A control-oriented model for combined building climate comfort and aquifer thermal energy storage system

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A Control-Oriented Model For Combined Building Climate Comfort and Aquifer Thermal Energy Storage System *

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***Abstract*—This paper presents a control-oriented model for combined building climate comfort and aquifer thermal energy storage (ATES) system. In particular, we first provide a description of building operational systems together with control framework variables. We then focus on the derivation of an analytical model for ATES system dynamics. The dynamics of stored thermal energy over time in each well of an ATES system is the most important concept for a building climate control framework. This concept is proportional to the volume and temperature of water in each well of an ATES system at each sampling time. In this paper we develop a novel mathematical model for both dynamical behavior of volume and temperature of water in each well of an ATES system and provide detailed steps for estimating the model parameters. To illustrate the applicability of our proposed model, a comparison based on an extensive simulation study using an aquifer groundwater simulation environment (MODFLOW) is provided.**

***Index Terms*—Combined Building Control and ATES System, ATES System Dynamics, Building Climate Comfort**

I. Introduction

Global energy consumption has been increasing over the past decades due to increasing population and economic growth. Considering the increasing energy demand worldwide, there has been a growing interest in energy saving technologies. A less well-known sustainable energy storage technology is Aquifer Thermal Energy Storage (ATES) that is used to store large quantities of thermal energy in underground aquifers enabling the reduction of energy usage and CO_2 emissions of the heating and cooling systems in buildings. An ATES system can be considered as a heat source or sink, or as a storage for thermal energy. It is especially suitable for heating and cooling of large buildings such as offices, hospitals, universities, musea (museums) and greenhouses.

A single ATES system generally consists of one or more pairs (doublets) of tube wells [1]. The well pairs simultaneously extract and infiltrate groundwater to store and extract thermal energy in aquifers, by changing the groundwater temperature in a heat exchanger which is coupled to the climate installation. Since ATES systems are connected to the building they provide with thermal energy, they tend to accumulate in urban areas which puts stress on the limited subsurface space [2].

Most buildings in moderate climates have a heat shortage in winter and a heat surplus in summer. Where aquifers exist, this temporal discrepancy can be overcome by seasonally storing and extracting thermal energy in and from the subsurface. ATES can contribute significantly to reduce energy use for space heating. One of the barriers for development of ATES systems is the mutual interaction between different (neighboring) ATES systems in urban areas [2], [3]. ATES systems have experienced a rapid growth in The Netherlands over the last two decades; despite successful experiments at the individual level, the overall performance of ATES systems and their contribution to energy savings remains below expectations [2], [4]–[6]. Total energy savings may be improved by more efficient/optimal employment of the available space in the subsurface.

The issue of mutual interaction and optimal use of subsurface space involves both planning and operation of ATES systems which also cause the limited performance and contribution to energy savings [2], [5]. Planning is important because the location of the wells determine the potential for interaction. Well location is not easily changed once installed, so during operation the control of ATES systems is the only way to manage subsurface space use and well efficiency and is therefore subject of this research. The building climate control system controls the ATES system and its subsurface space use. Thus any attempt to solve the problem of subsurface space use and mutual interaction should involve the building climate control systems. The key element/challenge for each ATES controller is to meet both its building's thermal energy demand as efficiently and cheaply as possible and to optimize subsurface space use.

To the best of our knowledge, an integrated analytical, control-oriented model for describing the efficiency and interaction between the building climate control system and ATES system has not been developed for a predictive control problem of building thermal comfort so far. In this work, we propose a unified framework to capture the dynamics of an ATES system integrated with the building thermal comfort control scheme. Such a scheme consists of a building climate control system in which we consider to have heating/cooling (thermal)

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network infrastructure with several components to achieve the desired building zone temperature for each sampling time. This building thermal network interacts with the ATES system, whose dynamics represent the transition of water temperature and volume of stored water in each well through time. We develop a mathematical model of the ATES system combined with a building thermal comfort model which is suitable for an optimal control problem formulation. The efficiency and practical feasibility of the proposed method is investigated in a simulation study. In particular, we compare the results of our proposed method with the groundwater simulator MODFLOW and demonstrate its performance.

This paper is organized as follows. In Section II the methods and components that are used in this study are formally introduced. In Section III we describe the elements of the building thermal comfort control system together with the interconnections between them and the control variables. The main results of this paper are summarized in Section IV where we present our new model for ATES system dynamics together with a discussion on the estimation of unknown parameters. A simulation study for a building thermal comfort control problem together with ATES system is presented in Section V. We conclude in Section VI with some remarks and future research directions.

II. Methods and Components

This section provides an overview of the methods developed together with detailed steps and components that are considered in this work. We first introduce an integrated framework which consists of building thermal comfort description with mathematical model for dynamics of ATES systems. Then we elaborate on the proposed scheme for developing an analytical ATES model.

A. ATES model integration with building dynamics

The required space for ATES in the subsurface depends on the energy demand of the associated building. Any attempt to optimize and/or coordinate subsurface space use of ATES systems should therefore include the properties, dynamics and systems characteristics of the building and its installation components. To minimize simulation time and enable a real-time model predictive control approach, we aim for an analytical description of the building thermal comfort together with a mathematical model for a single ATES system including several other components as illustrated in Figure 1. The building thermal comfort model consists of several parts. The first and most important part for this study is the dynamics of the ATES system that describes the temperature evolution and the growing/shrinking volume of warm and cold water in the wells over time. The second part of the model considers the energy transferred from the groundwater to the building in the heat exchanger, and third main component is the heat pump. We then consider the storage tank model dynamics, and the dynamics of the building zone temperature based on the supplied and returned water temperatures. The integrated model is developed based on the physical description and limitations of all parts that are considered in the thermal comfort network of the building control unit. Our goal with such a model is to formulate a framework for an optimal control problem with a yearly operation cycle using an analytical representation of warm- and cold-well water temperatures and their stored water volume dynamics.

B. Analytical ATES model

The building controller requires a simple analytical description of the amount of stored energy in the well. It needs to be analytical because the control algorithms computing the optimal operation strategy require a mathematical description of the relation between the stored energy and the control action. The stored energy is dependent on storage volume, storage temperature of ATES and thermal losses in the subsurface. Thermal losses occur during infiltration, rest, and extraction as a consequence of diffusion, dispersion, conduction, advection with ambient groundwater flow and interaction with other wells. These losses are dependent on system characteristics, such as flow rates/storage volume, distance between wells, filter screen length, storage cycle, etc. Thus based on known infiltration temperatures and volumes we need to calculate the expected losses in order to have a description of the temperature of the stored volume and amount of thermal energy available. An analytical description of ATES well temperature including these characteristics is not available in literature, thus needs to be developed. To do so we first describe the most important processes influencing the stored energy temperature.

