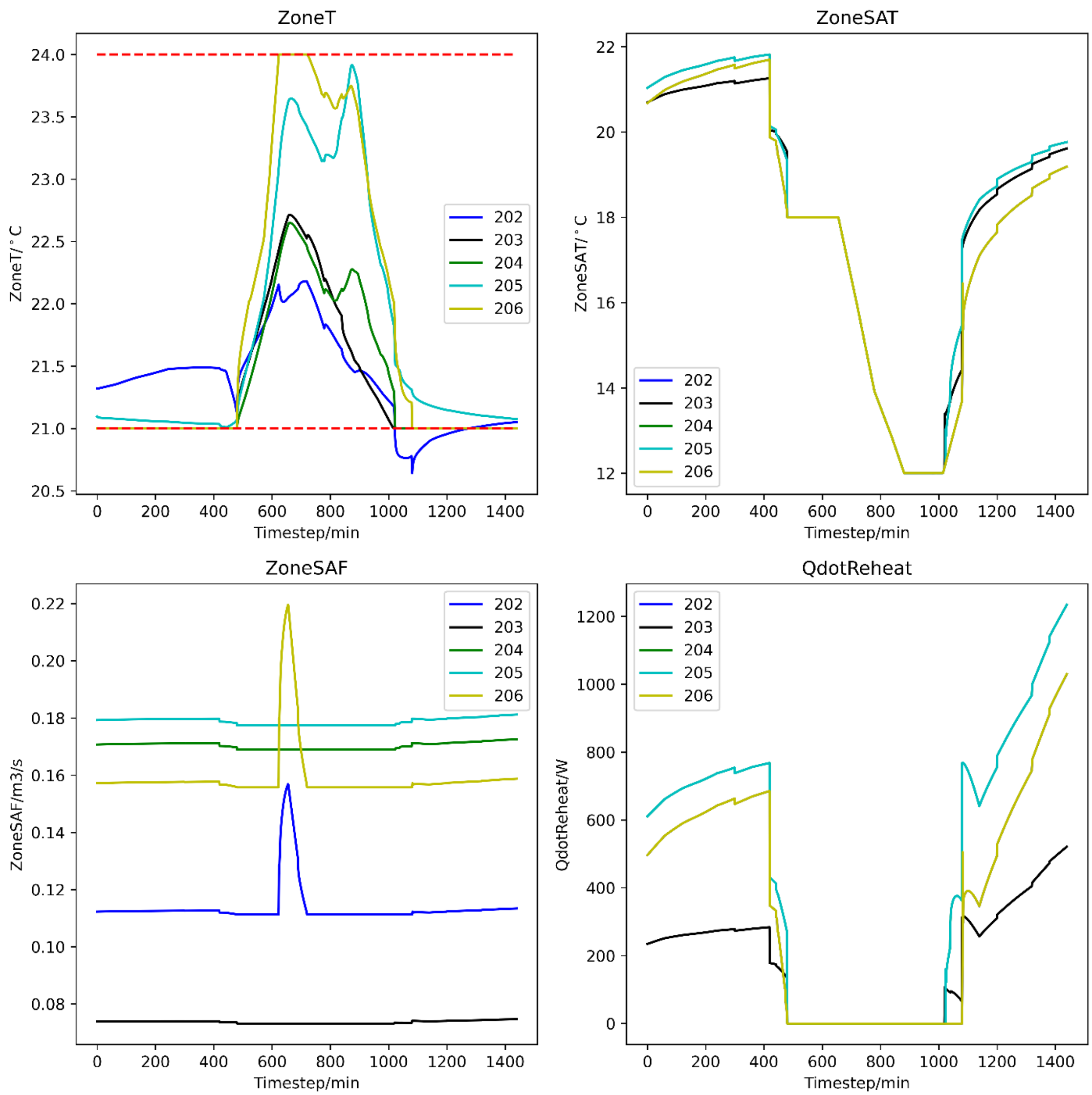

Figure A.18. Zone profiles on the second floor in the winter (A9).

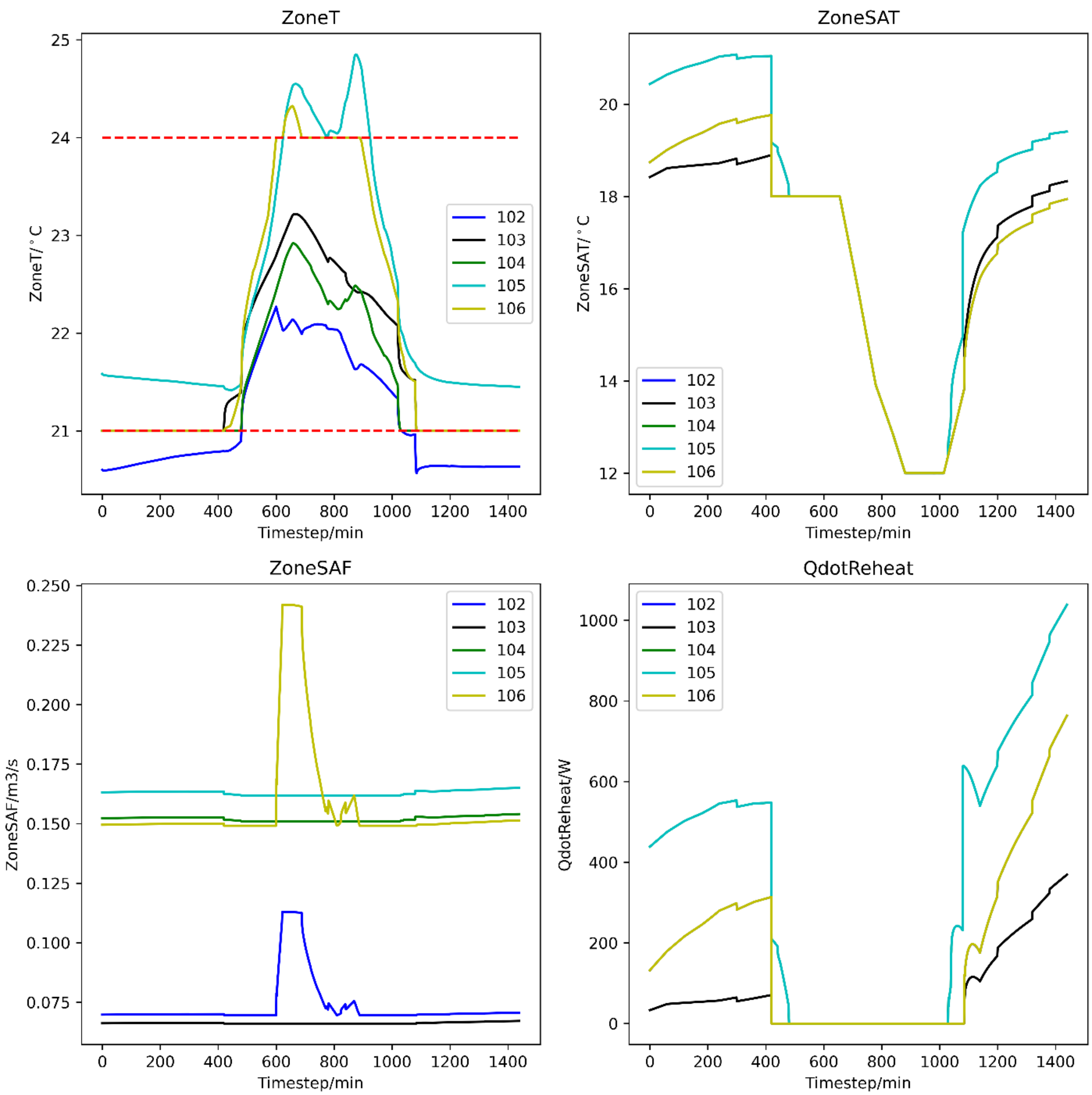

Figure A.19. Zone profiles on the first floor in the winter (A10).

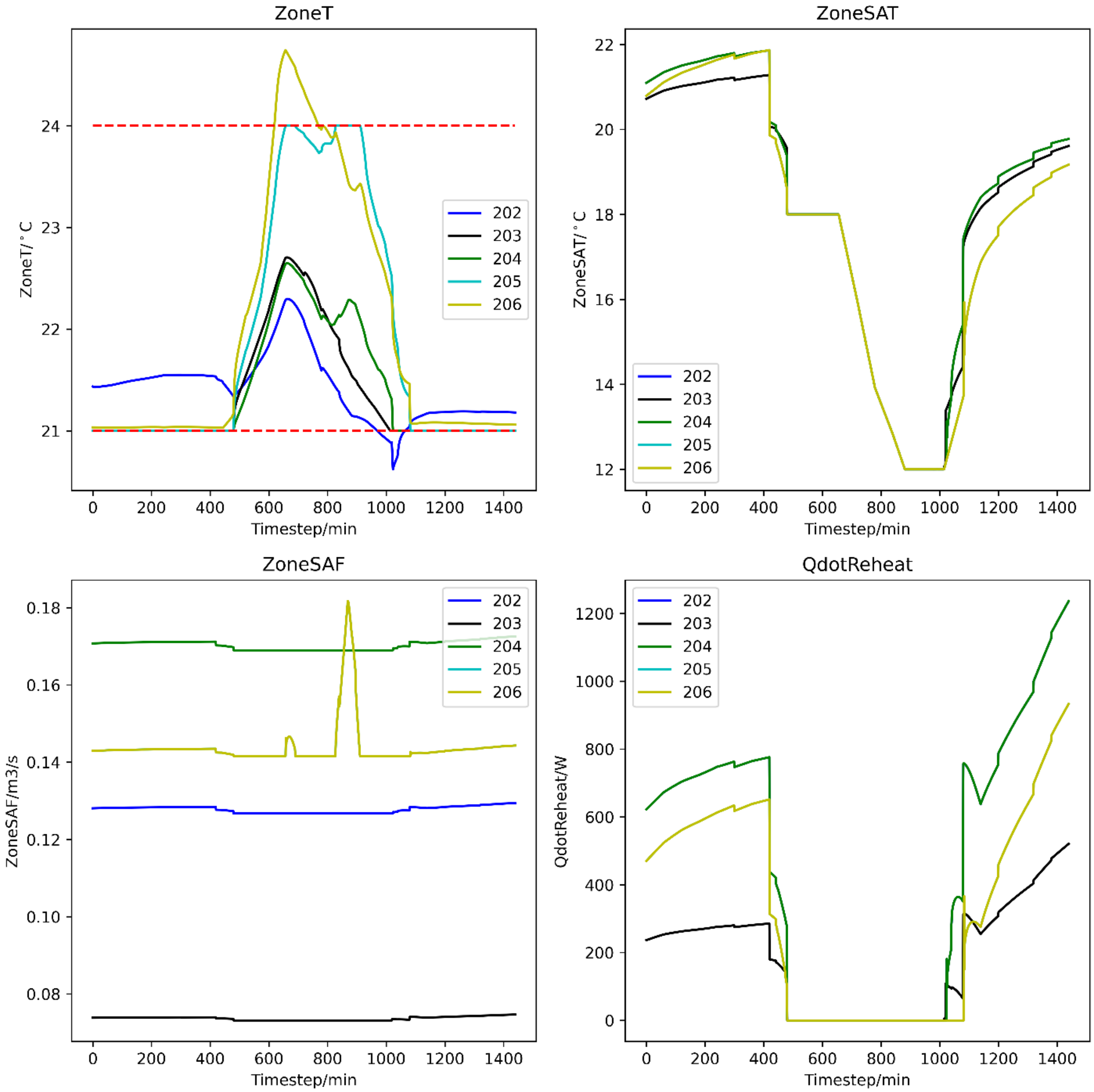

Figure A.20. Zone profiles on the second floor in the winter (A10).

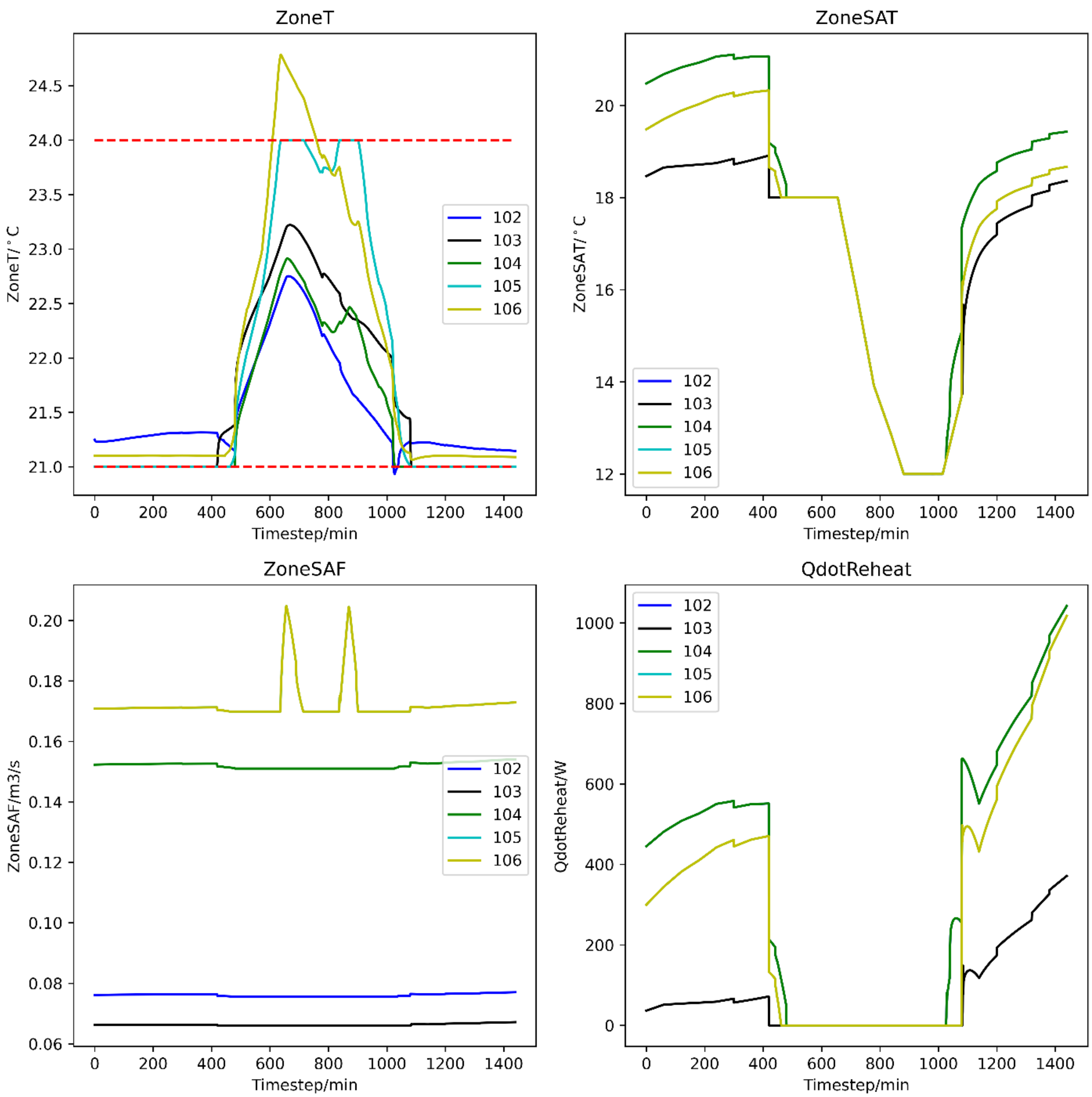

Figure A.21. Zone profiles on the first floor in the winter (A11).

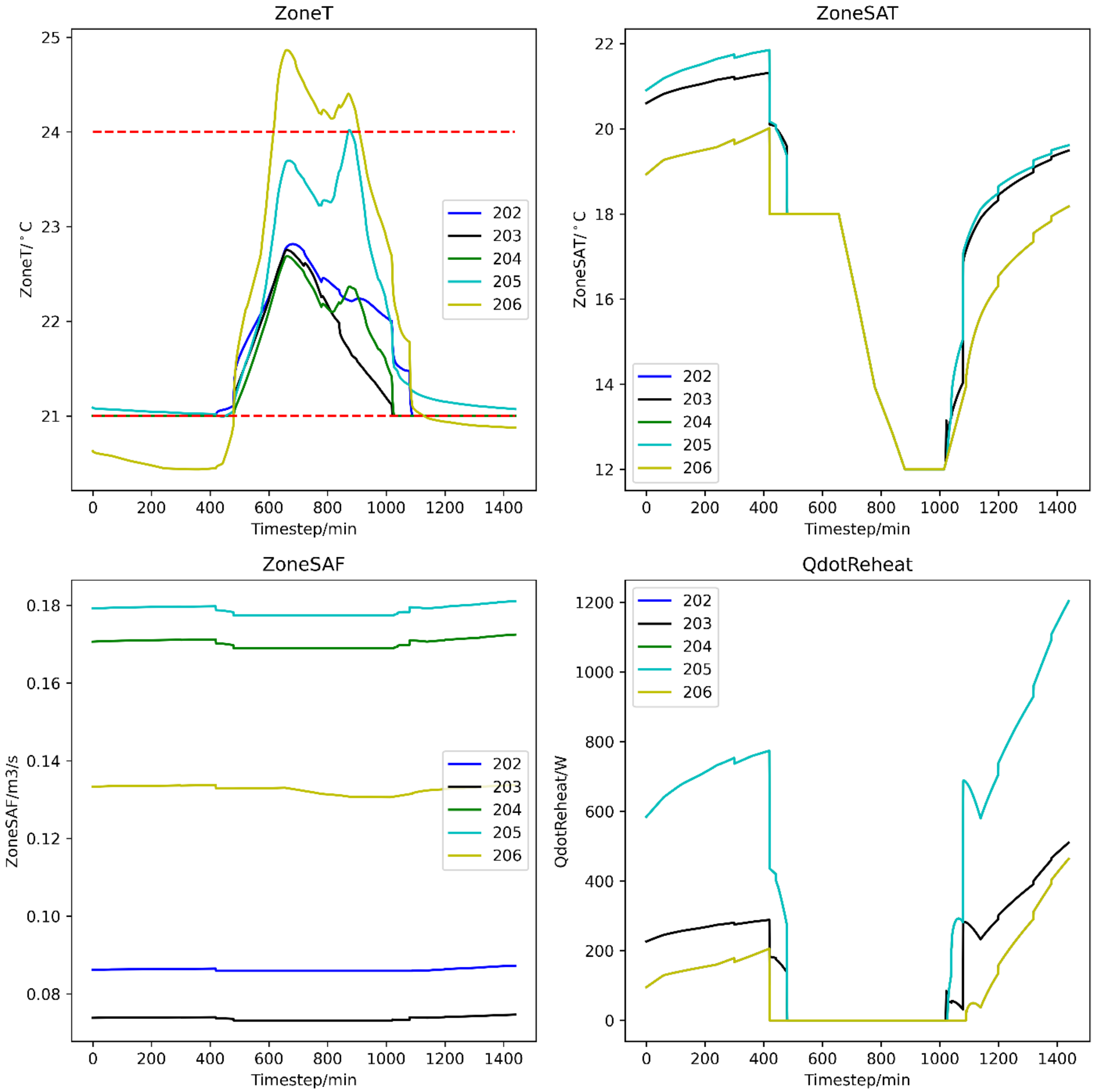

Figure A.22. Zone profiles on the second floor in the winter (A11).

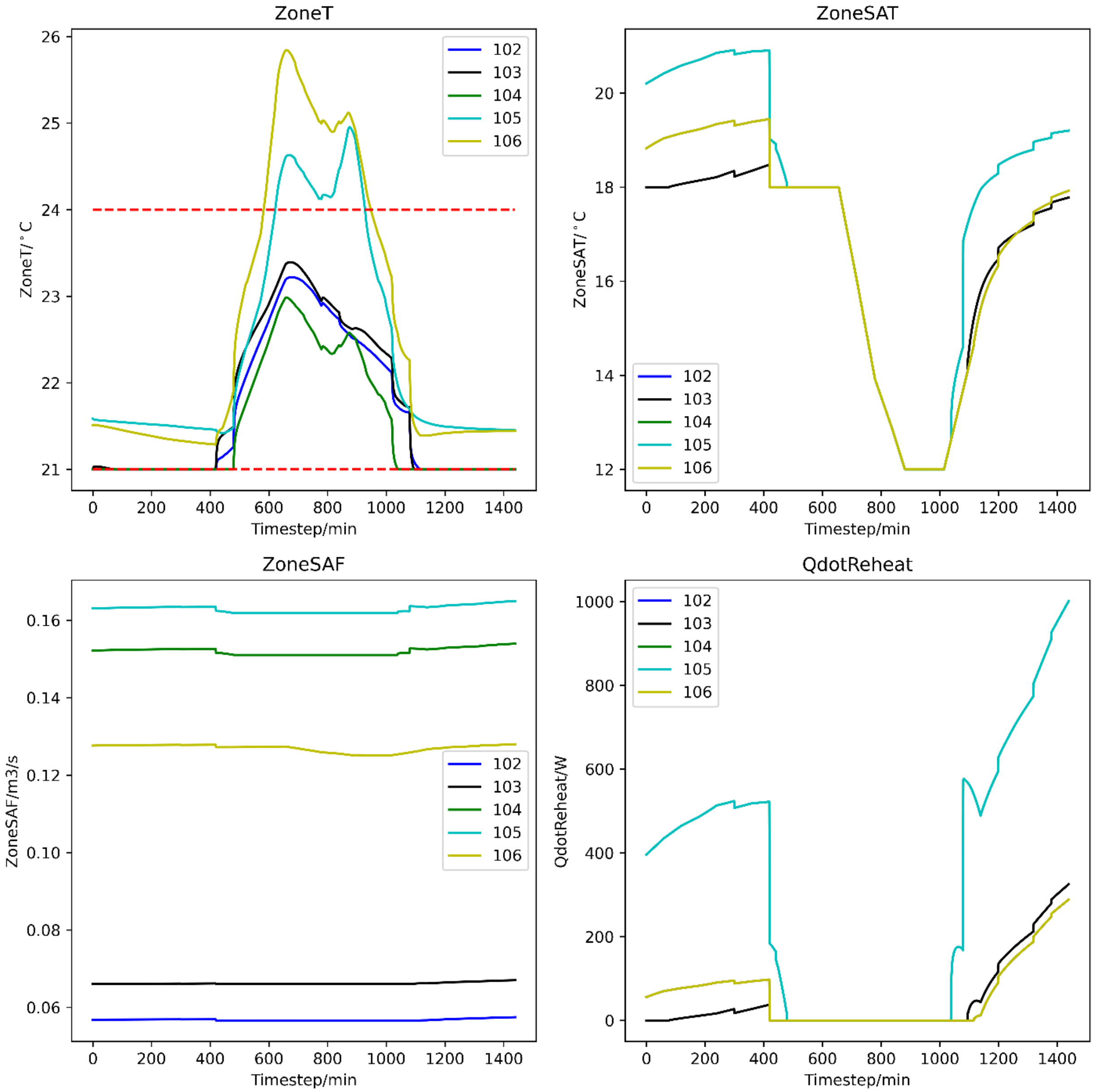

Figure A.23. Zone profiles on the first floor in the winter (A12).

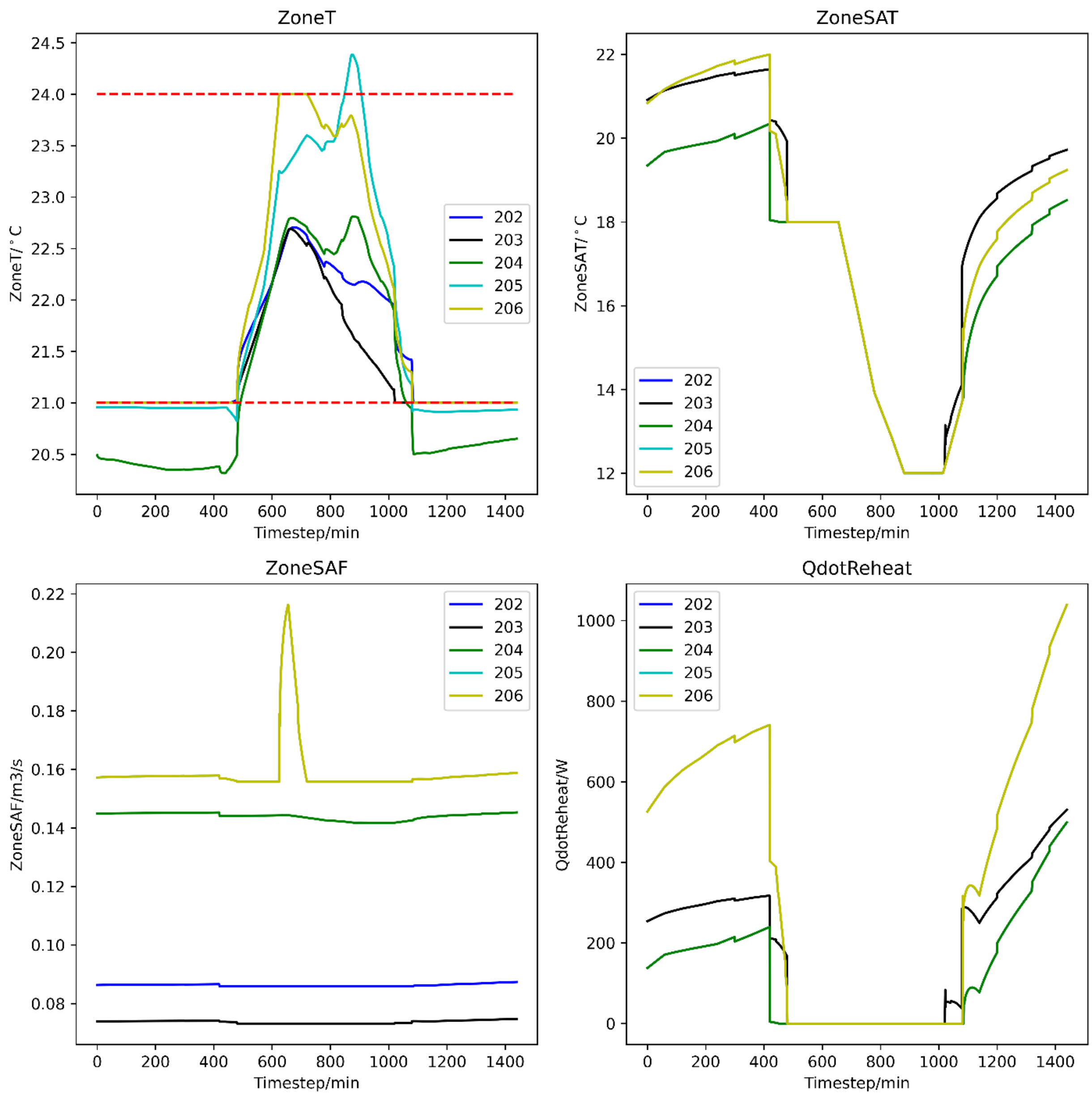

Figure A.24. Zone profiles on the second floor in the winter (A12).

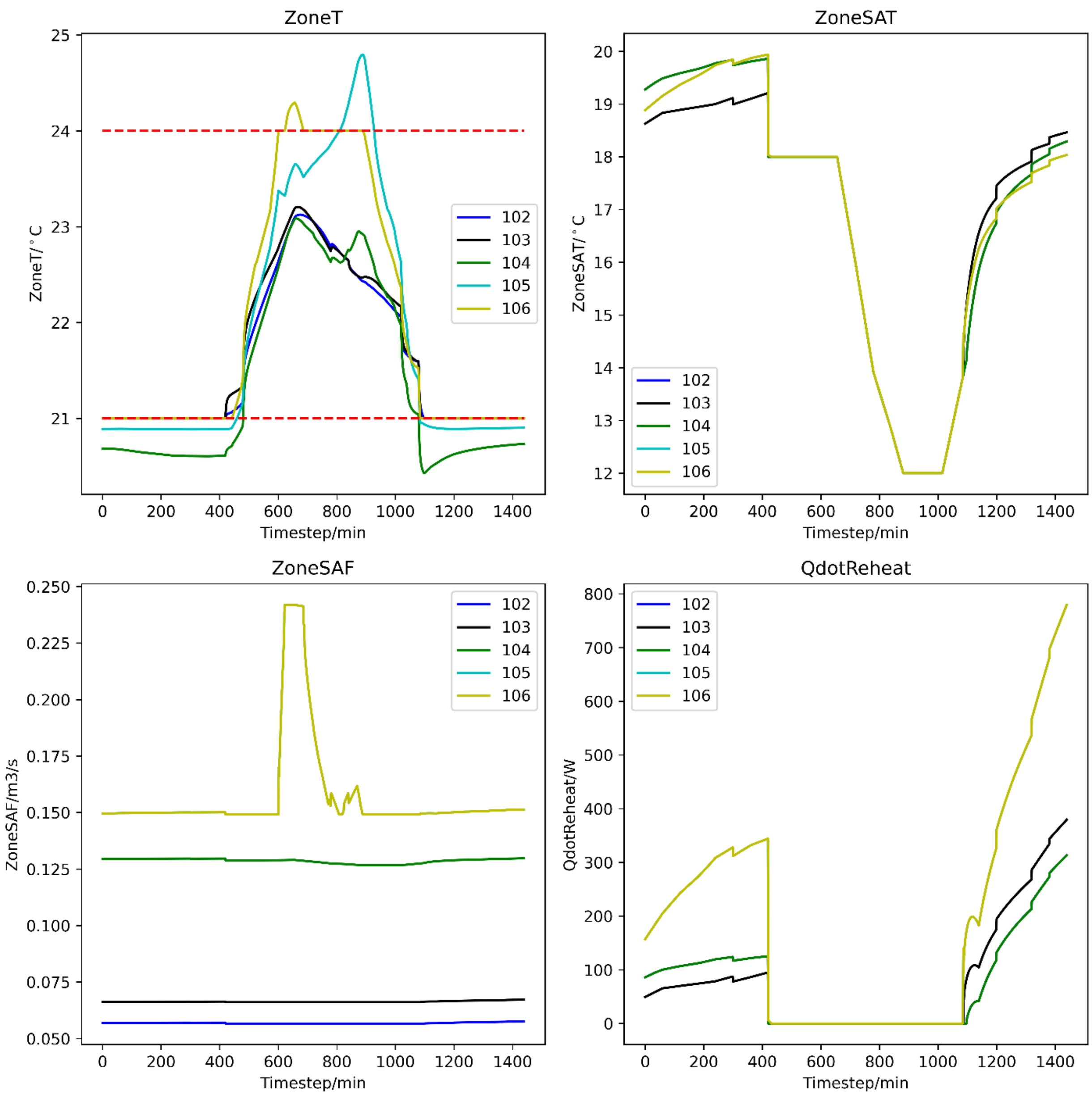

Figure A.25. Zone profiles on the first floor in the winter (A13).

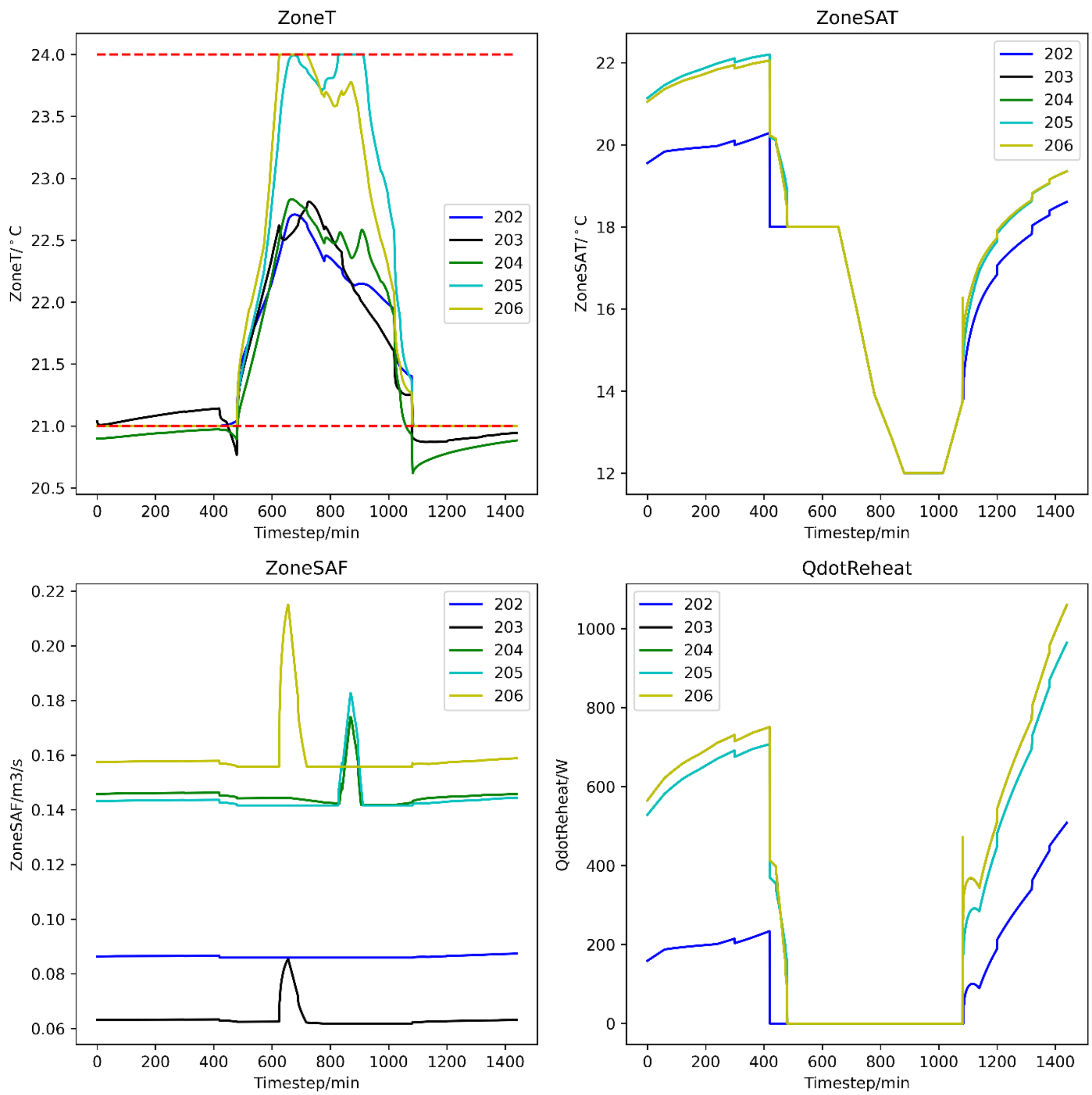

Figure A.26. Zone profiles on the second floor in the winter (A13).

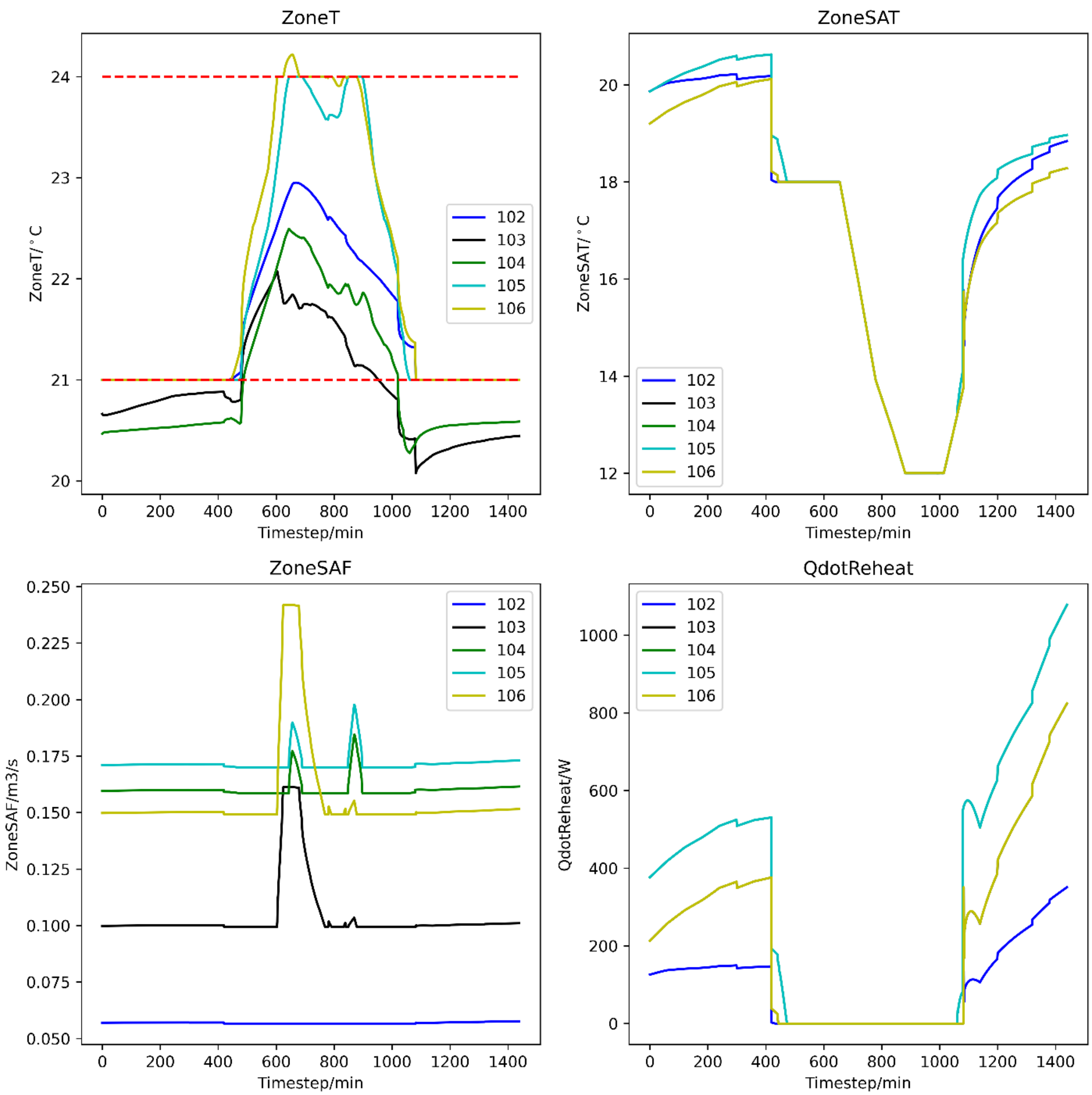

Figure A.27. Zone profiles on the first floor in the winter (A14).

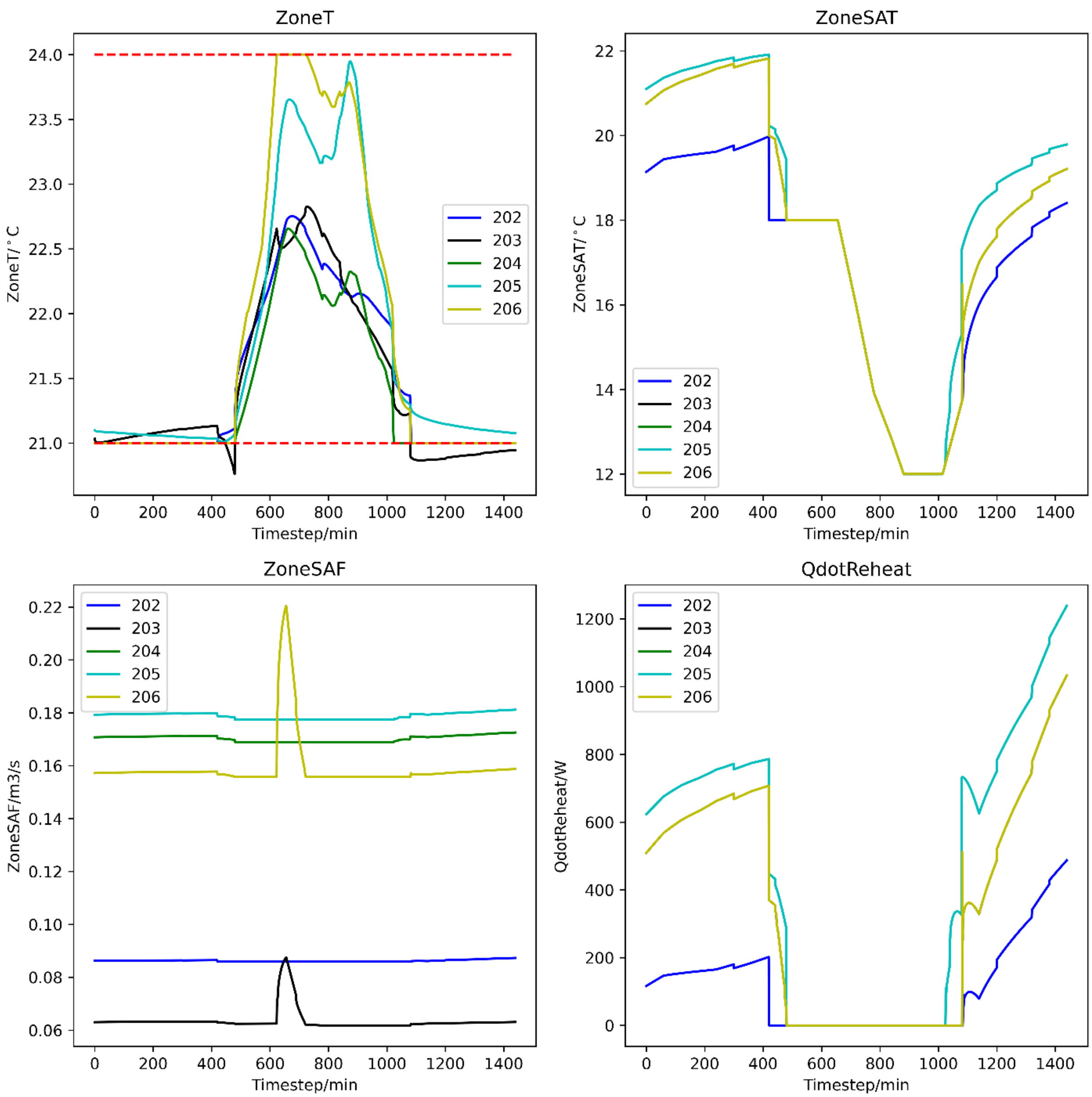

Figure A.28. Zone profiles on the second floor in the winter (A14).

