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Integration of Thermal Energy Storage Components with Buildings – Recent Development and Challenges

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Abstract

The main drawback of renewable energy sources is the variability and intermittence in their availability; causing significant mismatches between the time of energy demand and energy production. To make these future energy sources and conversion technologies a viable solution, it is necessary to use significant levels of energy storage technologies that enable matching of supply and demand. Energy storage technologies play a crucial role in designing and operating high performance sustainable buildings and districts, and are definitely needed for the efficient use of renewable energy resources by dealing with the intermittency of energy supply and demand. However, there is still a distinct lack of guidance on the effective integration and operation of thermal energy storage at the building or district levels.

The paper first gives an overview of the most recent development in modelling and validation of the energy storage system/components and its integration with buildings: It covers both active and passive technologies. The abilities and limitations of each technology for the integration, and the challenges of coupling of the model with energy simulation programs are also discussed. Based on these insights, the corresponding technological problems and future research directions for their applications are also described.

Keywords: thermal energy storage buildings, development, challenges

1. Introduction

Energy storage components represent a heart of the systems for higher utilisation of renewable energy sources in buildings and districts. Both thermal and electrical energy storage components can be used to save energy when it is available, for the time when it is needed; however it should be mentioned that their quality (exergies) will be different.

This paper presents a review of state of the art of all known technologies for thermal energy storage in buildings and districts: active storage, passive storage, solar hot water tanks, ground heat exchanges etc. Those technologies will be presented from the modelling and demonstration point of view.

The possibilities and challenges of integrating components models with building models and districts models will be discussed with the focus on whole system optimisation and automatization. This issue is also the focus of Annex 31 of the IEA-ECES research work.

2. Active storage technologies

2.1. Active PCM heat storages

Generally, a thermal energy storage is categorized as an “active storage” if it owns some characteristics including a heating/cooling element as the energy source for charging the storage as well as a control system to store and extract energy from the storage. Therefore, charging and extracting the stored energy from the storage normally requires further energy consumption. In this section, particular attention is paid to shell-and-tube heat exchangers.

Since a major part of energy consumption in buildings is devoted to HVAC systems, they have received considerable attention for PCM application. For instance, thermal storage has found application in precooling supply air of an air-conditioning system by means of off-peak charging of a PCM [1]. The system was modeled and experimentally validated. Based on the climate in Thailand, it was found that the PCM (RT20, Rubitherm) could reduce the energy consumption of the system by about 9% and save electricity cost by 5 USD/day with a payback period of about 4 years.

PCMs have also been used at heat rejection side of HVAC systems as an alternative to cooling towers. This is mainly due to the disadvantages of cooling towers especially their low performance in humid climates. Thermal storage in a packed bed [2] as well as a capillary tube storage [3] resulted in COP enhancement of the system. PCMs have found application in domestic refrigerators as well, which was mostly for cold storage at evaporator side of the system [4]. The main advantages were system performance enhancement, helpfulness in case of power outage, reduction of the grid’s peak hour consumption, reduction of the system noise, and reduction of overall cost. PCMs have also been utilized for heat storage at condenser side to reduce condensation temperature so as to have performance enhancement in the system.

Mathematical solutions and numerical models employed for the investigation of PCM's phase transformation have been reviewed in details [5-9]. Hu et al. [6] categorized the various mathematical formulations to numerically solve melting and solidification of PCMs based on the dominant heat transfer mechanism. Also, relative merits and disadvantages of each formulation were analysed. Zalba et al. [7] reviewed heat transfer in PCMs based on a theoretical point of view, considering different simulation techniques. Also, Al-Abidi et al. [8] reviewed various numerical modelling to study the heat transfer phenomena in PCMs using a commercial computational fluid dynamic (CFD) software and self-developed programming. Most recently, Liu et al. [9] reviewed various mathematical modelling approaches based on the heat transfer mechanism. There are essentially two main categories: conduction acting as the only heat transfer mechanism; and conduction and convection heat transfer mechanisms. It was concluded that in the melting process, the PCM changes its phase from solid to a mushy state, and then liquid, which is reversible during the solidification process. Hence there are six stages to finish a charging and discharging cycle. Therefore, it is possible to have more than one kind of heat transfer mechanisms acting at work in certain stages of the phase transformation process.