1) Energy Losses in An ATES Well: The temperature of an ATES well changes over time and is subjected to several influences:

- The direct conduction and dispersion losses as a consequence of interaction and mixing with the surrounding soil/groundwater is an important loss term [7], [8].
- There are two kinds of water flow in underground surfaces:
  1) Ambient groundwater flow, velocity and direction with respect to orientation of own and other warm / cold wells determines losses and interaction between wells.
  2) Buoyancy flow caused by mixing of salinity stratified aquifer. Both natural groundwater and buoyancy flow are important, but do not always occur.

  Buoyancy flow is only relevant when density differences between infiltrated and surrounding groundwater occur [9]; in salinity stratified aquifers or with high temperature differences (>25°C) between infiltrated and ambient groundwater [10]. Heat transport and its associated losses for the well under consideration caused by advection is relatively easy to incorporate using the principle of superposition [7].
- Interaction with other groundwater storage or extraction activities. Other energy storage systems result in a different surrounding groundwater temperature for the well under consideration. This aspect will therefore be taken account for the ambient groundwater temperature.

2) Establishing the Analytical ATES-well Temperature Model (AATM): The AATM is built by a step-by-step approach, starting with a single ATES system incorporating dispersion and conduction losses. After that the model will be extended with groundwater flow and interaction. This paper discusses only the first of these steps, but also includes the mutual interaction with other wells. We use Monte-Carlo simulations of ATES systems to model the well temperatures in order to identify and quantify the losses required to incorporate in the AATM. To realistically simulate subsurface dynamics, a geohydrological model describing the aquifer processes was developed using MODFLOW [11] and MT3DMS [12] to model the temperature [13]. MODFLOW and MT3DMS are finite-difference element packages and well-established models, widely used for the simulation of groundwater flow and transport. Based on energy demand profiles representative for ATES systems, the well temperature is evaluated.

III. Building Thermal Comfort Description

In this section we present a detailed description of building (zone) temperature over time as a dynamical system, for heating and cooling systems of a building that is called a thermal comfort model. We do so by introducing and defining the building's system components and properties, together with the description of energy demand calculation.

A. Operational Systems and Equipment

The heating and cooling system uses water to control zone temperature. The conceptual piping network of the water circulation is depicted in Figure 1 for different configurations of the building thermal modes. The thermal comfort model of the building consists of the following components:

- **Building:** The evolution of a building zone temperature over time is considered as a dynamical system. We assume the building has one single zone with wall layers. The lower surface of a zone (floor) is considered as a heating source via the supplied water temperature that flows into cyclic pipes. Cooling energy is supplied via the upper interior surface (ceiling) of a zone.
- **External Party:** This component represents an external source of thermal energy that can provide heat or cold energy. We define an external party to capture the possibility of transmitting surplus thermal energy from one building to another via heat pump in a campus of several buildings.
- **Boiler:** A closed vessel in which water is heated and it is used for additional heating if the heat pump cannot supply enough heat.
- **Chiller:** A closed vessel in which water is cooled via vapor-compression. It is used to further reduce the water temperature infiltrated into the ATES system in case the water output temperature on the evaporator side of the heat pump is not cold enough.
- **Storage Tank:** A container that holds water for the short term storage of thermal energy. The storage tank is placed between the heat pump and the heat exchanger to keep thermal energy at the desired level for each time period.

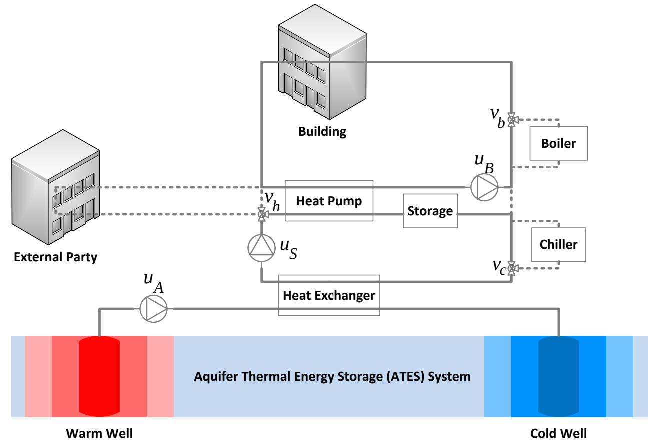

Fig. 1. Conceptual representation of building thermal comfort piping network together with an aquifer thermal energy storage (ATES) system.

- **Heat Pump:** These devices are designed to move thermal energy and consist of a condenser side (warmer side) and evaporator side (colder side). They can provide heat from a heat source (condenser) or cooling from a cold source (evaporator). A heat pump uses some amount of external power to accomplish the work of transferring energy.
- **Heat Exchanger:** This equipment is built for heat transfer from one medium to another. We consider to have a plate heat exchanger that is composed of multiple, thin, slightly separated plates that have very large surface areas and small fluid flow passages for heat transfer.
- **ATES:** This component contains a warm- and cold-well that are connected to an aquifer layer to store and retrieve thermal energy. An aquifer is a formation of water-bearing sand material in the soil that can contain and transmit water. Wells can be drilled into the aquifers and water can be pumped into and out of the aquifer layers. An ATES system is used as a long-term storage of water in the aquifer layers. When the building is cooled, cold water is taken from the cold-well and the return hot water that is extracted from the building is stored in the warm-well via a heat exchanger. This procedure is reversed when the building is heated.

We assume in our model that there is an ATES system inside the building thermal network that has two wells containing warm and cold water. A heat exchanger is installed to transfer the thermal energy from the stored water in the ATES system to the circulated water in the building thermal network. Note that the water in the two sides of the heat exchanger are not coming into contact. Next, a heat pump is placed to transfer energy from an ATES system to the building and keeping the high level of energy during the cold season. As a consequence, the heat pump uses some amount of external energy to accomplish the work. A storage tank is also considered in the way of return water from the heat pump to the heat exchanger. The role of storage tank is to hold water for the short term as a storage of thermal energy and to keep thermal energy at the desired level for each time period. We consider to have a boiler to generate hot water from circulated water inside the building thermal network. For the warm season, the evaporator side of a heat pump is used to reduce the temperature of circulated water in the building thermal network to the desired level. In order to obtain a generic model of the heating and cooling systems in the building, we consider to have a boiler and a chiller with bypass pipes together with valves. This makes it possible to turn on or off their effect on the heating and cooling system of the building with their desired level of contributions being manipulated variables. The circulated water is entering to the floor or ceiling of the temperature-controlled building zone to generate heat or cold, respectively. The various configurations of the considered integrated system model are discussed next. The main difference between all configurations is the activation of the corresponding devices with respect to the outside air temperature.