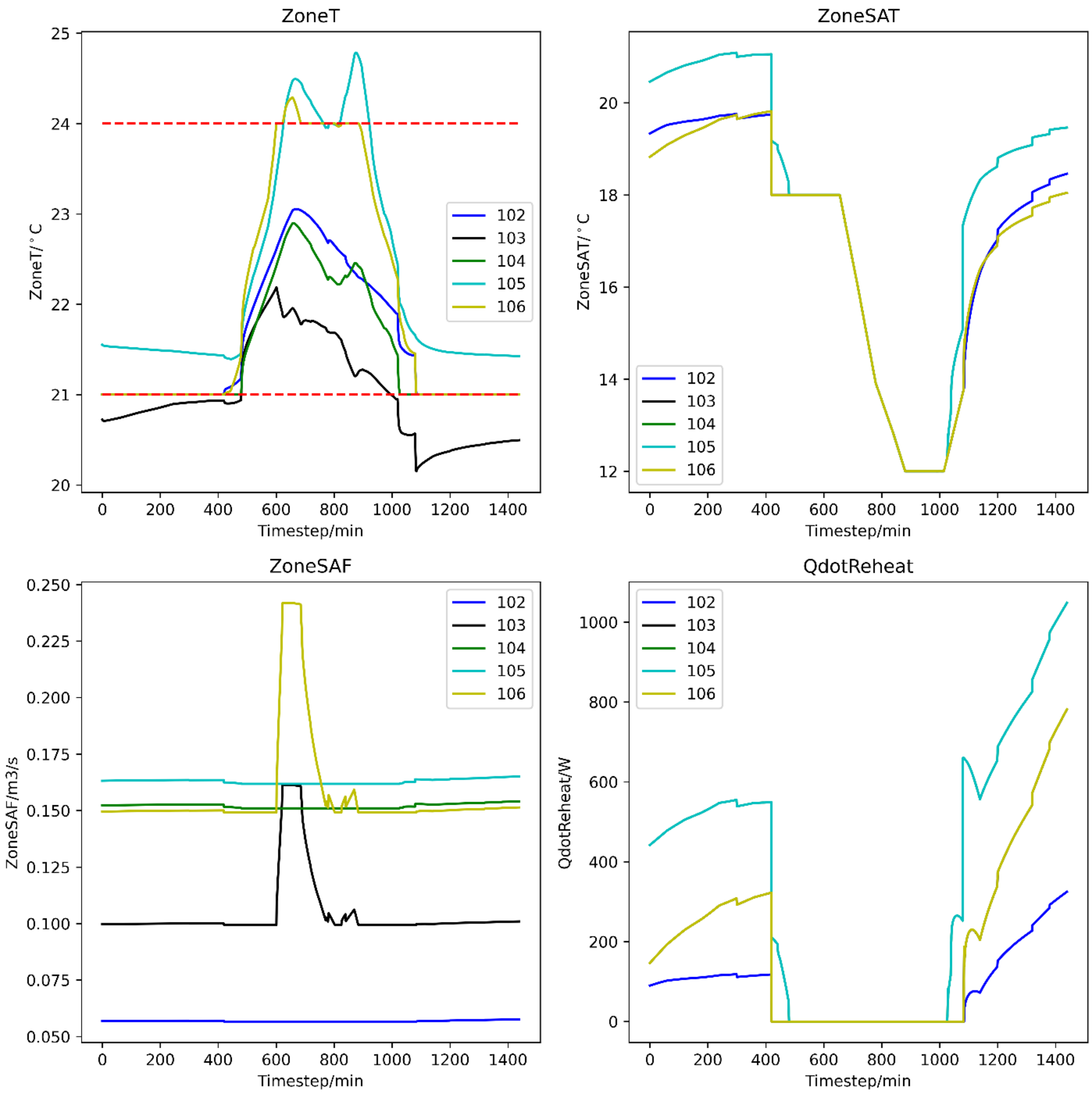

Figure A.29. Zone profiles on the first floor in the winter (A15).

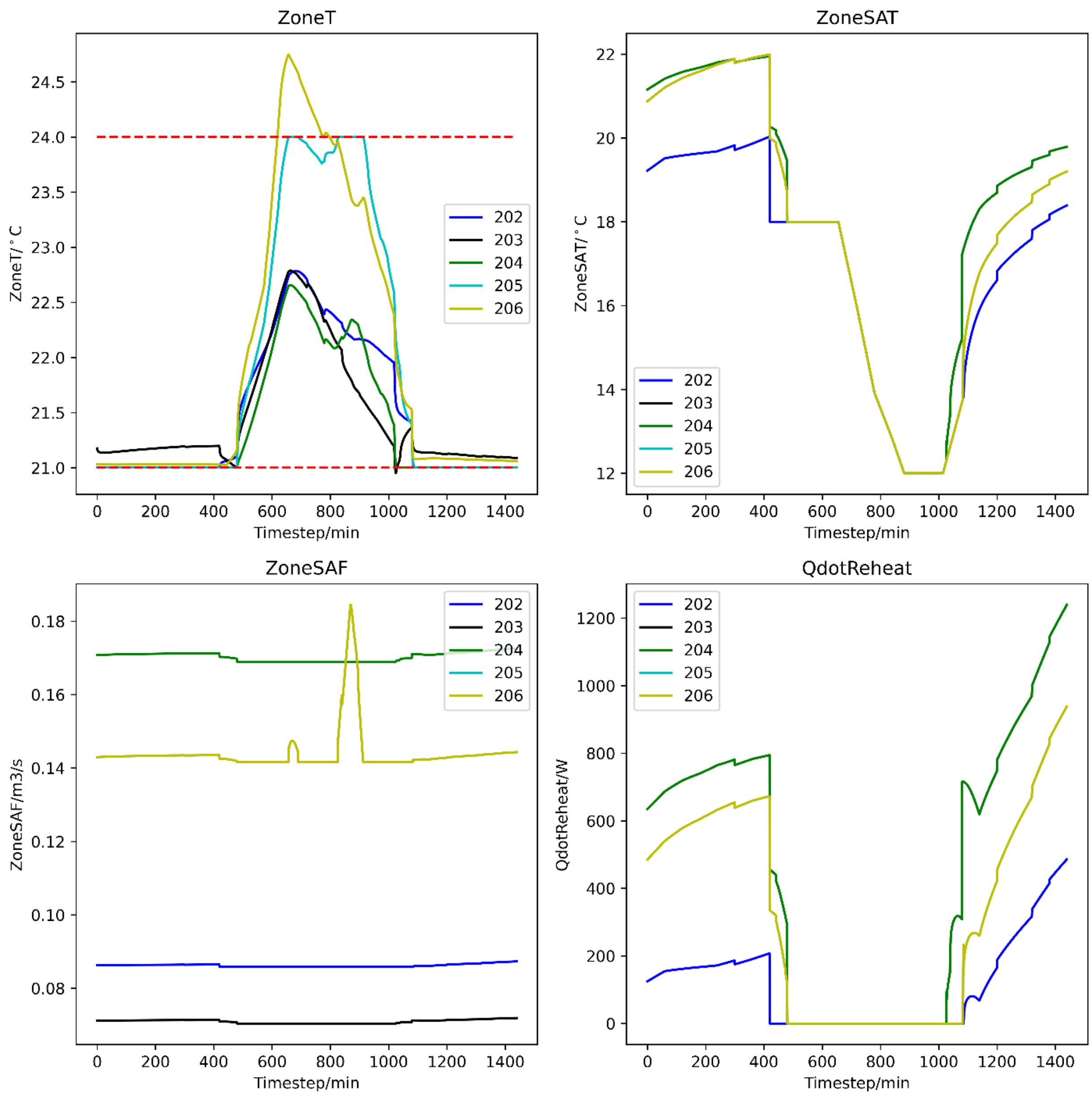

Figure A.30. Zone profiles on the second floor in the winter (A15).

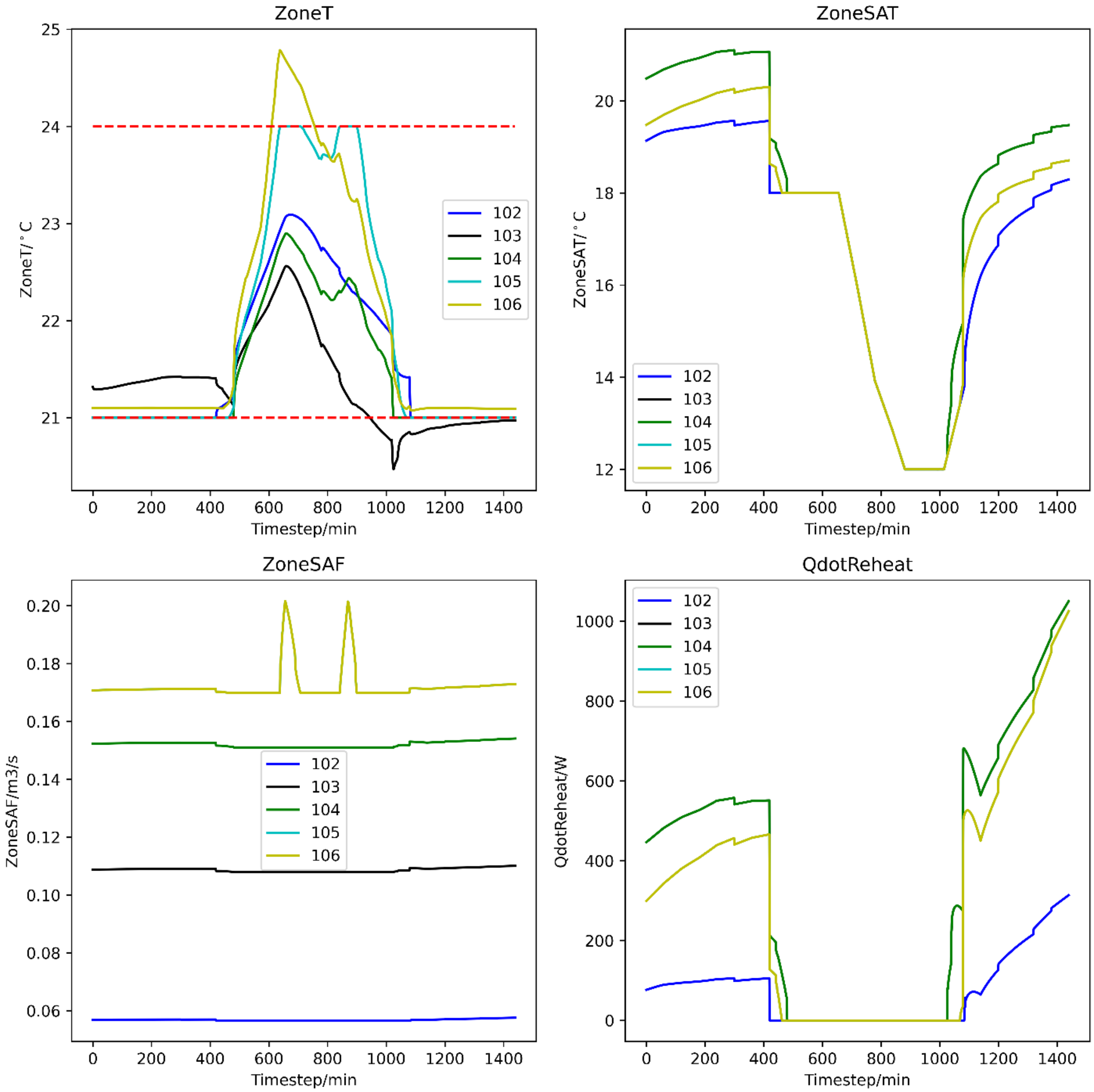

Figure A.31. Zone profiles on the first floor in the winter (A16).

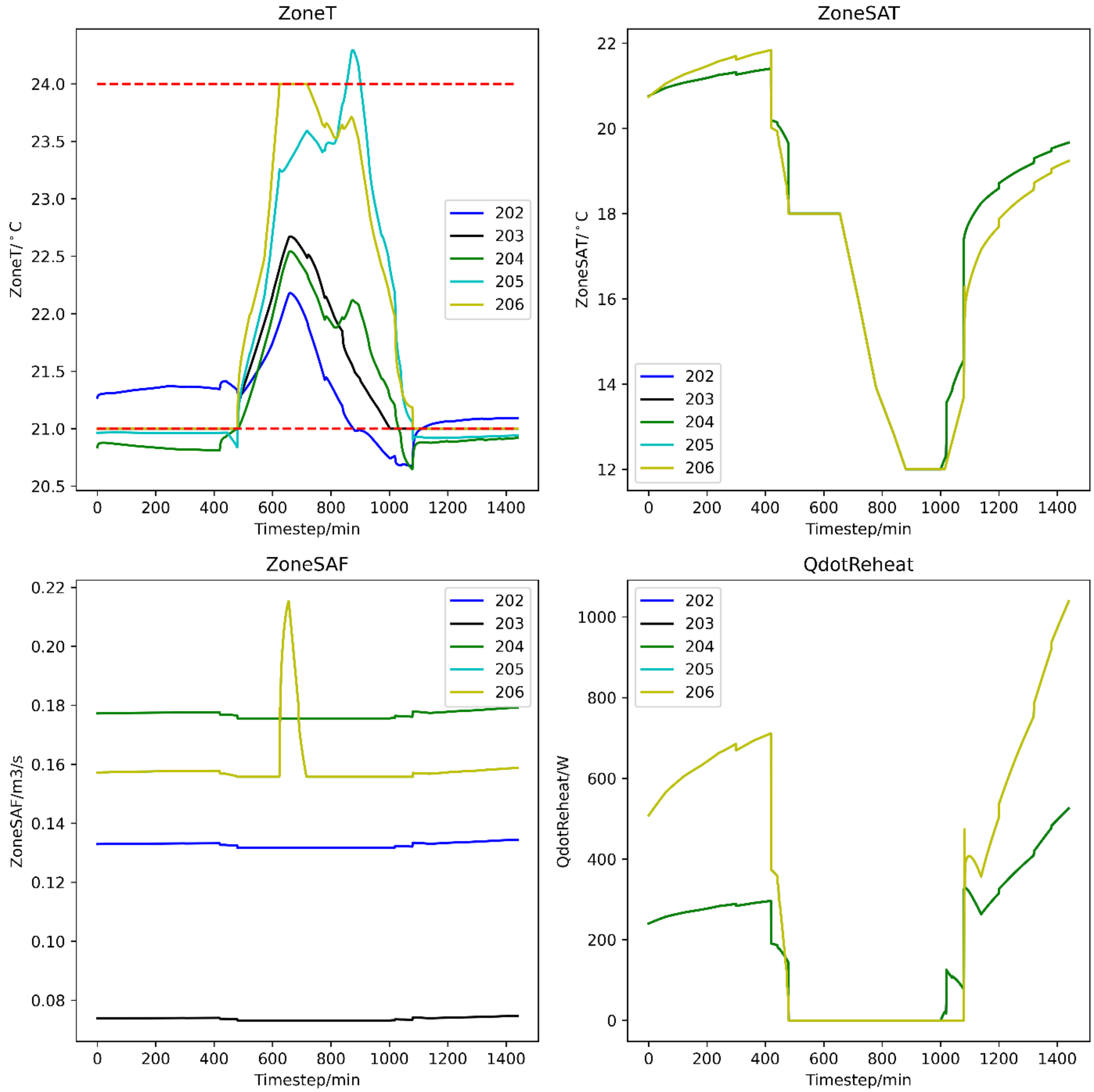

Figure A.32. Zone profiles on the second floor in the winter (A16).

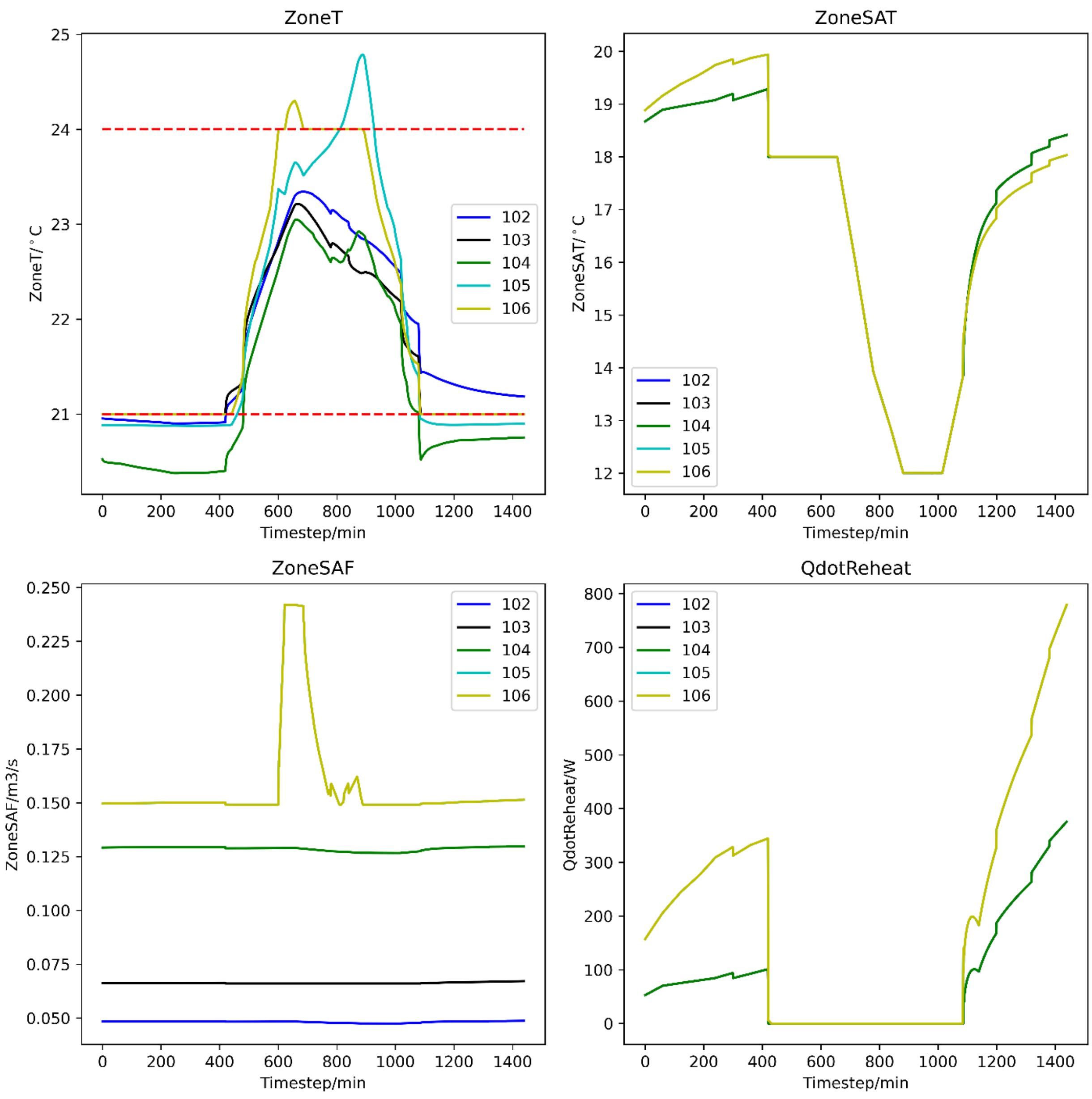

Figure A.33. Zone profiles on the first floor in the winter (A17).

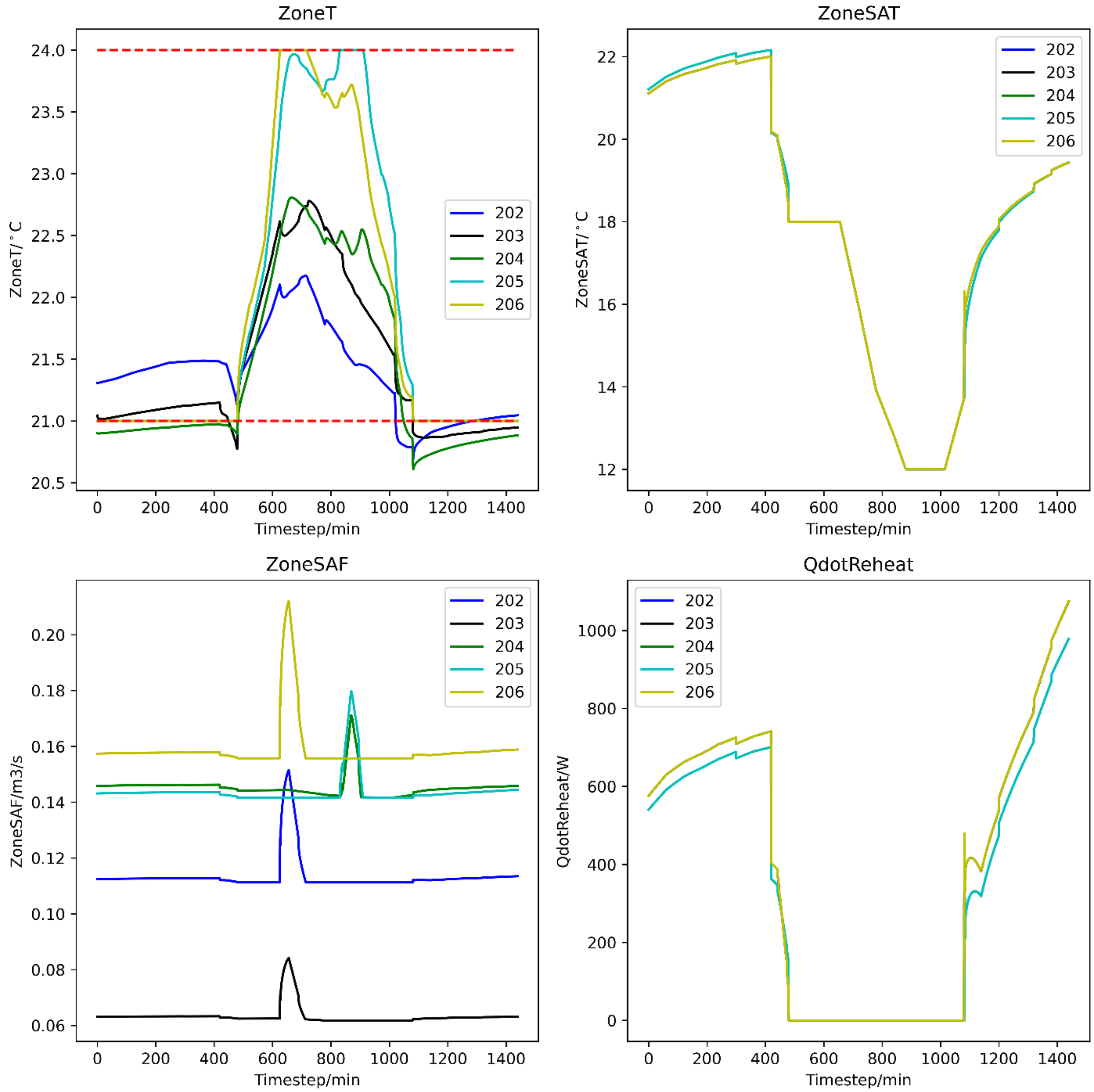

Figure A.34. Zone profiles on the second floor in the winter (A17).

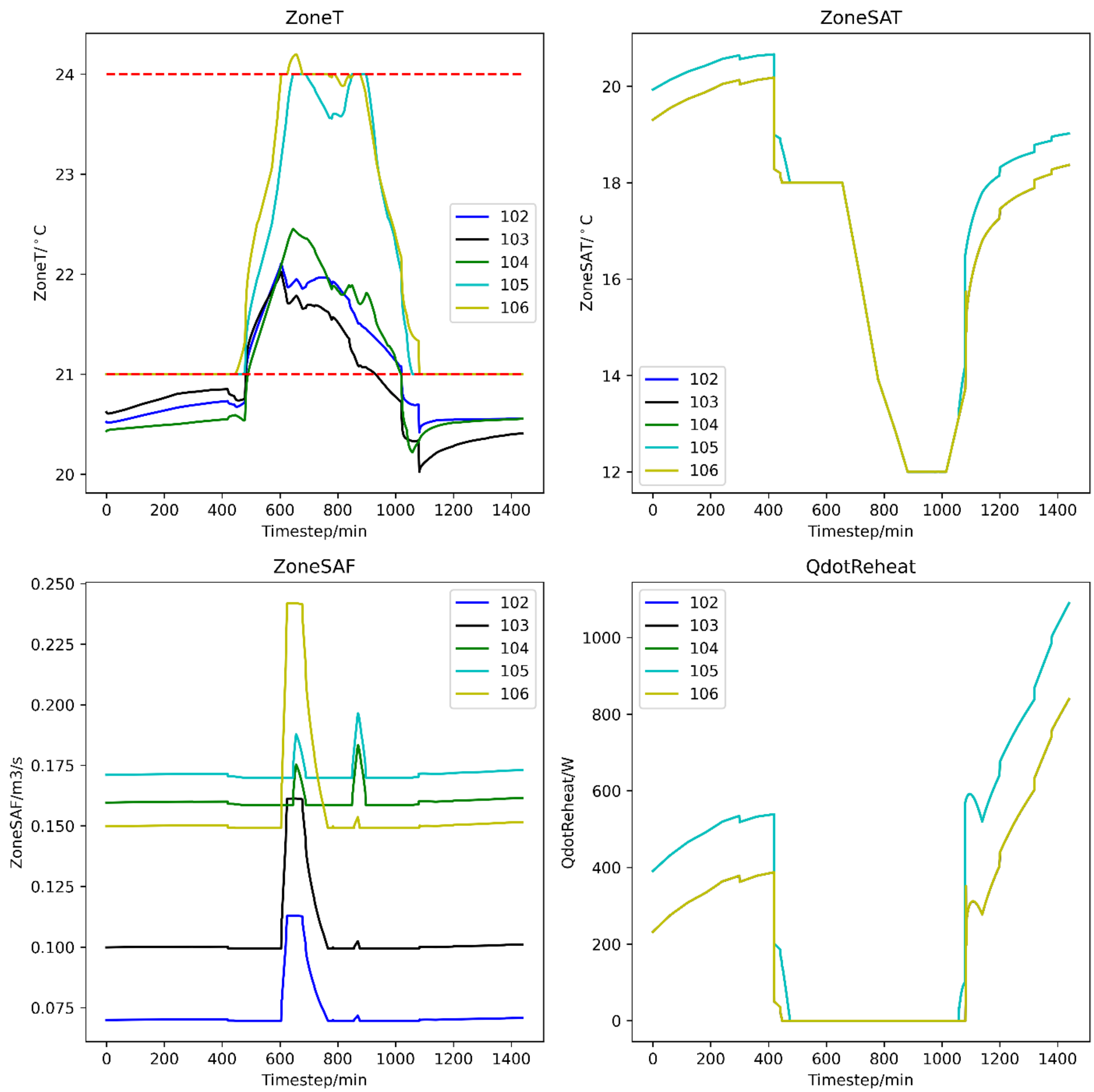

Figure A.35. Zone profiles on the first floor in the winter (A18).

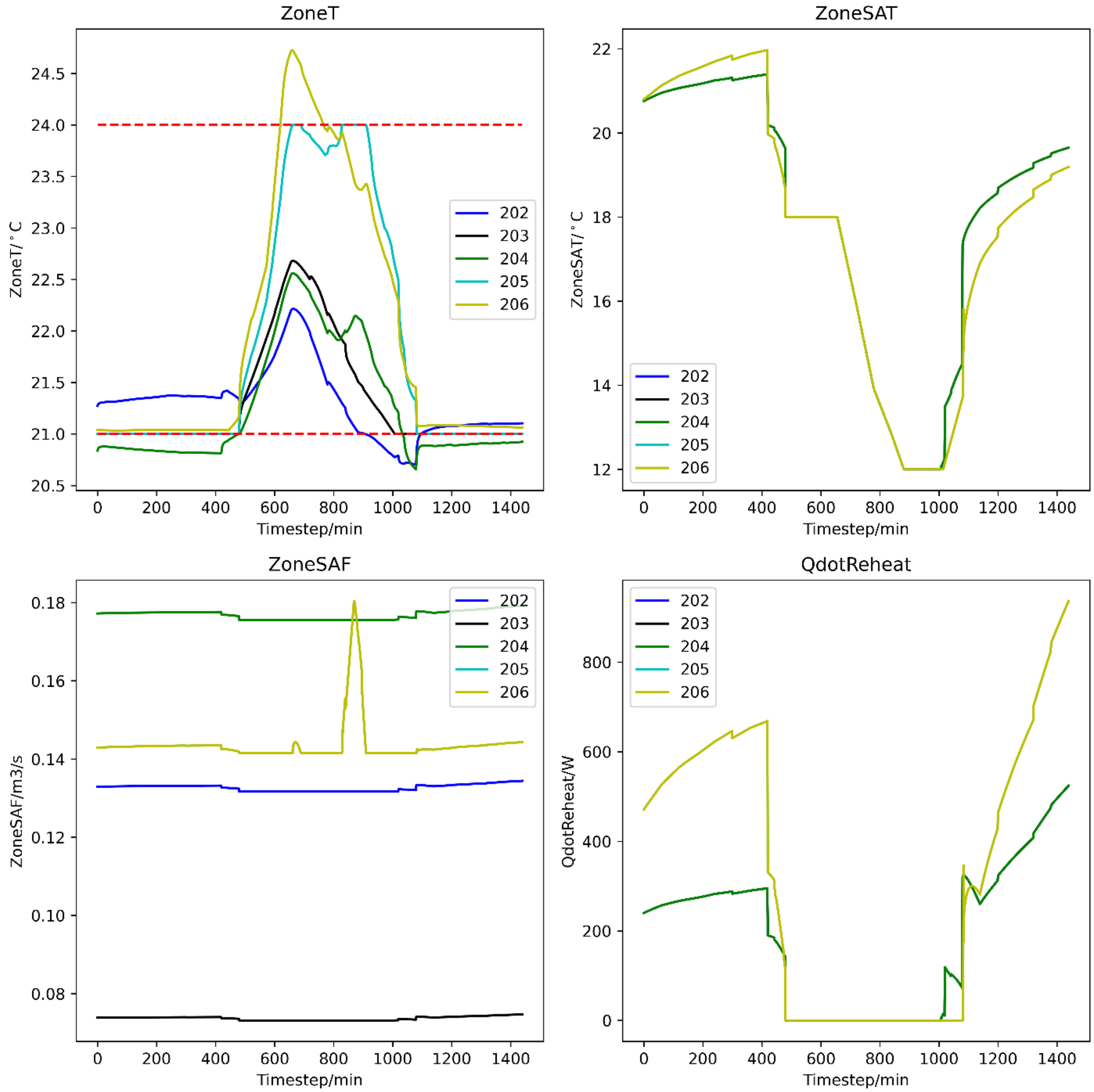

Figure A.36. Zone profiles on the second floor in the winter (A18).

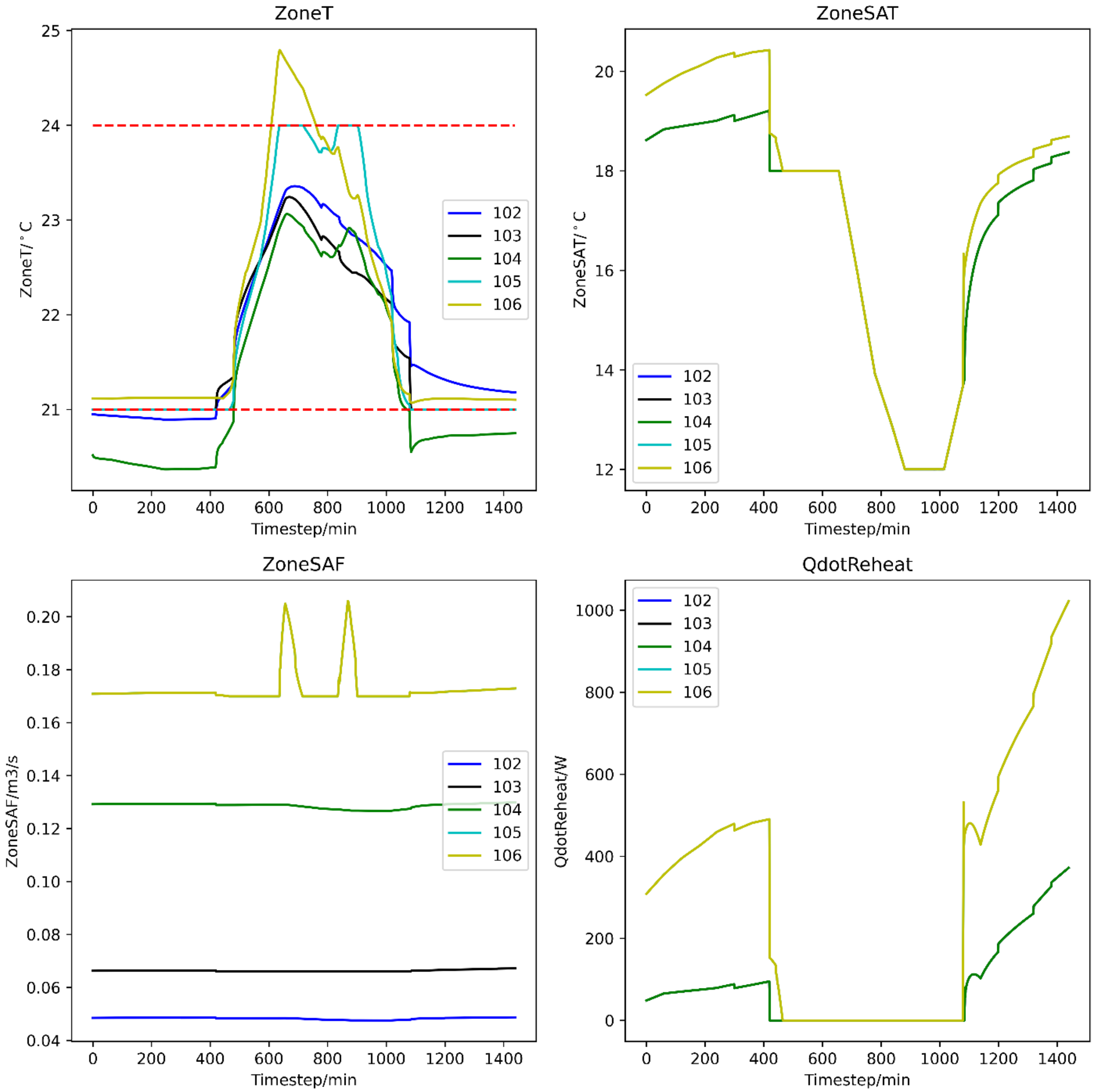

Figure A.37. Zone profiles on the first floor in the winter (A19).

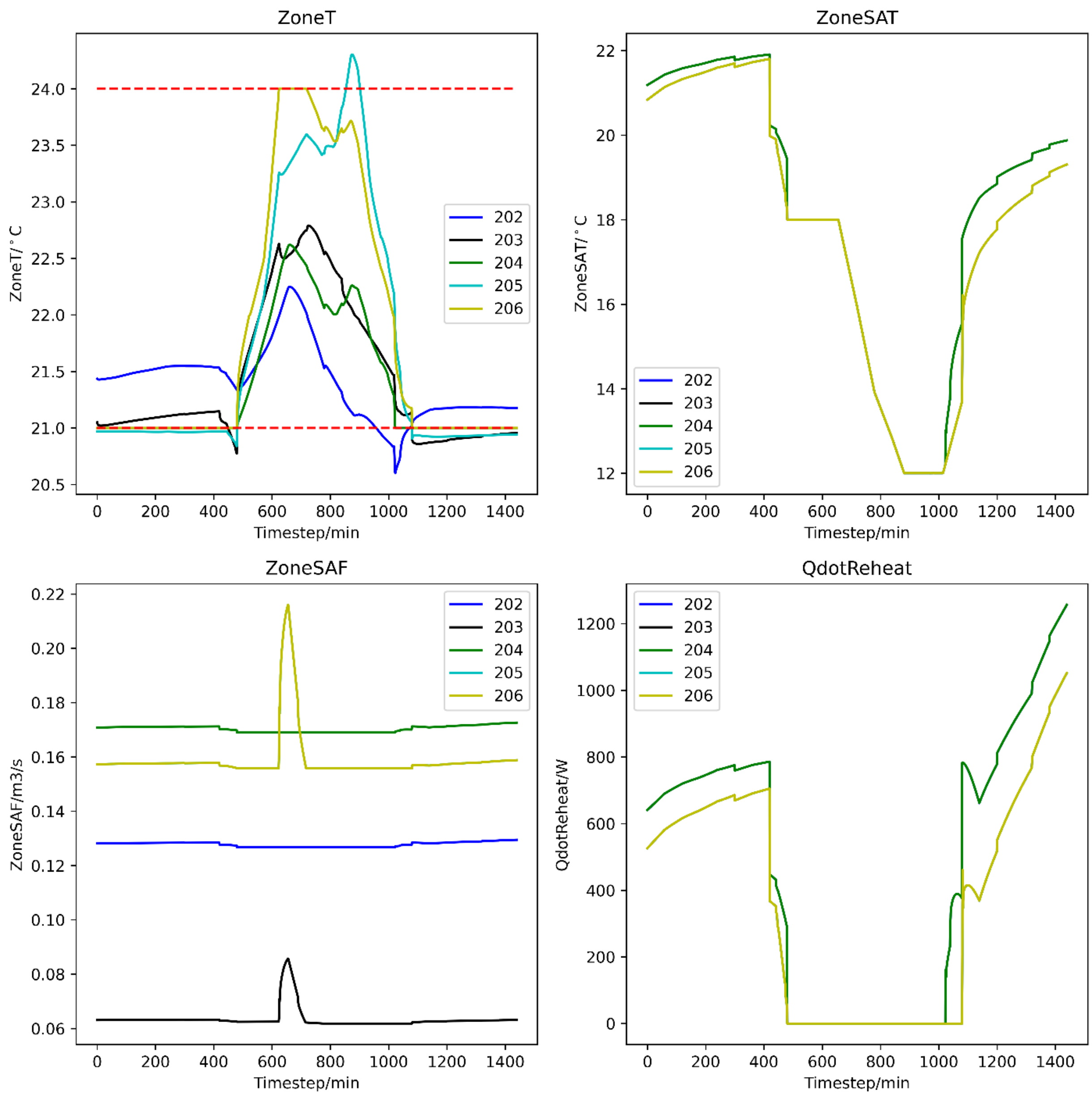

Figure A.38. Zone profiles on the second floor in the winter (A19).

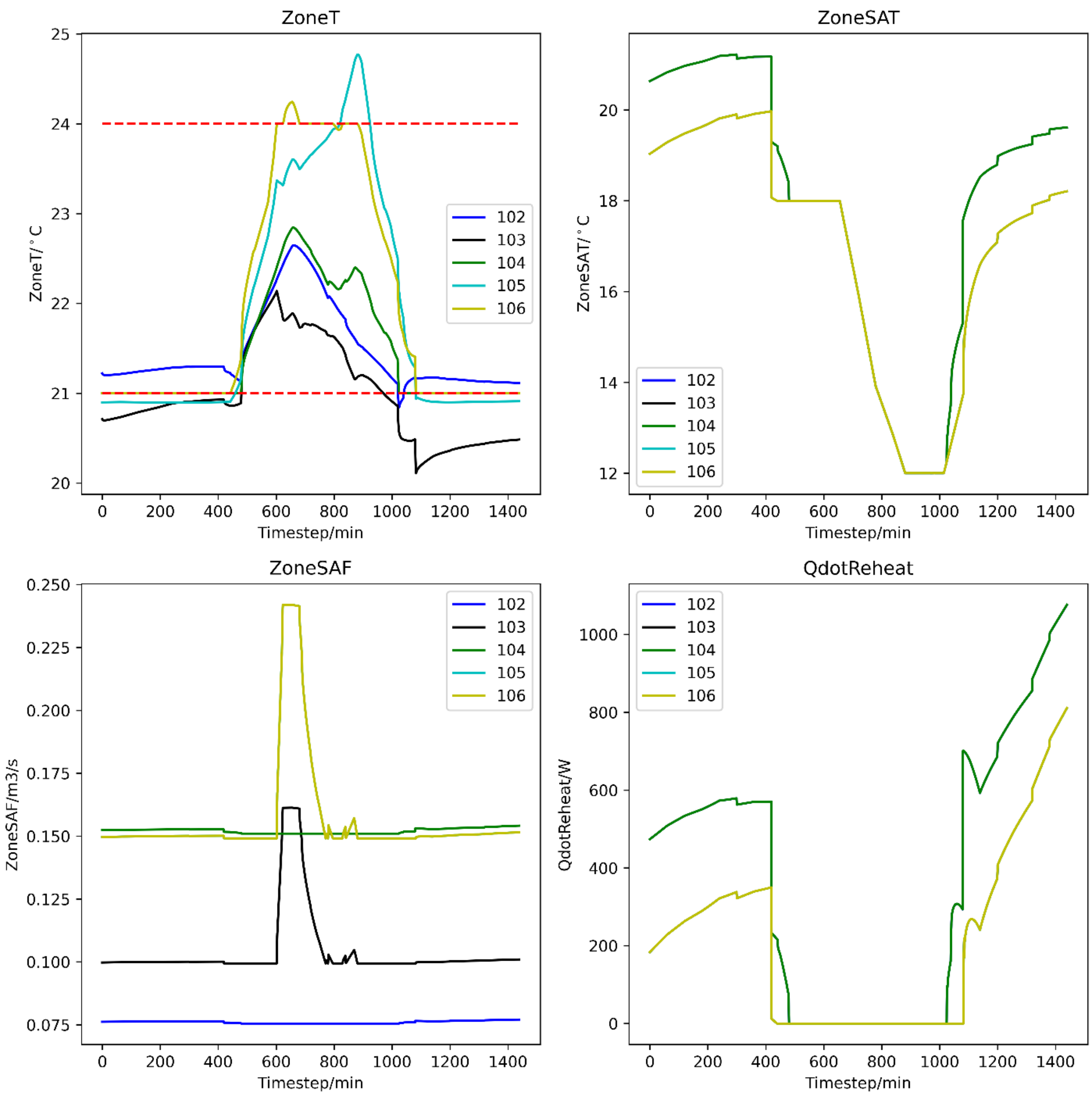

Figure A.39. Zone profiles on the first floor in the winter (A20).

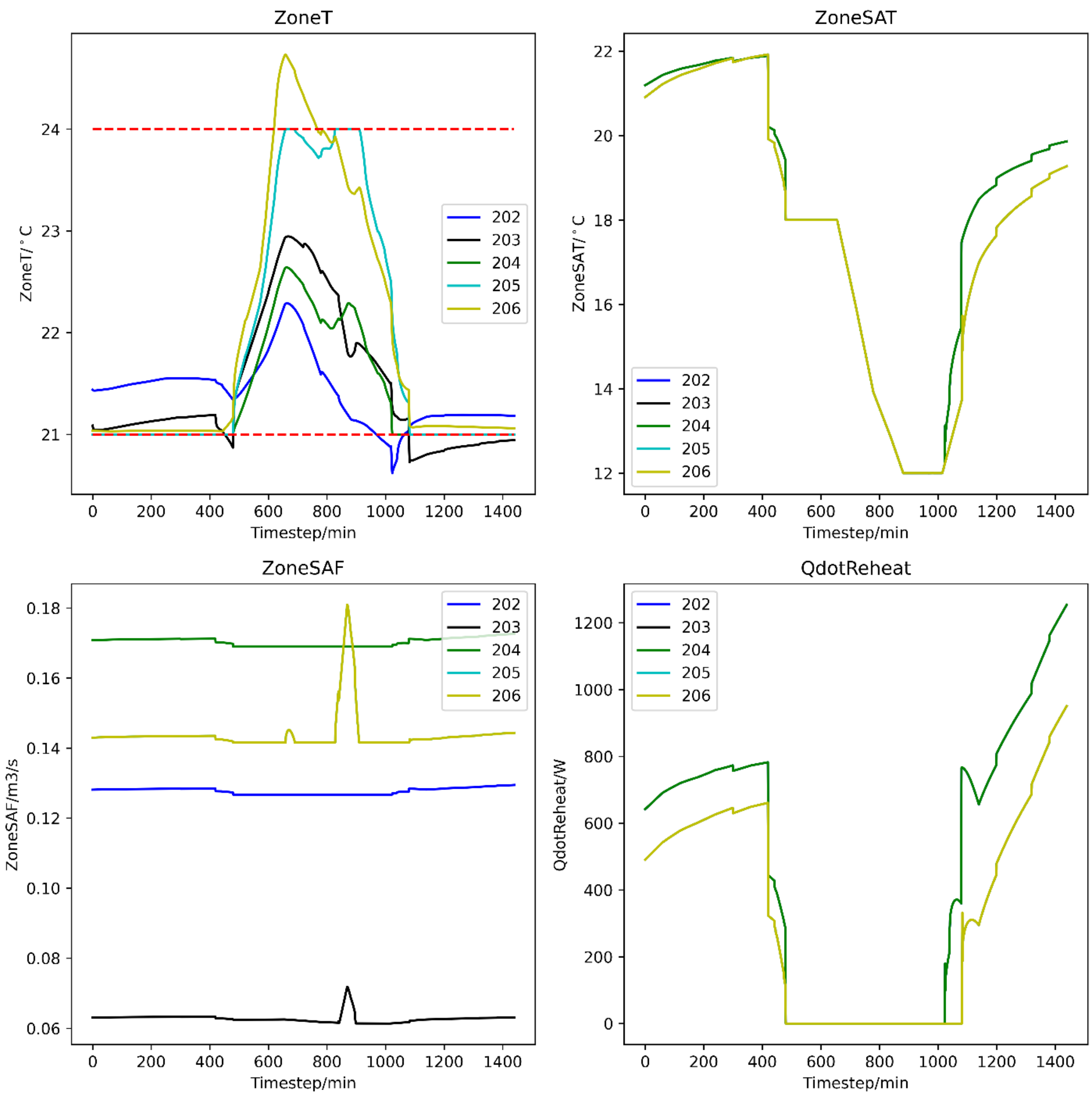

Figure A.40. Zone profiles on the second floor in the winter (A20).