Conduction was initially believed playing the most important role during the phase transformation processes [10-12]. With this assumption the two processes are the same in all essential features. Zivkovic and Fuji [11] and later Vyshak and Jilani [12] theoretically conducted a comparative study of the total melting time of PCMs packed in three containers of different geometric configurations: rectangular, cylindrical and shell-and-tube. It was concluded that the shell-and-tube vessel took the least time for storing an equal amount of energy, and this geometric effect was more pronounced with an increase in the mass of the PCMs.

However, many researchers argued that natural convection is the most important mechanism in the phase change process, in particular in the melting process. Sparrow et al. [13] performed a pioneer study and concluded that natural convection could not be ignored in the analysis of phase change problem. Hasan [14] concluded that the convection heat transfer plays an important role in the melting process, and a simplified model by only considering the conduction heat transfer does not describe the melting process properly. Recent experimental and computational studies [15-19] conducted on shell-and-tube heat exchanger, which is believed to be the most intensely studied LHTES system [5], revealed that the method of heat transfer in the PCM is a combination of convection and conduction. It was concluded that the convection mode of heat transfer played an important role during the melting process, while conduction was significant during the solidification process. Most recently Seddegh et al. [19] numerically compared the thermal behaviour and heat transfer characteristics of a vertical cylindrical shell-and-tube unit using a pure thermal conduction model and a combined conduction-convection heat transfer model, and concluded that the combined convection and conduction model can better describe the energy transfer in the PCMs during melting process. In terms of total solidification time, the two models show little difference since the conduction heat transfer is most significant during the discharging process [20, 21].

In summary, the main challenge in modelling the phase change process in PCMs is the effect of natural convection in the process and whether or not to take it into account in different geometries. Despite many research works in the heat transfer mechanism, it was revealed that still there is a challenge in the literature on how to weight the percentages of conduction and

convection heat transfer and how the dominant heat transfer mechanism differs in various geometries during the charging and discharging processes.

2.2. Ground heat exchangers

To utilize the thermal capacity of the ground, the most favorable type of ground heat exchanger (GHE) is the vertical closed-loop GHE, also known as the borehole heat exchanger (BHE). To accurately design a borehole thermal energy storage system (BTES), a reliable thermal response model is essential and the response model's effectiveness is maximized when it is integrated with a dynamic building simulation (BS) due to the dynamic nature of building's heat load and corresponding operation and control.

A significant work into the response and design of a BHE was performed by Eskilson [22]. Using a 2-D (radial-axial) numerical model, Eskilson proposed the temperature response form also known as the g-function. Although the first g-function was generated using the numerical approach, it can be generated using various methods such as, analytical, numerical or by the hybrid approach. The g-function concept has received attention, and many dynamic BS programs have incorporated it.

DOE-2.1E is the first BS program that integrates BHE simulation [23]. In the DOE-2.1E, the response model used a 1-D model based on a simplified coaxial geometry with an equivalent diameter [24]. However, the model neglects the thermal properties of the grout and circulating fluid. Therefore, the accuracy of early-time response is not guaranteed. The heat transfer between a BHE and the ground is calculated using the infinite line source (ILS) model [25]. For the long-term response, Eskilson's g-function is used. The limitations of the first version were improved in DOE-2.2. The multipole method proposed by Bennet et al. [26] was incorporated to calculate the steady state borehole thermal resistance. Additionally, to extend Eskilson's g-function to the short-term response the short time g-function developed by Yavuzturk and Spitler [27] was incorporated.

In HVACSIM+, the module for BHE system was developed by the research group at Oklahoma State University [28]. As with the DOE, HVACSIM+ also used both the long time and short time g-functions [27, 29] for the temperature response. Subsequently, the short time g-function based on 2-D model was replaced by simplified 1-D (radial) model [30].

TRNSYS has adopted three response models. A familiar model is the Duct ground Storage (DST) model [31]. DST is a hybrid model that uses an analytical approach for calculations internal to the BHE [26, 32] and a numerical approach for the ground regions. The other model is the ErdWärmeSonde (EWS) model [33] which provides a response only for a single BHE. The EWS model solves 1-D heat equations for cylindrical coordinates for each ground layer. A 2-D thermal network model is used for the heat transfer along the flow channel within the BHE. The final model is the Superposition Borehole Model (SBM) developed by Eskilson [22] where Hellström's [37] model was used to calculate R_b .

