University of West Hungary

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Theses of the doctoral (PhD) dissertation

Modeling of seasonal thermal energy storage possibilities for wooden frame homes

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1. Introduction

Nowadays, improving the energy efficiency of buildings as well as reducing the carbon dioxide footprint of those is an important aspect of their design process, construction and maintenance. Wooden buildings (e.g., wood frame residential houses) seem to have some advantage over traditional solutions concerning their carbon dioxide footprint, and there exist adequate thermal insulation technologies which have remarkable role in achieving the aims mentioned above. Considering the fact that in the temperate and cold climate zones, space heating and hot water production together account for a major part of the total energy demand for buildings (about 80% in Europe), we can reach a significant amount of energy savings regarding building maintenance by using various innovative solutions in this field. In the name of environment consciousness, energy supply needed for space heating of wooden buildings during winter period can be accomplished by preferring renewable energy over conventional forms (e.g., coal, natural gas, crude-oil, wood, etc.), though availability of the former one is not always equally distributed over time. In case of utilizing solar energy, it is desirable to store surplus energy collected during the summer period in some way, and to cover energy demand of space heating partially or completely by that storage.

Period of storing energy used for space heating in buildings may have different time scales (e.g., diurnal, seasonal), therefore required size of the storage medium shows great variation. Studying, developing and maintaining large-scale seasonal (i.e., with yearly cycle) thermal energy storage systems has been being in focus for decades, mostly in developed regions of the world, and in fact there exist several design variations of those solutions (e.g., borehole, aquifer, etc.). However, due to the improvements on heat insulation of the buildings, experiments evolved for small-sized, uniquely designed thermal energy storage systems for heating single-family detached homes, and so far the results are promising. Those studies and developments can be speed up by political leadership of a given region, providing support through various government programs. Such financial opportunities exist in the European Union as well as in Hungary, too, and had a major role in the background of this doctoral work.

A large number of development studies focuses on thermal energy storage solutions for which energy accumulation happens in a sensible form, i.e., it causes the storage medium to rise its temperature. Such systems are called sensible thermal energy storage systems (sensible TES systems) in related English literature. Besides the projects about these systems, extensive researches are conducted on thermal energy storages based on other storage mechanisms (thermochemical and latent), too. With those systems, it could be gained much higher energy storage density, however they still have some problem to solve (e.g., stability, safety) in order to reach the market widely. In my dissertation, I give a brief overview of the three main category of thermal energy storage systems, with increased focus on sensible solutions.

2. Aim of the research

In the frame of a common research project of the Innovation Center of University of West Hungary and Ubrankovics Ltd., a seasonal, sensible thermal energy storage system was assembled and started in an experimental wood frame residential house at Ágfalva. Computational modelling of the heat transfer characteristics of this TES was the main topic of my doctoral study, and for this purpose finite element method was used. One of the aims of this research was to check if the experimental thermal energy storage system would be able to cover space heating demand of the wood frame home during winter period, given a set of assumptions, and to calculate heat loss through the surface of the heat storage unit. Further questions were that of how closely we can follow the thermal processes of the experimental storage and what properties the largest effect has on the effectiveness of the system. Another aim was to build a finite element model with many parameters in order to be able to easily alter characteristics of the virtual storage, by simply changing its geometric and material properties, so in a future work different versions could be compared, and optimization studies may be accomplished.

3. Research method

For thermal monitoring, several K-type thermocouples and some heat flux sensors as well as air flow meters were installed inside and on the surface of the experimental seasonal TES built in Ágfalva. Measurement data were recorded by a custom software running on a personal computer, which was placed inside the experimental wood frame residential house. After filtering and smoothing experimental data, a couple of two and three dimensional (stationer and transient) finite element models were built and calculated. During the research, different versions of COMSOL Multiphysics® were used due to its capabilities in the field of multiphysics. In order to run a simulation, model geometry was constructed in the first step, then Heat Transfer module and CFD module of the program were chosen to set the weak form of the partial differential equation system on which the numeric solutions were based. After that, corresponding initial and boundary conditions and material properties were given on every spatial domain and boundary, for each modelling task. In the next step, discretization (meshing) of geometry was accomplished, then some special program parameters were set, and simulations were conducted. Calculation results were interpreted and in some cases compared with measurement data (validation).