The circulation of water in the piping network of the building thermal model for the cooling purpose together with an ATES system during warm season is described as follows. In this configuration an ATES system together with a heat exchanger and a heat pump is activated. In case the outside air temperature is not very warm, one can use direct connection of the ATES system together with a heat exchanger for the cooling purpose of the building and turn off the heat pump as it is depicted in Figure 1 using value v_h and dashed line toward internal building pipe network.

For heating purposes of the building during cold season, the condenser side of heat pump is used. Since the stored warm water in the warm-well of ATES system is not hot enough, the heat pump is on for all configurations during the cold season. In this configuration the outside air temperature is very cold and there is a need to heat up the water circulating inside the building thermal network. Therefore it is important to turn on a boiler. Since in this condition the outflow water temperature from the building is not cold enough, a chiller is used to provide lower water temperature in order to store in the ATES system cold-well. When the supplied water temperature from the condenser side of the heat pump is hot enough, the boiler is turned off. However, the outflow water temperature is still not cold enough and a chiller is used to provide lower water temperature in order to store in the ATES system cold-well.

The configuration that operates with an external thermal resource during cold and warm season is also considered. The reason for employing this mode of operation is that if the outside air temperature is not very cold, external thermal energy may be available that is cheaper than that obtained through operating an ATES system. Therefore, it may be worth to turn off the heat exchanger with the ATES system. These configurations consist of a heat pump to transport thermal energy from an external party to the building.

B. Building Thermal Comfort Variables

We define boundary conditions for operating each device in a particular mode of operation with respect to the outside air temperature $\mathrm{T}_o(t)$. The desired building zone temperature is equal to $\mathrm{T}^{\mathrm{B}}_{\mathrm{des}}(t)$ and if $\mathrm{T}^{\mathrm{B}}_{z}(t)$ resides between $\mathrm{T}^{\mathrm{B}}_{\mathrm{des}}(t) \pm 2°\mathrm{C}$, there is no need for cold or heat thermal energy and all components are in off mode. If the outside air temperature $\mathrm{T}_o(t)$ exceeds the upper boundary of building zone temperature $\mathrm{T}^{\mathrm{B}}_{z,ub}$ but still lower than the boundary of warm temperature $\mathrm{T}^{\mathrm{B}}_{z,ub}+5°\mathrm{C}$, there is a request for a light cooling energy meaning that we can use the stored cold energy in the cold-well of ATES system without using the evaporator side of a heat pump. In case the outside air temperature $\mathrm{T}_o(t)$ goes beyond $\mathrm{T}^{\mathrm{B}}_{z,ub}+5°\mathrm{C}$, we have to turn on the evaporator side of a heat pump. The counterpart of above conditions are as follows. If the outside air temperature $\mathrm{T}_o(t)$ drops below the lower boundary of building zone temperature $\mathrm{T}^{\mathrm{B}}_{z,lb}$ but still above the boundary of cold temperature $\mathrm{T}^{\mathrm{B}}_{z,lb}-5°\mathrm{C}$, there is a request for a light heating energy meaning that we can use the stored hot energy in the warm-well of ATES system without using the condenser side of a heat pump. In case the outside air temperature $\mathrm{T}_o(t)$ drops below $\mathrm{T}^{\mathrm{B}}_{z,lb}-5°\mathrm{C}$, we have to turn on the condenser side of a heat pump. When the outside air temperature $\mathrm{T}_o(t)$ drops further below, it is time to use a boiler as an additional heat source for the building thermal network. In all above conditions, there is a possibility to use an external party to contribute to the required amount of thermal energy. However, there is also a limitation for the external resource. It is considered to have a possibility of using the heat pump with partial capacity in a parallel mode with direct connection to the heat exchanger by defining a valve to control the input water of the heat pump together with a bypass pipe.

The aforementioned operating modes are defined for all sampling times $k \in \{1,2,3,\cdots\}$ along with the following control input decision variables:

- Continuous variables: we consider pump flow rates and valve positions with the following definitions.
  1) Pump flow rates: define $u_{\mathrm{B},k}, u_{\mathrm{S},k}, u_{\mathrm{A},k} \in \mathbb{R}_+$ to be the pump flow rate in the building thermal network, in the storage tank and in the ATES system side, respectively.
  2) Valve positions: consider $v_{b,k}, v_{c,k}, v_{h,k} \in [0,1]$ to be the valve positions for the boiler, the chiller and the heat pump in the building thermal comfort network, respectively. Their values are interpreted as

$$\begin{cases} v_{b,k}, v_{c,k}, v_{h,k} = 1 & \text{full working capacity} \\ 0 < v_{b,k}, v_{c,k}, v_{h,k} < 1 & \text{partial working capacity} \\ v_{b,k}, v_{c,k}, v_{h,k} = 0 & \text{zero working capacity} \end{cases}$$

- Discrete (integer) variables: we define $s_{n,k} \in \{0,1\}$ to be an integer variable that corresponds to the operating status mode of the building thermal network. We distinguish between the different season-related operating modes of the building thermal network by using $s_{c,k}, s_{w,k} \in \{0,1\}$ to specify the cold season and warm season, respectively:

$$s_{n,k} := \begin{cases} 1 & \text{operating with the heat exchanger and ATES} \\ 0 & \text{operating with the external party} \end{cases}$$

$$s_{c,k} := \begin{cases} 1 & \mathrm{T}_{o,k} < \mathrm{T}^{\mathrm{B}}_{z,lb} \\ 0 & \mathrm{T}_{o,k} \geq \mathrm{T}^{\mathrm{B}}_{z,lb} \end{cases}, \text{ and } s_{w,k} := \begin{cases} 1 & \mathrm{T}_{o,k} > \mathrm{T}^{\mathrm{B}}_{z,ub} \\ 0 & \mathrm{T}_{o,k} \leq \mathrm{T}^{\mathrm{B}}_{z,ub} \end{cases}.$$