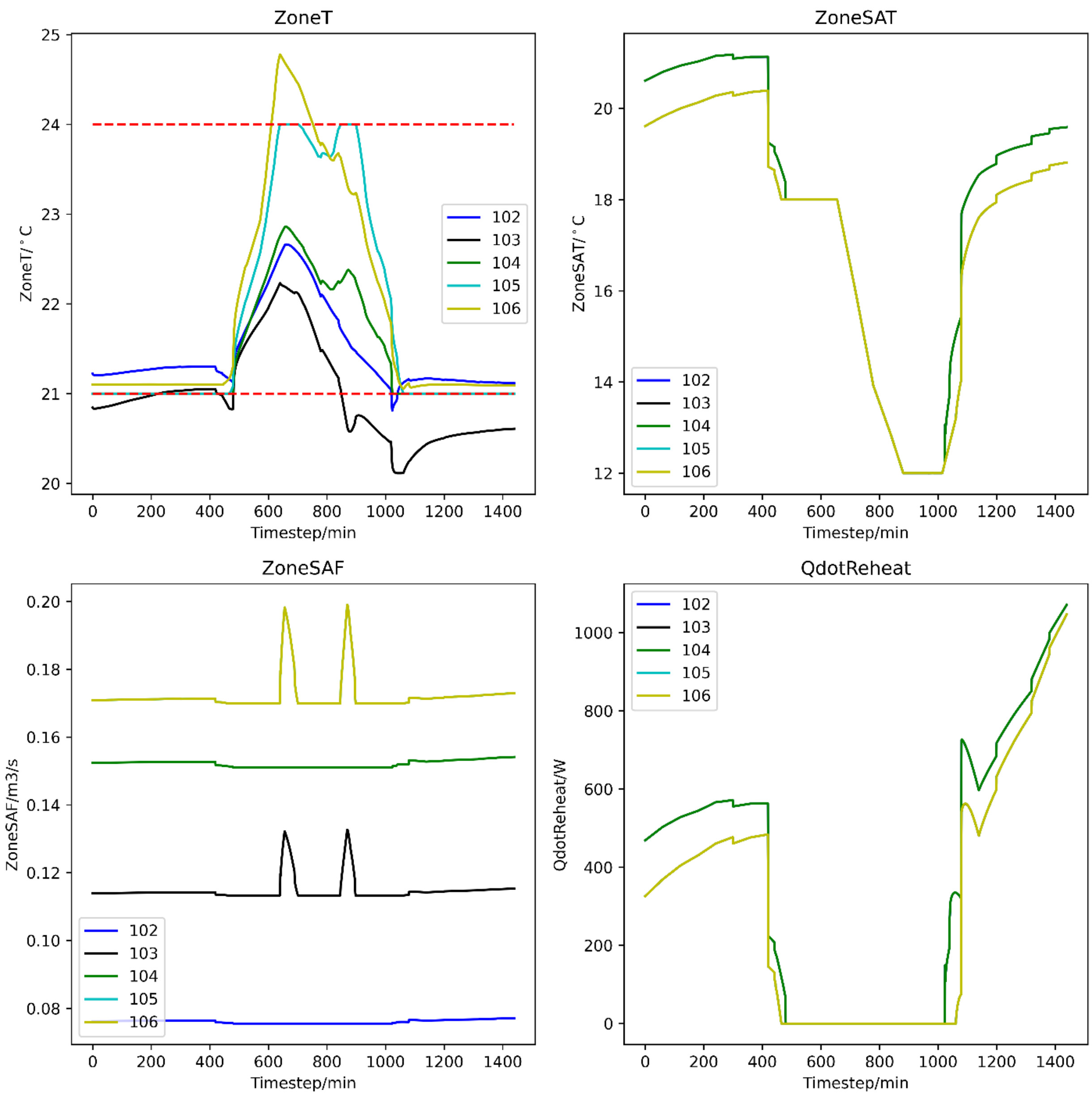

Figure A.41. Zone profiles on the first floor in the winter (A21).

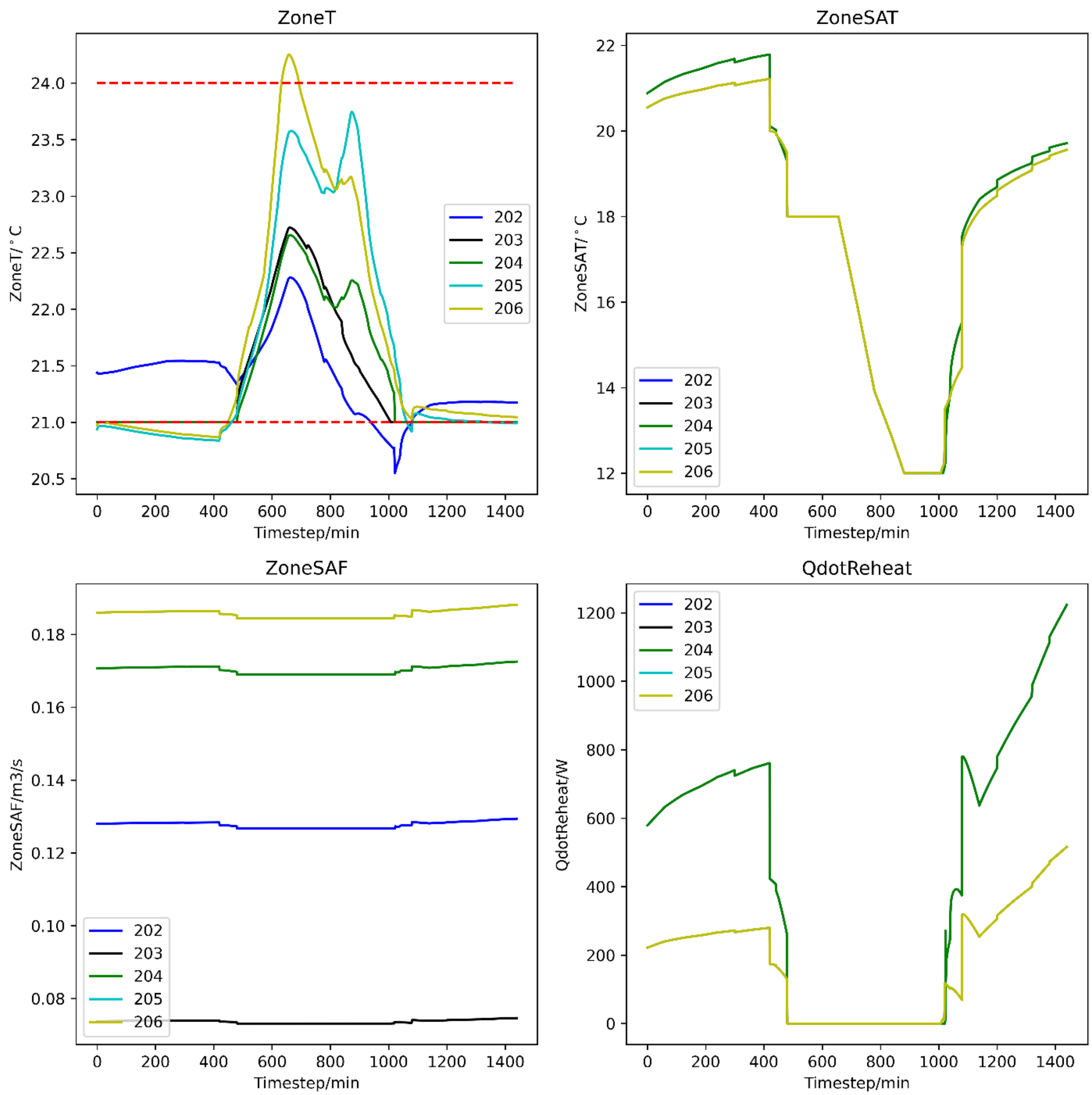

Figure A.42. Zone profiles on the second floor in the winter (A21).

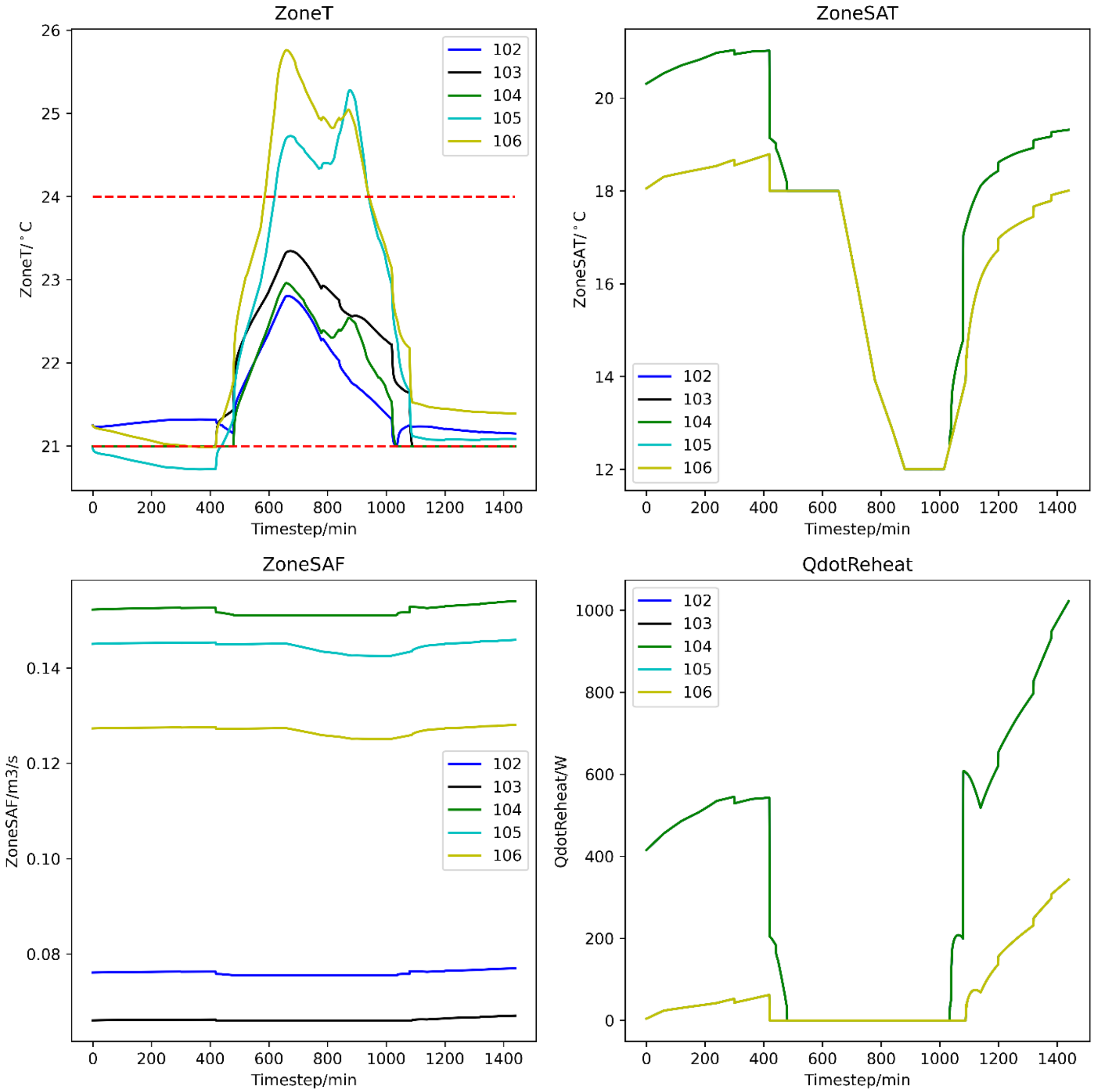

Figure A.43. Zone profiles on the first floor in the winter (A22).

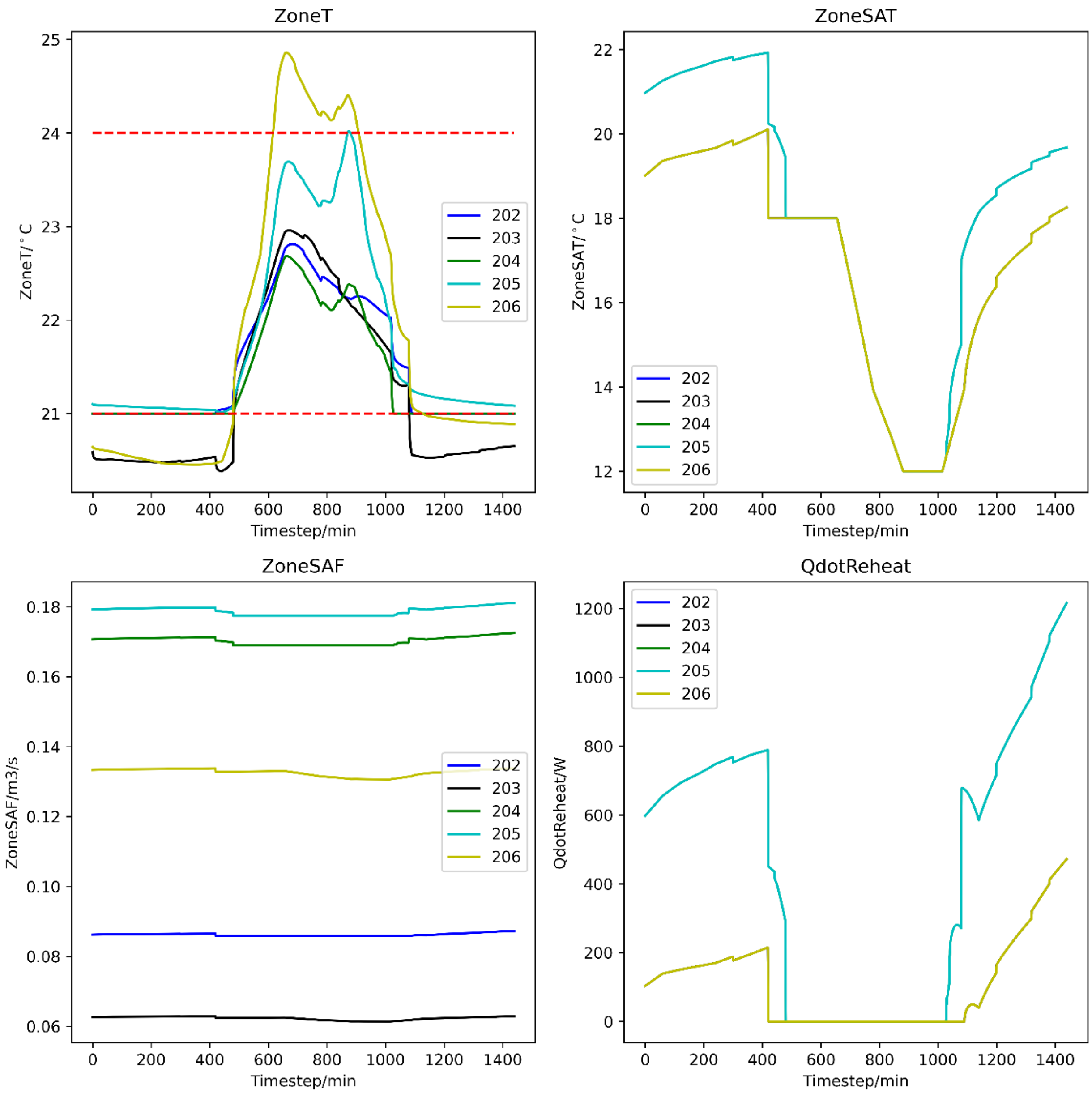

Figure A.44. Zone profiles on the second floor in the winter (A22),

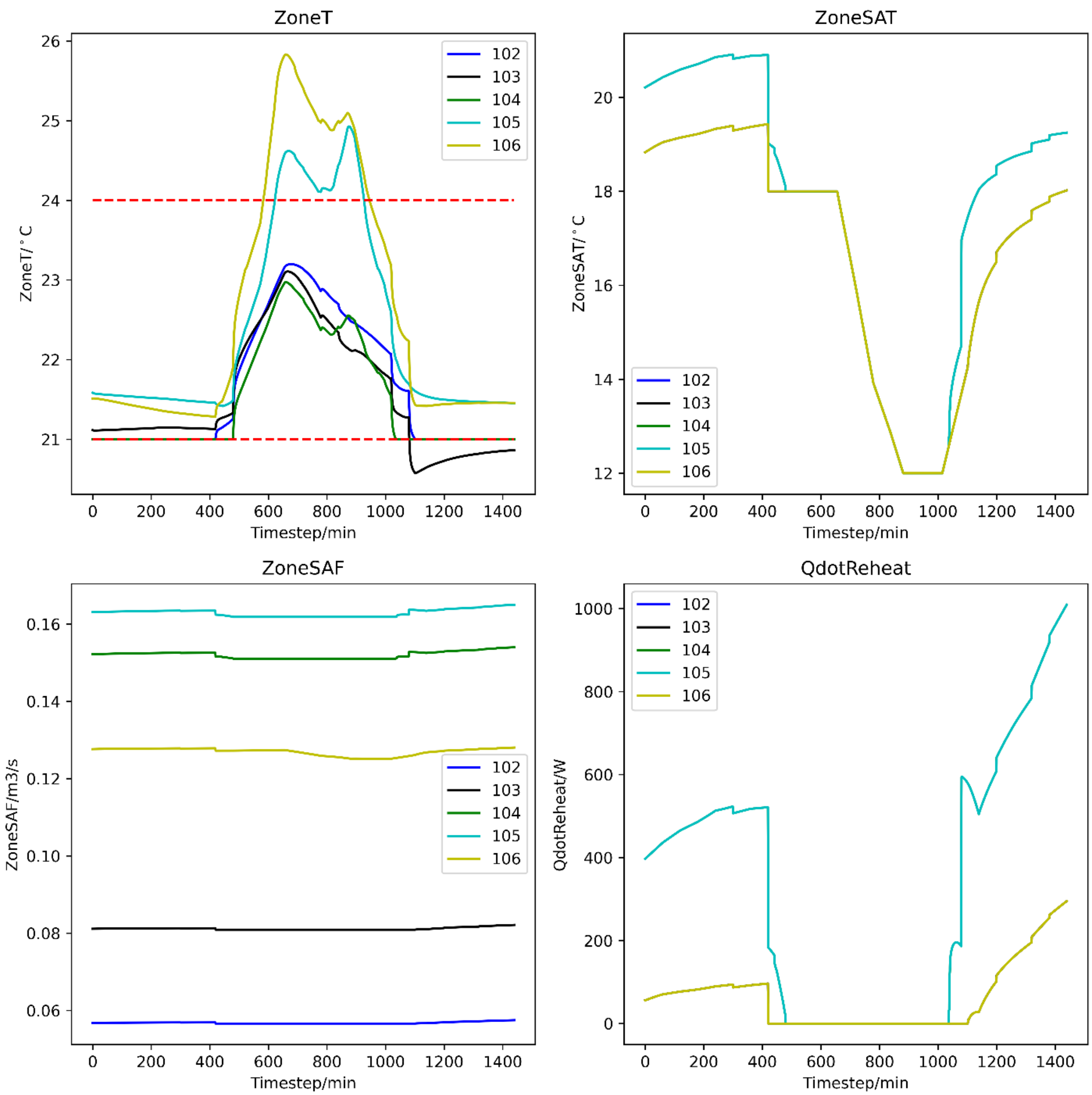

Figure A.45. Zone profiles on the first floor in the winter (A23).

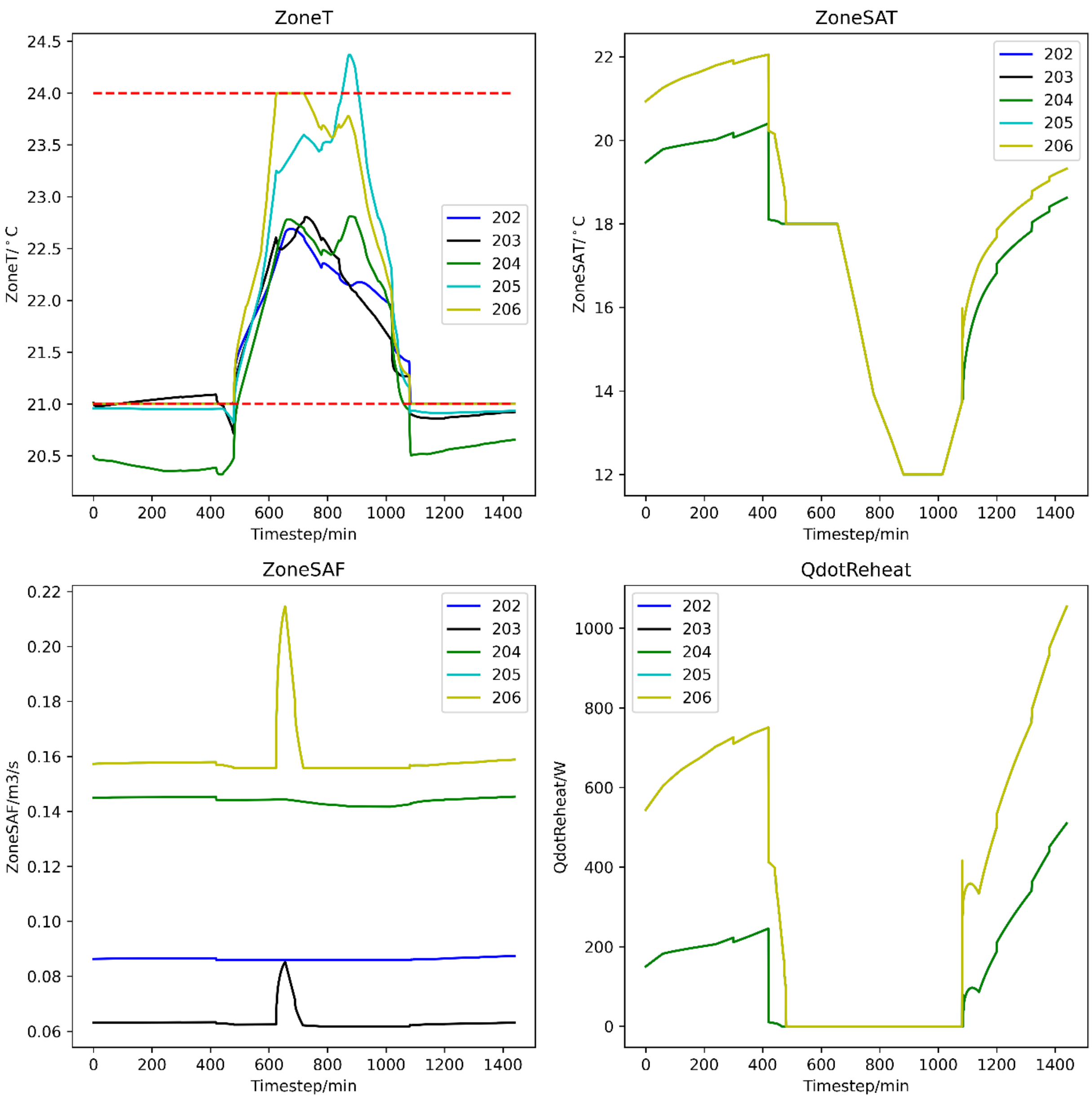

Figure A.46. Zone profiles on the second floor in the winter (A23).

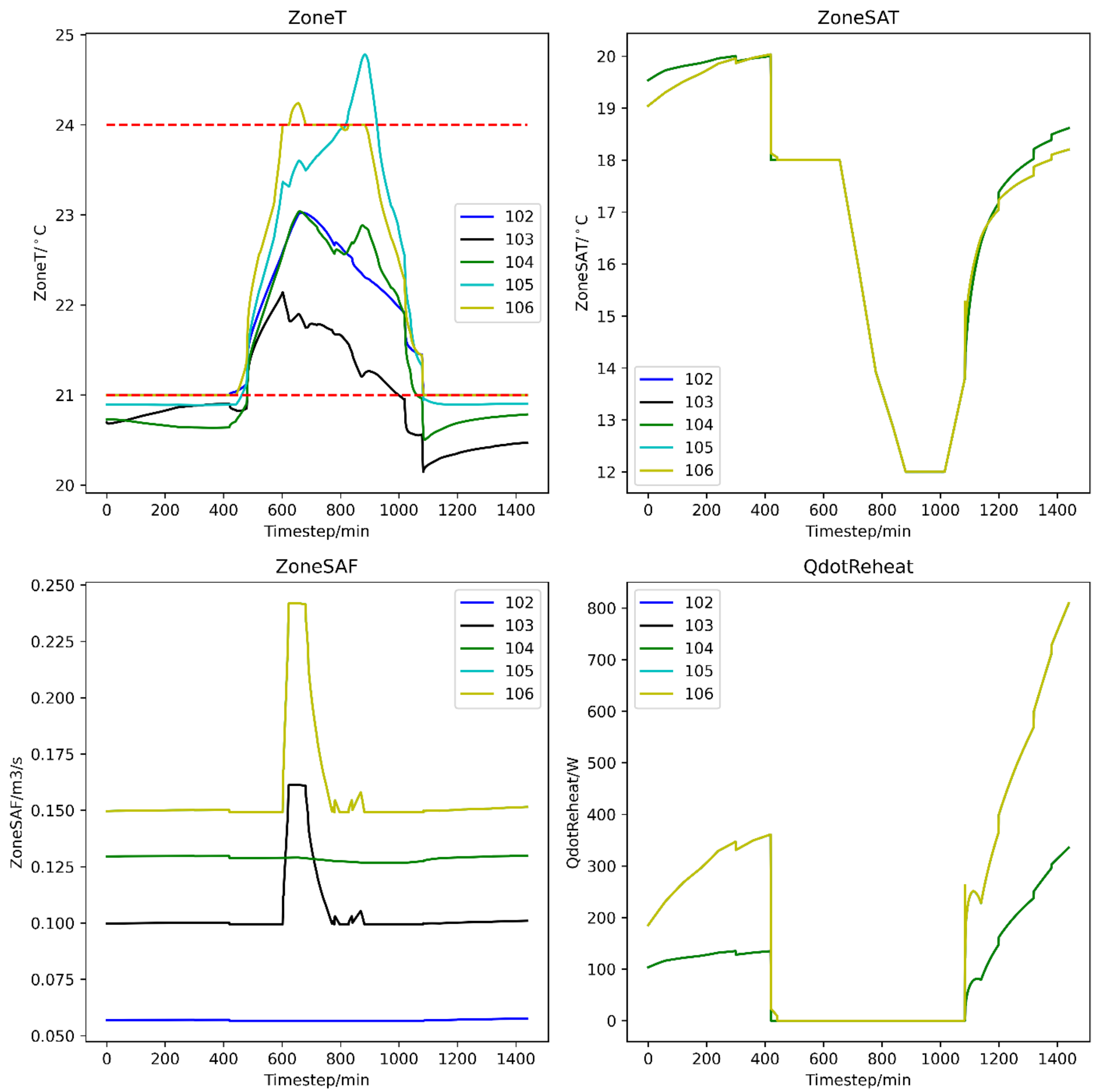

Figure A.47. Zone profiles on the first floor in the winter (A24).

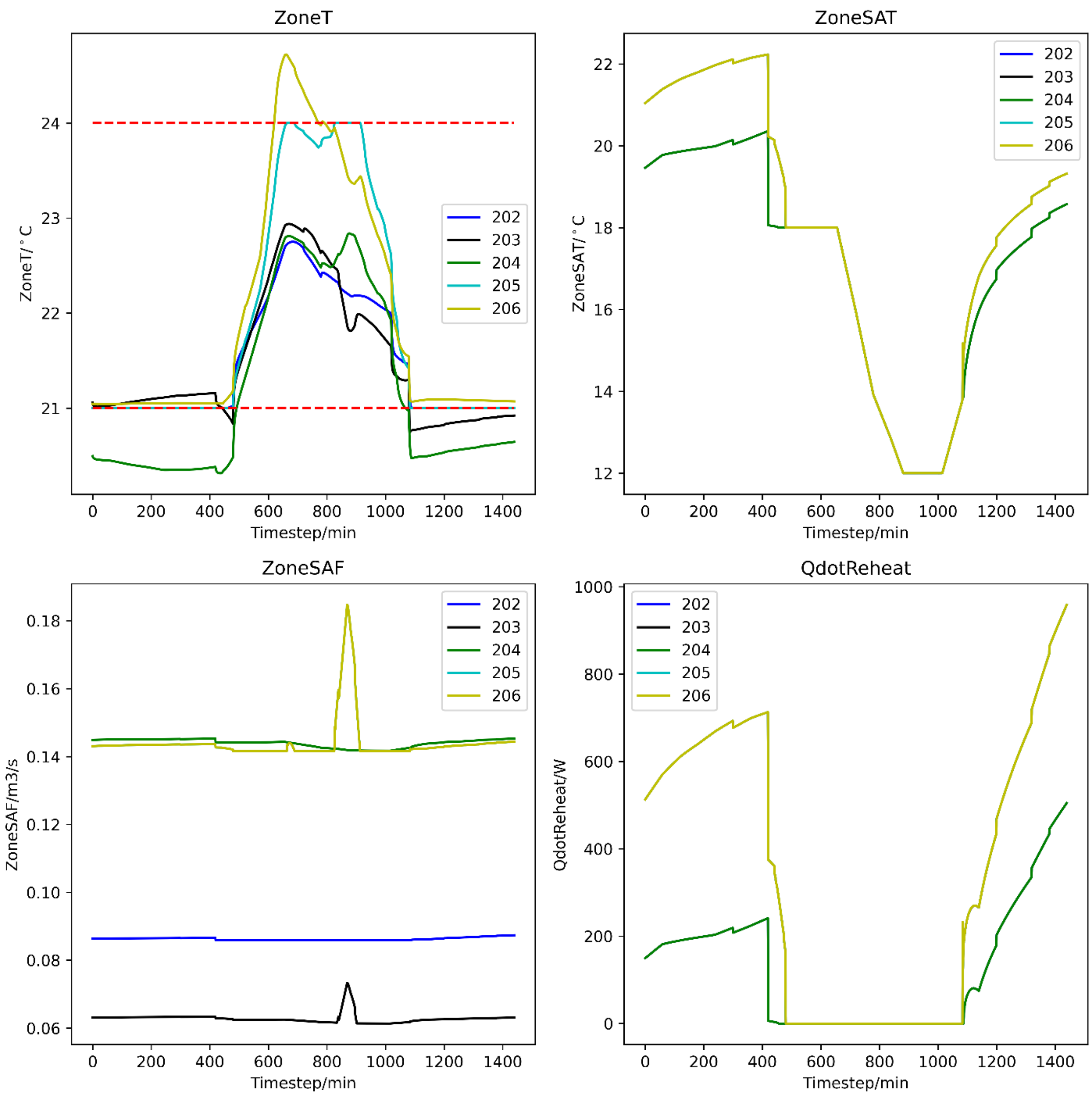

Figure A.48. Zone profiles on the second floor in the winter (A24).

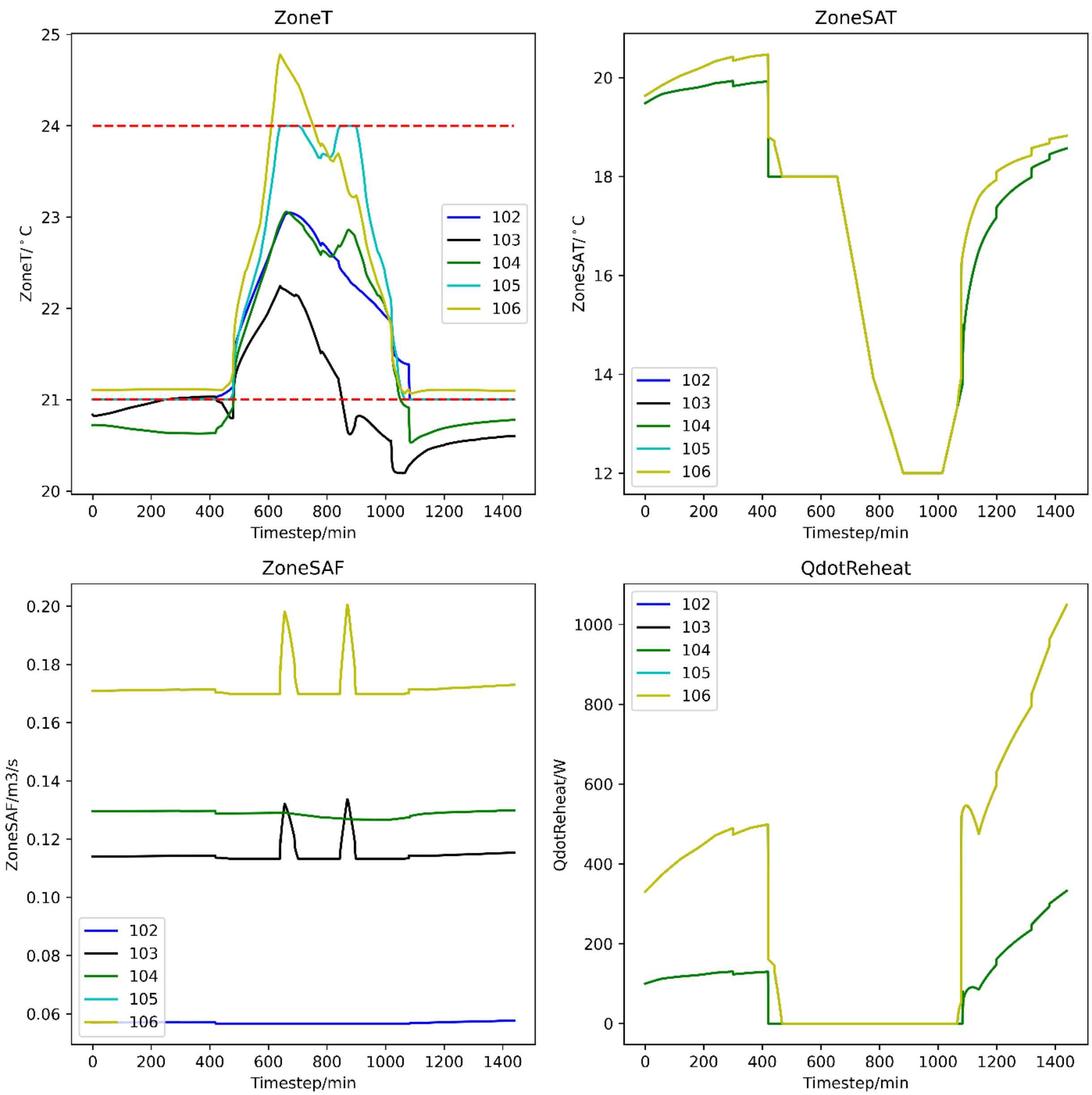

Figure A.49. Zone profiles on the first floor in the winter (A25).

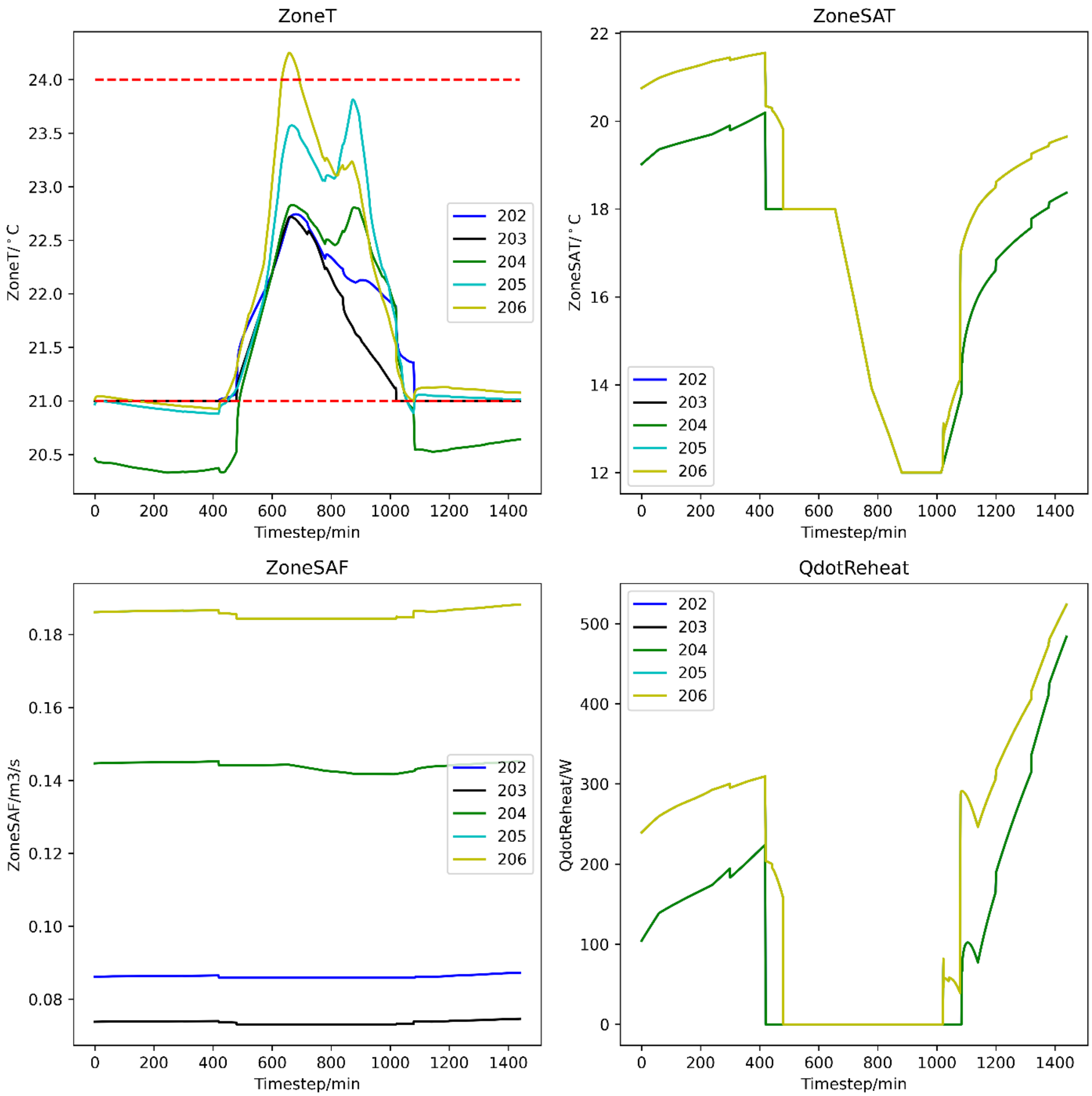

Figure A.50. Zone profiles on the second floor in the winter (A25).

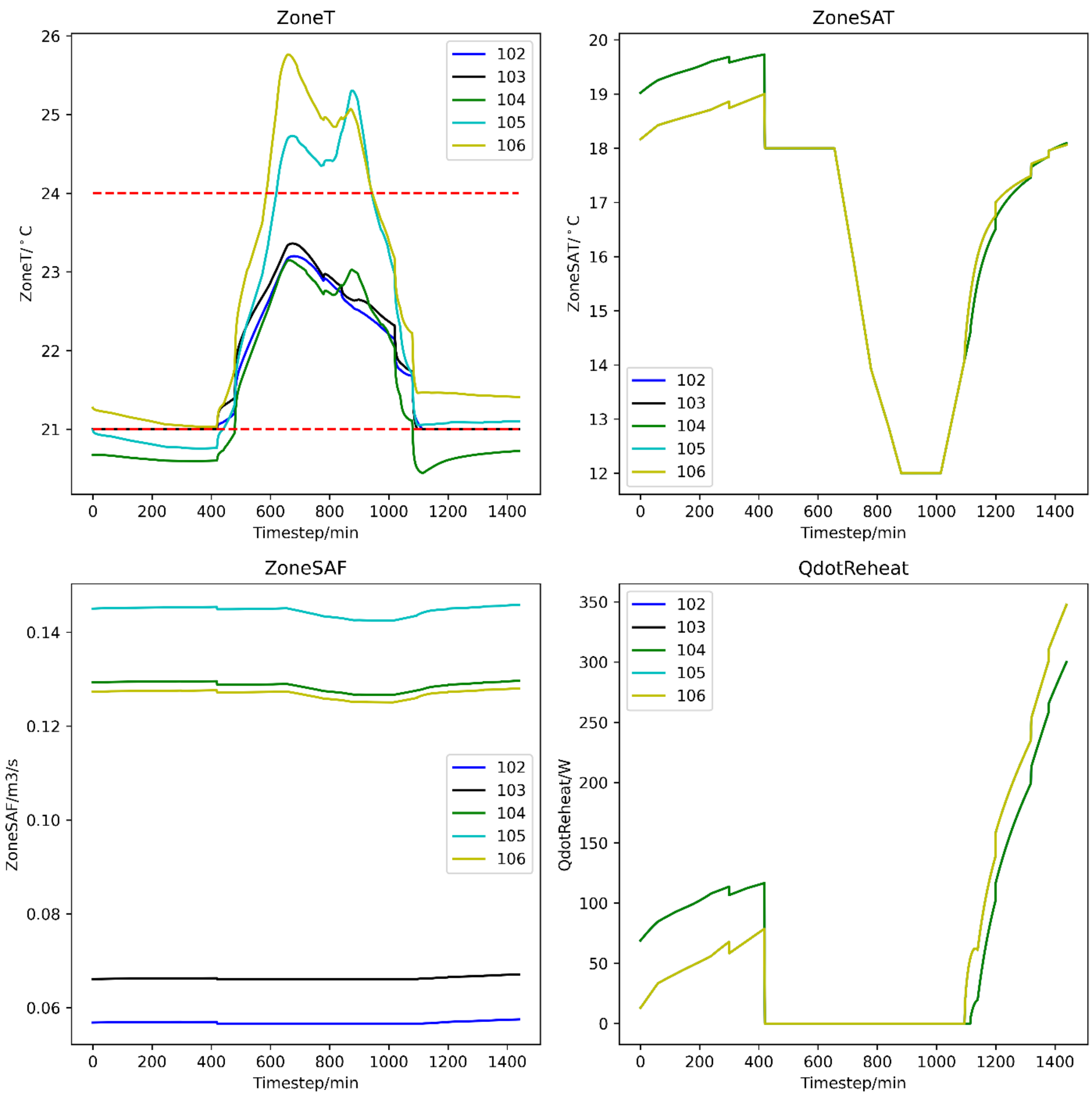

Figure A.51. Zone profiles on the first floor in the winter (A26).