Modelica is has gained popularity after Lawrence Berkeley National Laboratory released the Modelica Buildings Library open source code [34]. The library [34] includes a BHE model which is the Modelica version of EWS model in TRNSYS. Recently, the hybrid step response model (HSRM) was developed [35]. HSRM applied different models for different time scales. For long-

term response, a finite line source analytical model developed by Claesson and Javed [36] was used. For short-term response, HSRM adopted a thermal resistance and capacity model [37].

Considering the dynamic nature of building loads and corresponding system operations, the response models should have reliable accuracy for all time scales. However, some models have limitations in predicting short or long term responses. Therefore, a new robust model should be developed and validated. Additionally, to solve the flexibility and large computational cost issues of the numerical approach based g-function, a g-function based on an analytical method has significant potential considering its computational speed and flexibility.

2.3. Solar assisted heat pumps

The exploitation of solar energy and the use of heat pumps are two typical features of zero energy buildings. When the thermal output from solar collectors is integrated within the heat provided by the heat pump (HP), this is called a “solar assisted heat pump”. Usually, the heat pump is a geothermal one (GHP) and the solar output is thermal energy that is used in various modes. Even though other possible configurations exist, the combination of geothermal energy and solar thermal energy gives rise to a set of interesting different configurations – that are referred to as of Solar Assisted Ground Source Heat Pumps (SAGHP) – where energy storage plays a key role in overcoming the limitations of both sources and of the loads.

Compared to systems that use only the technology of geothermal heat pump, in SAGHP systems [38], for a given users energy requirement, the amount of heat extracted from the geothermal source is lower, thanks to the simultaneous production of thermal energy from the solar collectors. Solar energy can be exploited in two different ways (“parallel” and “serial” systems), as a function of how the thermal output of solar collectors is used. Into parallel systems the solar collectors and the heat pump provide heating energy in parallel to one or more heat storages, placed at the use side. Into serial systems the thermal energy made available by solar thermal collectors is used as a heat source at low temperature, directly or indirectly, by the heat pump, thus increasing the evaporator temperature of the HP. The solar energy integration allows one or more of the following benefits: a reduction of the hours of operation of the heat pump, an increase in the global COP of the system [39], a possible regeneration of the geothermal source by means of the thermal output of the solar collectors and a lower overall energy consumption of the system.

The thermal energy storage is one of the most important features of a solar assisted heat pump to be designed. It can be done by water but also ice (when the HP performs also in cooling mode), soil, PCM, and it can be placed at both the source side and use side and can perform different functions.

When the main concern is to operate the GHP as close as possible to a fixed design point, thermal storages placed at the user side are employed in order to smooth the thermal loads required by the space heating or domestic hot water (DHW) production (that are typically time variable). These are typically water storages (hydraulically connected to the water of the heating system, and connected through a heat exchanger to the heat pump) and are sized as a function of the variable thermal loads. The heat pump works in order to restore in the storage a set point temperature.

Moreover, into a SAGHP, the ground itself works as a storage (see paragraph below), and it can also be used in order to store the excess thermal energy from the solar source. This is one of the

main benefits of such systems, because the injection of the solar energy into the ground – usually during hot periods – avoids the thermal depletion of the ground that may occur with the years, thus maintaining a constant COP of the heat pump.

Since the performance of such system is complex and time variable in the long term (the thermal depletion of the ground can occur in a period of several years), it is evident that it is not sufficient to analyze data from monitoring but there is the need to use detailed transient simulation models for the design and optimization of the various system layouts, uses and operation parameters of the storages. The combination of different levels of analysis and different modules (ground heat exchanger, heat pump performance, water storage performance, building loads variation, etc.) makes the use of modular transient simulation programs, such as TRNSYS, very useful for the layout organization and for the degree of detail of each sub-module.

Various studies has shown that the increase in the global COP of the system due to the solar integration (serial systems) ranges from 0.45 % in cold climates to 12% in hot climates [39, 40], anyway the payback time of the system can be shorter for cold climates where the heat pump has higher electricity demand. Furthermore, in order to be economically feasible, the solar integration and the thermal storage should be designed in order to reduce the size of the borehole heat exchanger that has a large initial investment cost.