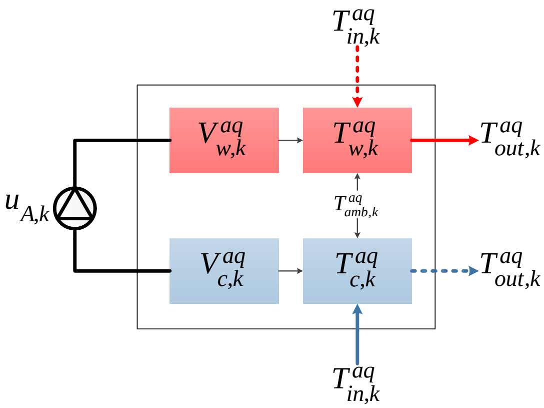

Fig. 2. The ATES system model block diagram showing the relation between the ATES system input, state and output variables. Solid line represents the heating mode (cold seasons) and dashed line represents the cooling mode (warm seasons). Depending on the operation seasons, the operational mode of the ATES system is changing.

The following section describes an ATES system model that we have developed to capture both dynamical behaviors of temperature and stored volume of water in warm- and cold-well. To the best of our knowledge this is the first work that attempts to model ATES system dynamics for an optimal control formulation of building comfort purpose. We then discuss how to estimate unknown parameters of the developed model and how to evaluate the estimated parameters using a groundwater simulator.

IV. Aquifer Thermal Energy Storage Model

This section describes a detailed mathematical model for the dynamics of the ATES system. We first describe the behavior of the volume of water in each well together with their temperature profile transitions. Then, we present the approach and results how the required parameters of the developed model were established.

A. Dynamics of ATES System

Consider an ATES system that works as follows; The ATES system consists of two wells containing either warm or cold water. Depending on the season, the operation of the ATES system changes. Figure 2 shows a schematic representation of the ATES system under consideration. Depending on the working mode (heating or cooling), one of the pumps will be activated and the other one will be turned off. During a cold season, the cold water is stored in the cold-well and the direction of water is from the warm-well to the cold-well through a heat exchanger to extract a required thermal energy from the water. This procedure is opposite during a warm season, since there is a demand for cooling; the stored cold water is used to cool the building.

The most relevant features that describe the status of an ATES system for control purposes are the stored water temperature and the volume of water in each well. Please note that groundwater supply can be assumed to be unlimited, so when the storage of a well is depleted, continued water extraction will have either the ambient groundwater temperature or the temperature of a neighboring well. Therefore it is of importance not only to consider the amount of storage (volume), but also the quality (temperature level). A free manipulated (controlled) variable in this setting is the pump flow rate that is used to circulate water from one well to the other through the heat exchanger. Therefore, we define the states that can describe the ATES system status to be the water temperature and the volume of water in each well. Their dynamic relationship is described as the following first-order difference equations:

$$\mathrm{V}^{\mathrm{aq}}_{w,k+1} = \mathrm{V}^{\mathrm{aq}}_{w,k} + (s_{w,k} - s_{c,k})\ \mathrm{V}^{\mathrm{aq}}_{in,k}\ , \tag{1a}$$

$$\mathrm{V}^{\mathrm{aq}}_{c,k+1} = \mathrm{V}^{\mathrm{aq}}_{c,k} + (s_{c,k} - s_{w,k})\ \mathrm{V}^{\mathrm{aq}}_{in,k}\ , \tag{1b}$$

$$\mathrm{T}^{\mathrm{aq}}_{w,k+1} = \frac{\mathrm{V}^{\mathrm{aq}}_{w,k}}{\mathrm{V}^{\mathrm{aq}}_{w,k} + s_{w,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}\mathrm{T}^{\mathrm{aq}}_{w,k} + \frac{s_{w,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}{\mathrm{V}^{\mathrm{aq}}_{w,k} + s_{w,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}\mathrm{T}^{\mathrm{aq}}_{in,k} - \frac{\alpha(\mathrm{T}^{\mathrm{aq}}_{w,k} - \mathrm{T}^{\mathrm{aq}}_{\mathrm{amb},k})}{\mathrm{V}^{\mathrm{aq}}_{w,k} + s_{w,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}, \tag{1c}$$

$$\mathrm{T}^{\mathrm{aq}}_{c,k+1} = \frac{\mathrm{V}^{\mathrm{aq}}_{c,k}}{\mathrm{V}^{\mathrm{aq}}_{c,k} + s_{c,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}\mathrm{T}^{\mathrm{aq}}_{c,k} + \frac{s_{c,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}{\mathrm{V}_{c,k} + s_{c,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}\mathrm{T}^{\mathrm{aq}}_{in,k} - \frac{\alpha(\mathrm{T}^{\mathrm{aq}}_{c,k} - \mathrm{T}^{\mathrm{aq}}_{\mathrm{amb},k})}{\mathrm{V}^{\mathrm{aq}}_{c,k} + s_{c,k}\mathrm{V}^{\mathrm{aq}}_{in,k}}, \tag{1d}$$

where $\mathrm{V}^{\mathrm{aq}}_{w,k}[\mathrm{m}^3], \mathrm{V}^{\mathrm{aq}}_{c,k}[\mathrm{m}^3], \mathrm{T}^{\mathrm{aq}}_{w,k}[\mathrm{K}], \mathrm{T}^{\mathrm{aq}}_{c,k}[\mathrm{K}] \in \mathbb{R}$ denote the volume and the temperature of the warm- and the cold-well at each sampling time k, respectively. $\mathrm{V}^{\mathrm{aq}}_{in,k}[\mathrm{m}^3] \in \mathbb{R}$ corresponds to the input volume of water that is injected into the warm- or cold-well and extracted from the counterpart well and it can be determined by $\mathrm{V}^{\mathrm{aq}}_{in,k} := \tau u_{\mathrm{A},k}$ where $u_{\mathrm{A},k}$ $[\mathrm{m}^3\mathrm{s}^{-1}]$ is the ATES system pumping flow rate at each sampling time k and τ [s] is the sampling period. The accumulating volume of water in each well of the ATES system is assumed to take the shape of a cylinder with growing and shrinking radius and a fixed height L [m]. Thus, each well of an ATES system is assumed to be a growing reservoir with respect to their horizontal domain represented by cylinder with a fixed filter screen length L [m] and a growing thermal radius R_{th} [m].