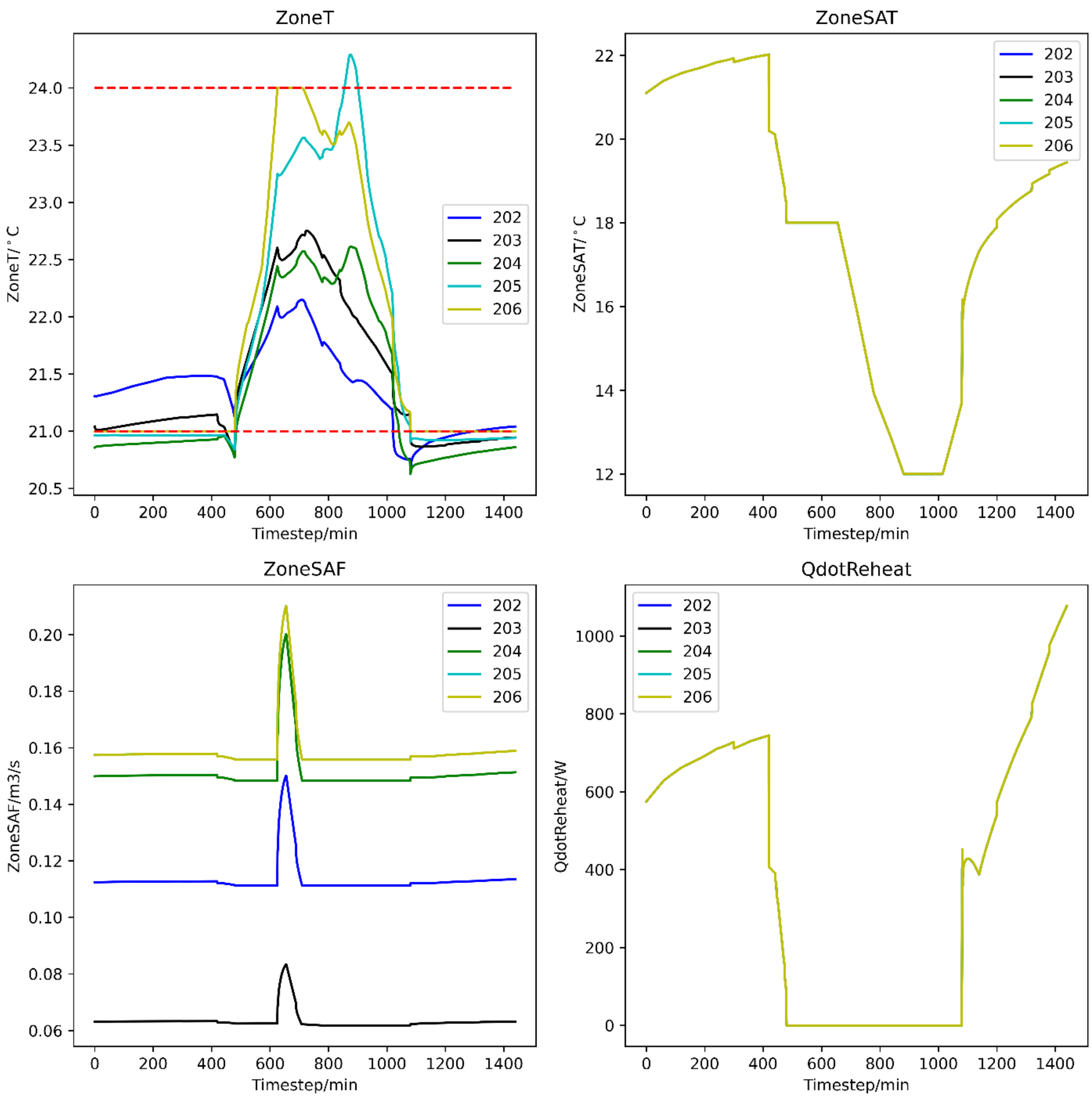

Figure A.52. Zone profiles on the second floor in the winter (A26).

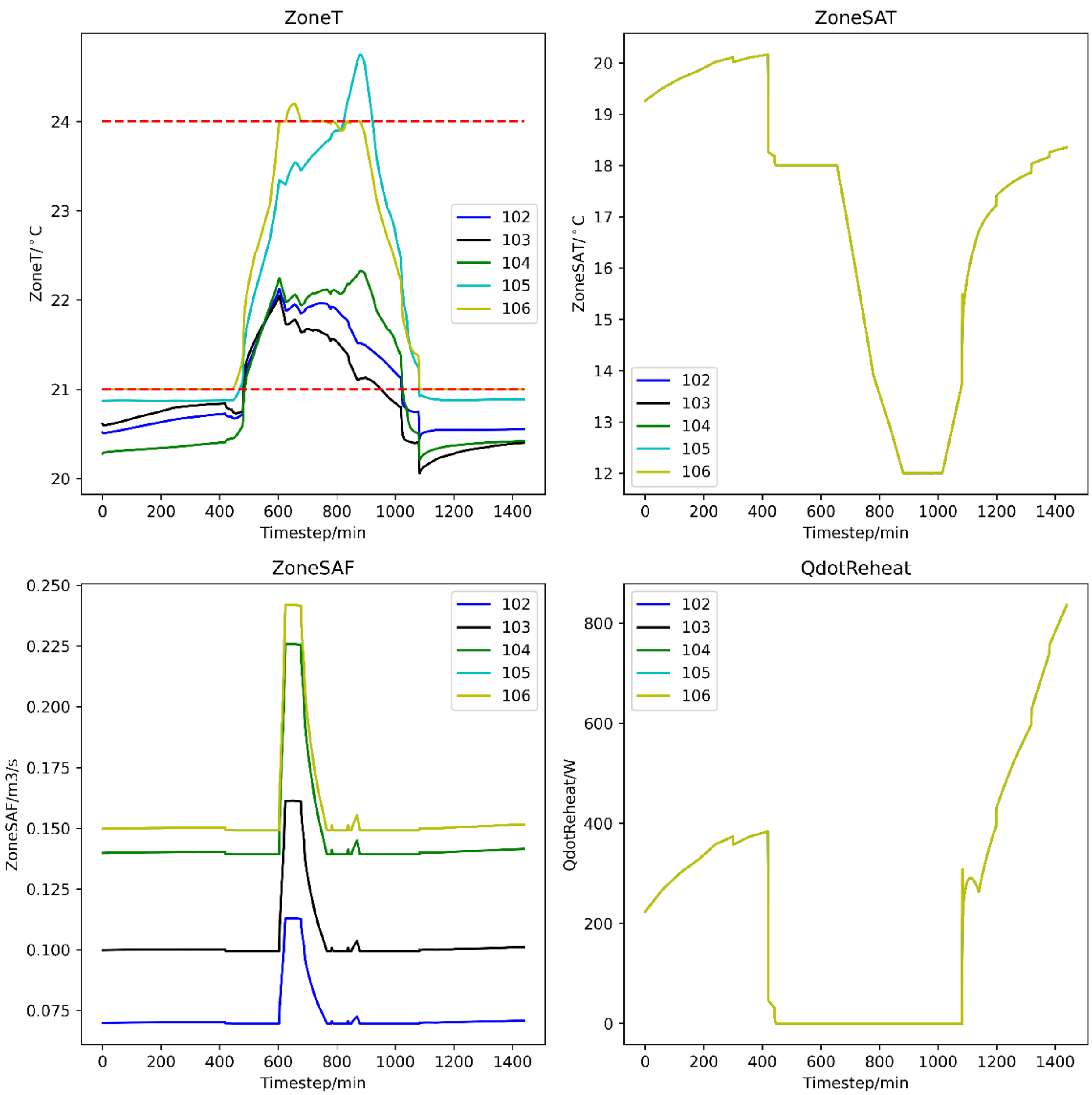

Figure A.53. Zone profiles on the first floor in the winter (A27).

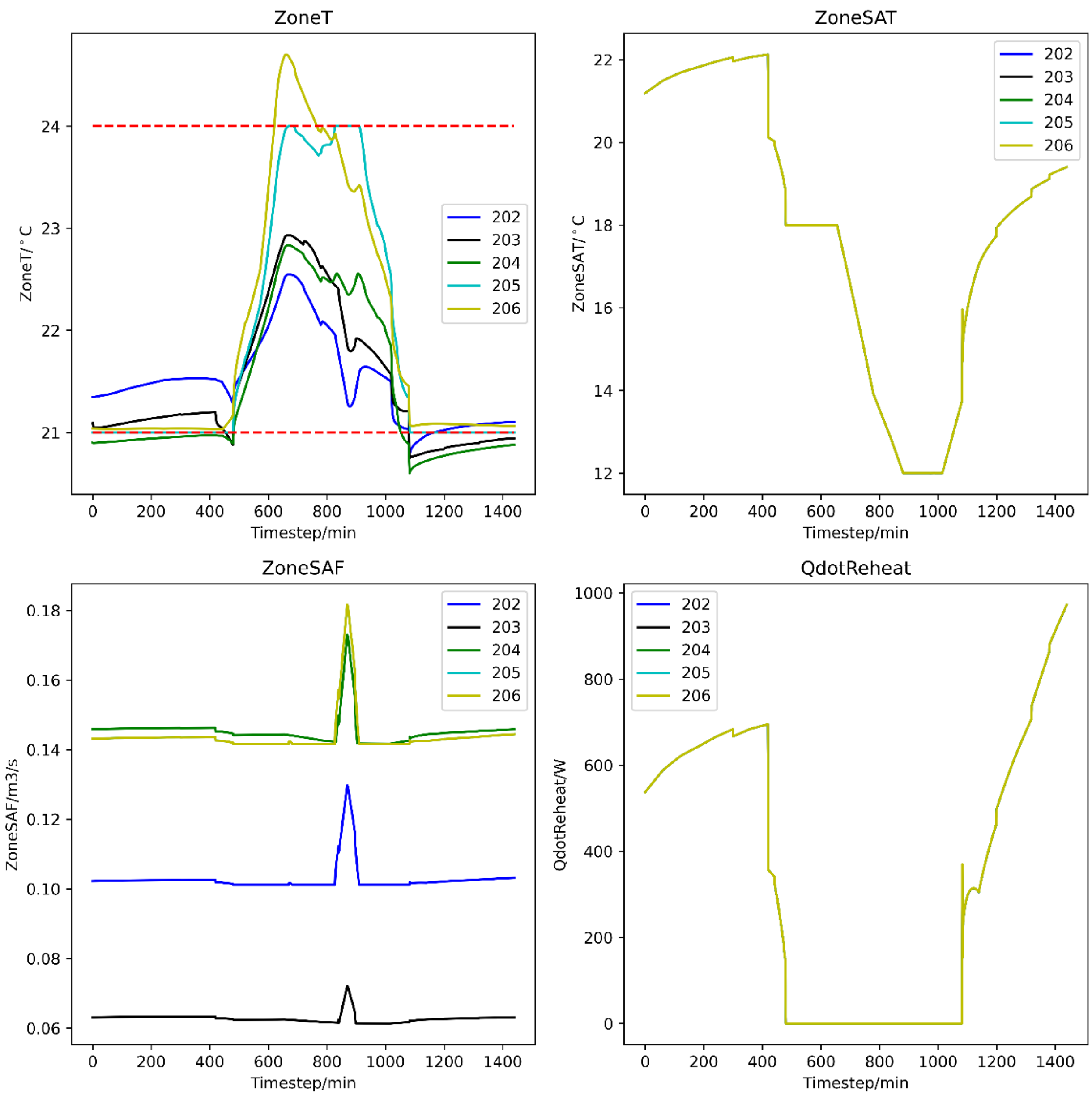

Figure A.54. Zone profiles on the second floor in the winter (A27).

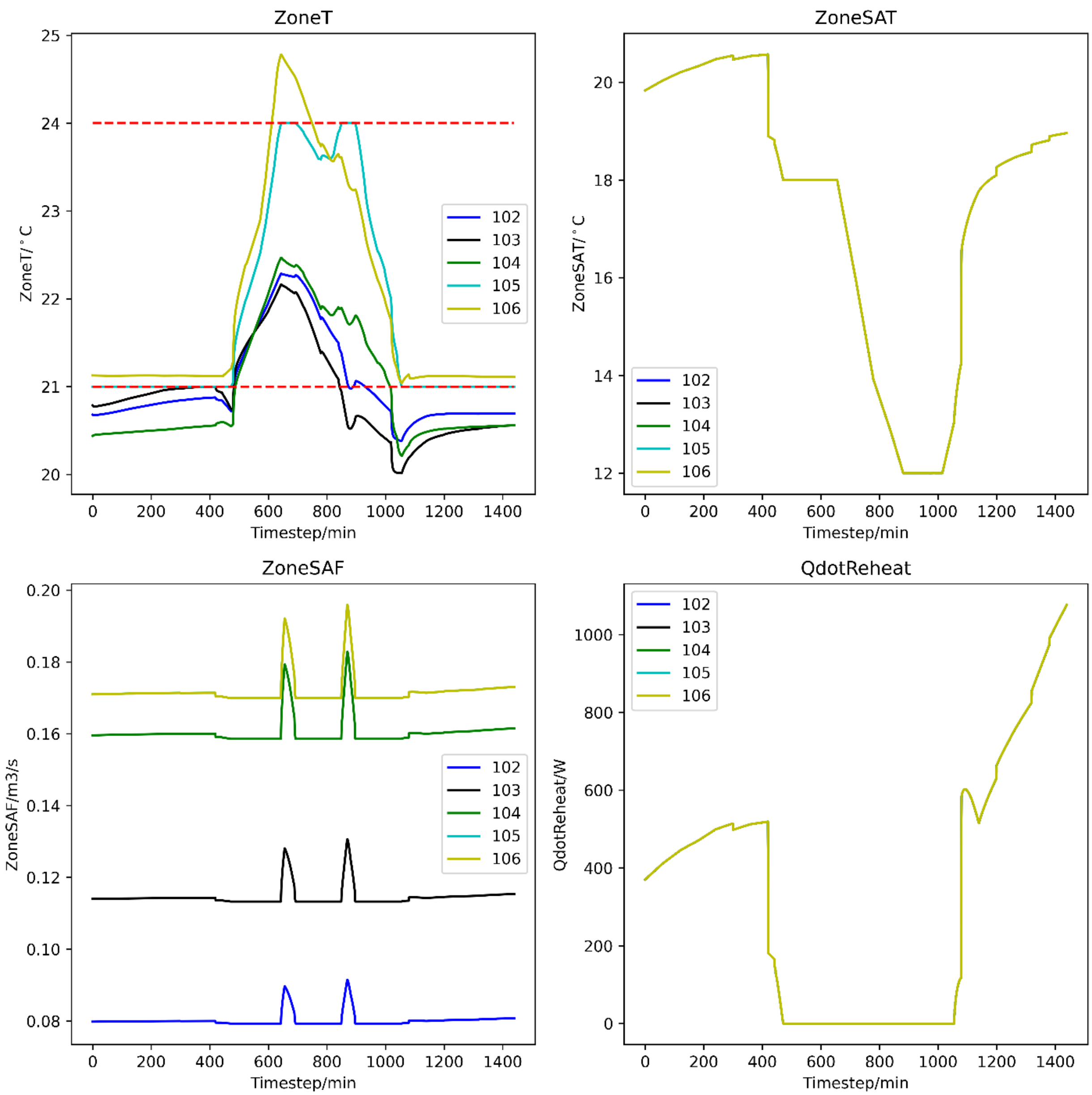

Figure A.55. Zone profiles on the first floor in the winter (A28).

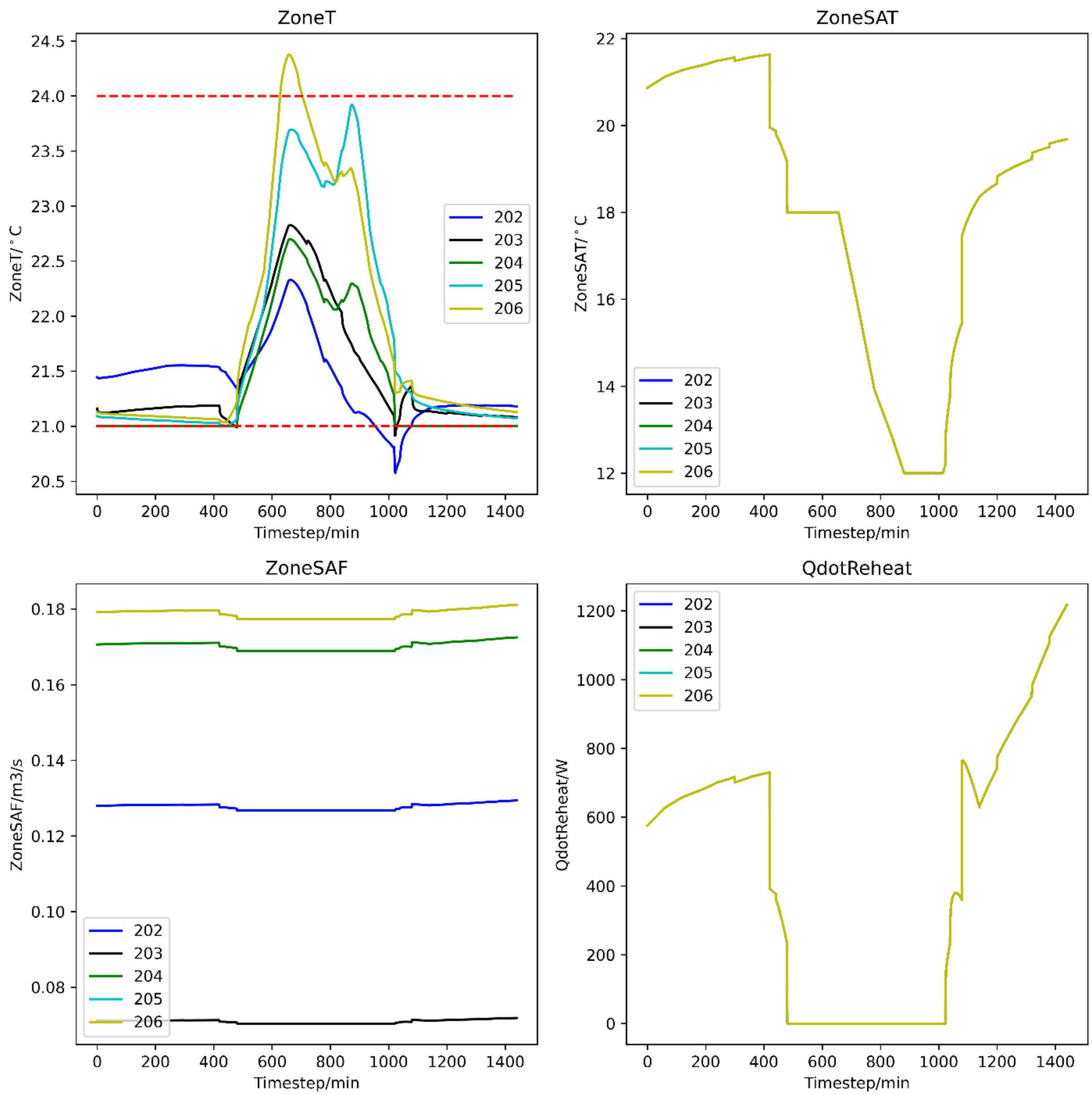

Figure A.56. Zone profiles on the second floor in the winter (A28).

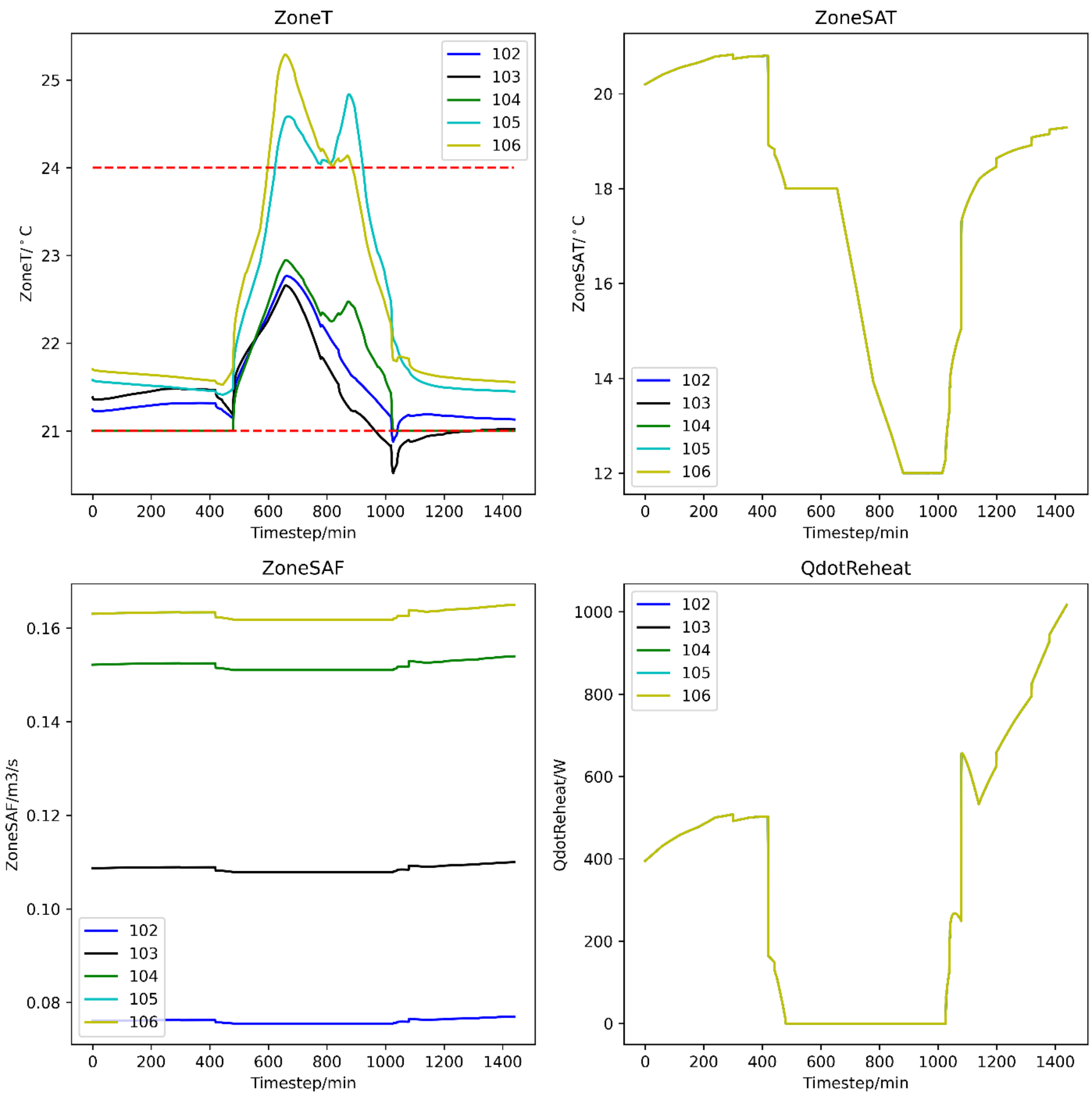

Figure A.57. Zone profiles on the first floor in the winter (A29).

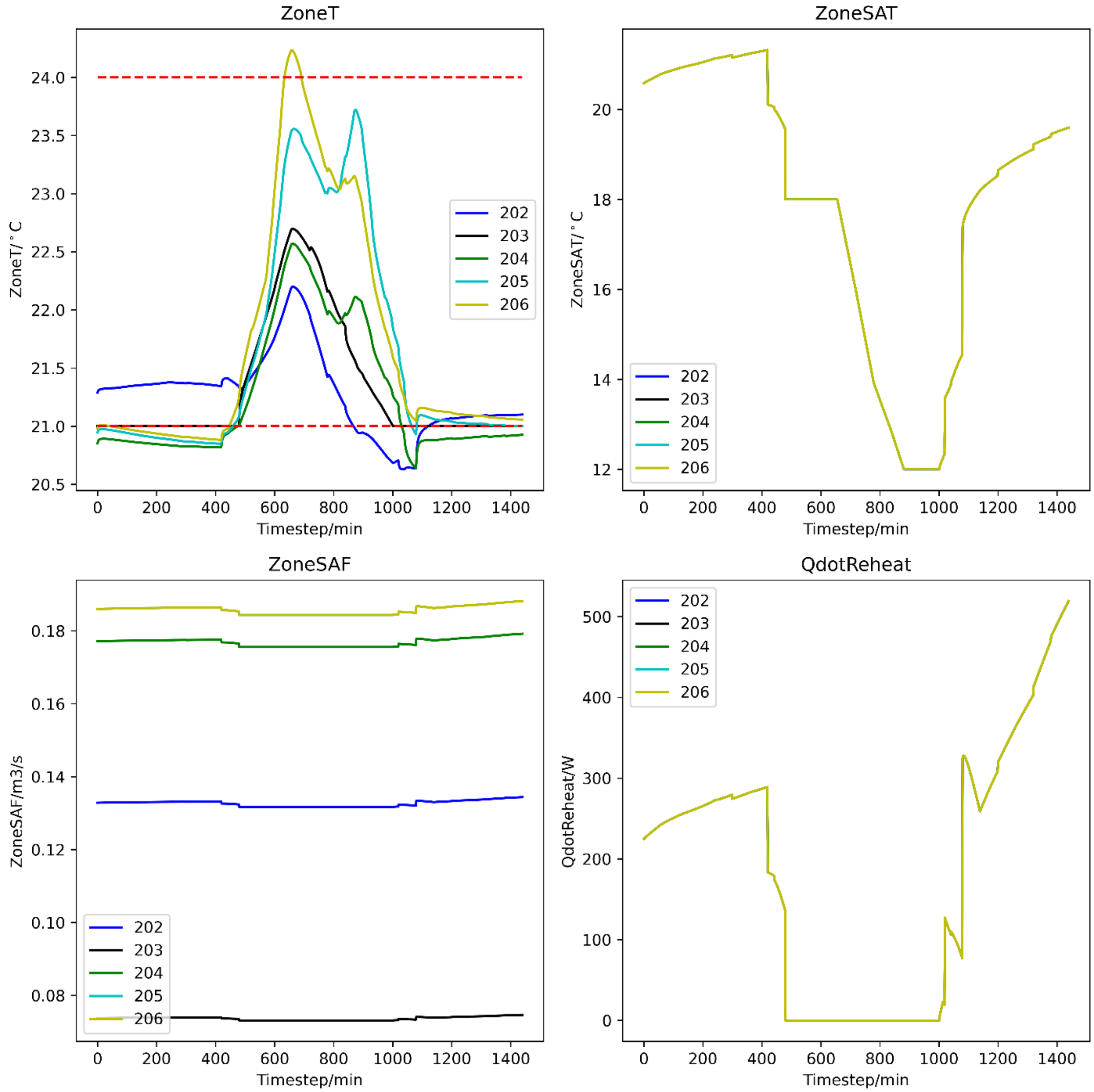

Figure A.58. Zone profiles on the second floor in the winter (A29).

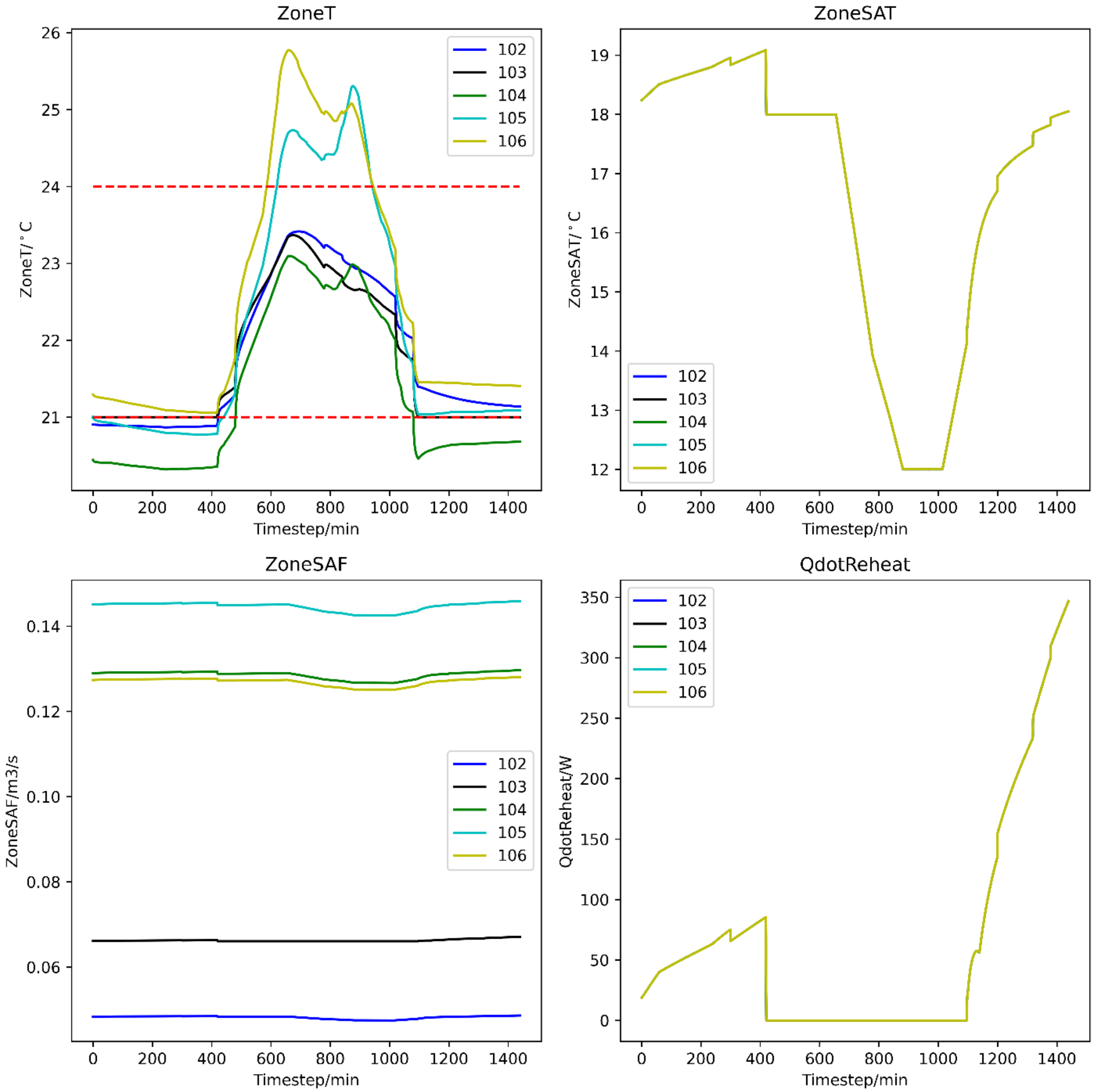

Figure A.59. Zone profiles on the first floor in the winter (A30).

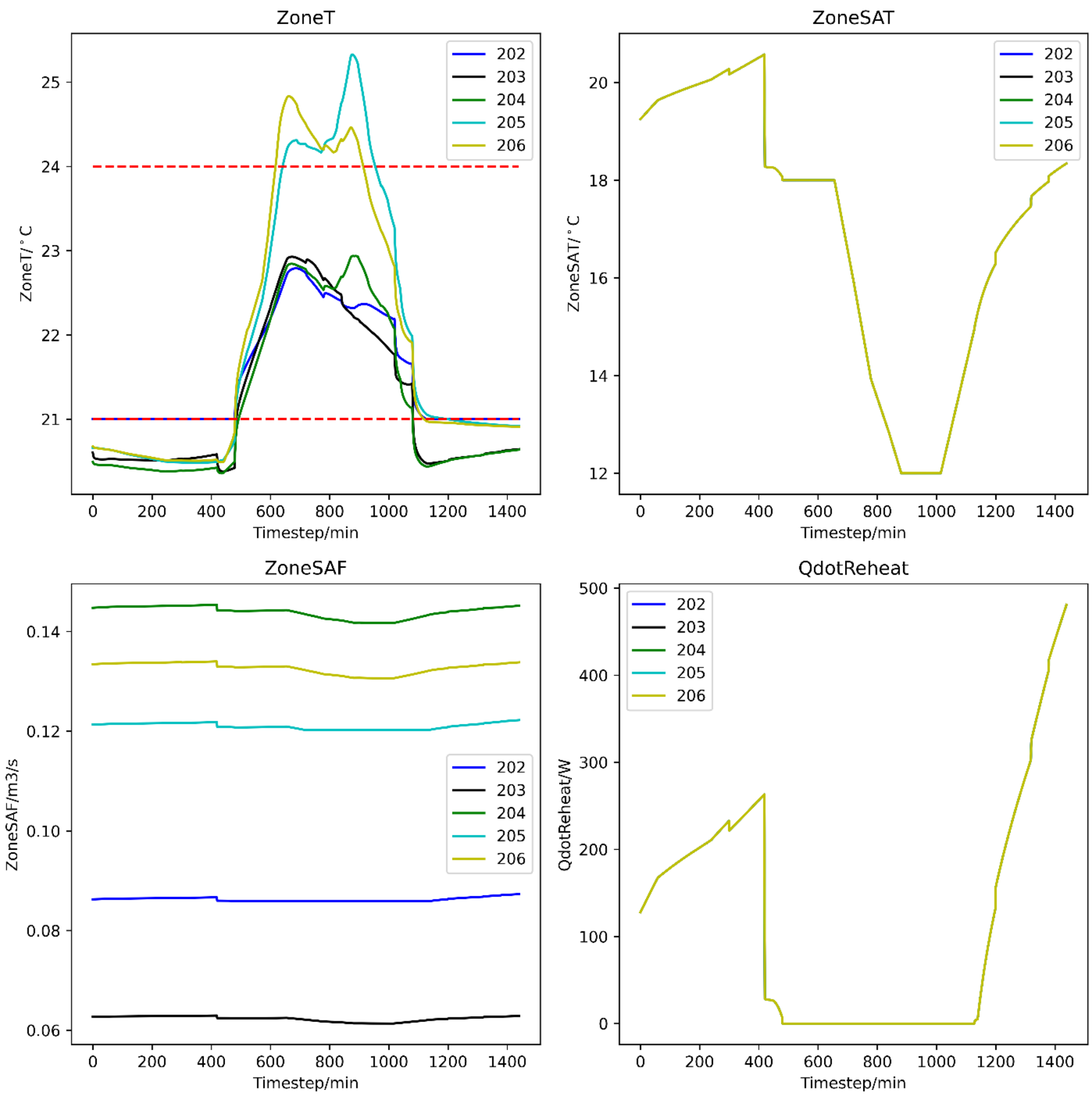

Figure A.60. Zone profiles on the second floor in the winter (A30).

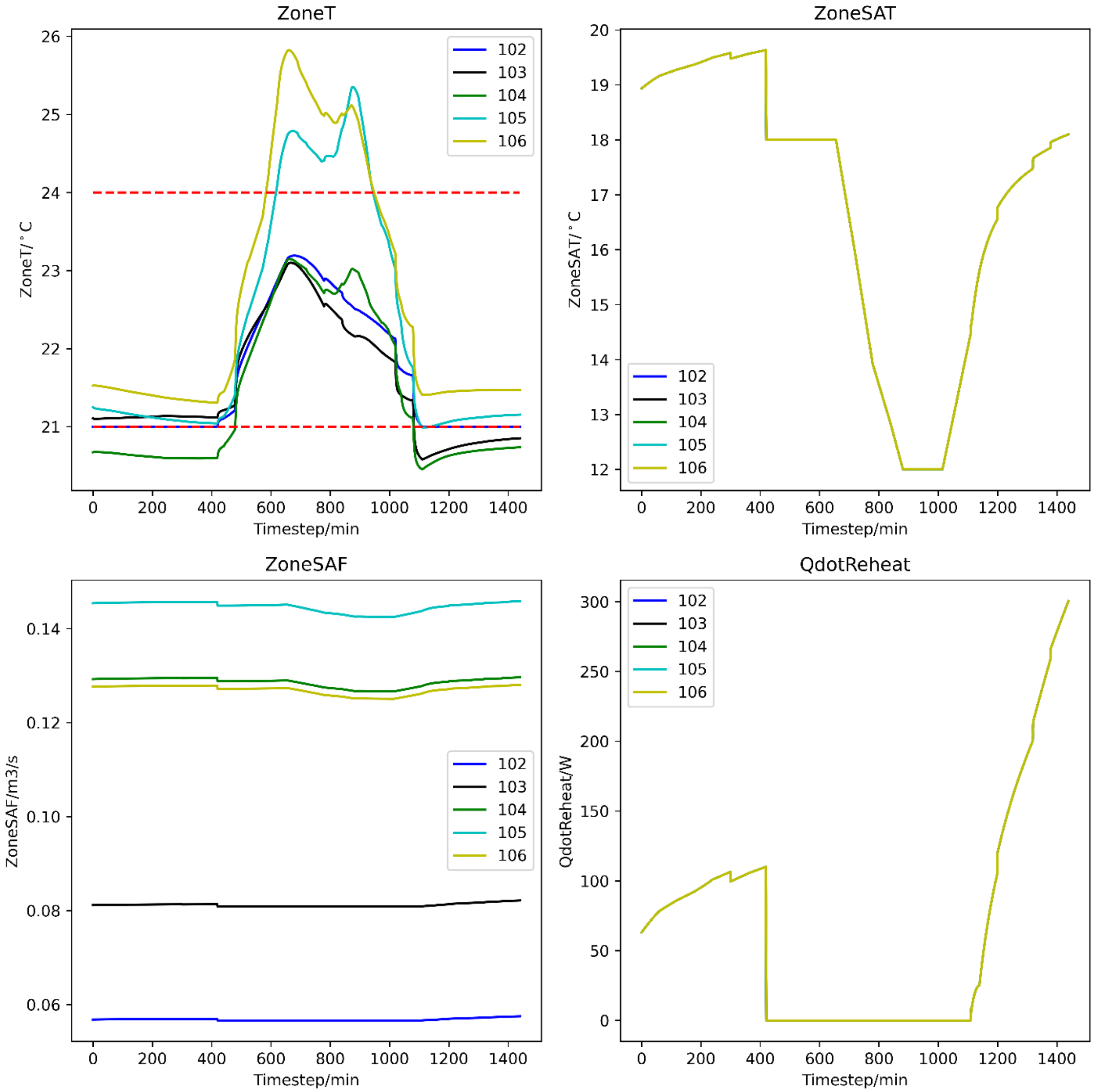

Figure A.61. Zone profiles on the first floor in the winter (A31).

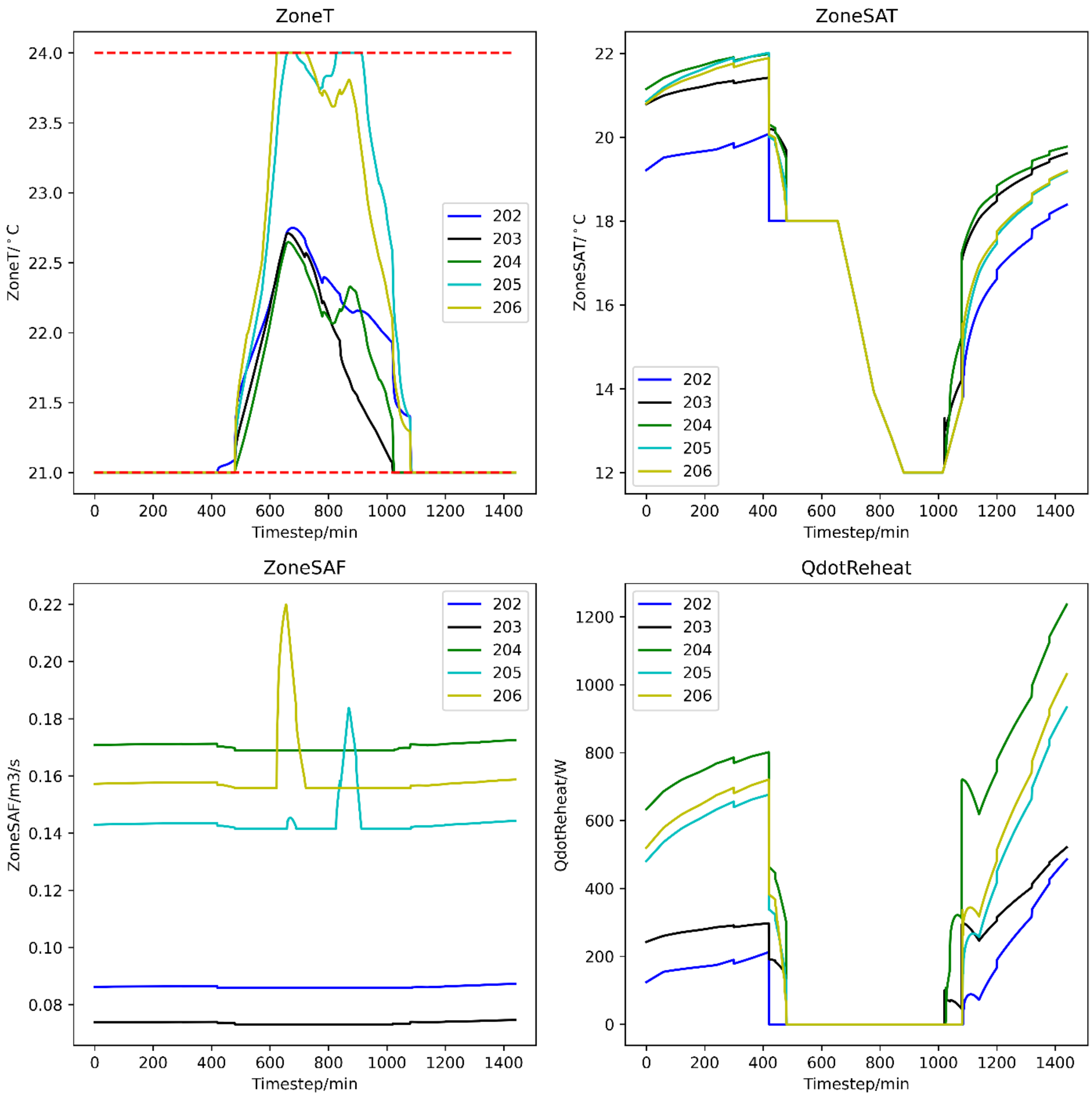

Figure A.62. Zone profiles on the second floor in the winter (A31).