Even though design guidelines and simulation packages of such systems exist, the operation and the long term performance of GSHP systems are very sensitive to the local conditions (climate, geological conditions, hydraulic parameters, energy storage ratio, etc.) and should be considered for each case. From the modelling point of view, in many cases there is still the need to use customized models of some of the components and the control of such systems, thus preventing a wide adoption of the technology.

3. Passive storage technologies

Heat storage materials (sensible and latent heat) are used in a variety of building applications as a passive or an active component of the structure [41]. As mentioned, in active systems, the heat transfer is actuated by a mechanical system (fan, pump, etc.), providing the possibility to store or release heat on demand. In passive systems, on the other hand, storage materials are integrated into specific elements of the building, as a means to increase thermal inertia, minimize the usage of mechanical heating/cooling devices, lower the indoor temperature fluctuation and preserve the occupant's comfort. After the installation of such systems, the operational cost of the building is not increased / burdened, as no extra mechanical means are used.

The main applications of passive storage are found in the integration of PCM with the building envelope materials. The most studied concepts are multifunctional façade systems and living walls [42]. Heat transfer reduction through building walls could be achieved by integration of PCM on walls. Cooling load reduction due to application of PCM on walls have been numerically investigated for tropical climate in Singapore [43]. Energy performance of the building was enhanced by application of PCM to the exterior surfaces. Besides, it was found that even though higher phase change temperatures could improve the adaptability of the system against ambient temperature changes, lower phase transition temperatures resulted in higher

energy savings due to the complete phase change cycles. In order to evaluate and demonstrate that those systems are innovative energy efficient, various configurations has been studied including non-ventilated and naturally ventilated curtain walls. A thermal storage technique for free heating/cooling during winter/summer of office buildings has been numerically and experimentally investigated [44]. The results indicated that the maximum efficiency of the system occurred when the temperature difference between day and night (whether in summer or winter) was high enough to provide complete phase change in the PCM. A concrete slab has also been experimentally investigated as a potential location for PCM integration for active cooling [45]. Although the system performance was enhanced, fan energy consumption was not balanced and the savings were compromised.

Advanced passive storage façade systems are becoming important architectural elements in modern buildings. While many façade systems are installed for architectural reasons, they can be utilized to perform multiple functions such as heat storage using PCM-enhanced components for example. The mechanism of heat storage, its transfer and transport involves complex physics. This complex physics is phenomenal and difficult to model with the state of the art whole-building simulation tools. In order to overcome this lack of modelling techniques advanced design procedure, simulation tool to model and optimize different configurations of envelope materials and layouts has been developed [18]. The method can also be used to compare building alternatives with different materials in order to obtain the optimal choice of envelopes and quantify the effect of climate change on buildings in accordance with the optimal conditions of comfort and energy use.

In the case of passive design, a tool is needed to relate the design parameters and the time required to fully melt a PCM. Time required to charge a PCM integrated building envelope is the key for an effective design: The wallboard must be fully charged during off-peak hours. Bastani and Haghight developed a graphical tool to correlate the design parameters of a PCM integrated building envelope (its thickness and thermos-physical properties) to the charging duration [47].

4. Conclusions

Energy storage technologies such as active storage (PCM storage, ground heat exchangers, solar hot water tanks, etc.) and passive storage are a central element of designing and operating intelligent buildings and districts and are needed for efficient use of energy resources and dealing with the intermittency of energy supply and demand.

The main challenge in modelling the phase change process in PCMs is the effect of natural convection. Despite many research works in the heat transfer mechanism, it was revealed that still there is a challenge in the literature on how to weight the percentages of conduction and convection heat transfer and how the dominant heat transfer mechanism differs in various geometries during the charging and discharging processes.

At ground heat exchangers the response models should have reliable accuracy for all time scales. However, some models have limitations in predicting short or long term responses. Therefore, a

new robust model should be developed and validated. Additionally, to solve the flexibility and large computational cost issues of the numerical approach based g-function, a g-function based on an analytical method has significant potential considering its computational speed and flexibility.

The operation and the long term performance of GSHP systems are very sensitive to the local conditions and should be considered for each case. From the modelling point of view, in many cases there is still the need to use customized models of some of the components and the control of such systems, thus preventing a wide adoption of the technology.

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