The dynamics of the ATES systems can be derived from Figure 2, which represents the relation between the ATES system input, state and output variables. The solid line represents the heating mode (cold season) and the dashed line represents the cooling mode (warm season). Depending on the operating seasons, the operational mode of the ATES system is changing. Equations (1a) and (1b) describe the evolution of the stored water volume in the warm- and cold-well, respectively. We assume the switch of warm season is on, $s_{w,k} = 1$, when the water is injected in the warm-well and extracted from the cold-well. If this process is reversed, meaning that the water is extracted from the warm-well and injected into the cold-well, the switch of cold season is on, i.e. $s_{c,k} = 1$. When an ATES system is working in the storage mode and it is not involved in the building thermal model, $s_{n,k} = 0$, then the pump flow rate is zero. We have simulated the above ATES system dynamics over a period of two years with an artificial pump flow rate

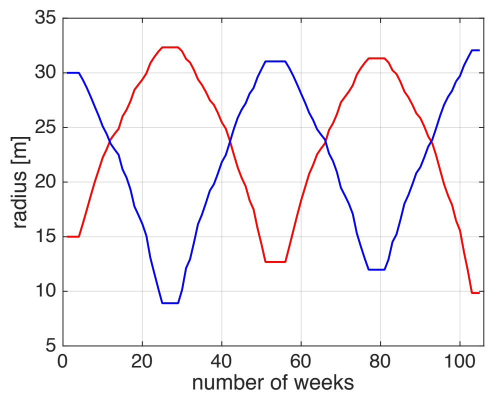

Fig. 3. Dynamics of ATES system thermal radius. The blue line shows the radius of the cold-well and the red line corresponds to the radius of the warm-well.

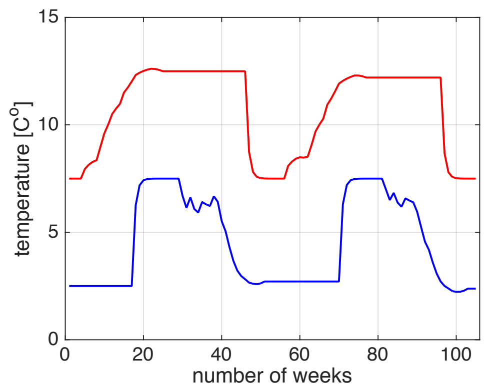

Fig. 4. Water temperature dynamics of the ATES system wells. The blue and red lines show the water temperature of extracted/infiltrated water of the cold-well and warm-well, respectively.

$u_{\mathrm{A},k}$ and $\mathrm{T}^{\mathrm{aq}}_{in,k}$. The dynamically changing thermal radius of the ATES system wells are shown in Figure 3. The blue line shows the radius of the cold-well and the red line corresponds to the radius of the warm-well. Notice that in this simulation example the stored volume is not depleted during the following season.

The water temperature transition of the warm- and cold-well of an ATES system over time described in our model by (1c) and (1d), respectively. The proposed model also includes a loss term that represents the effect of dispersion and conduction $\mathrm{T}^{\mathrm{aq}}_{\mathrm{amb},k}$. The loss term is inversely proportional to the water volume inside the well, so when the stored water volume is increasing then the relative loss is decreasing. The loss is increasing when the water volume is decreasing and eventually the well's water temperature converges to $\mathrm{T}^{\mathrm{aq}}_{\mathrm{amb},k}$ with a fixed rate α. Figure 4 depicts the dynamically changing temperature of ATES system wells. The blue line shows the water temperature of the cold-well and the red line corresponds to the water temperature of the warm-well.

Define $x_{\mathrm{A},k} := [\mathrm{V}^{\mathrm{aq}}_{w,k}, \mathrm{T}^{\mathrm{aq}}_{w,k}, \mathrm{V}^{\mathrm{aq}}_{c,k}, \mathrm{T}^{\mathrm{aq}}_{c,k}] \in \mathbb{R}^4$ to be the state vector. The internal input variable is $v_{\mathrm{A},k} := \mathrm{T}^{\mathrm{aq}}_{in,k}$, the control input variable is $u_{\mathrm{A},k}$ and the integer variables are $s_{w,k}, s_{c,k}$. Given an initial condition $x_{\mathrm{A},0}$, consider now the discrete-time ATES dynamical model with sampling period of τ for each sampling time k as follows.

$$x_{\mathrm{A},k+1} = \mathrm{F}_{\mathrm{A}}(x_{\mathrm{A},k}, u_{\mathrm{A},k}, v_{\mathrm{A},k}, s_{w,k}, s_{c,k}, \tau) \ , \tag{2a}$$

$$y_{\mathrm{A},k} = \mathrm{G}_{\mathrm{A}}(x_{\mathrm{A},k}, s_{w,k}, s_{c,k}) \ . \tag{2b}$$

The output performance of the ATES system dynamics $y_{\mathrm{A},k}$ is the water temperature $\mathrm{T}^{\mathrm{aq}}_{out,k}$ leaving the ATES system defined as

$$\mathrm{T}^{\mathrm{aq}}_{out,k} := s_{c,k}\ \mathrm{T}^{\mathrm{aq}}_{w,k} + s_{w,k}\ \mathrm{T}^{\mathrm{aq}}_{c,k} \ . \tag{3}$$

The developed model (2) is a nonlinear hybrid system due to the dependency on both continuous and discrete variables. In the following section we explain how to identify the loss term of the developed model (α).

B. Parameter Estimation of ATES System

We now consider the single ATES well temperature profile. The loss-term in our description (1c) (1d), the rate of convergence (α) needs to be validated in order to describe thermal losses accurately, resulting in a gradual change of the extraction temperature towards ambient groundwater temperature. In such a loss-term the rate of convergence is of importance because it determines how fast the well temperature converges to ambient temperature during extraction, the extraction temperature is of importance for the functioning of ATES and building system. In practice the rate of convergence changes over time because in a full storage, extraction temperature will be approximately the same as the infiltration temperature, while when the storage is almost empty the temperature converges fast to ambient temperature. Based on this reasoning, it is concluded that the rate of convergence needs to be dependent on the relative rate of change of storage volume, as was shown in (1c) and (1d). Losses occur during infiltration, rest and extraction, however, for practical/mathematical reasons the loss term is only active during extraction, to prevent the storage temperature to become higher (for warm wells) or lower (for cold wells) than the extraction temperature. When there is no extraction or infiltration, the loss-term will also become zero.