A.2 SENSOR LOCATIONS WITH MEAN SENSORS

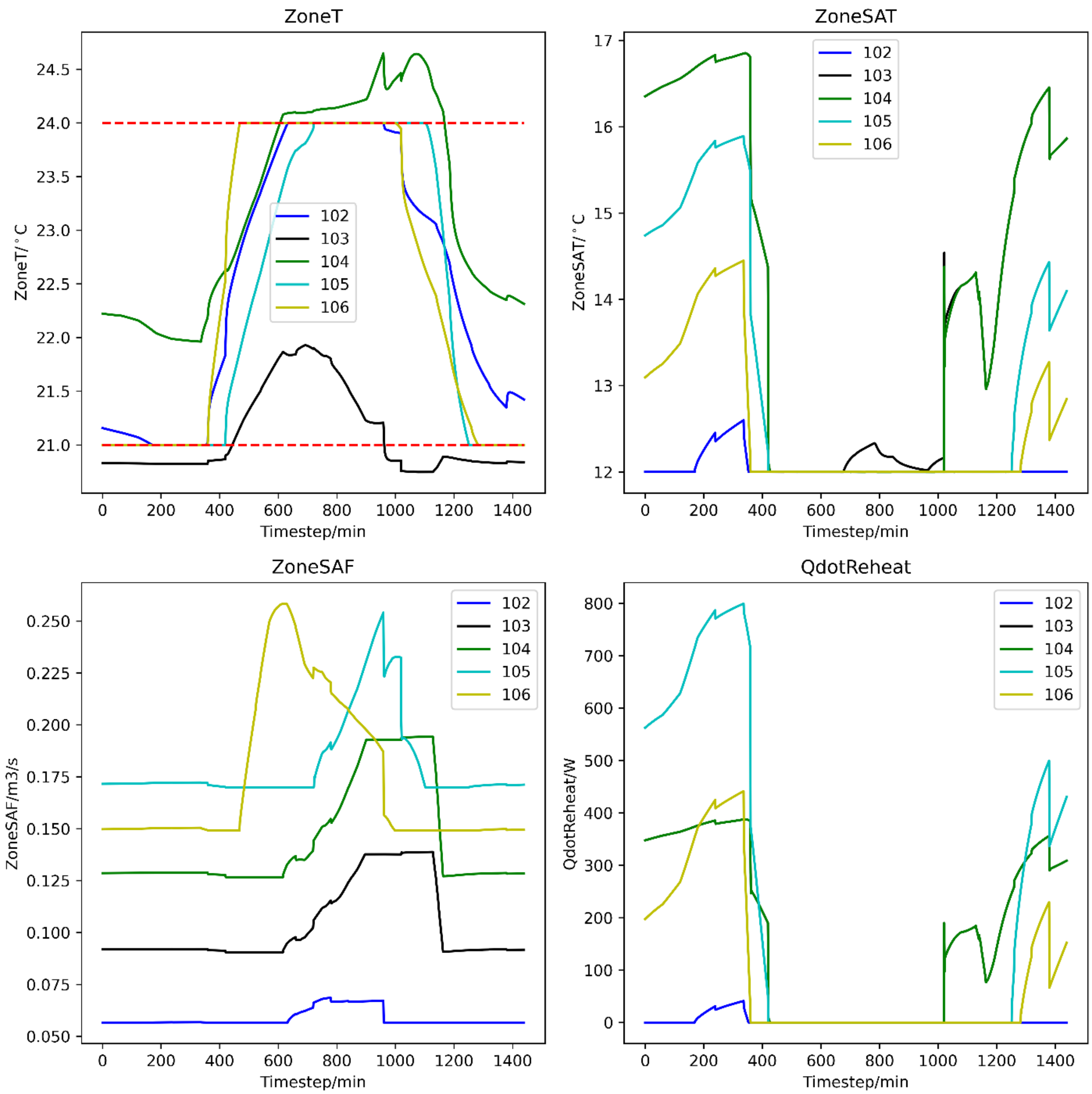

Figure A.63. Zone profiles on the first floor in the winter (B1).

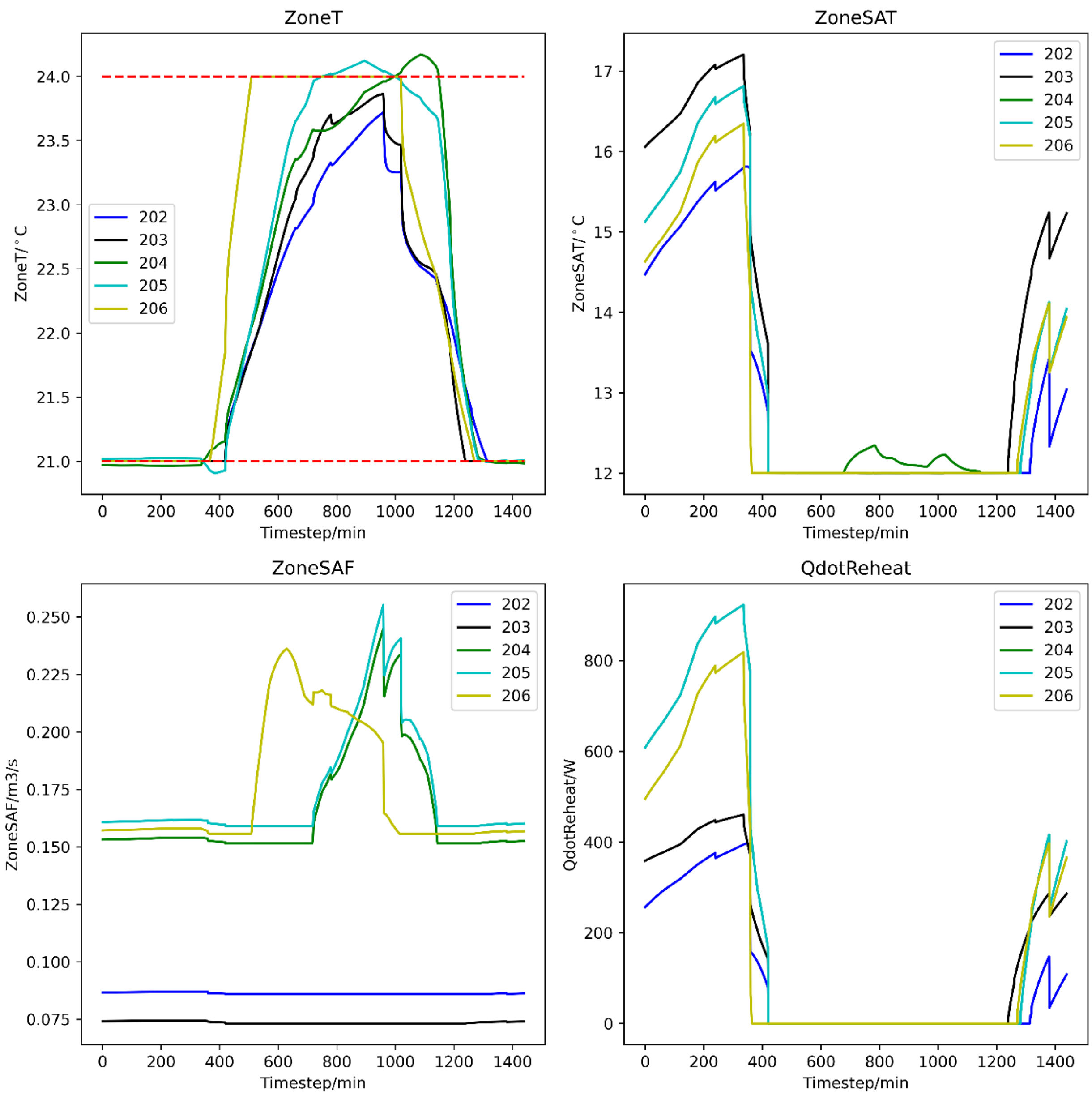

Figure A.64. Zone profiles on the second floor in the winter (B1).

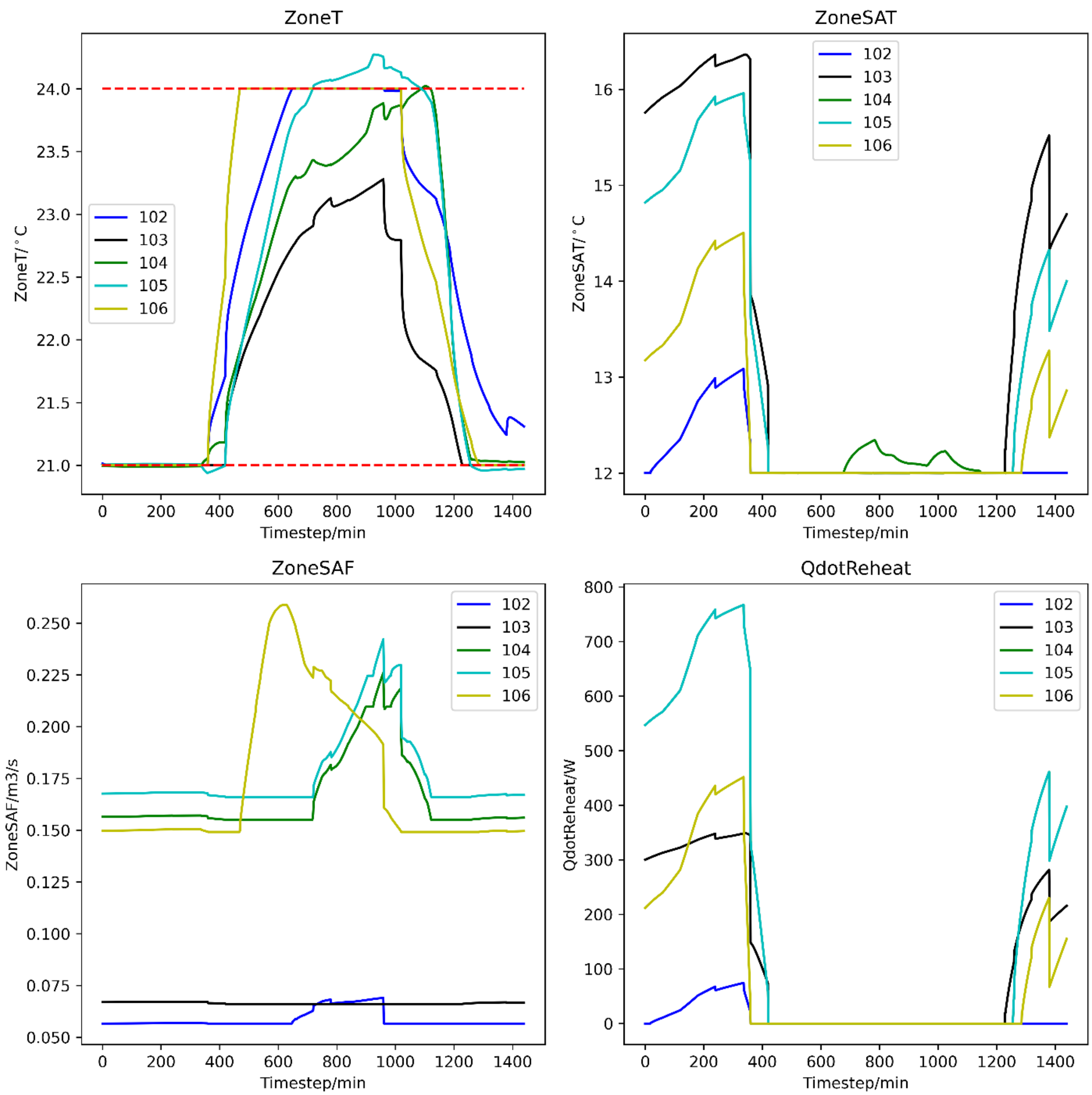

Figure A.65. Zone profiles on the first floor in the winter (B2).

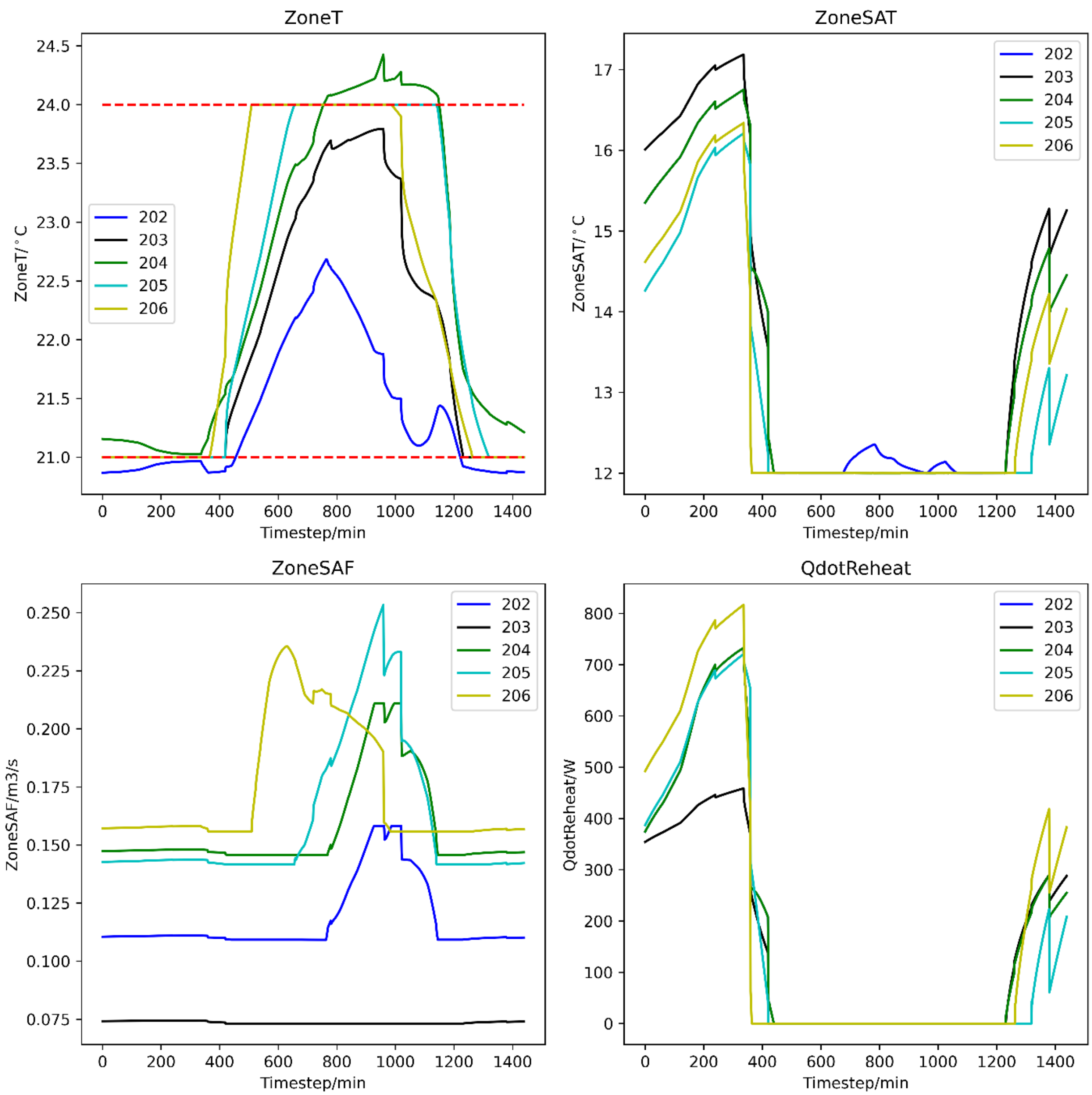

Figure A.66. Zone profiles on the second floor in the winter (B2).

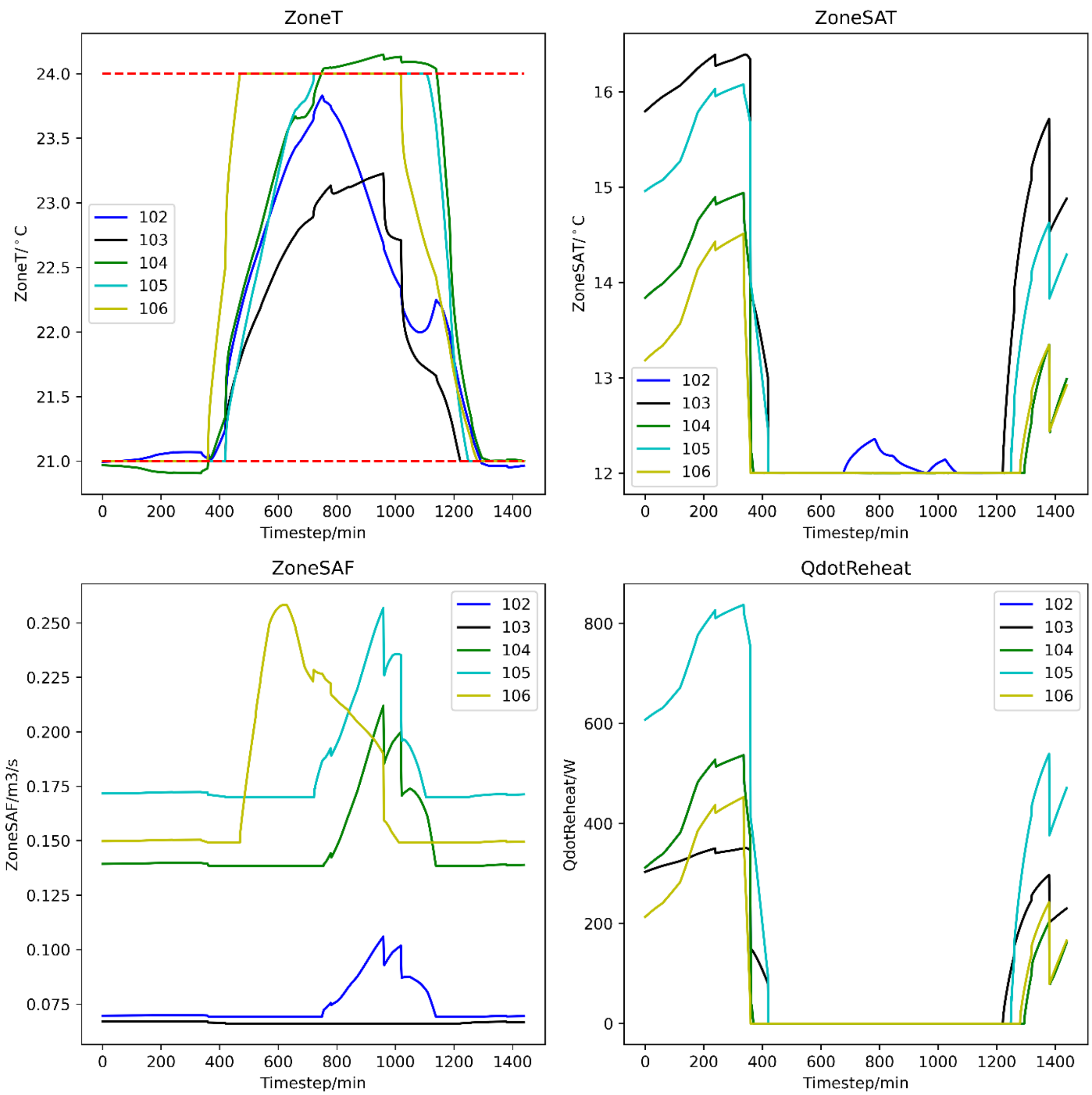

Figure A.67. Zone profiles on the first floor in the winter (B3).

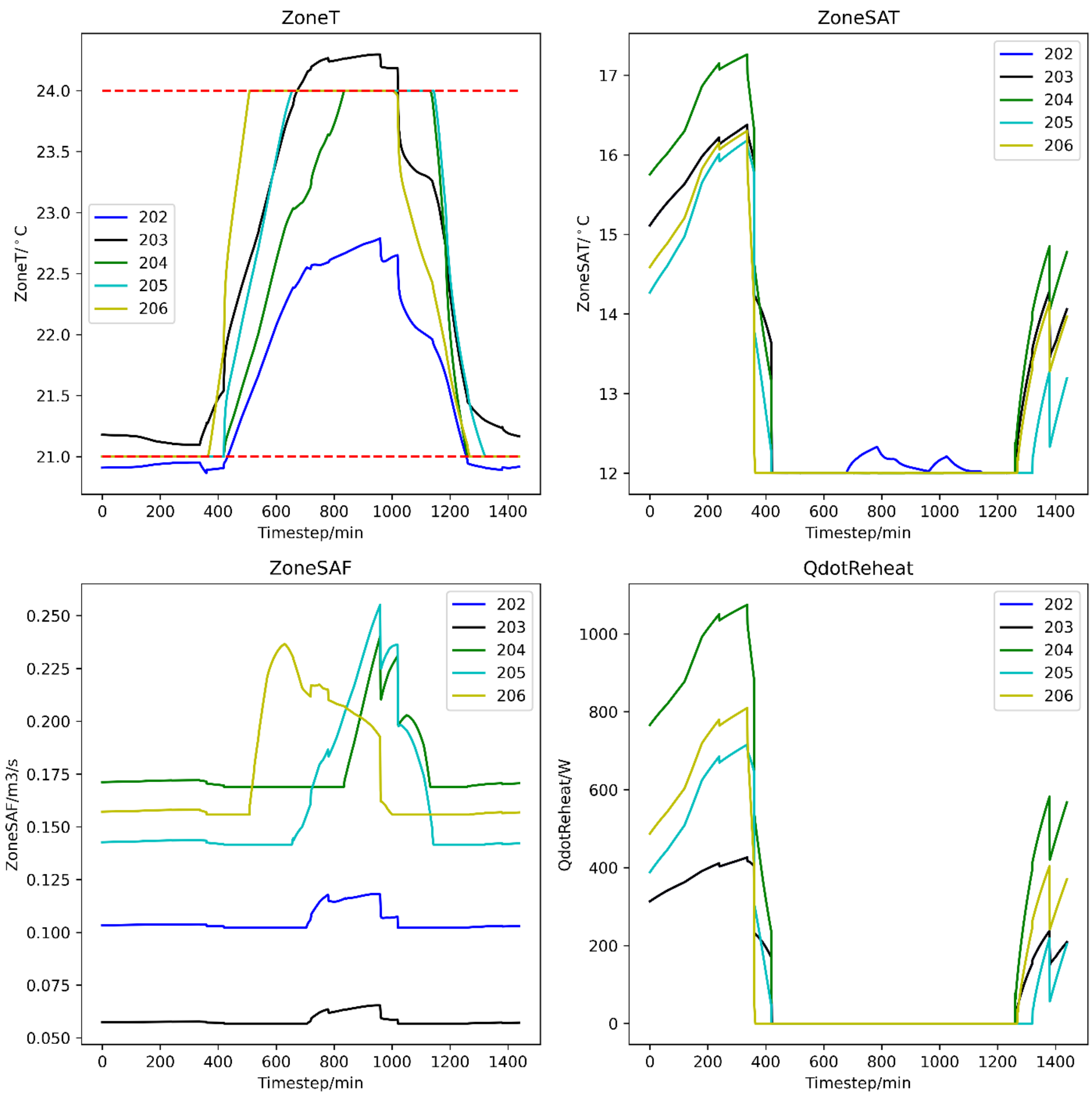

Figure A.68. Zone profiles on the second floor in the winter (B3).

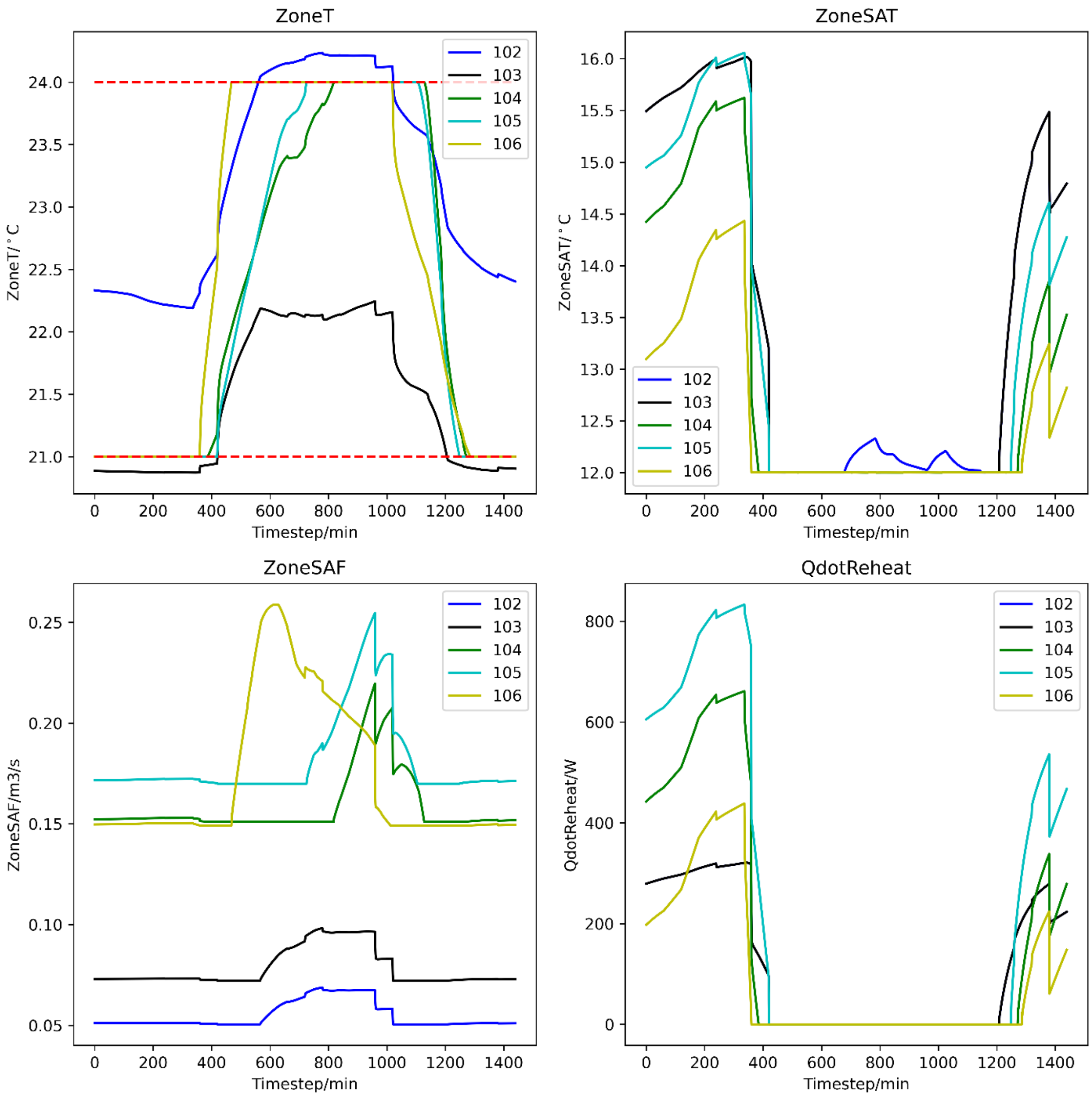

Figure A.69. Zone profiles on the first floor in the winter (B4).

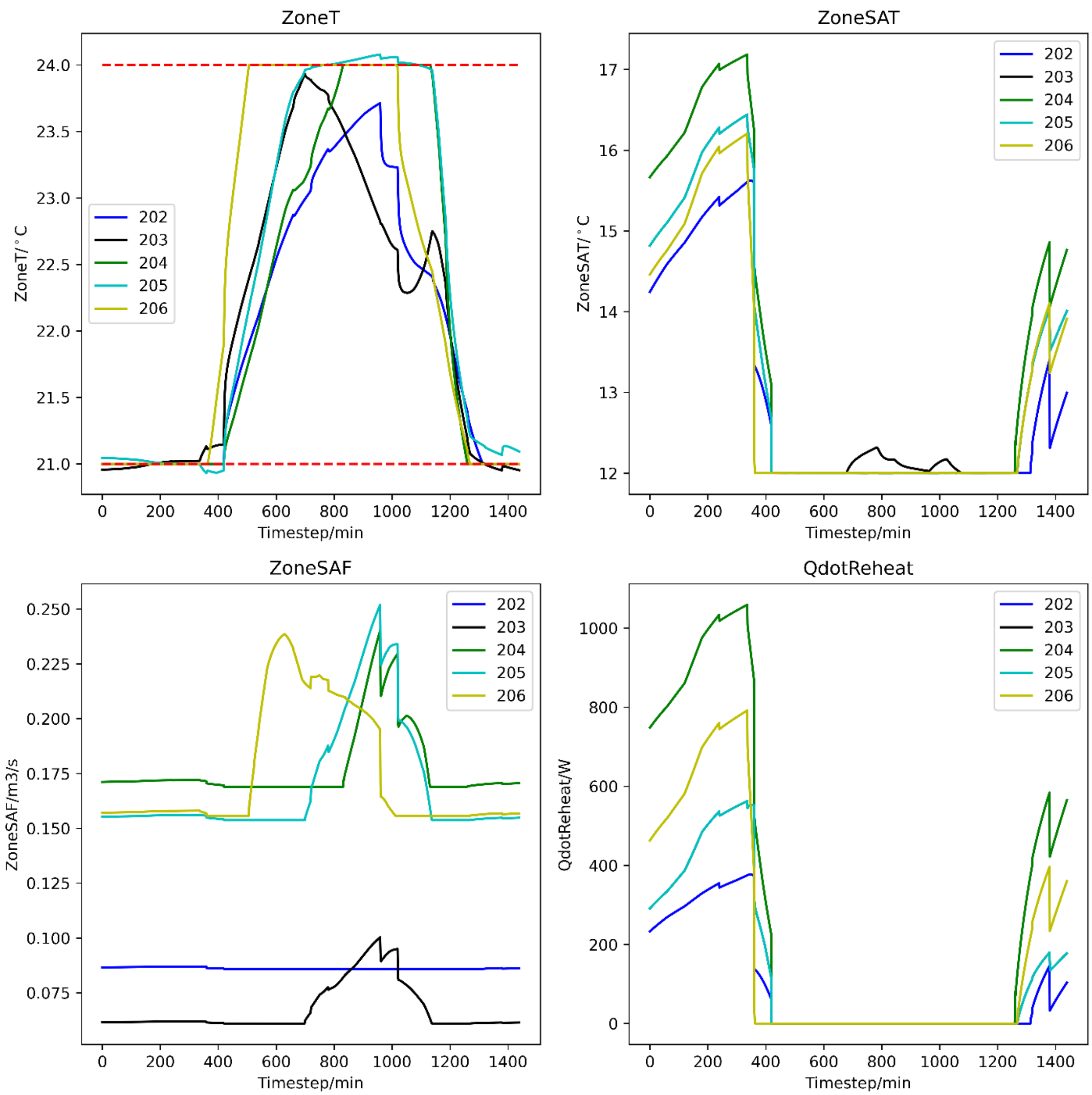

Figure A.70. Zone profiles on the second floor in the winter (B4).

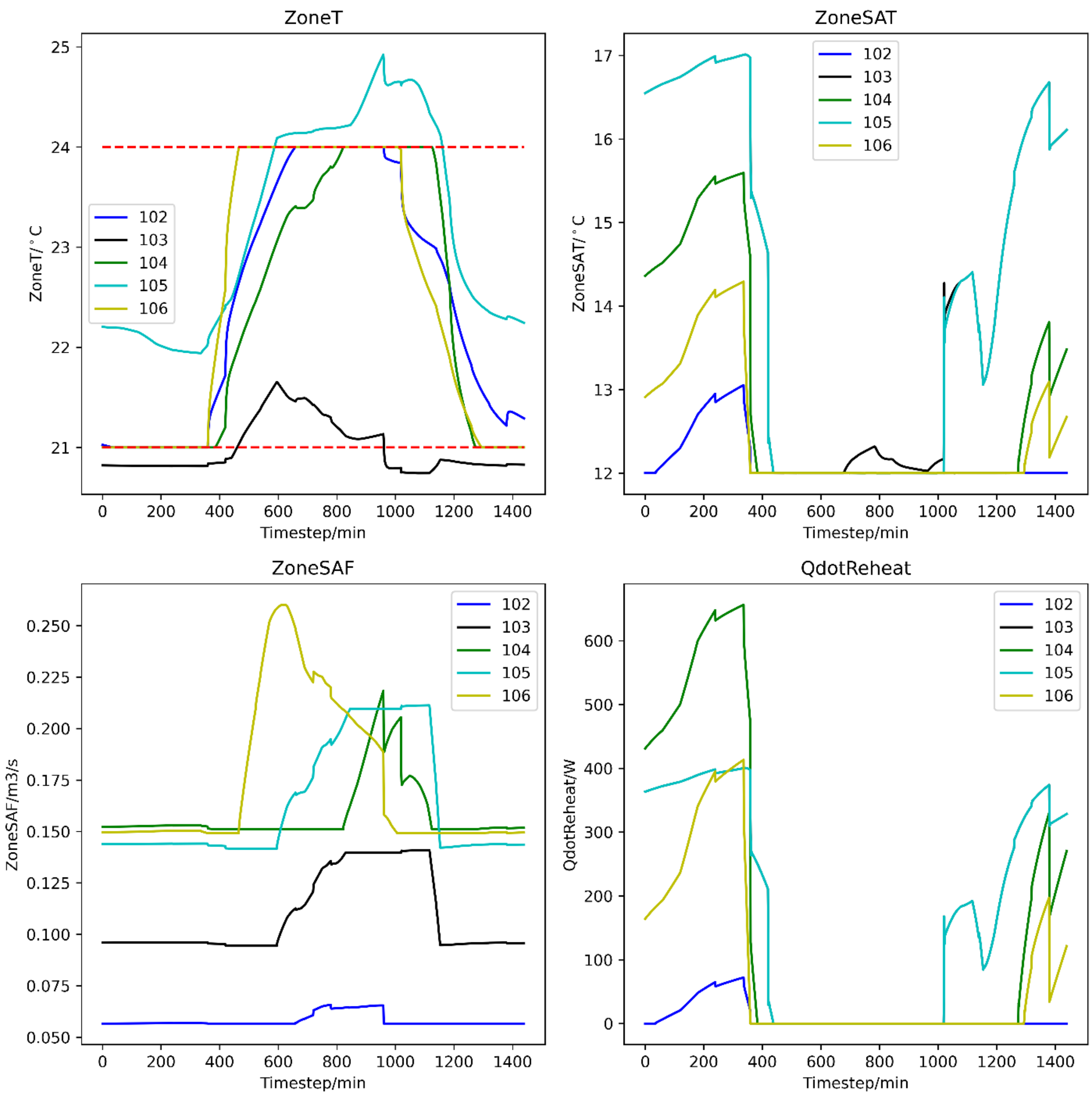

Figure A.71. Zone profiles on the first floor in the winter (B5).

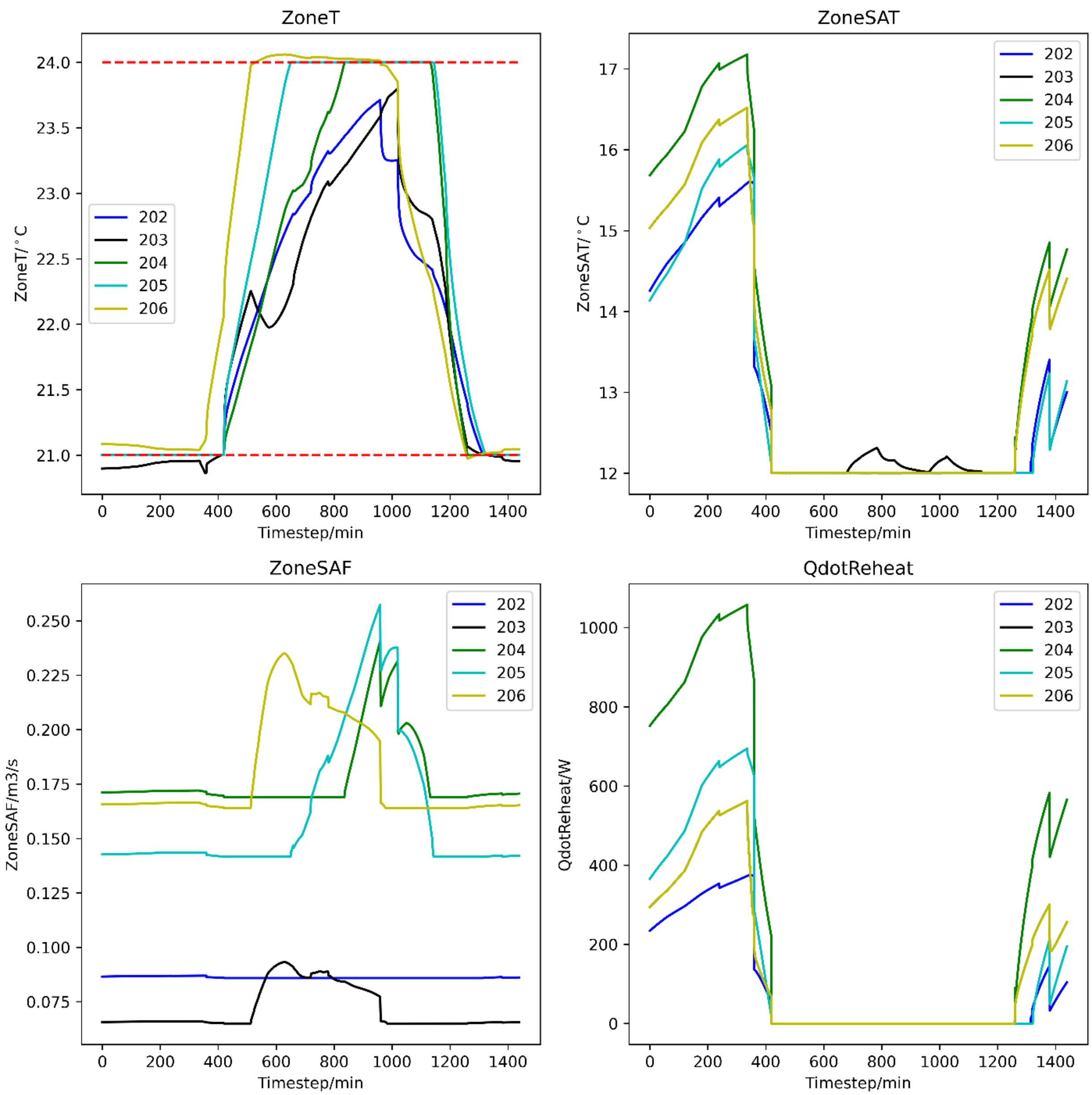

Figure A.72. Zone profiles on the second floor in the winter (B5).

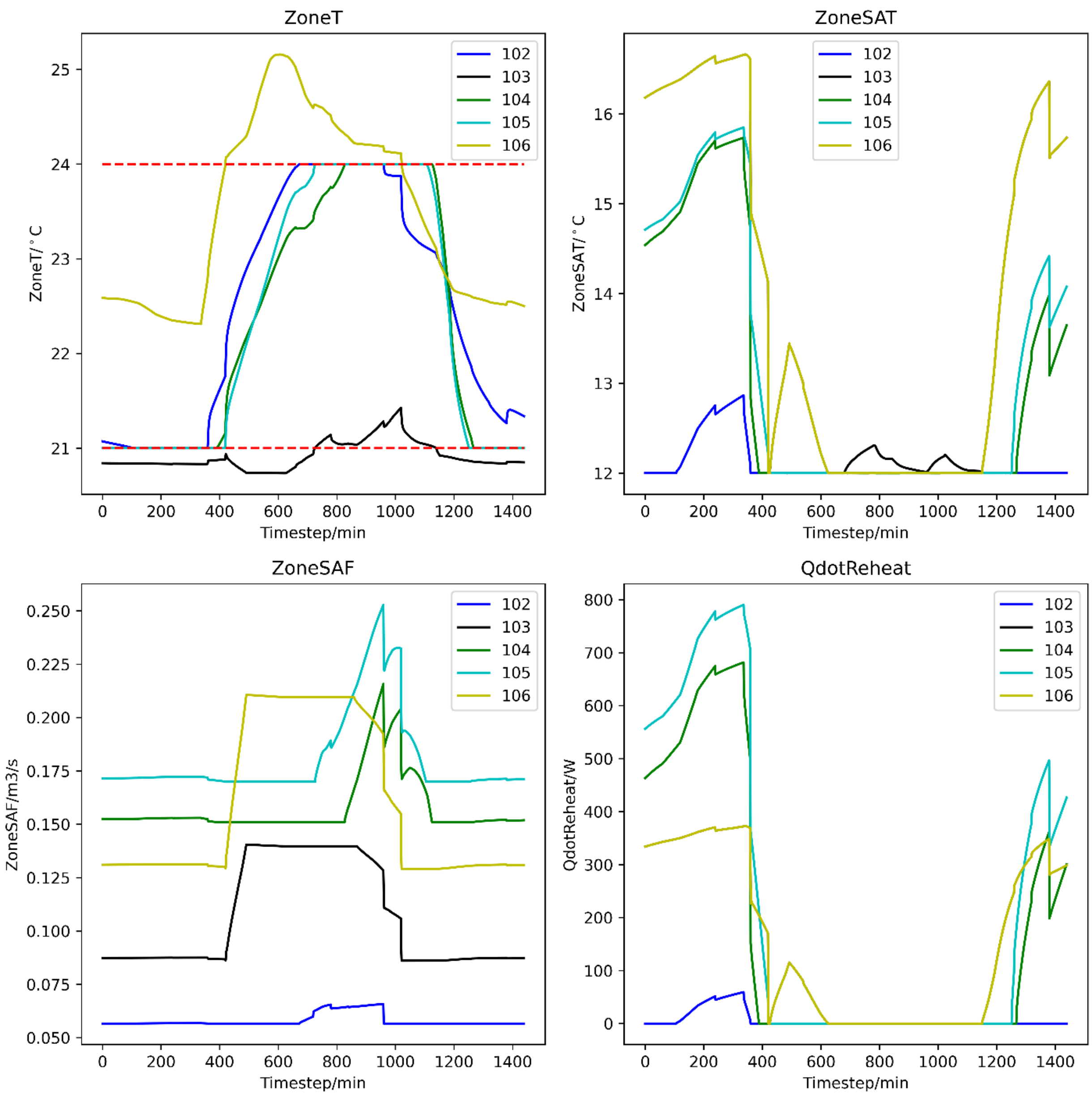

Figure A.73. Zone profiles on the first floor in the winter (B6).

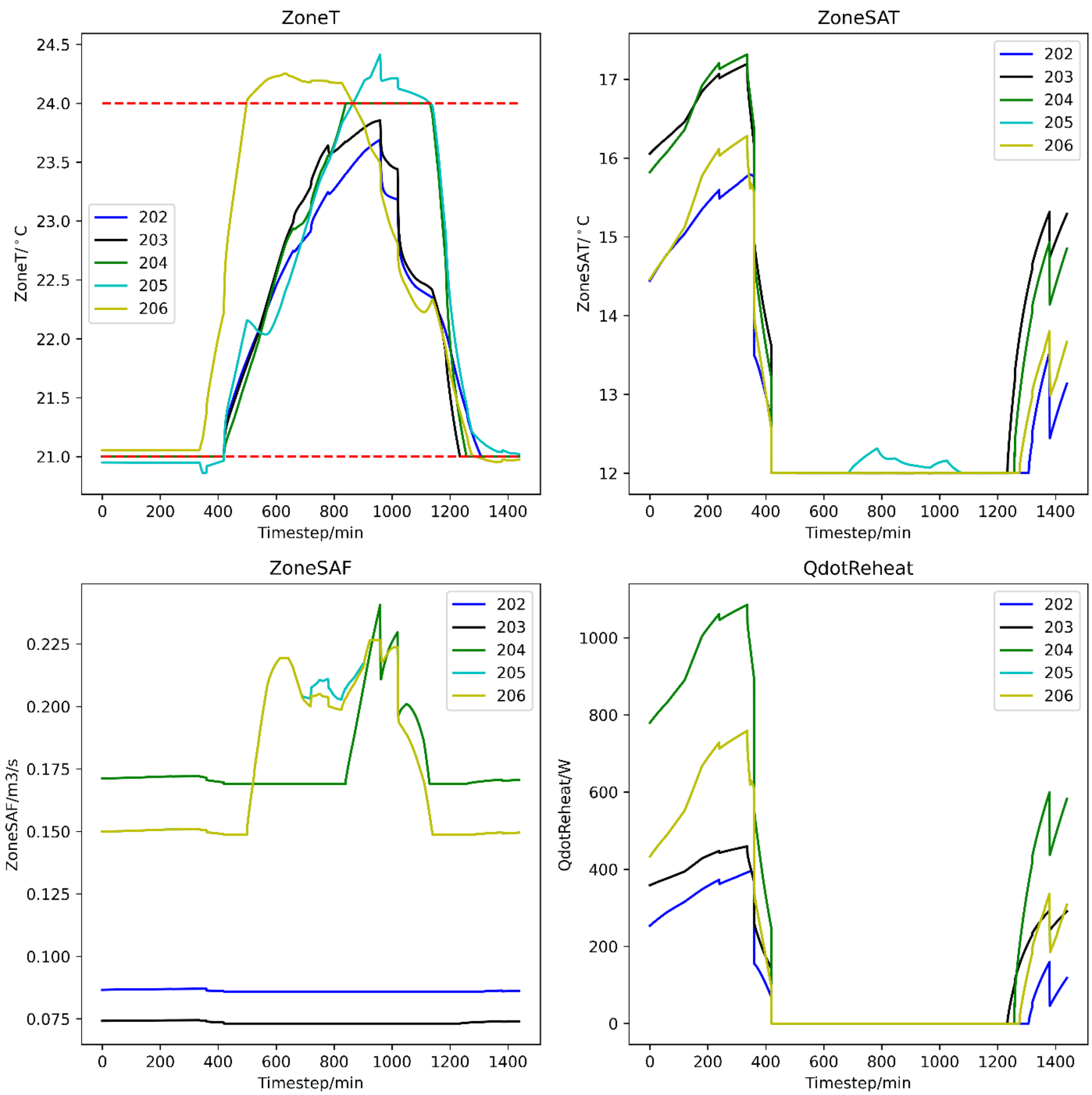

Figure A.74. Zone profiles on the second floor in the winter (B6).