To find a relation between α and the ATES system characteristics we follow the following steps:

1) Determine α for a large number of simulations with a wide range of system characteristics. The reason is that in both Equations (1c) and (1d) it is considered to have fixed filter screen length L which may influence the relationship in the loss coefficient α.
2) Evaluate α with respect to the system characteristics to verify the existence of a relationship between α and one or more system characteristics.
3) Implement the found relation in AATM, verify its behavior and choose final model.

Note that when the α is dependent on system characteristics which change over time, this may change the behavior of the AATM. If so, it might be necessary to repeat step 1 and 2.

As the first step we determine a possible candidate for α as follows; we performed 84 simulations of 10 years of operation for different sizes and designs of ATES systems. We simulated different energy demand profiles, different systems sizes and different well designs with the following information:

- Storage volume per meter filter screen length: 2500, 4000, 5000, 7500, 10000, 12500 $[\mathrm{m}^3\mathrm{m}^{-1}]$
- Filter screen lengths: 5, 10, 25, 50 [m].
- Distance between warm and cold well: 1,25; 2; 3; 5; 7 times thermal radius R_{th}. The distance between warm and cold well applied in the model is based on the expected thermal radius (max storage capacity). Three times the thermal radius is the industrial practice in The Netherlands [1]. However when space allows, often larger distances are applied, while the purpose of this research is to responsibly minimize distance between wells [2], [4], [5], [14].
- Thermal energy demand profiles are as follows:
  1) fixed energy demand with a strictly seasonal operation and closed energy balance (all in/all out).
  2) fixed energy demand and closed energy balance, but more realistic spread over the year (gradual), representative for Dutch climate.
  3) varying energy demand based on weather conditions as retrieved from observation data and climatic projections [15].

  The demand also has influence on interaction; thermal radius is bigger in demand profile 1 compared to demand profile 2 and 3.
- Model discretization: 5m $\times$ 5m at well location, logarithmically growing to 250m $\times$ 250m, at the model boundary. Model extent: 3000m $\times$ 3000m with weekly time steps.

The system characteristics used are derived from design data of 330 ATES systems in 5 Dutch provinces. The characteristics of these systems are presented in Table I. In this table V and V/m denote the yearly storage volume $[\mathrm{m}^3]$ and yearly storage volume per meter filter screen $[\mathrm{m}^2]$, respectively. For each of the simulation results the best α was determined based on minimizing the root mean square error (RMSE) using Equation (4) between the simulation and the results of both AATM models which is described by:

$$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(\alpha_i-\bar{\alpha})^2} \tag{4}$$

where α_i corresponds to the best α for i-th simulation, $\bar{\alpha}$ is the average α for all simulations and $n = 84$ number of simulations.

In the second step, we evaluate the optimal values for α by defining the Pearson correlation with different system characteristics such as the filter screen length, distance, thermal radius, storage volume or combinations of these as illustrated in Table II. In this table the distance between warm and cold well [m] is denoted by D. The analytical formula describing the temperature of the well allows us only to find a dimensionless relation for α, therefore we evaluated the correlation of different dimensionless combinations of system characteristics. As can be seen there is no system characteristic which has a strong correlation with α. But there are several combined dimensionless characteristics which have a reasonable correlation. The correlation coefficient does not tell us anything about the possibility to describe the relation mathematically. Therefore we examined the results to see which of the relations could be best described with an analytical formula. With the quick trend line tool from MS Excel we evaluated all the relations between system characteristics and α, from which we found that the two best representable system characteristics are L/D and $L/(D-R_{th})$ as shown in Figure 6. This figure shows that α variation is limited for systems with a small L/D-ratio (< 0.2). Only for larger filter screen lengths and/or smaller distances the rate of convergence increases significantly which logically follows from the increased losses under these circumstances. Figure 6 also indicates that there is a locally optimal L/D-ratio, which corresponds with Doughty [8].

We now implement and test the determined relation in AATM as the last step toward our parameter estimation. The relationship shown in Figure 6 was implemented in the AATM to be tested. Based on *RMSE* we manually optimized the constants in the polynomial description of rate of convergence; $\alpha = a(L/D)^2 + b(L/D) + c$, with $a = 0.45, b = 0.5, c = 0.33$. For the testing we used only type 2 and 3 energy demand profile, but with a different demand pattern for type 2 and different weather conditions for type 3 than was used in step 1. We also used other (configuration of) system characteristics. The L/D model performs best, based on the RMSE-values, which results in the relation given in Equation (4).

We also explored the performance of other relationships, beyond those already presented in Table II, but they all gave poorer results than the ones presented in Figure 6. The relations dependent on varying characteristics such as storage volume (V) and thermal radius (R_{th}) did not lead to satisfactory results at all, since these operational aspects are already incorporated in (1c) and (1d). Including them in the expression for α would make the extraction temperature double dependent on operational aspects. From that we conclude that for each ATES system α is a constant factor only dependent on filter screen length and distance between wells. This of course makes sense because well distances and filter screen lengths influence losses and thus the rate of convergence to ambient groundwater temperature.

We also performed a sensitivity analysis on the constants in the formula for α where we varied the constants individually and simultaneously by $-25\%, -10\%, 10\%$and 25% to find their sensitivity on the obtained temperature from the AATM as shown in Table III. From this analysis it can be seen that the α is not sensitive to variations in the constants derived in this research.

Figures 7 and 8 show simulation results of the calibrated AATM model. The results show that the model represents well temperature very well for the regular demand pattern (2). However for the more variable weather dependent demand

TABLE I
ATES SYSTEM CHARACTERISTICS

	Capacity/Well	L-installed	V/m
	$[m^3y^{-1}]$	[m]	$[m^3y^{-1}m^{-1}]$
Percentile 0,1	24.000	12	1.967
Average	121.976	33	3.725
Percentile 0,9	790.590	56	14.168

TABLE III
RESULTS OF SENSITIVITY ANALYSIS

Variation Range	-25%	-10%	10%	25%
all	-6,4%	-3,2%	3,8%	10,2%
a	-0,4%	-0,2%	0,2%	0,5%
b	-1,8%	-0,8%	0,8%	2,1%
c	-6,0%	-2,7%	2,9%	7,6%

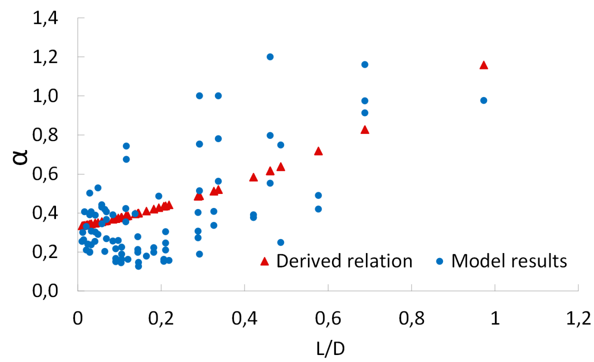

Fig. 6. Relation between α and systems characteristics

pattern the simple analytical AATM model does not perform well, with respect to temperature level. In both cases however the monitoring of energy stored in the aquifer is satisfactory.