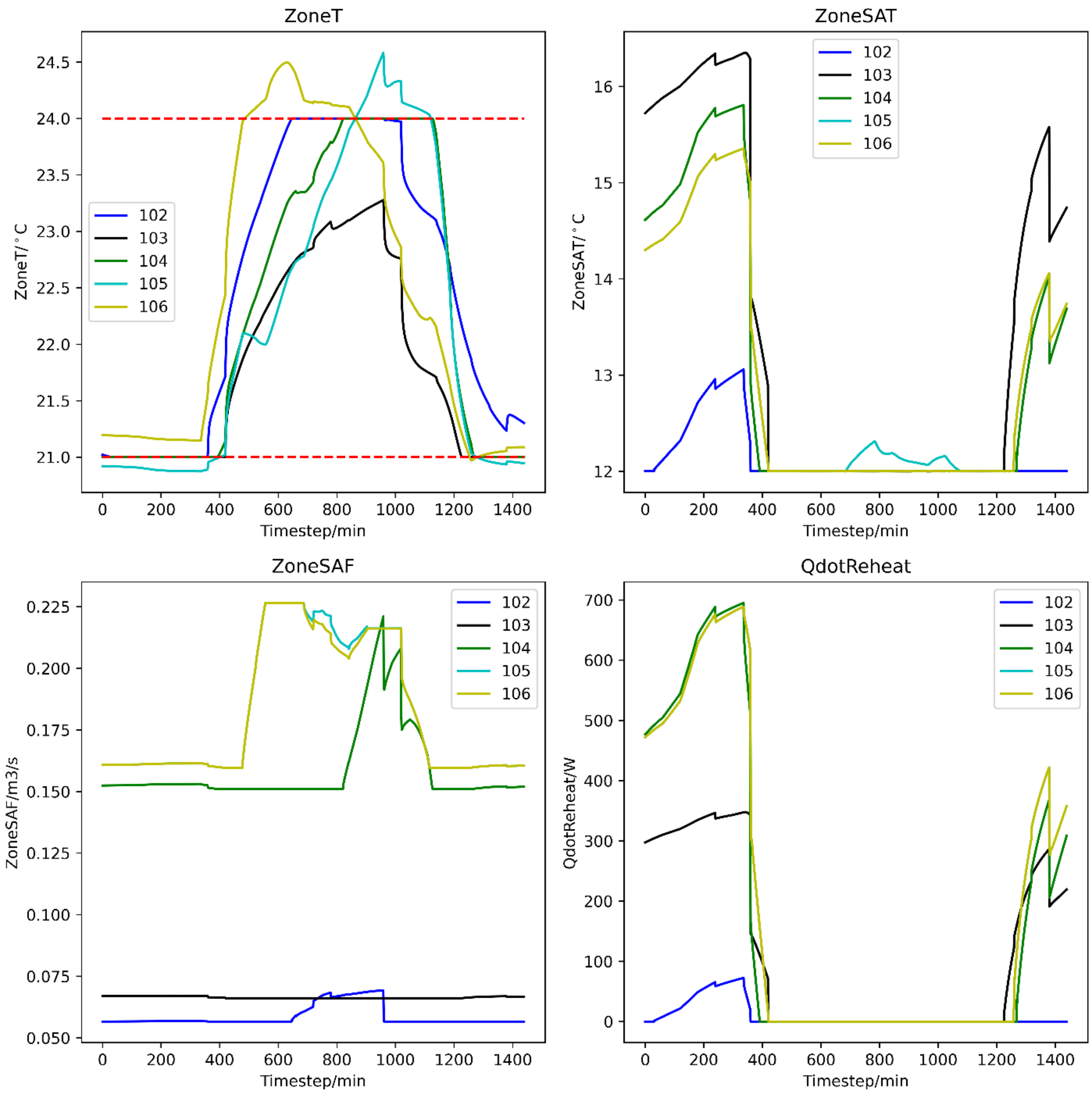

Figure A.75. Zone profiles on the first floor in the winter (B7).

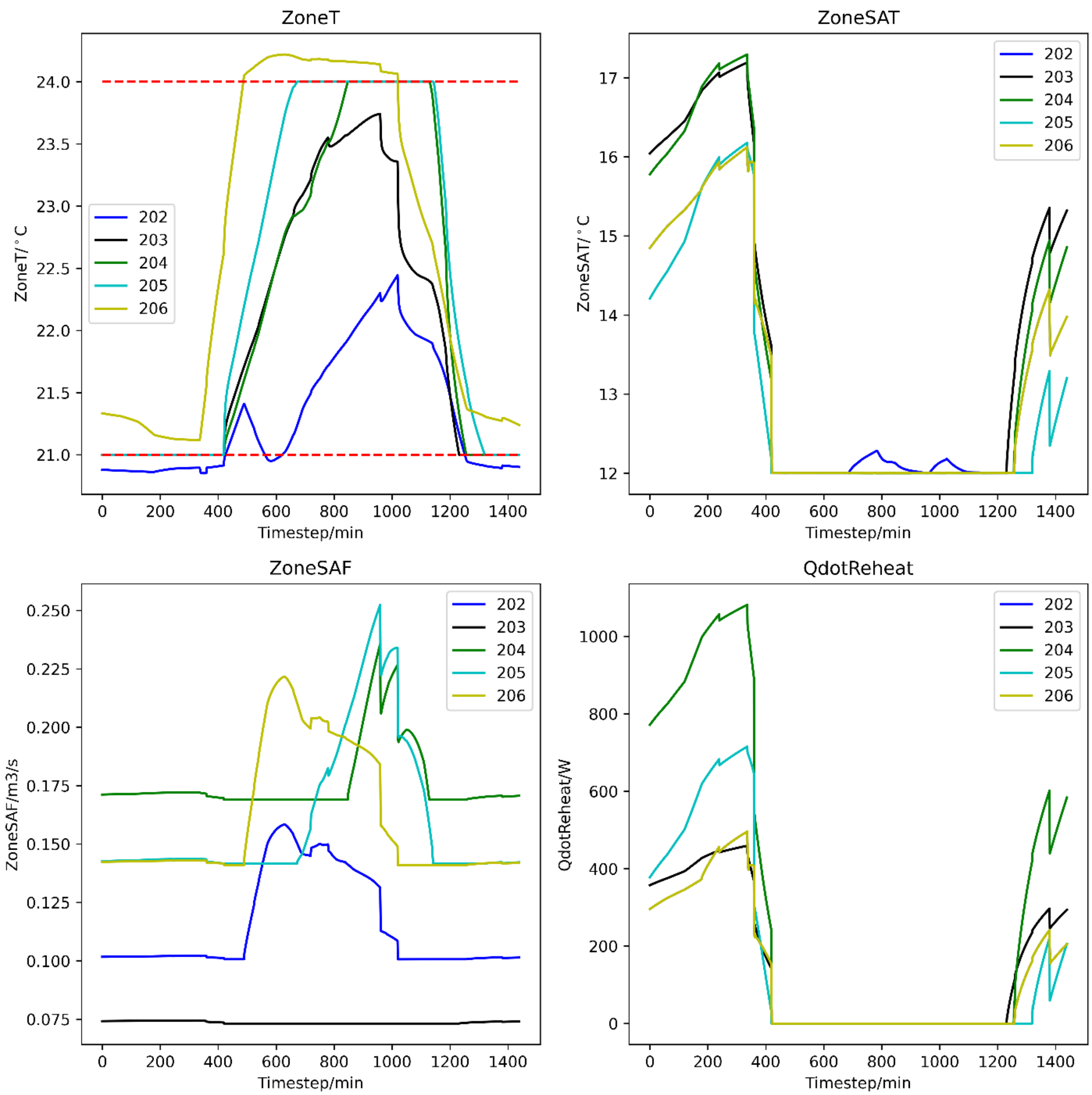

Figure A.76. Zone profiles on the second floor in the winter (B7).

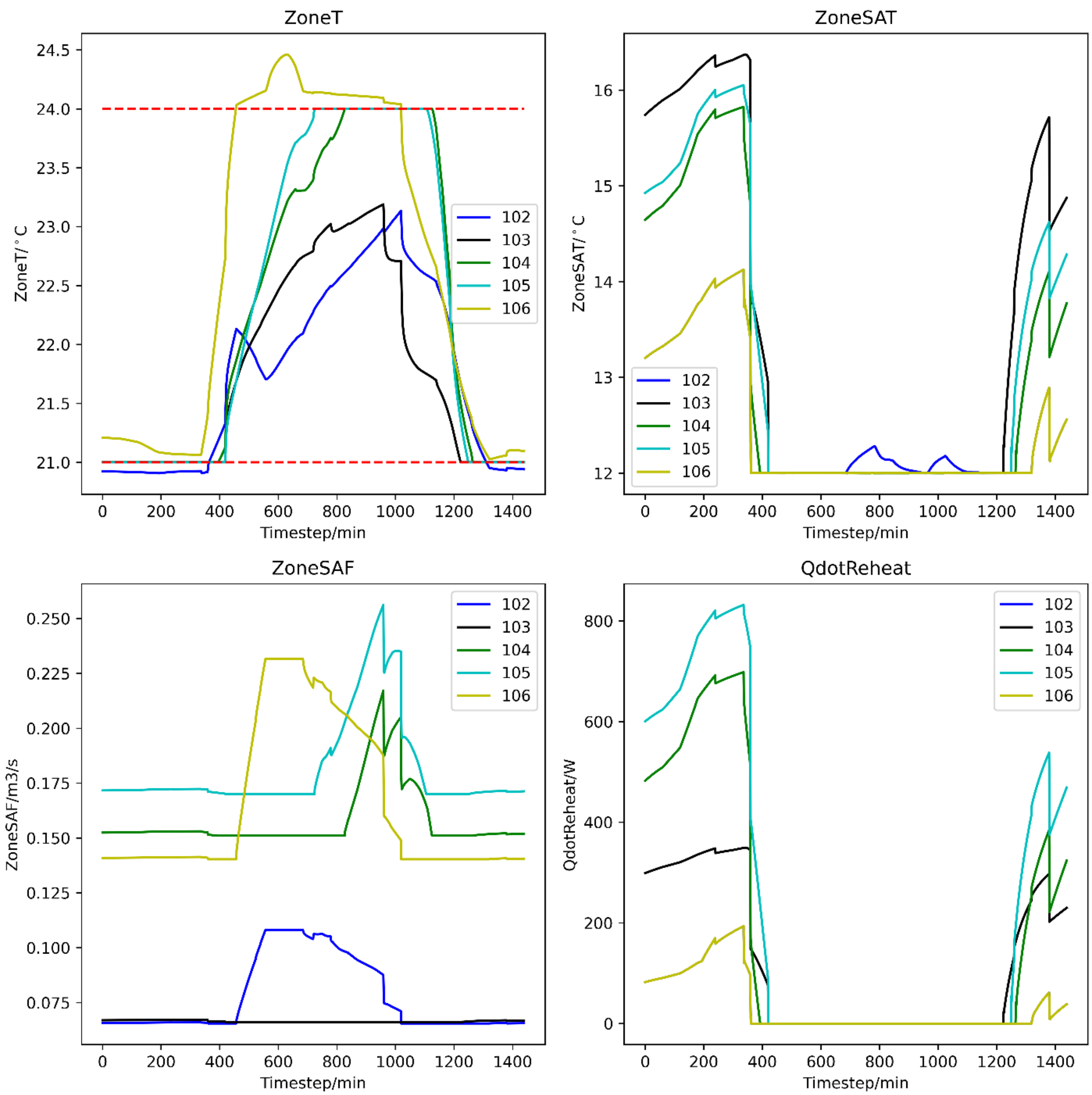

Figure A.77. Zone profiles on the first floor in the winter (B8).

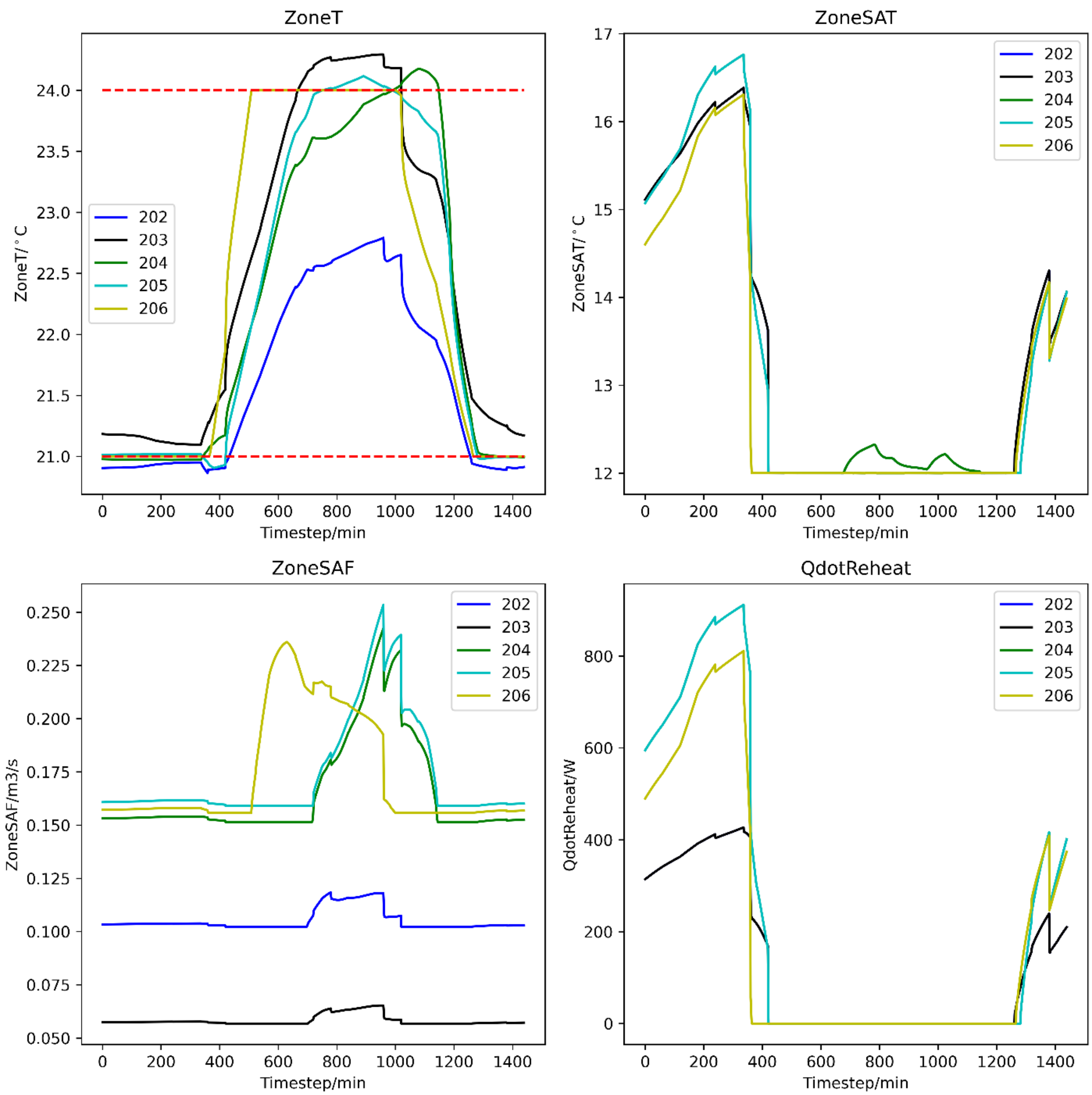

Figure A.78. Zone profiles on the second floor in the winter (B8).

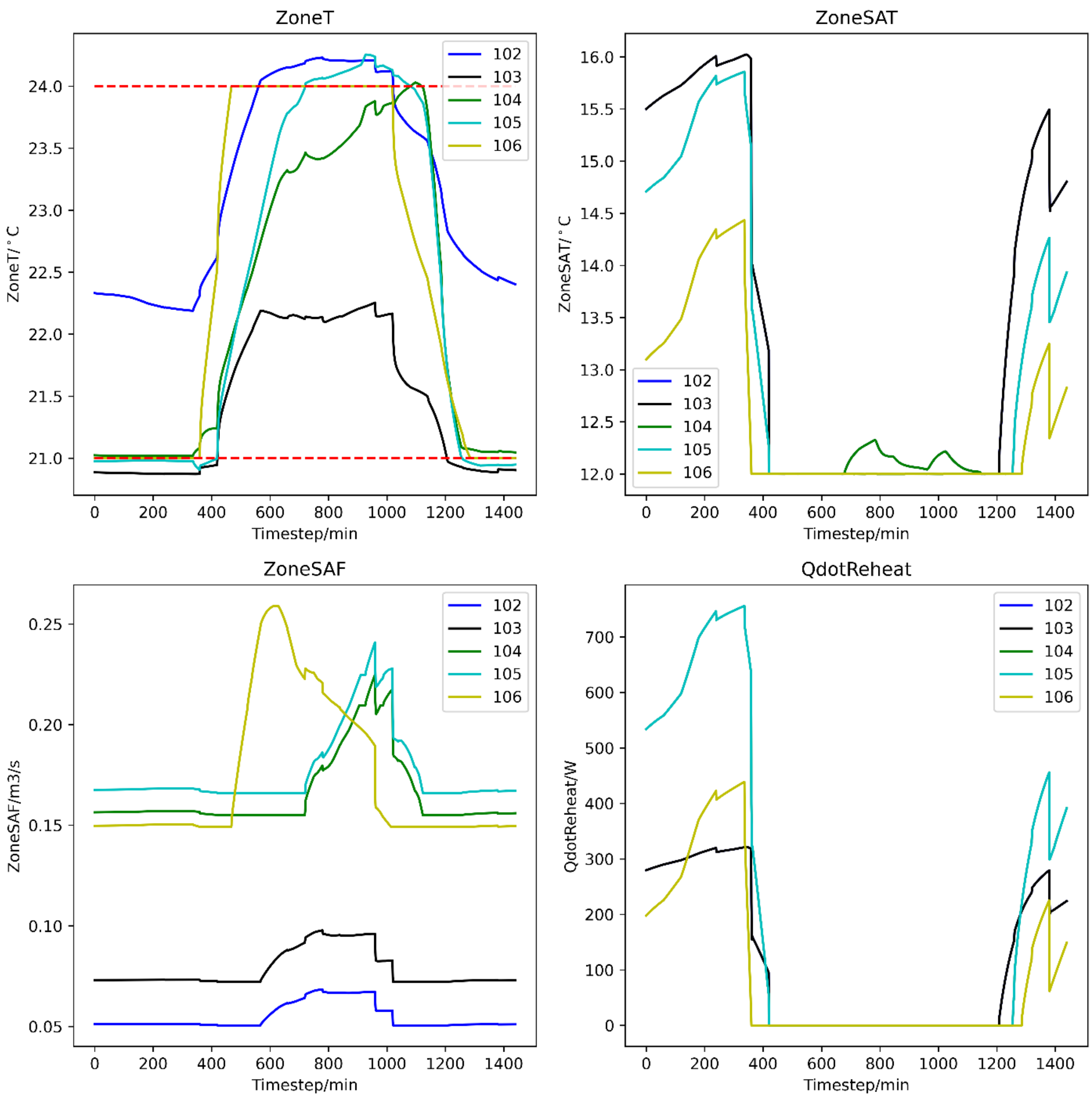

Figure A.79. Zone profiles on the first floor in the winter (B9).

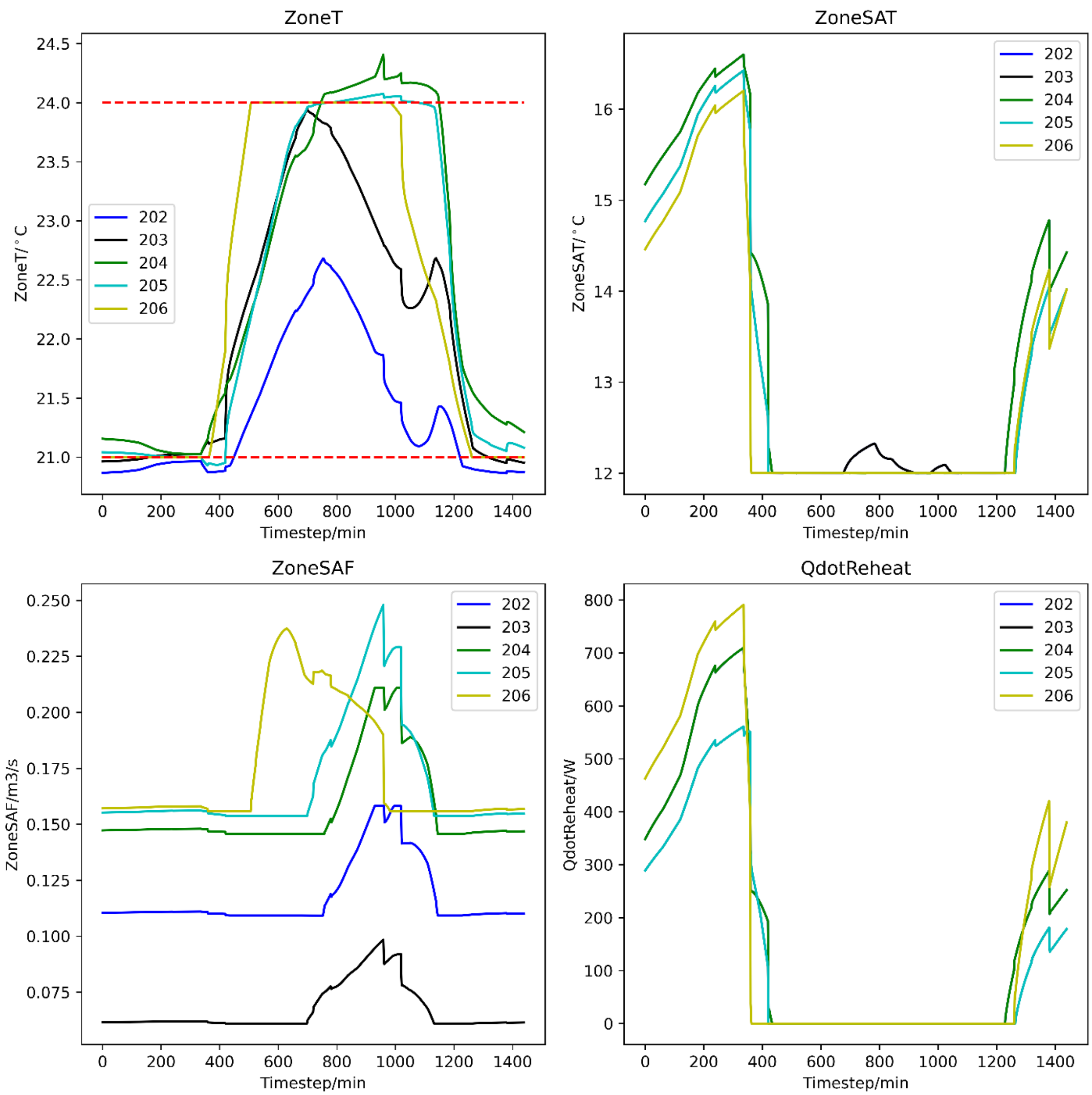

Figure A.80. Zone profiles on the second floor in the winter (B9).

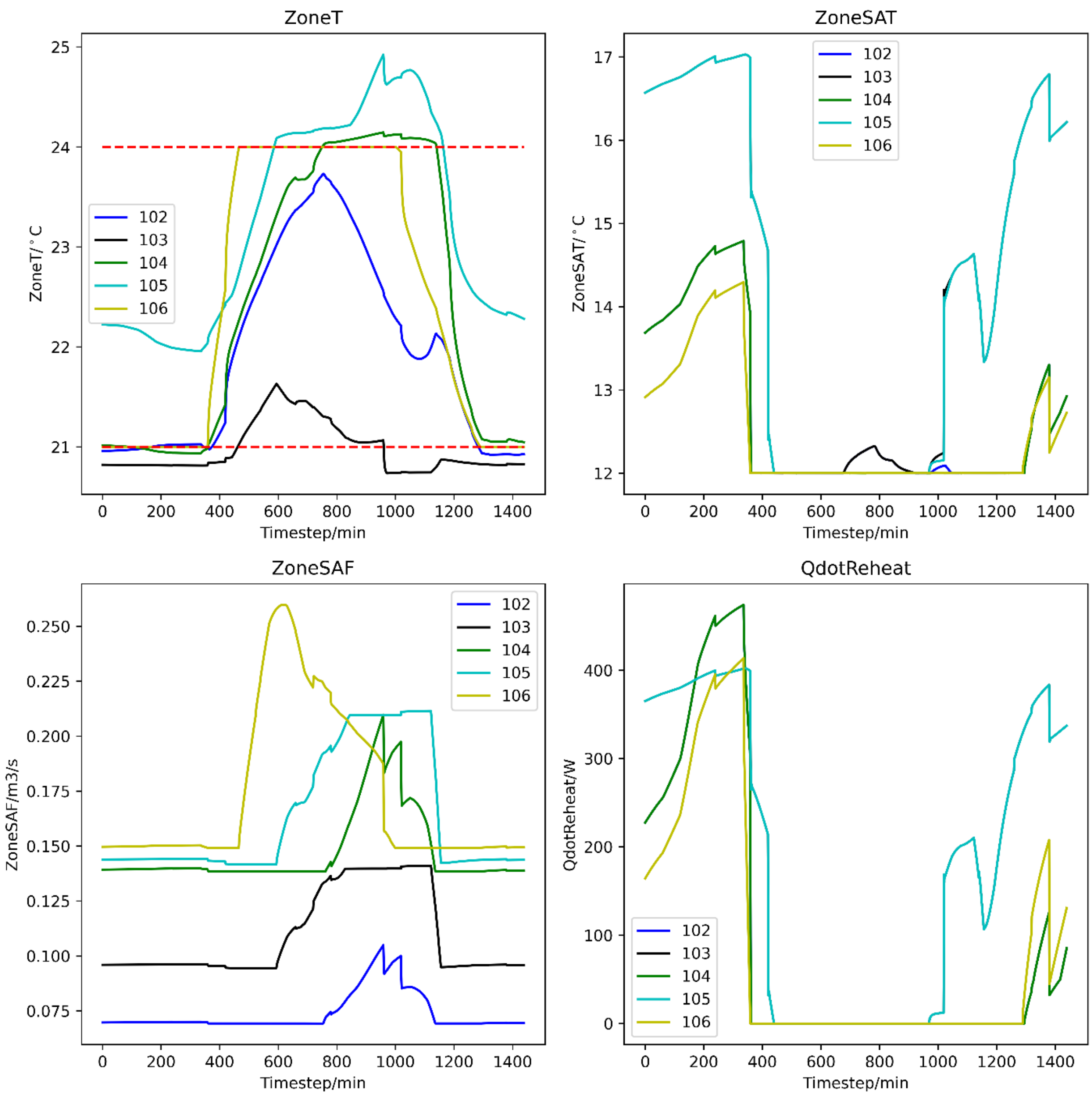

Figure A.81. Zone profiles on the first floor in the winter (B10).

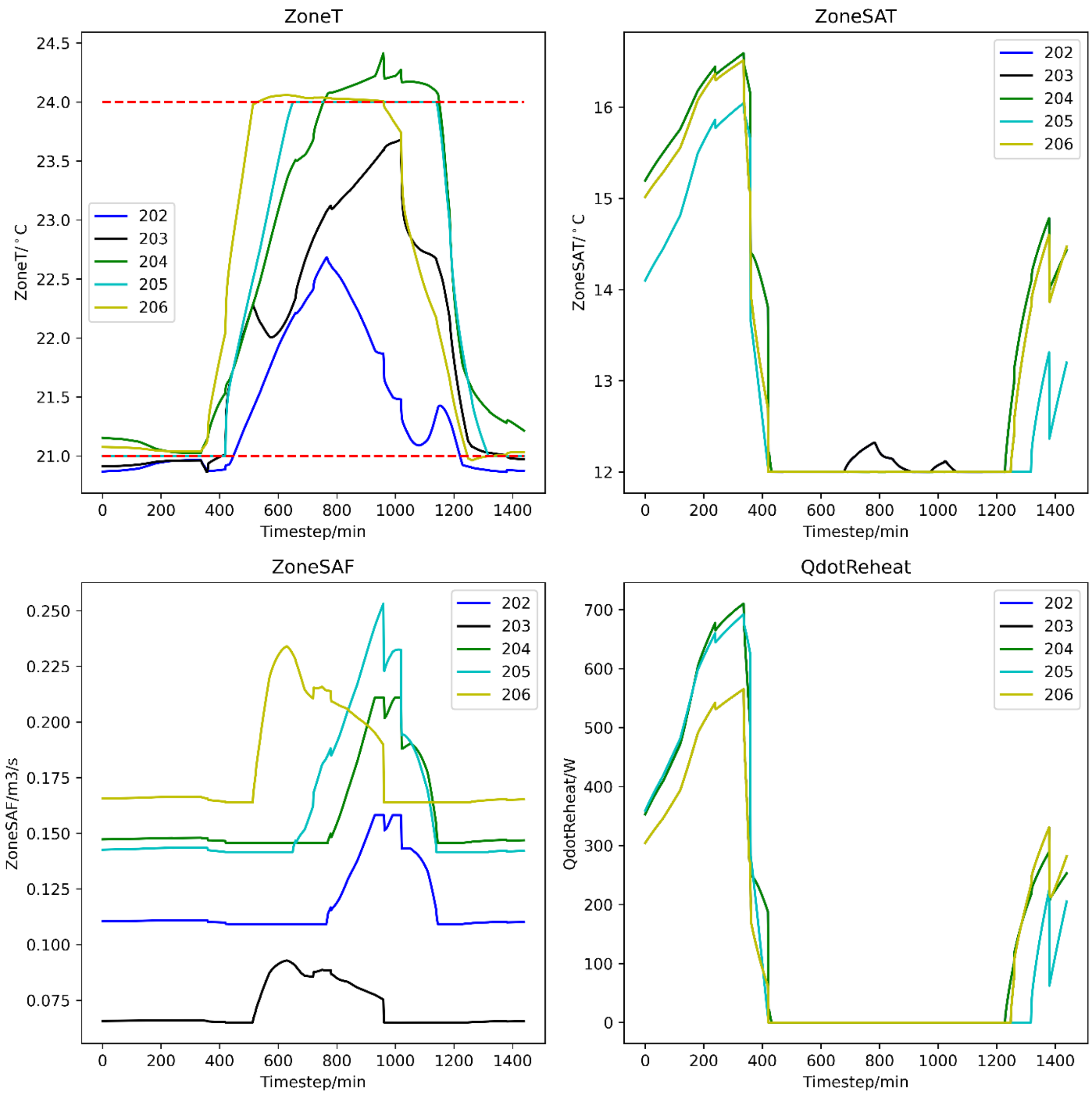

Figure A.82. Zone profiles on the second floor in the winter (B10).

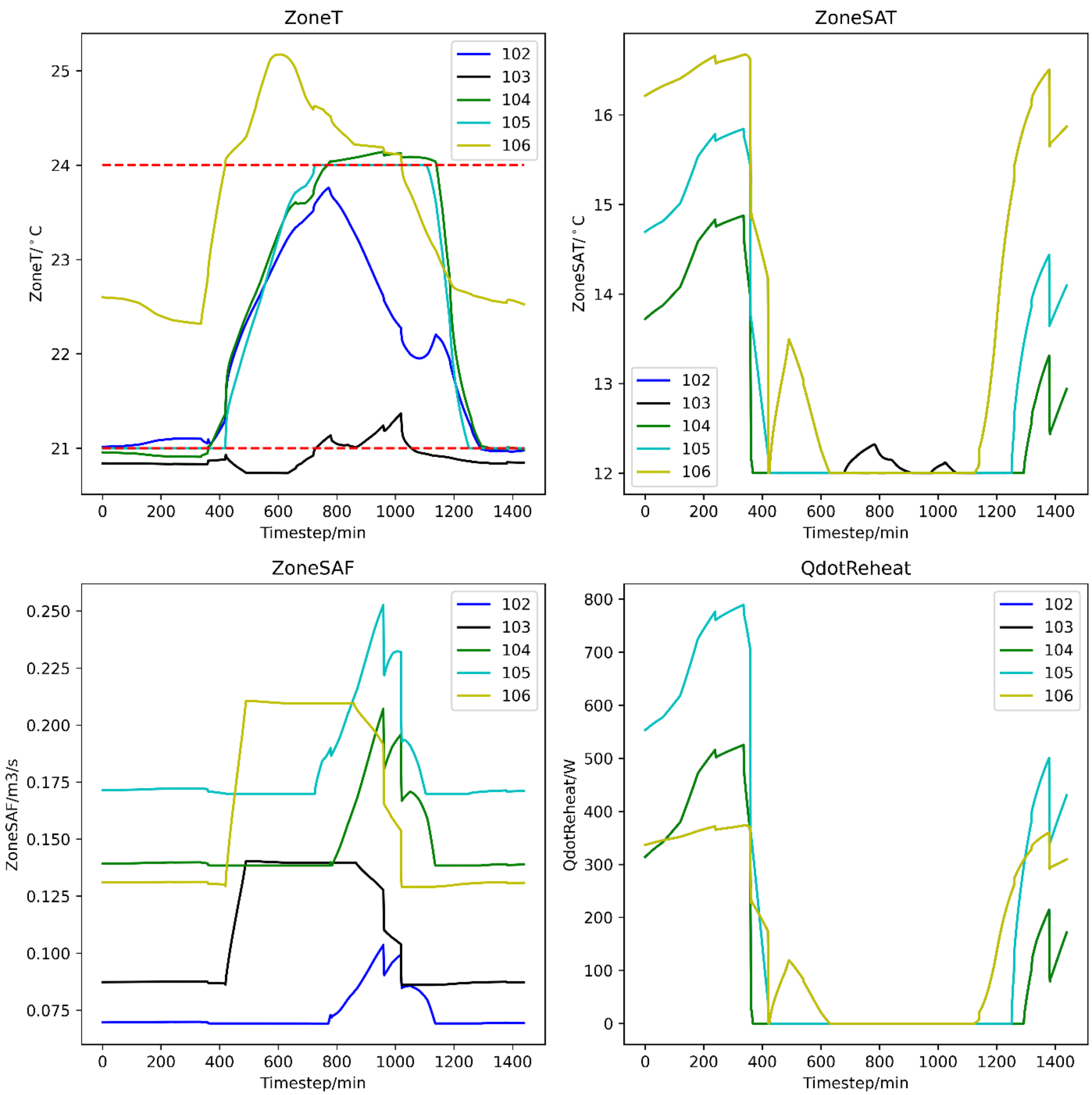

Figure A.83. Zone profiles on the first floor in the winter (B11).

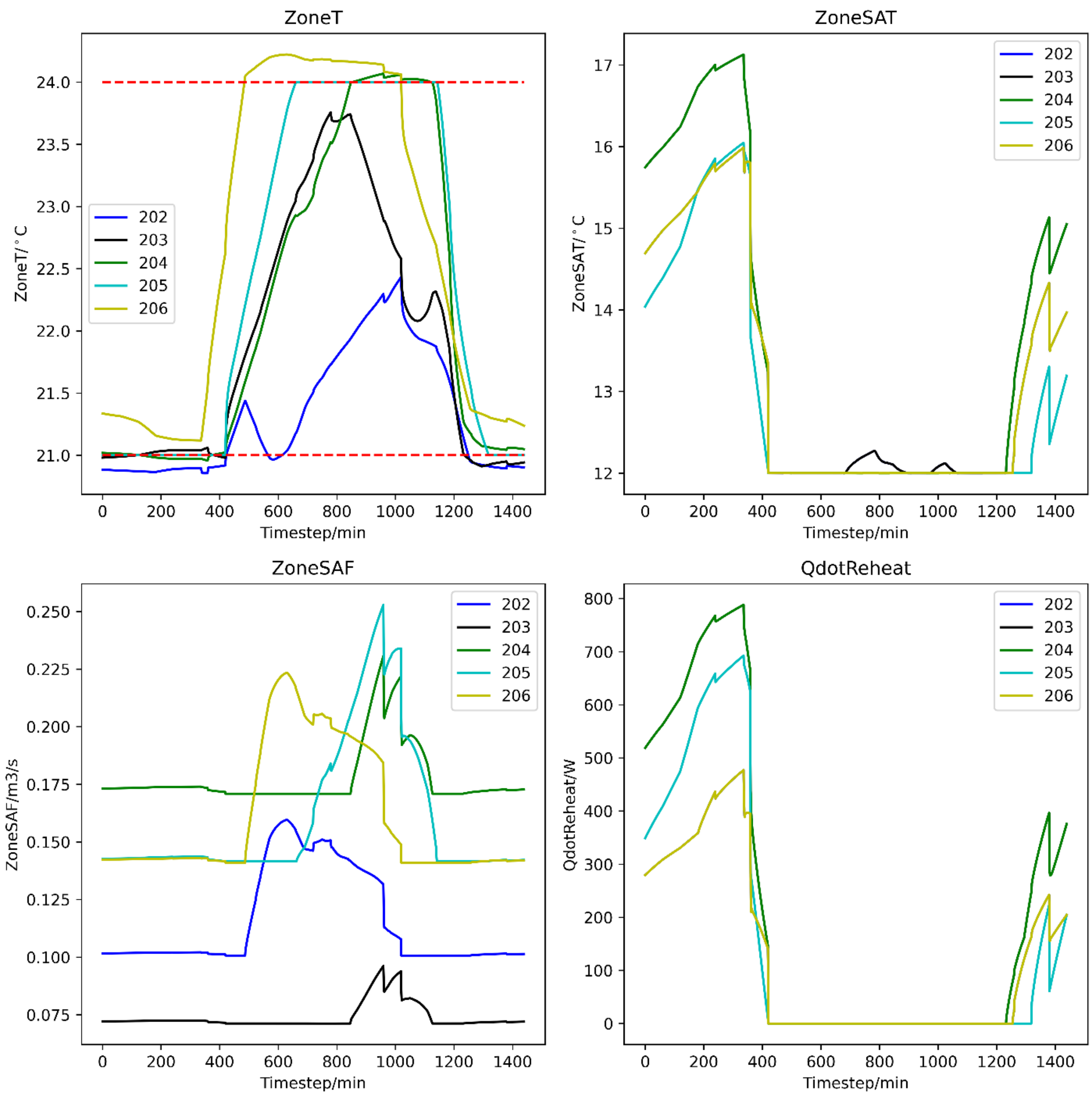

Figure A.84. Zone profiles on the second floor in the winter (B11).

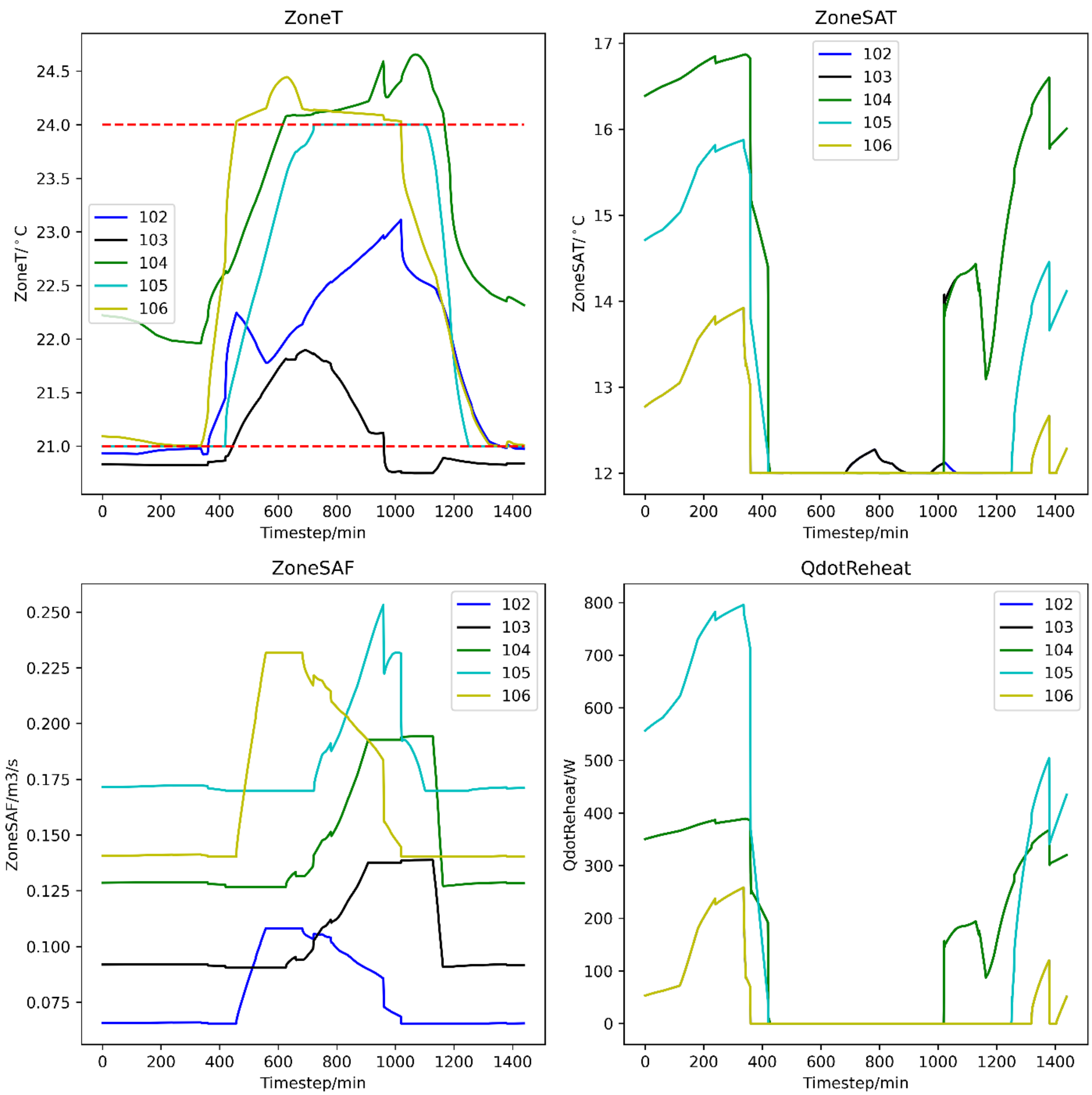

Figure A.85. Zone profiles on the first floor in the winter (B12).