V. SIMULATION STUDY

In this section we provide a simulation study to illustrate the feasibility and performance of our proposed model and framework.

We formulate a model predictive control framework as was done by Rostampour [16] where it is considered to have a day-ahead prediction horizon length with hourly-based sampling time. As the real building system behavior, we consider to have uncertain outside air temperature, solar radiation, and wind velocity. We refer the interested readers to the annual project report [17], [18] for our detailed building comfort model together with mathematical descriptions of other involved components. Due to the non-convexity issue that is raised because of inherent mixed-integer problem formulation, we cannot employ the proposed stochastic framework in [17], thus we assumed to be given the average behavior of uncertain parameters of the building comfort model, and then, we formulate a deterministic model predictive control framework.

During the simulation we were faced with computational time issues which may be expected due to the final optimization problem which leads to mixed-integer multi-dimensional polynomials (signomial geometric) nonlinear programming. We therefore chose to focus our simulation study on one month, March 2010, given the outside weather data from the weather station in Delft, The Netherlands [15]. The simulation environment was MATLAB using the solver 'fmincon' together with the YALMIP toolbox [19] as an interface.

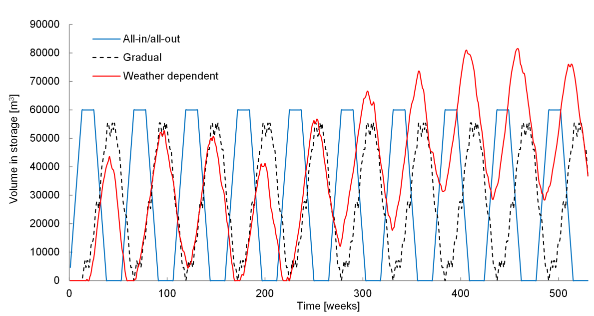

Fig. 5. Different energy demand patterns applied in the simulations

Figure 9 depicts pump flow rates at each sampling time of our building thermal comfort model. The 'green' line represents the pump flow rate of ATES system u_A, and the 'blue' line corresponds to the pump flow of storage tank u_S. In our building model, we consider to have heating and cooling sources from floor and ceiling in each zone, respectively, by using pipes that are installed inside compositions of ceiling and floor with the surface ratio of 25%. The 'red' line is related to the pump flow of building piping network u_B. In Figure 10 we demonstrate the dynamics of temperature of indoor and outdoor air together with circulated water in our integrated thermal comfort network. In this figure, 'red' line corresponds to the outside air temperature which is uncertain and given to our control problem. The solid' black' line represents the temperature profile of the building walls through time, whereas the 'blue' line is related to the circulated water temperature in building floor pipes. We consider to have the boundaries of our desired building zone temperature which is shown by dashed lines and finally, the 'green' line shows the dynamical behavior of building zone temperature over time. As it is clearly depicted in Figure 10, the building zone air temperature is kept within the boundaries through-out the simulation by using our proposed control framework.

In this specific simulation of one month, the ATES well temperature does not have a great impact on the results. This simulation was to illustrate the functioning of the combined building and ATES model. However when we start applying longer horizons, using model predictive control (MPC) for the building climate and take into account neighboring systems; the well temperature starts playing an important role in finding the optimal control strategy.

VI. CONCLUSION AND FUTURE WORKS

This paper provided a modeling framework which allows to evaluate and simulate the effect of building climate control on subsurface processes. These results are the first step in an attempt to optimize subsurface space use. Due to the fact that the dynamical behavior of ATES systems are much slower

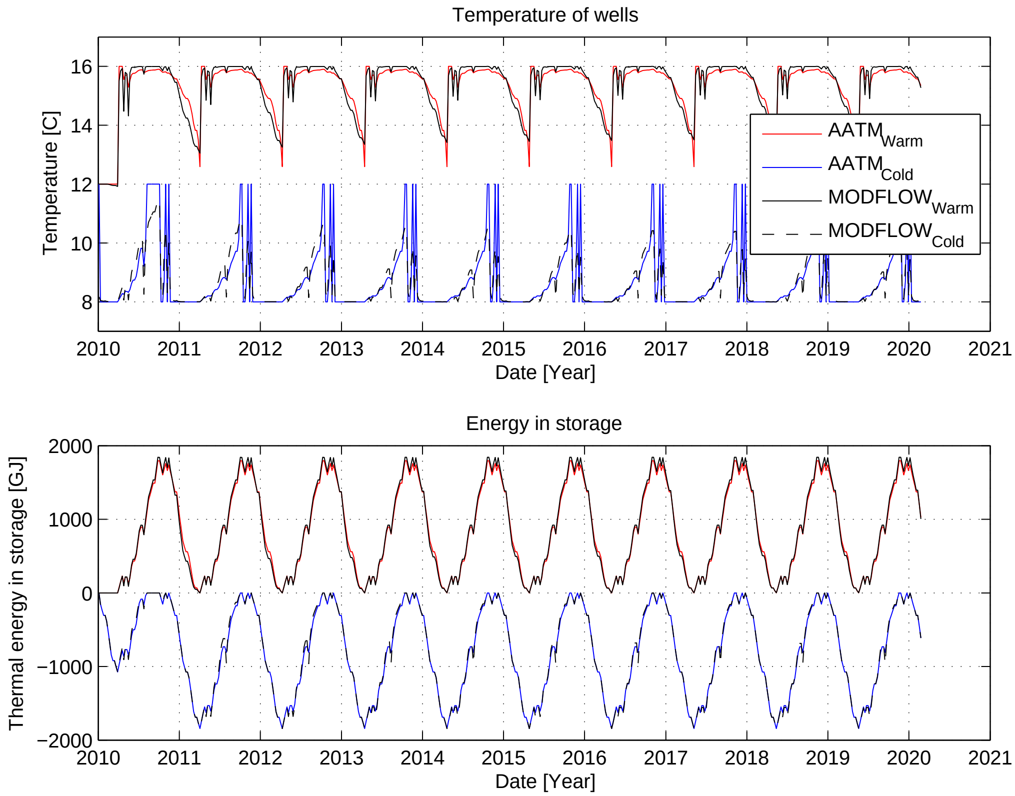

Fig. 7. Results of AATM for demand profile 2. In this example we consider D, L and V/m to be $2R_{th}$, 33m and 3600m^2, respectively.