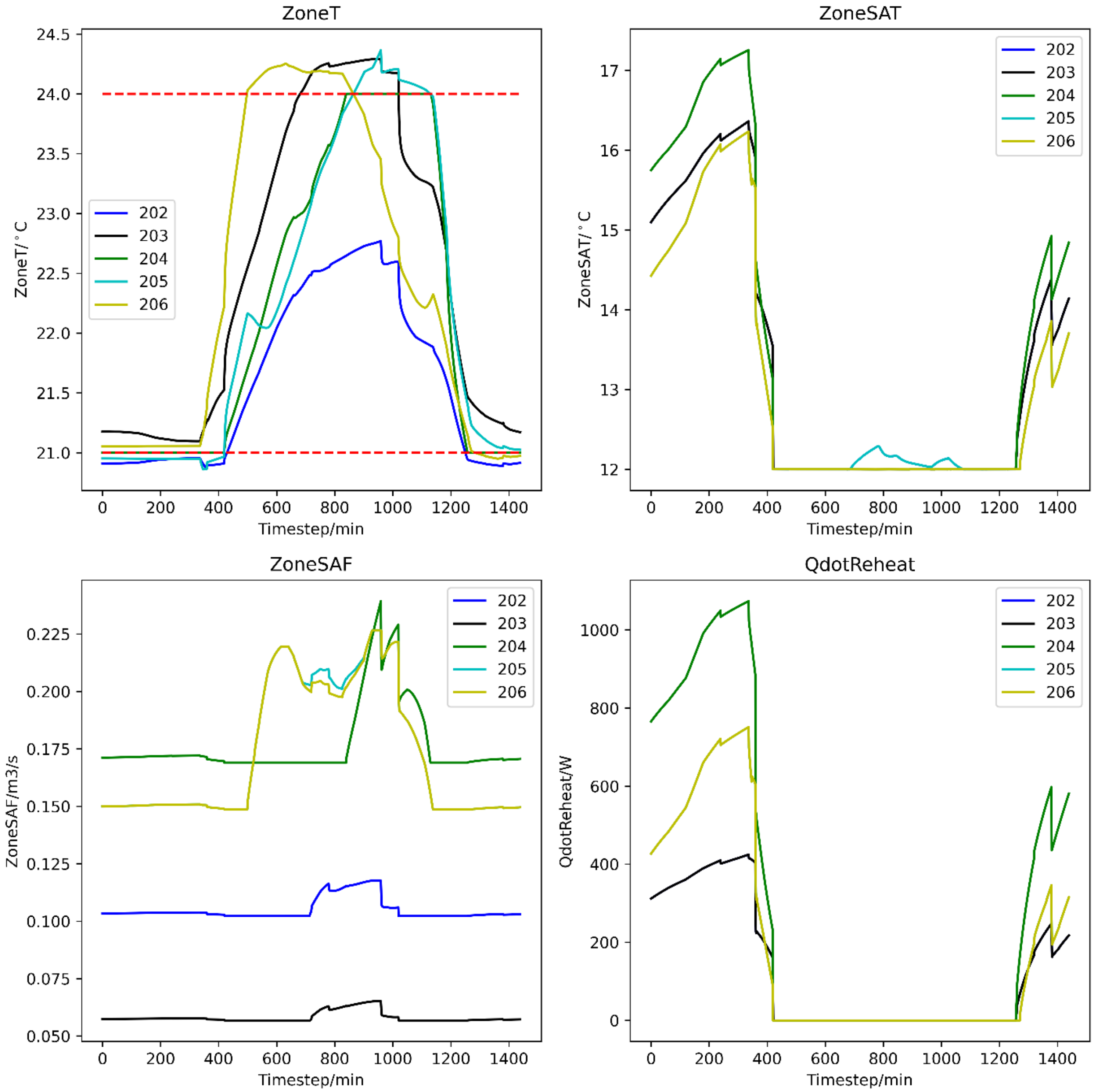

Figure A.86. Zone profiles on the second floor in the winter (B12).

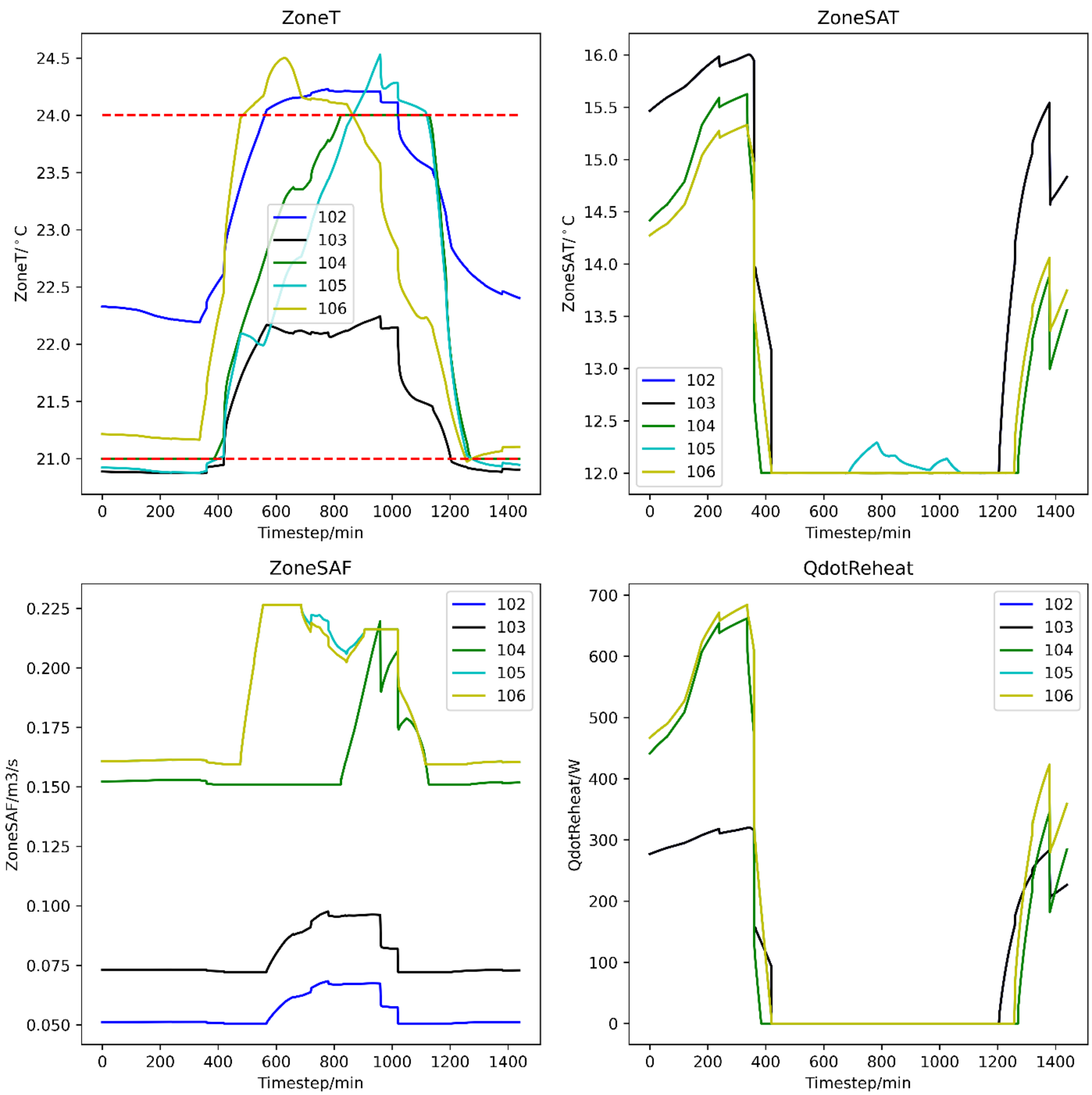

Figure A.87. Zone profiles on the first floor in the winter (B13).

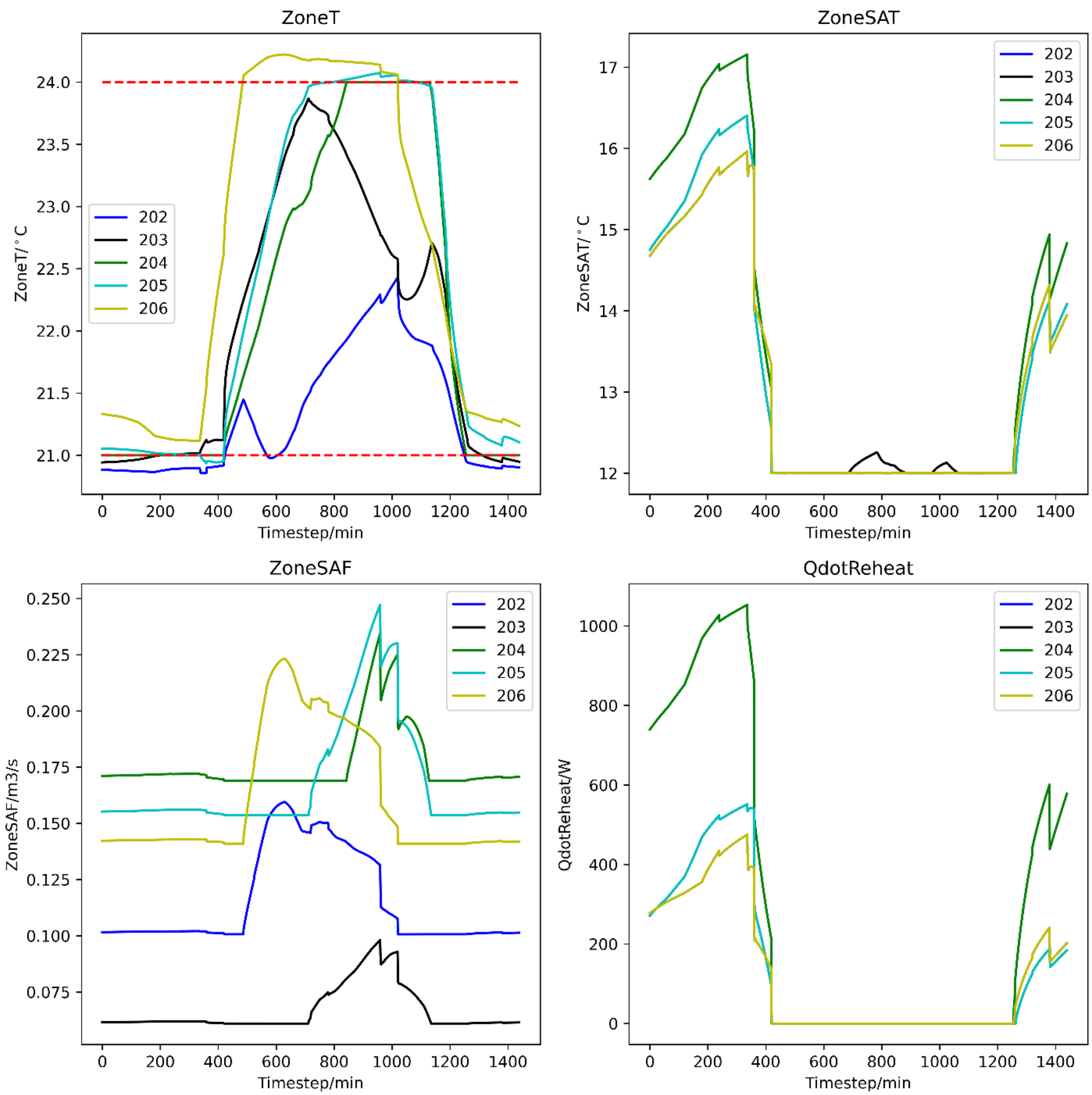

Figure A.88. Zone profiles on the second floor in the winter (B13).

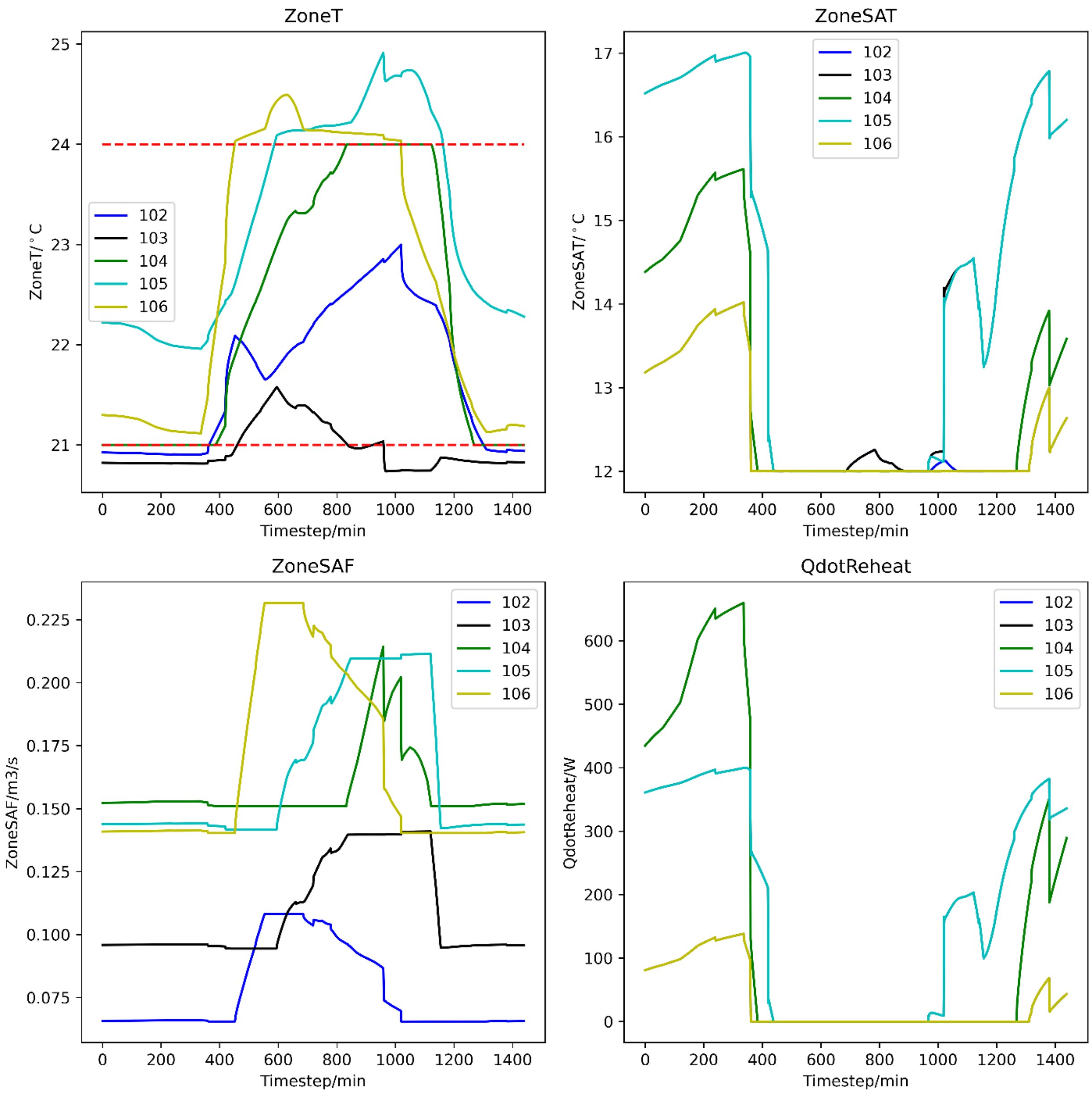

Figure A.89. Zone profiles on the first floor in the winter (B14).

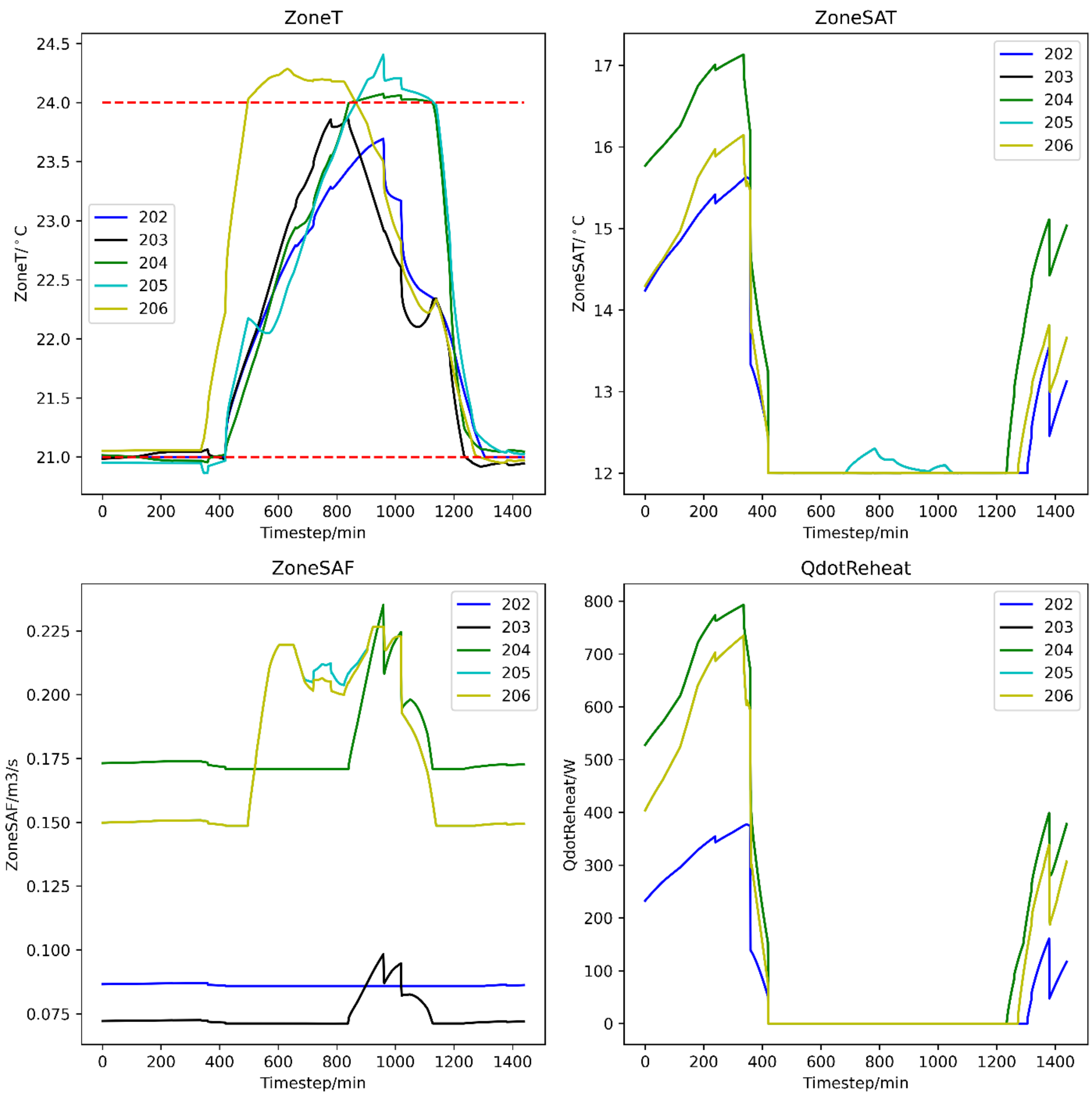

Figure A.90. Zone profiles on the second floor in the winter (B14).

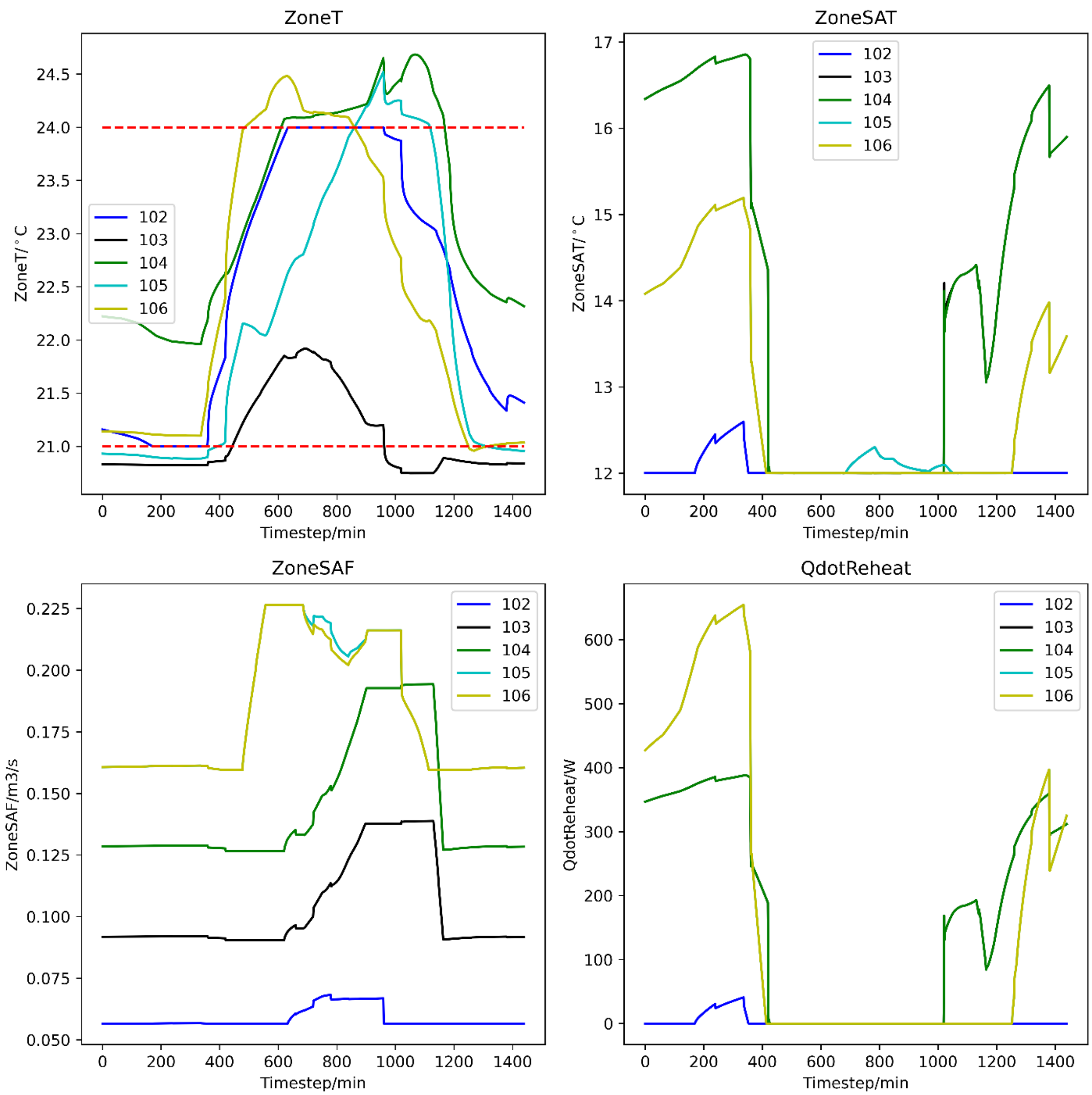

Figure A.91. Zone profiles on the first floor in the winter (B15).

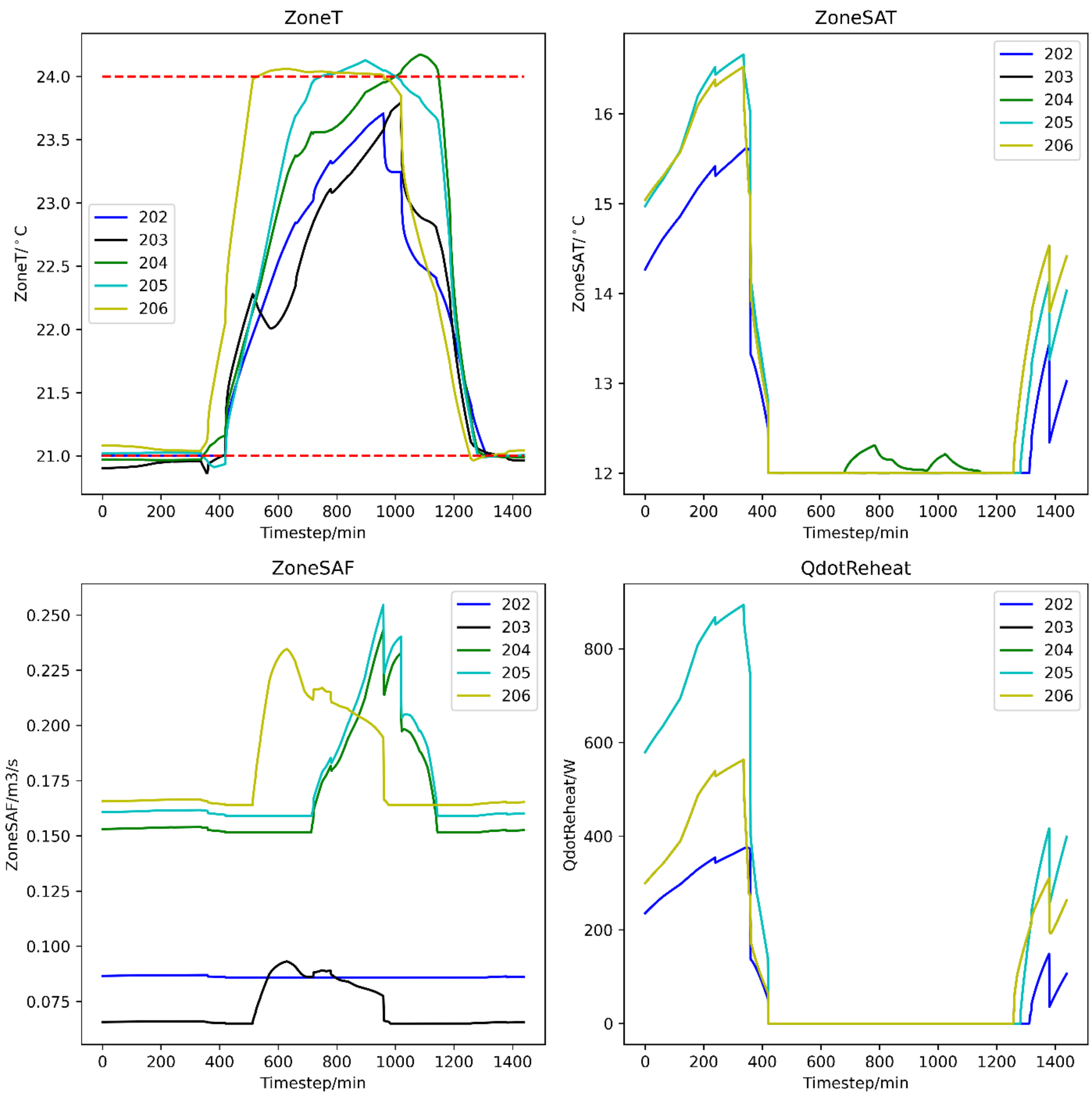

Figure A.92. Zone profiles on the second floor in the winter (B15).

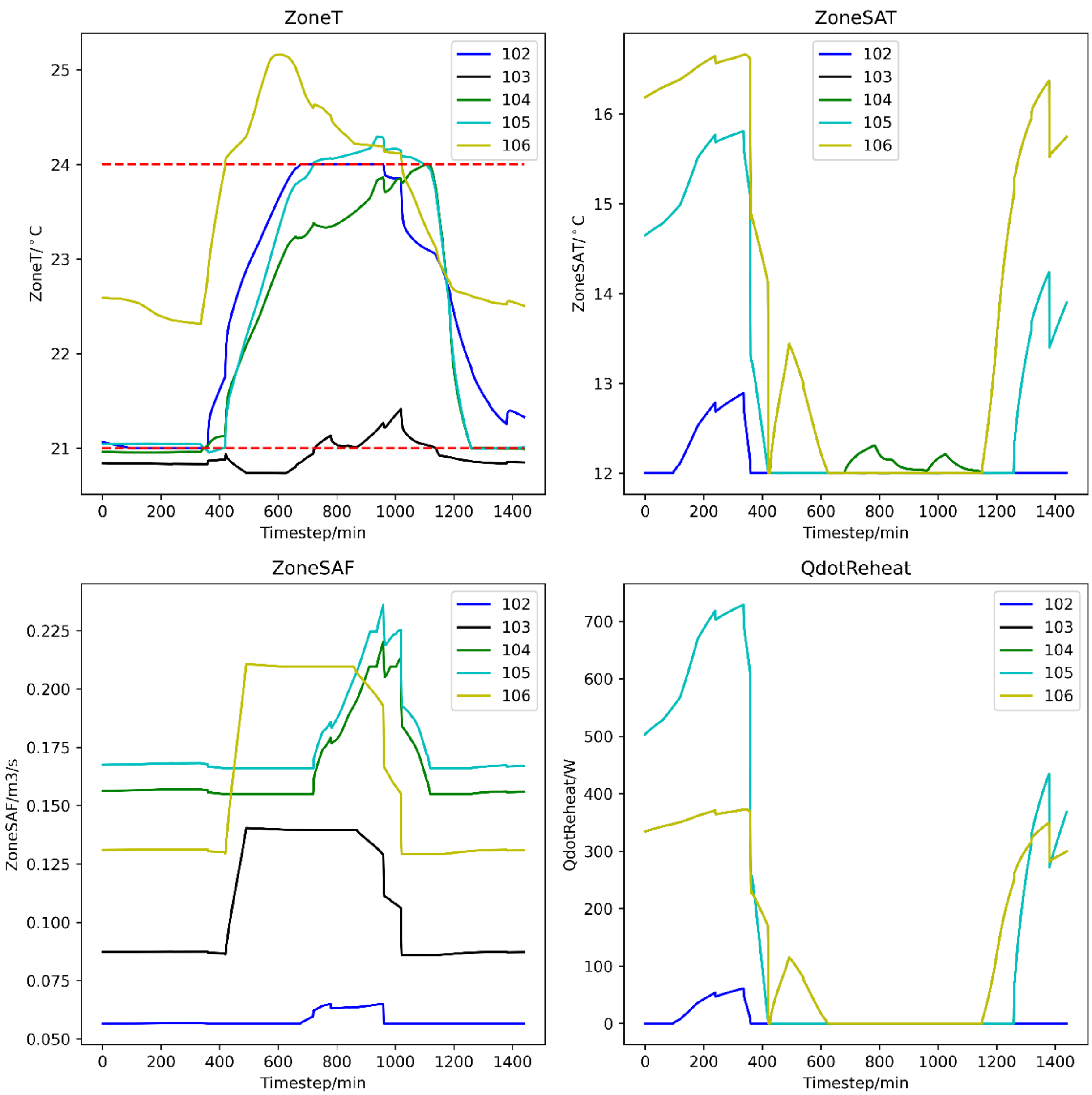

Figure A.93. Zone profiles on the first floor in the winter (B16).

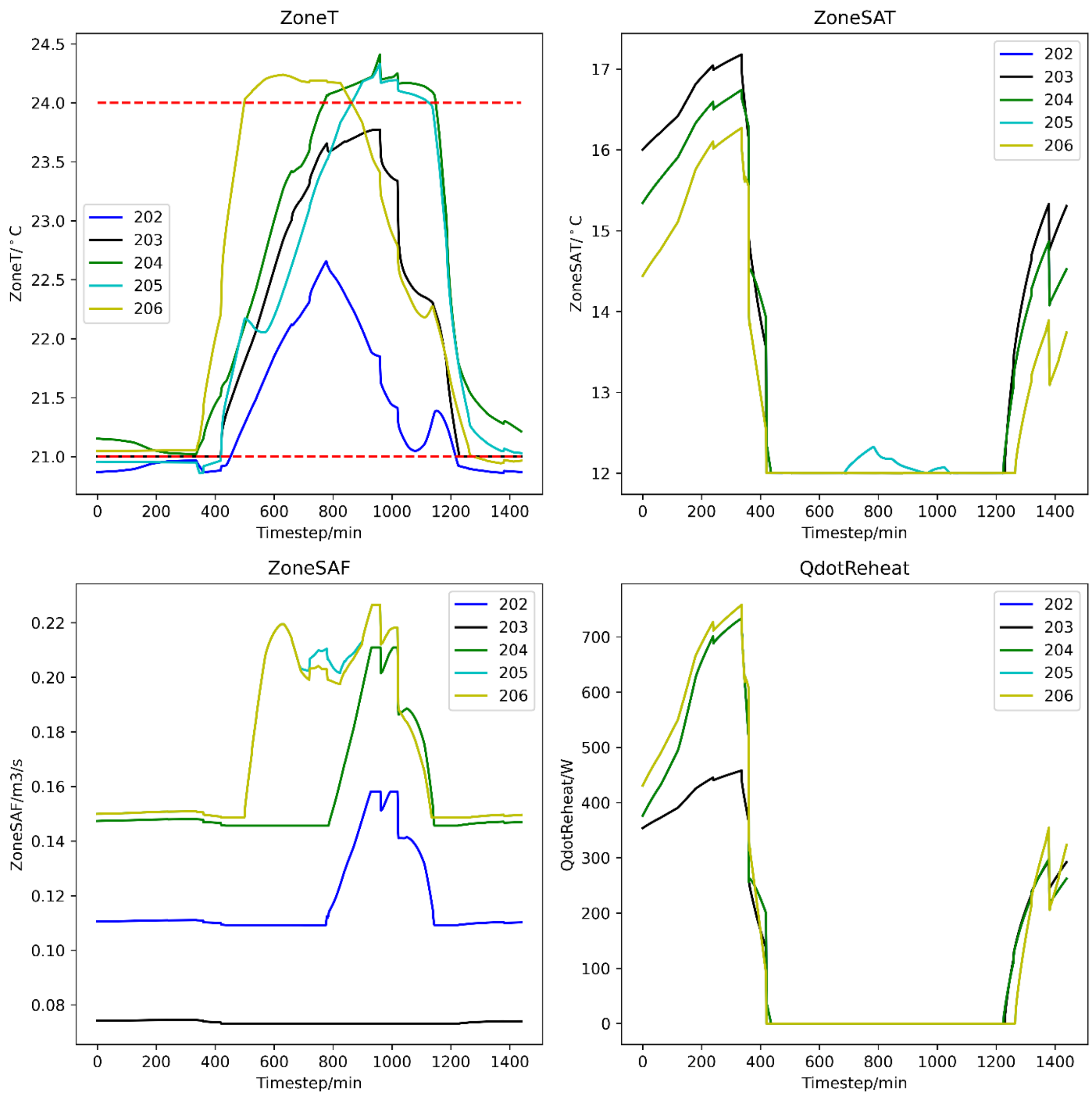

Figure A.94. Zone profiles on the second floor in the winter (B16).

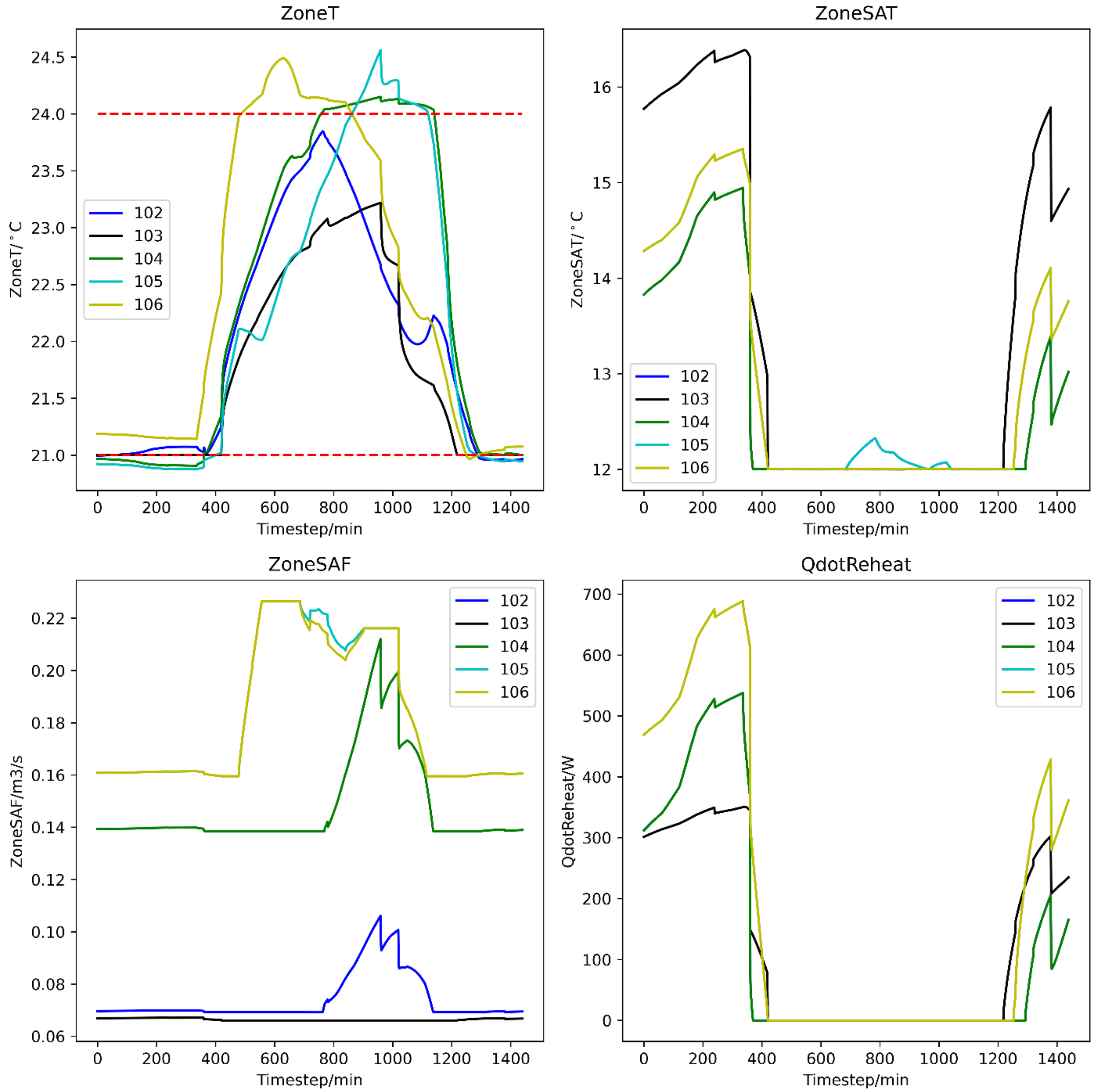

Figure A.95. Zone profiles on the first floor in the winter (B17).

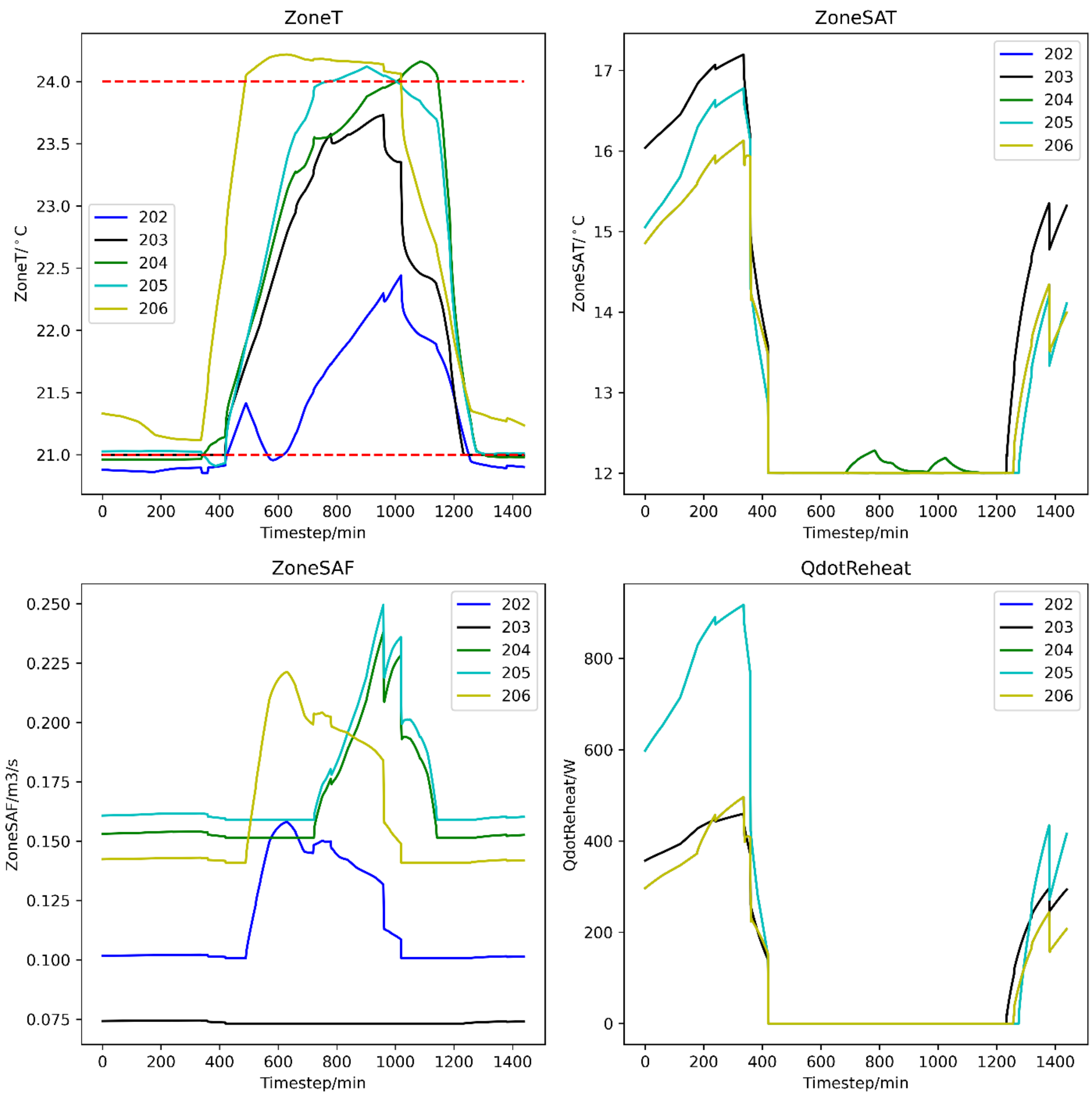

Figure A.96. Zone profiles on the second floor in the winter (B17).

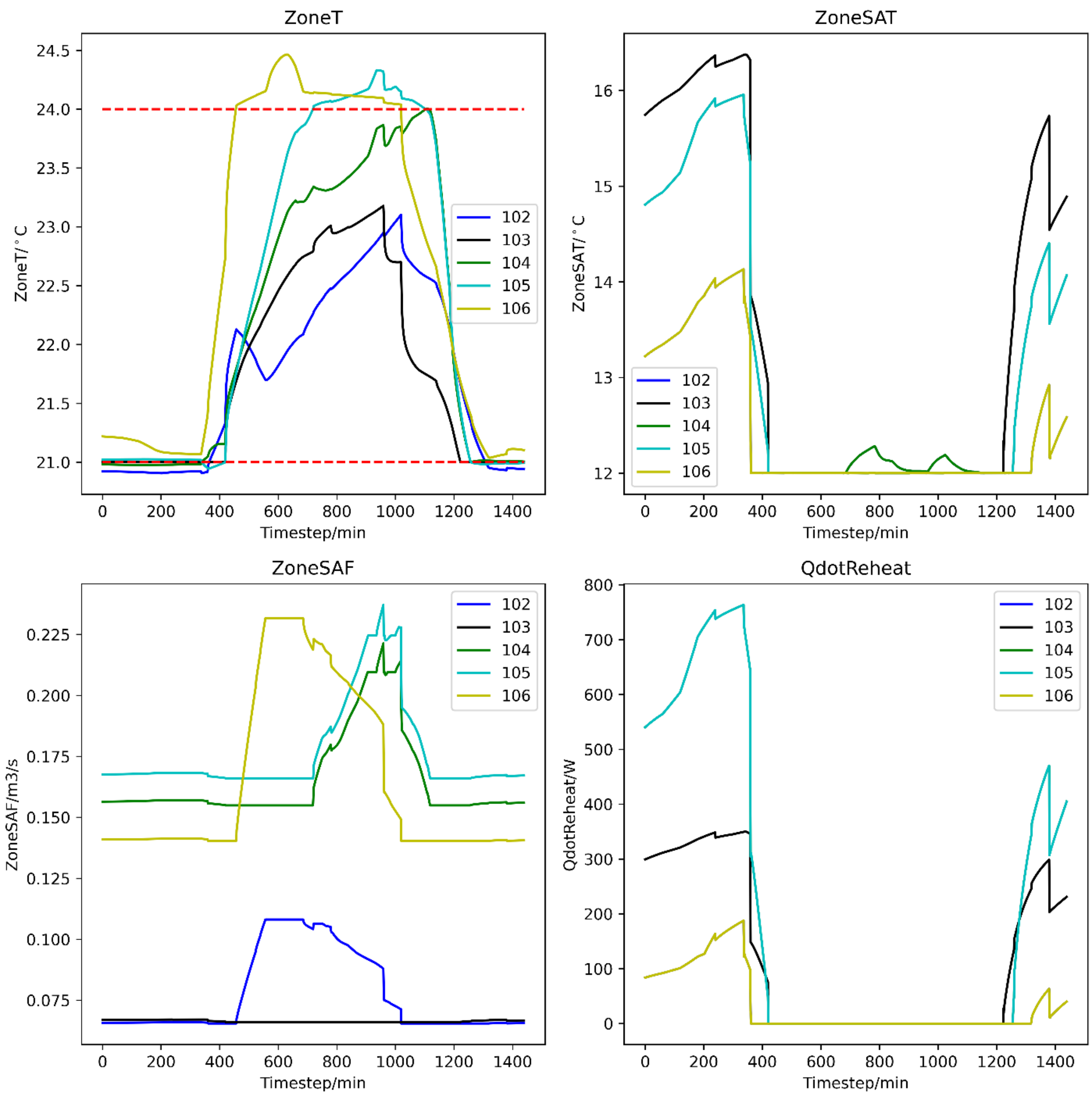

Figure A.97. Zone profiles on the first floor in the winter (B18).

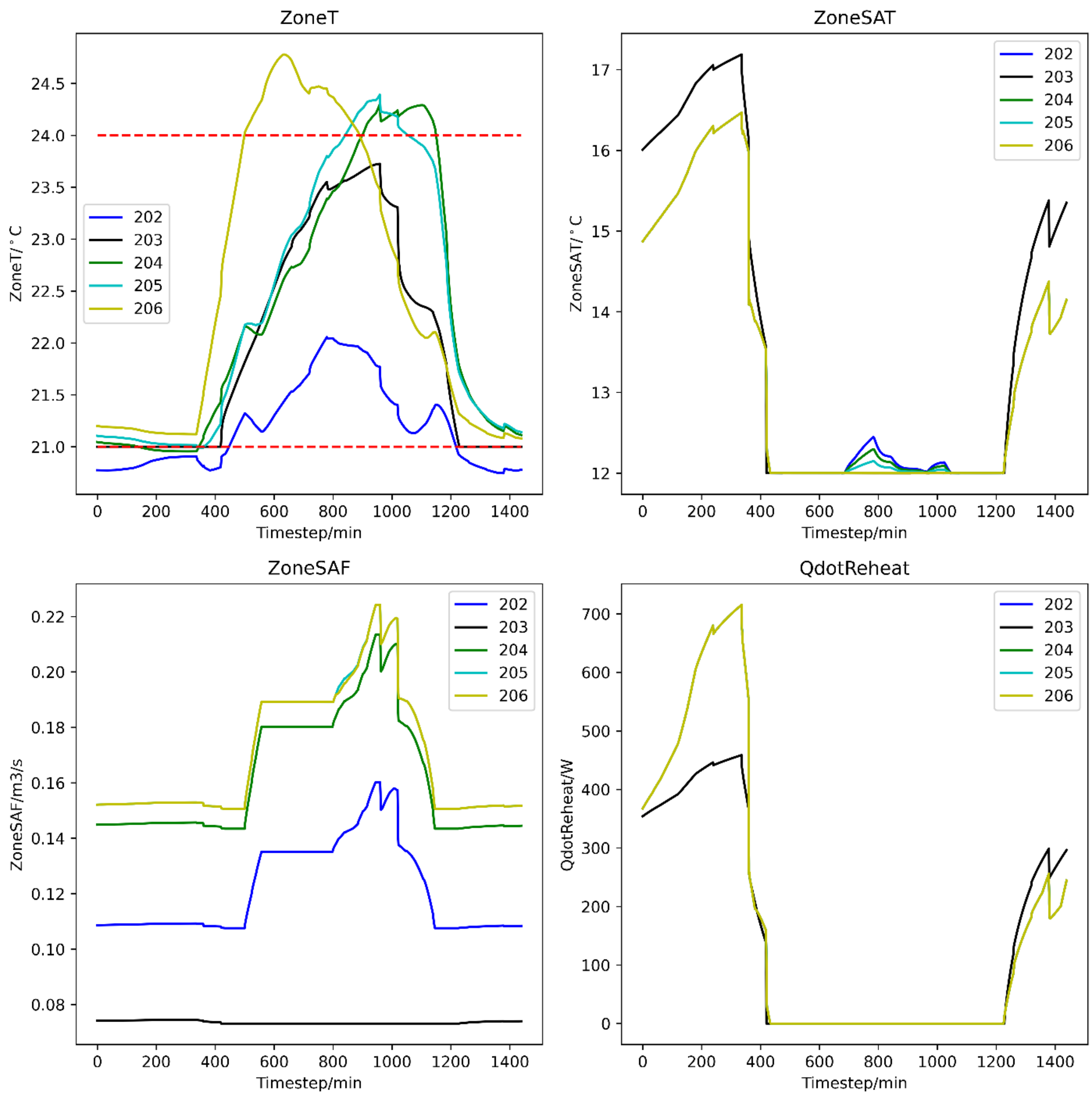

Figure A.98. Zone profiles on the second floor in the winter (B18).

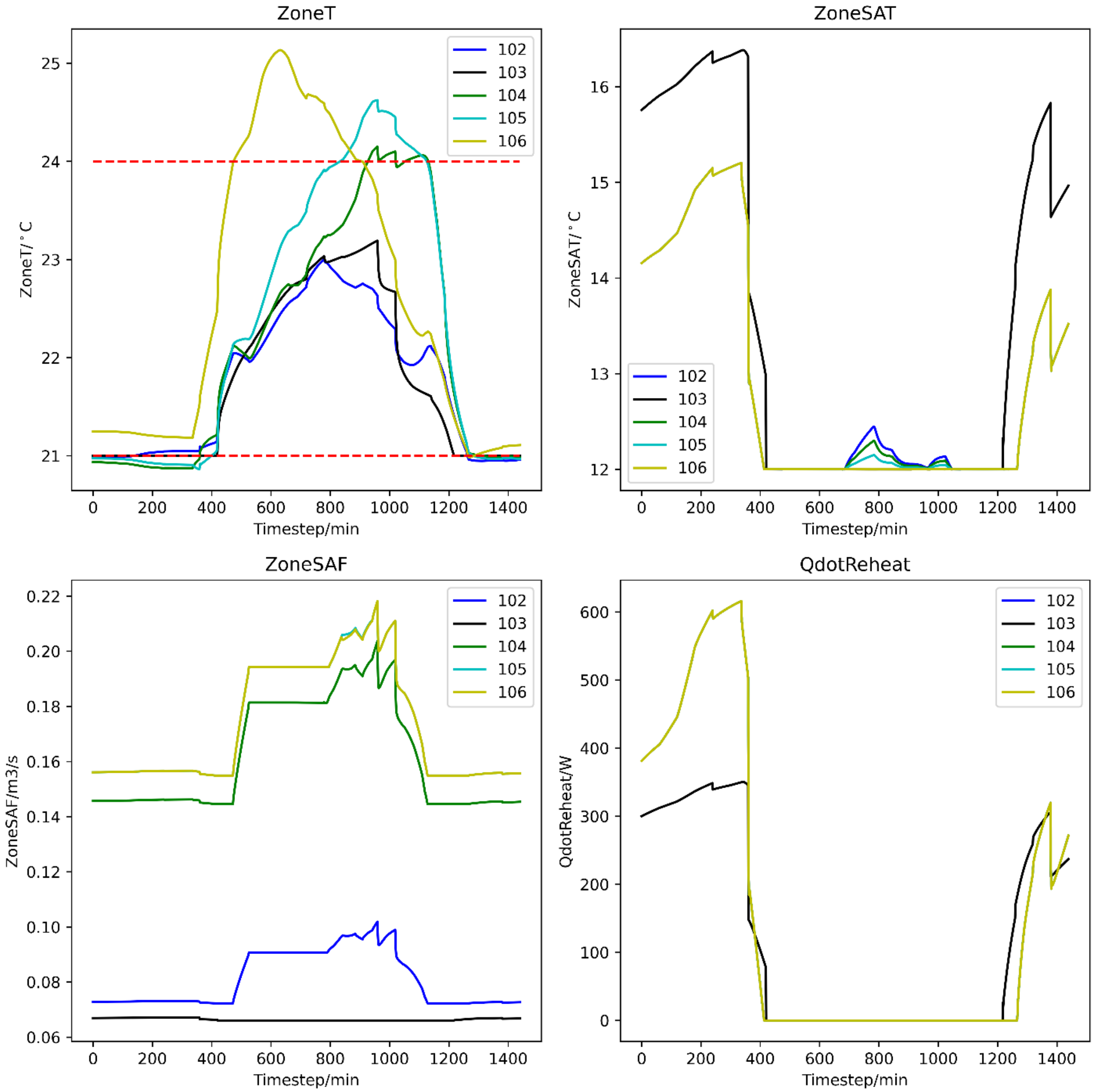

Figure A.99. Zone profiles on the first floor in the winter (B19).

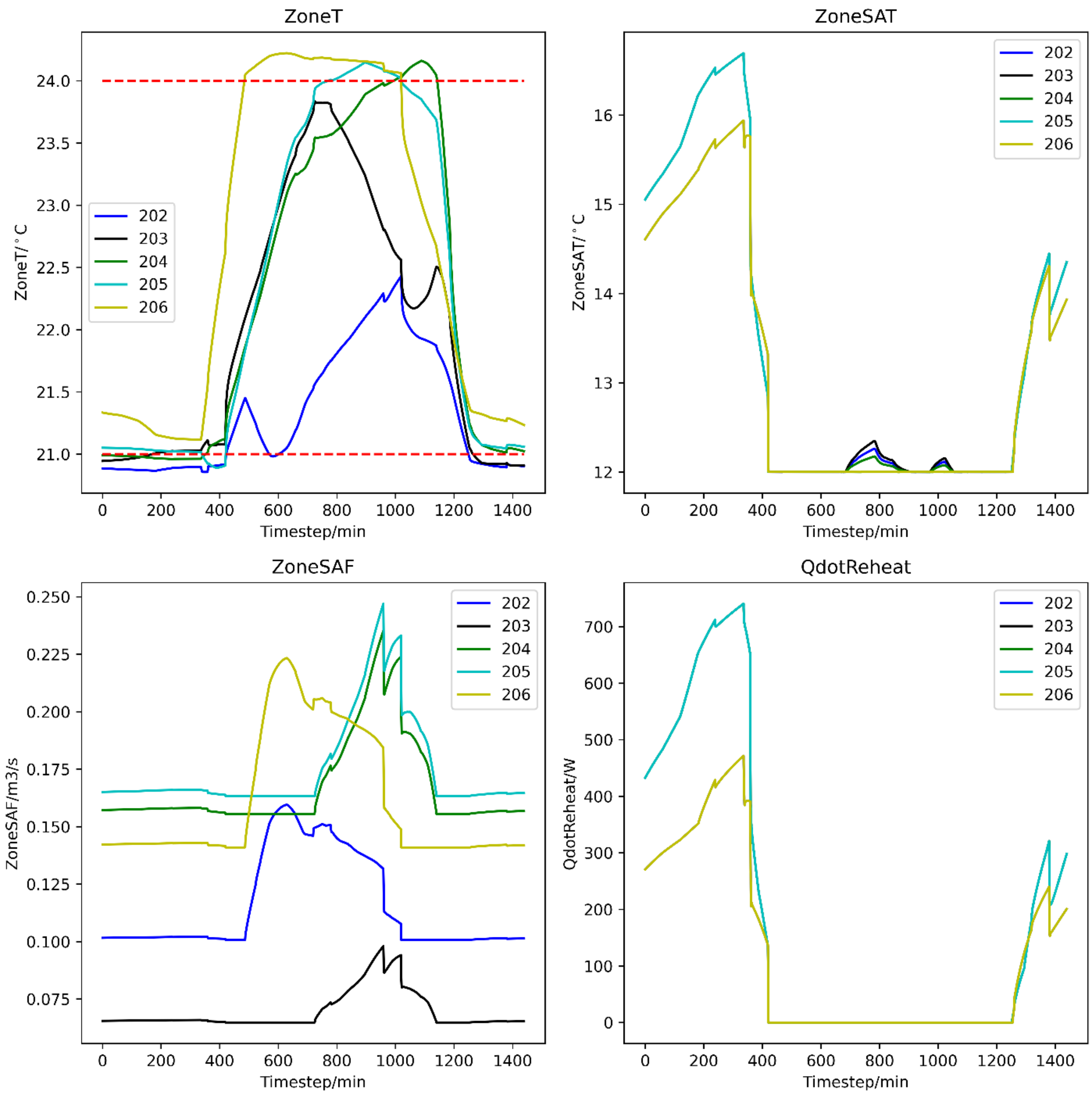

Figure A.100. Zone profiles on the first floor in the winter (B19).

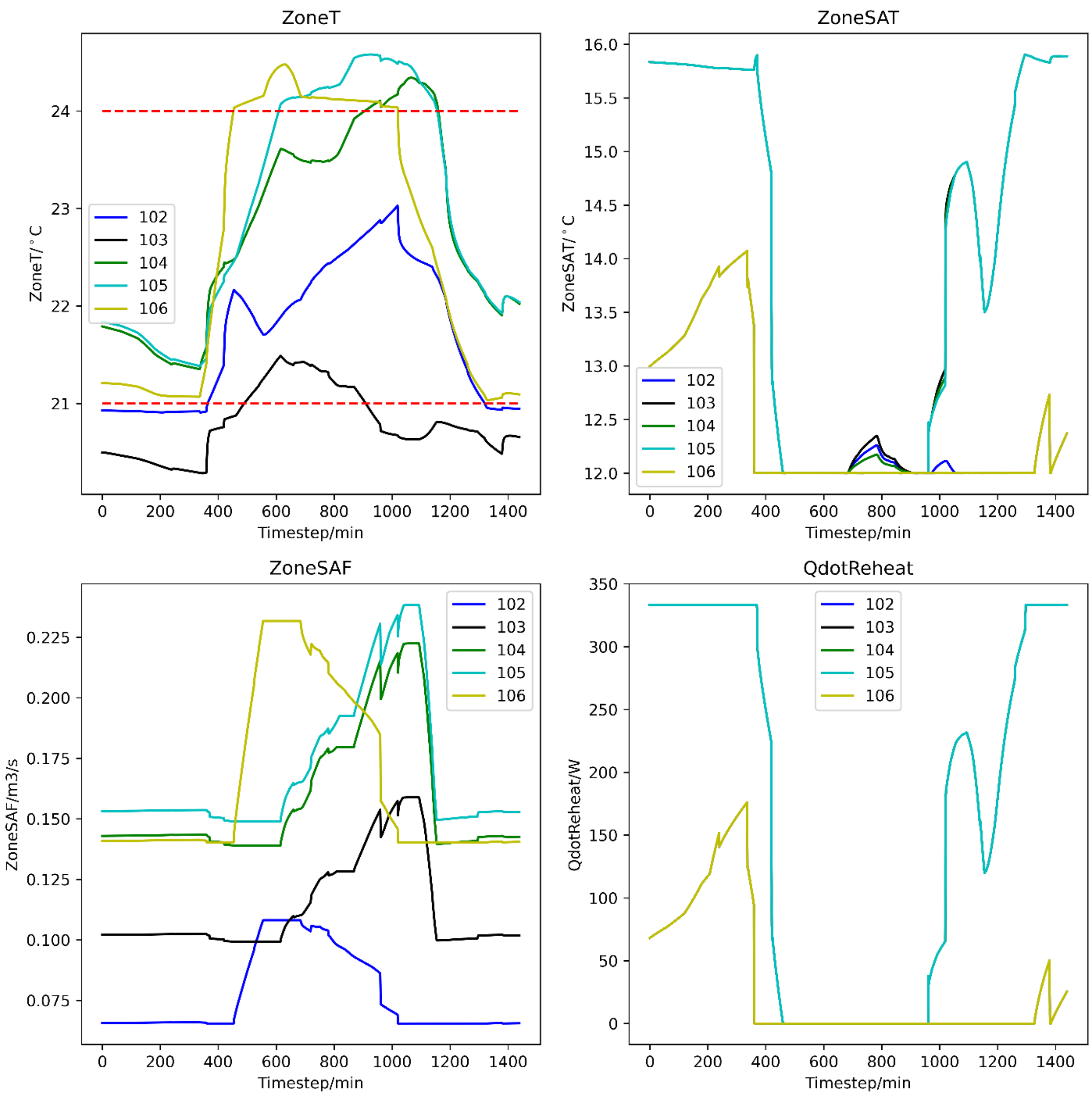

Figure A.101. Zone profiles on the second floor in the winter (B20).

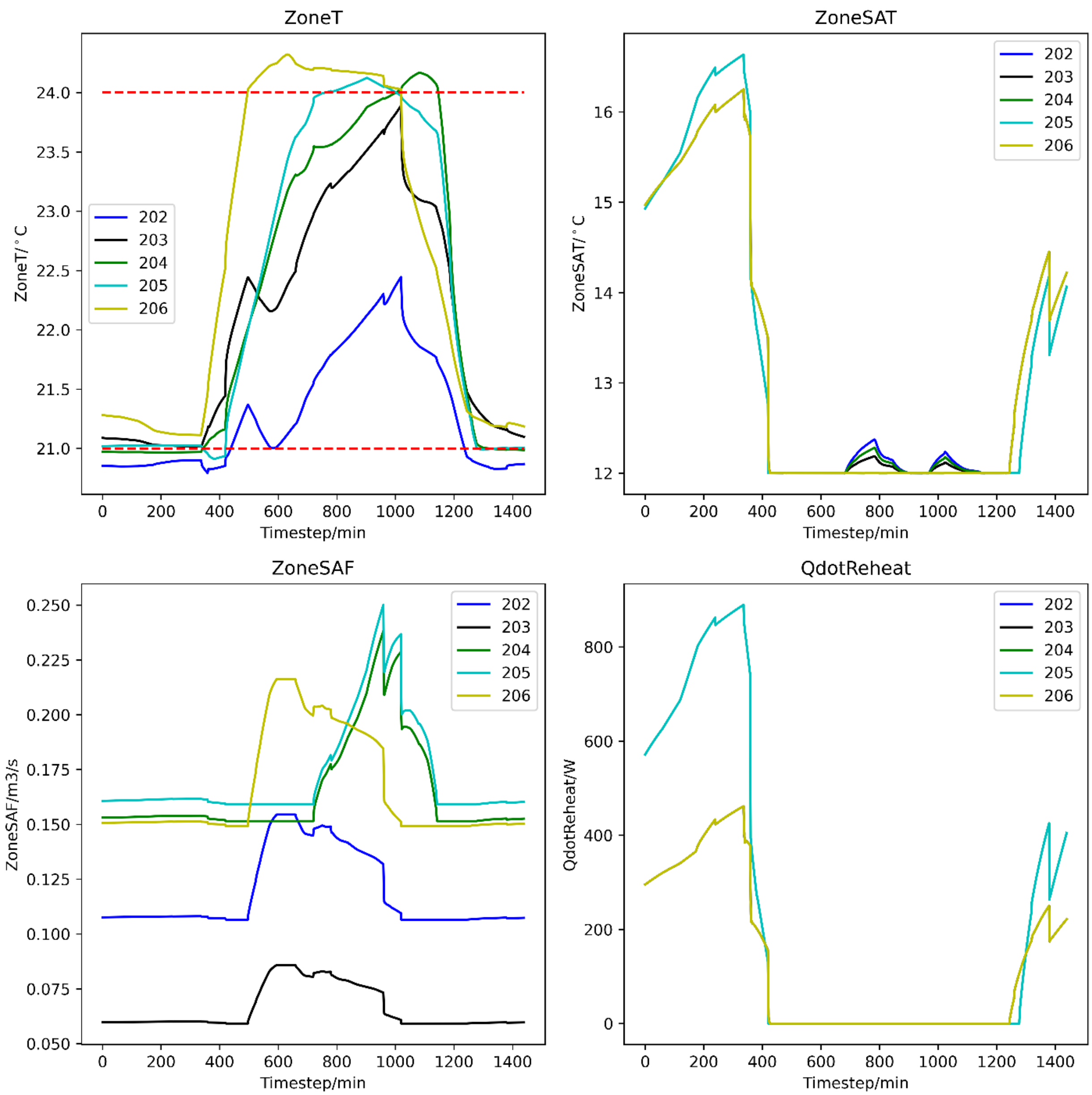

Figure A.102. Zone profiles on the second floor in the winter (B20).

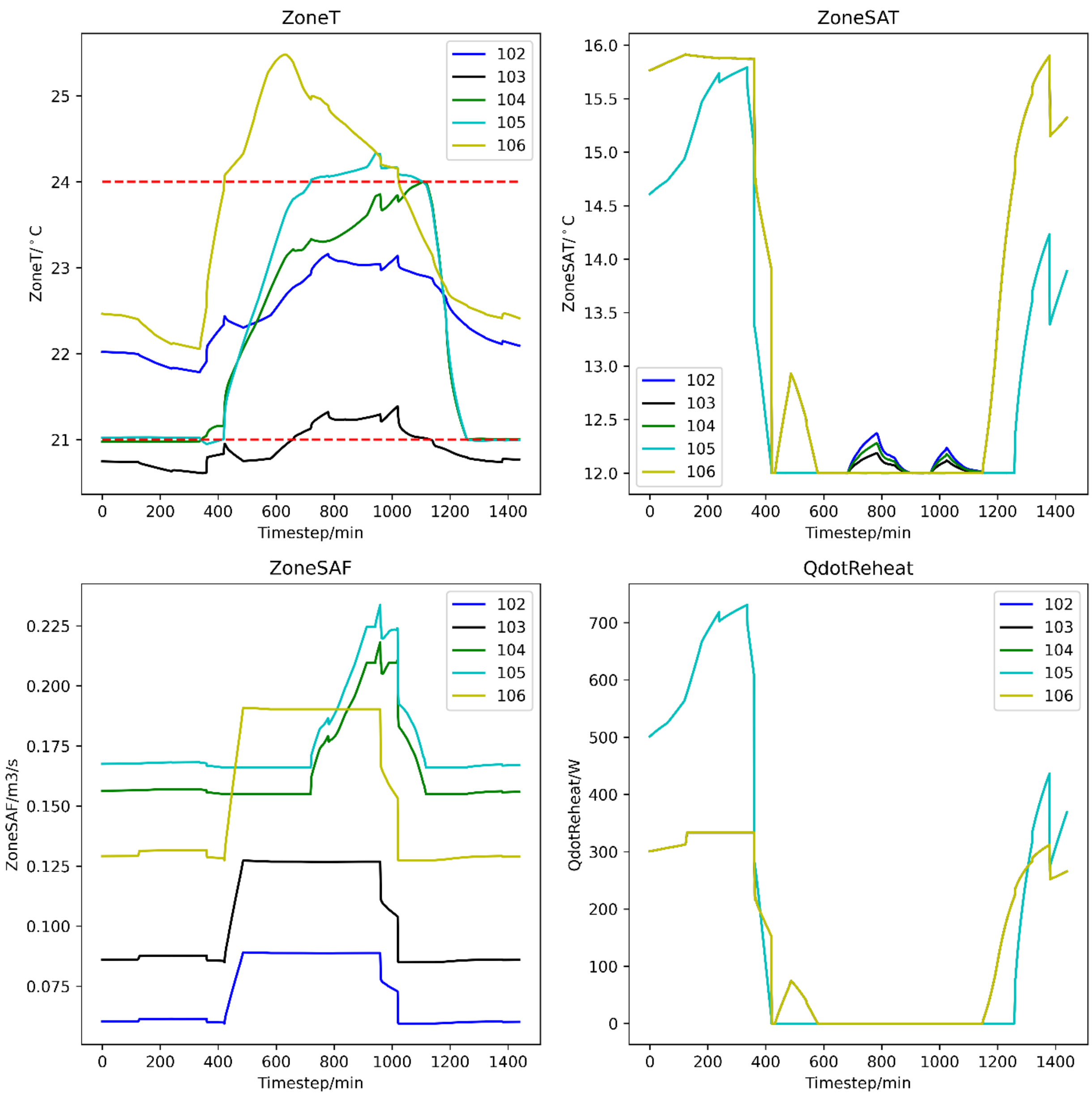

Figure A.103. Zone profiles on the first floor in the winter (B21).

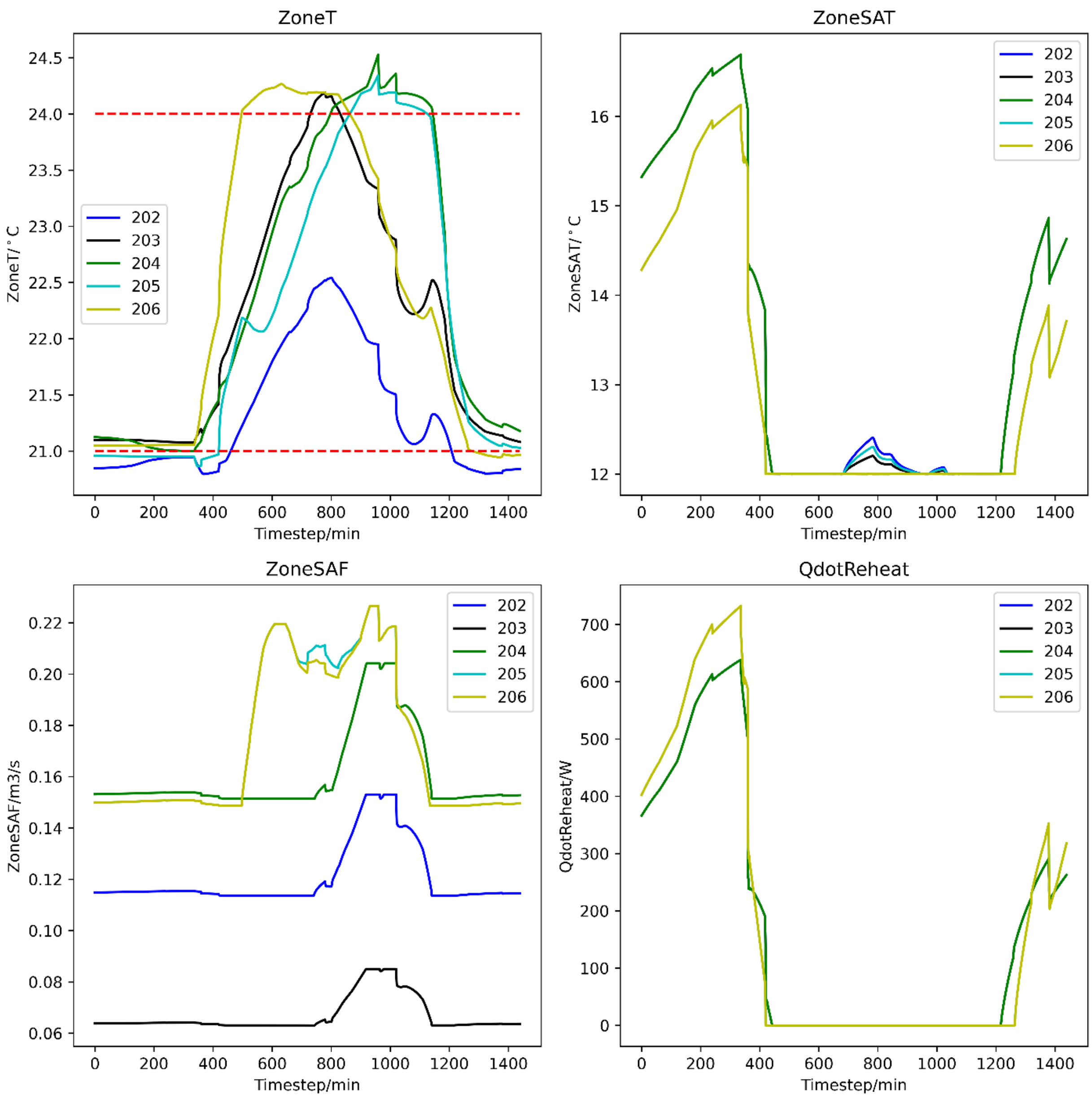

Figure A.104. Zone profiles on the second floor in the winter (B21).

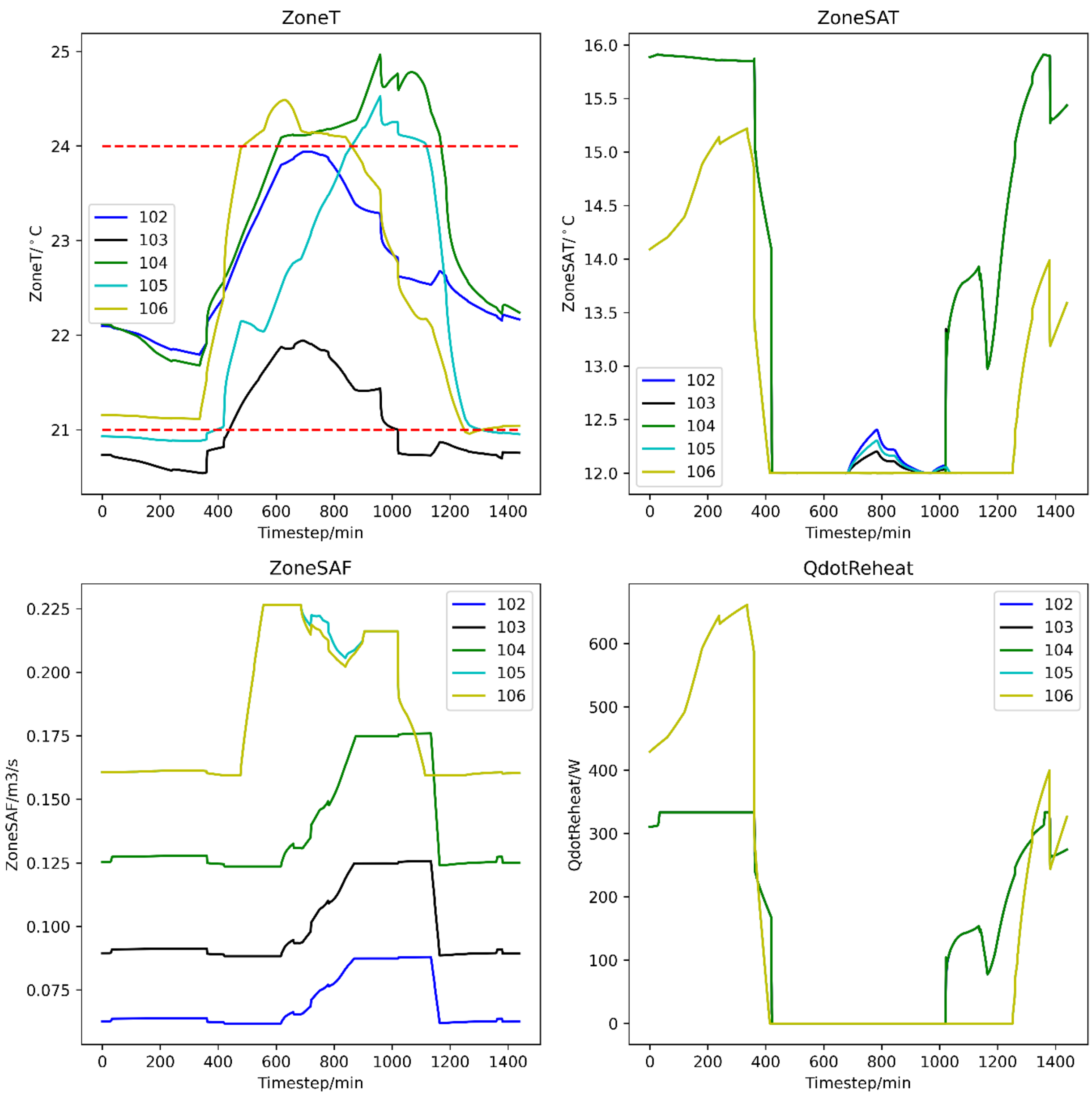

Figure A.105. Zone profiles on the first floor in the winter (B22).

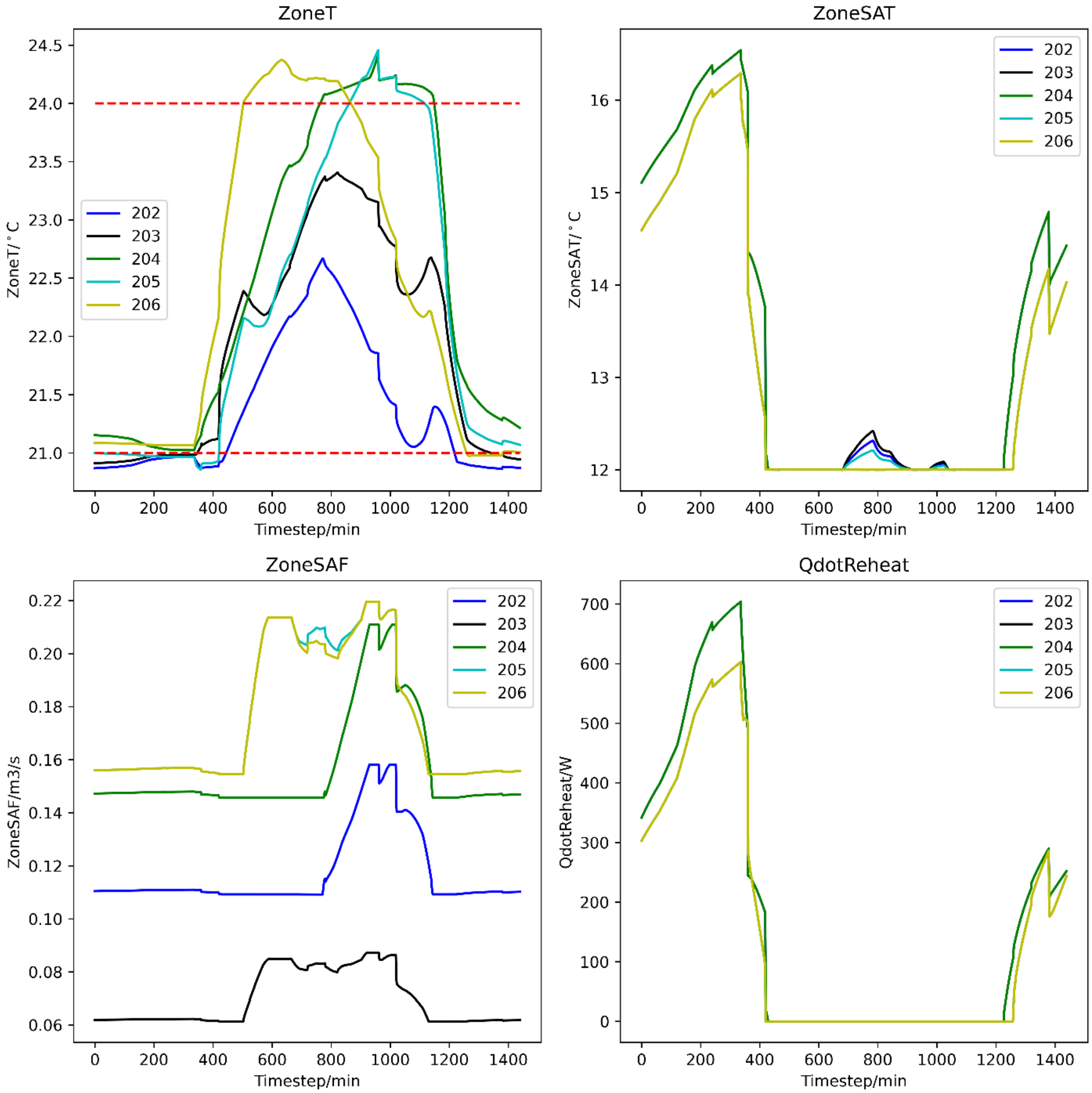

Figure A.106. Zone profiles on the second floor in the winter (B22).

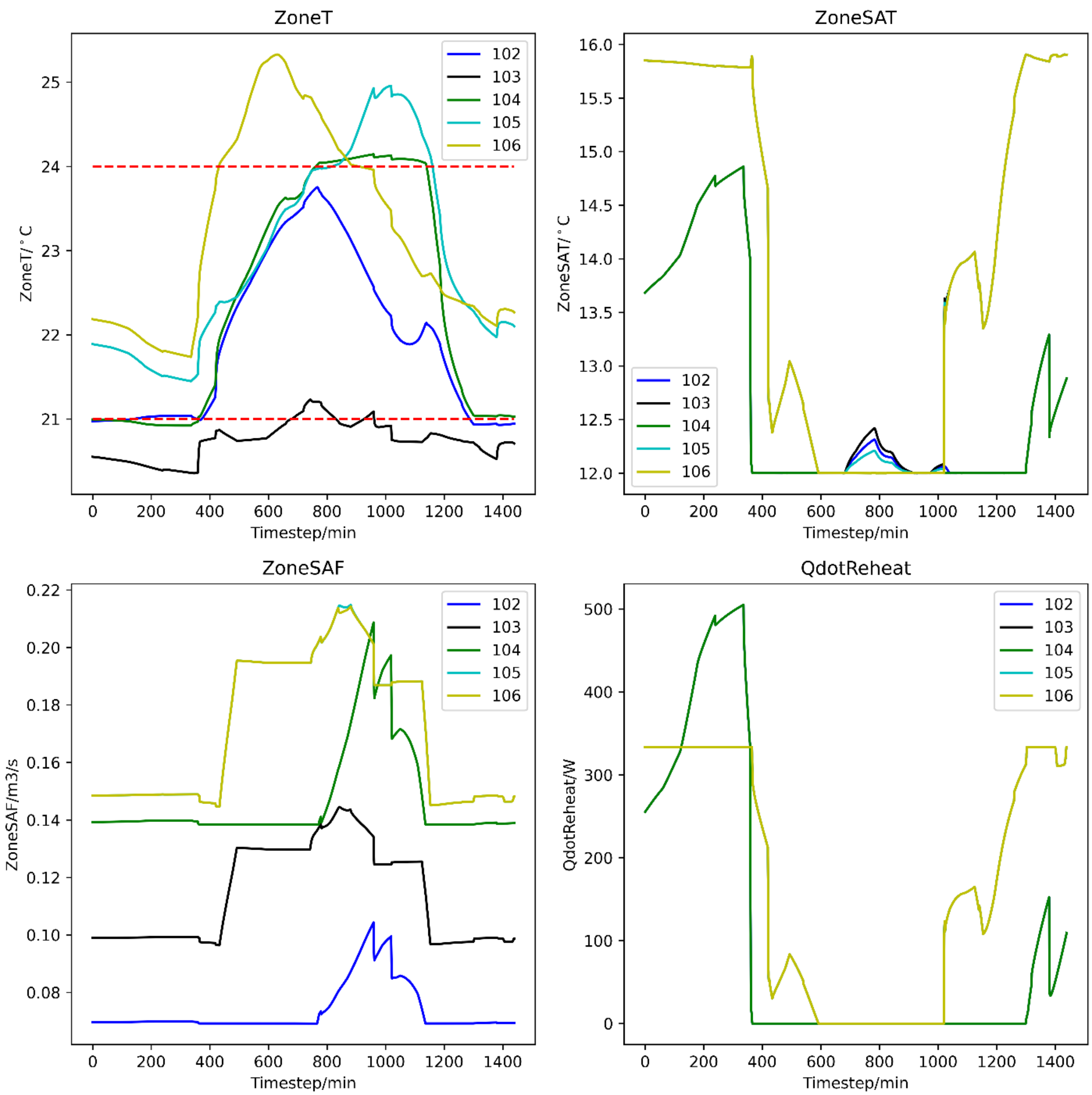

Figure A.107. Zone profiles on the first floor in the winter (B23).

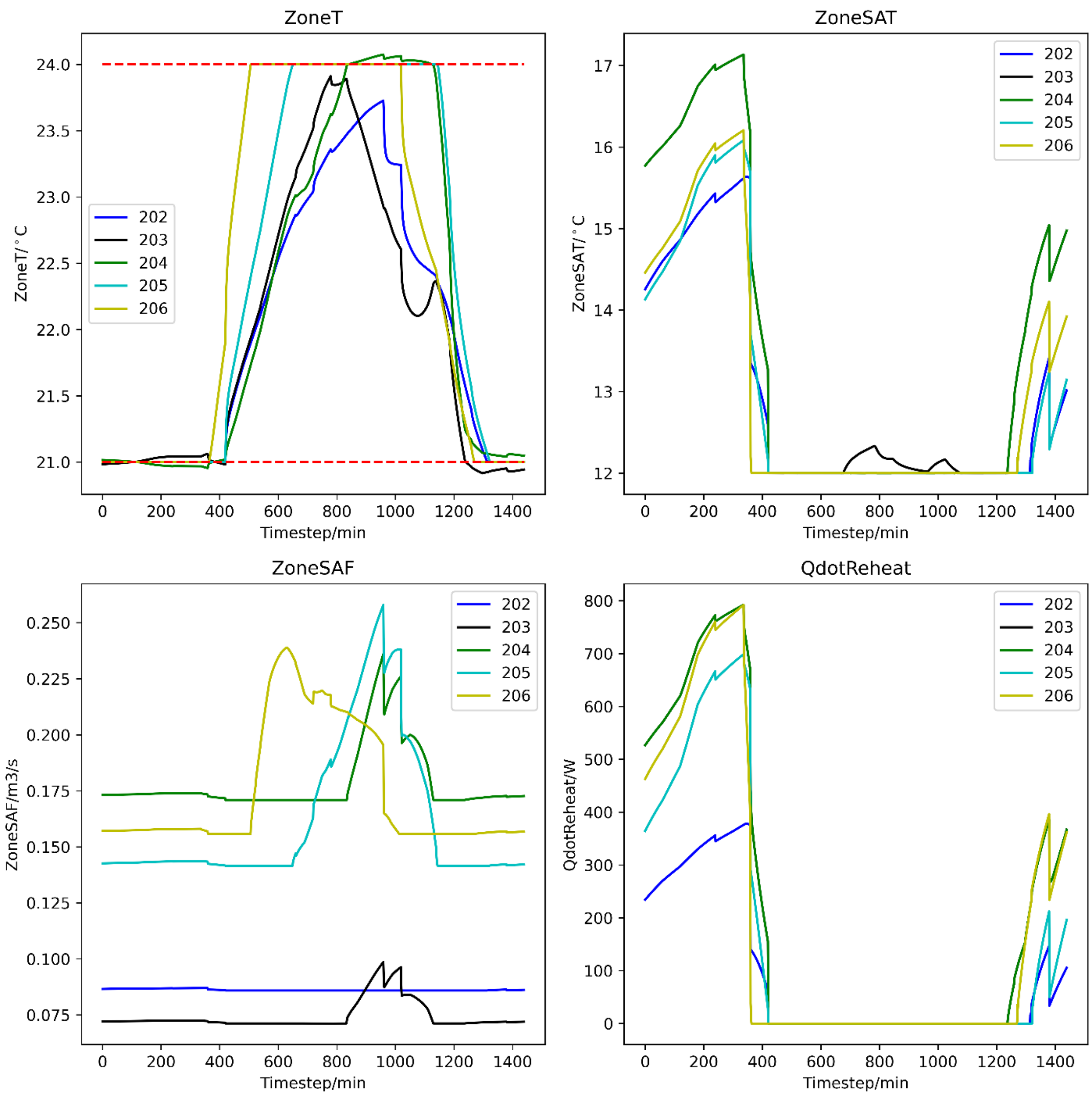

Figure A.108. Zone profiles on the second floor in the winter (B23).