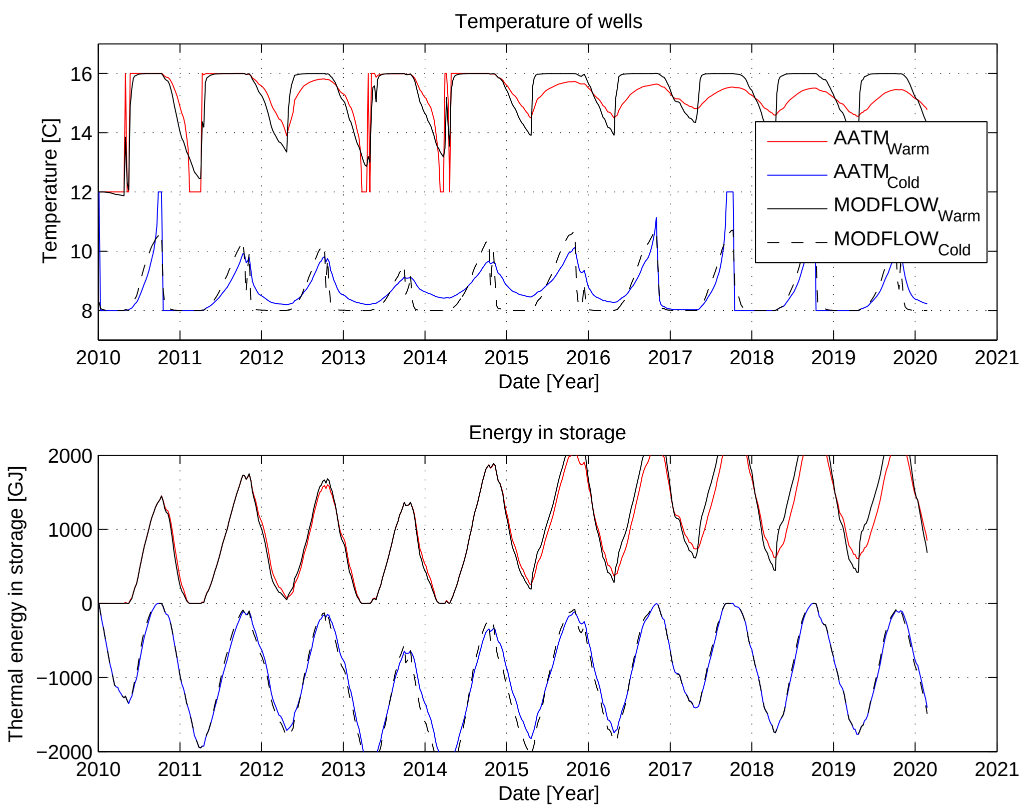

Fig. 8. Results of AATM for demand profile 3. In this example we consider D, L and V/m to be $3R_{th}$, 33m and 10000m^2, respectively.

TABLE II
CORRELATION COEFFICIENT FOR α AND DIFFERENT SYSTEM CHARACTERISTICS

	D	R_{th}	L	V	V/m	L/D	LL/D/D	L/R_{th}	LL/D/R_{th}	L/(D-R_{th})
Thermal Radius	-0,57	-0,8	0,10	0,01	-0,18	0,62	0,65	0,64	0,63	0,63
Volume	-0,58	-0,19	0,11	-0,01	-0,20	0,65	0,68	0,64	0,64	0,61

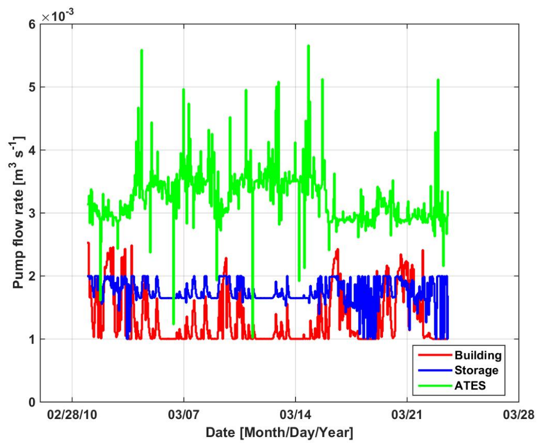

Fig. 9. Pump flow rates of building thermal comfort network. 'Green' line represents the pump flow rate of ATES system u_{A}, 'blue' line corresponds to the pump flow of storage tank u_{S}, and 'red' line is related to the pump flow of building piping network u_{B}.

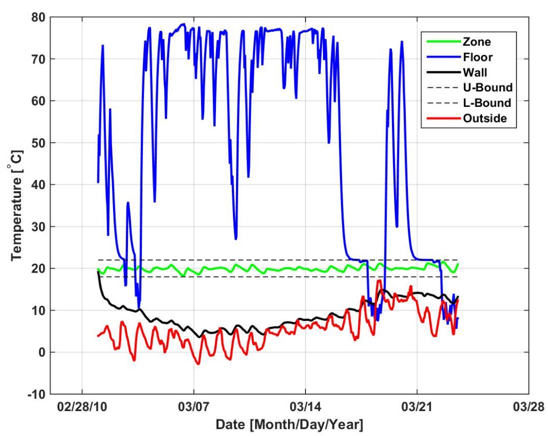

Fig. 10. Dynamics of building temperatures over time together with control unit. 'Red, black, blue' and 'green' are related to the temperature of building outside air, building walls, building pipes inside floor and building zone, respectively. Dashed lines correspond to the boundaries of our desired building zone temperature.

than building thermal comfort models, our future work will focus on developing a control framework to accommodate this time-scale separation. We will investigate how to incorporate the developed ATES system dynamics into our proposed thermal grid framework in [17]. Possible alternatives for such a problem include using a multi-rate sampling dynamical system for MPC or a hierarchical MPC in which the higher layer contains ATES system dynamics (slower system) and the lower layer is responsible for building thermal comfort model.

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