4. Results

Because of the time stepping characteristics of the finite element software used for modelling, two filtering algorithms were developed during this doctoral research in order to speed up transient simulations. By applying these methods, the size of time series dataset of storage heating power calculated from measured data of voltage and current was reduced by about 90%, while main shape of the power function was preserved, and wall-clock time of the transient modelling was shortened significantly.

It was proved by the finite element model with simplified geometry that altering the speed of the heat withdrawal from TES has a significant effect on the maximum length of time period for recuperating energy from the storage. On the other hand, increasing the thickness of the second layer (FOAMGLAS) inside the three-layered heat insulation system of TES caused minor changes in the length of that time period. Results of the simplified model showed that about 30-62% of the total heat loss of the storage has to be counted as heat leakage for the studied cases, although three quarters of that seepage had convective characteristics, so by installing such TES inside the building, that type of heat loss could be utilized for space heating. In a further investigation, simplified model for intermittent heating of TES was validated, and it was found that thermal simulations of experimental storage could serve just for qualitative purposes, by using this model.

For a more exact characterization of thermal processes, another model with detailed geometry of TES was constructed with many parameters, therefore it is suitable for running optimization studies. With this model, simulations of TES heating were conducted for three different time periods, each of them was one week long. Calculated temperature data were compared with measured ones, and it was concluded that for quantitative modelling of thermal processes for TES system, it is essential to set correct material properties and initial temperature field, and for the latter one, number and placement of thermocouples have to be planned carefully.

From the results of two and three dimensional finite element modelling of the heat exchanger unit of TES, it was revealed that in the case of the original (reference) geometry, velocity field of the airflow is highly uneven, therefore efficiency of the heat withdrawal from the storage does not meet the preliminary expectations. In order to improve the effectiveness of heat exchanger, several simulations were conducted with altered geometry, and results showed an efficiency gain of about 10%. On the other hand, modifications of experimental TES by using chimney brushes led to an improvement in effectiveness up to 30%.

5. Further research possibilities

During the modelling of the experimental storage placed at Ágfalva, thermal characteristics of the system has been successfully investigated to some extent, however there are a lot of other attributes which were not examined yet, due to the time frame and computational resources available so far. It is an important task to study the properties of the heat withdrawal process in the case of the TES as a whole system, and the model with detailed geometry seems to be a good starting point for that purpose. Thanks to the modular structure of the finite element software used, simulation of forced convection in the heat exchanger could be carried out after some model modification, using sufficient computational power resources. The model is suitable for other TES variants with similar structure, by altering its parameter values (dimensions, number and distribution of elements, material properties). It is also possible to simulate thermal energy storage systems with significantly different structure, although in general similar experimental storages are needed for their validation.

6. Theses of the dissertation

I. In order to choose suitable time steps for transient modelling of the heating of seasonal thermal energy storage, filtering algorithms were developed and coded ((„δ-method”, „φ-method”). By applying these methods, the size of time series dataset of storage heating power calculated from measured data was reduced significantly (by about 90%), while main shape of the power function was preserved. Wall-clock time of the transient modelling was shortened significantly, as a result of filtering.

II. It was stated that altering the speed of heat withdrawal (Q_r), which was a parameter of the cooling model with simplified geometry, has a significant effect on the maximum length of time period for recuperating energy from the storage [2,4]. On the other hand, by lowering the heat recuperation rate from 400 W to 100 W, length of heating period covered by seasonal TES increases to hardly more than double of the original value. The reason for that should be the change in the ratio of the gained heat to the sum of convective heat loss and downward leakage, i.e., lowering the speed of heat withdrawal results in a higher fraction of heat loss.

III. From the results of the simplified cooling model, it was stated that increasing (doubling) the thickness of the second layer (FOAMGLAS) inside the three-layered heat insulation system of the seasonal, sensible thermal energy storage had minor effect on the length of the time period for heat withdrawal [2]. This behaviour can be explained by the fact that when the experimental TES was planned, thermal insulation system was designed to meet high standards. Therefore, further increase in the thickness of the heat insulation leads to minor changes in the reduction of heat losses.

IV. Results of the cooling model with simplified geometry showed, that total heat loss of TES is considerably high (~30-62% in the studied cases), while significant part of that leakage (74-77%) is convective loss through free surfaces of the storage. By installing the storage unit inside the building, that type of heat seepage could be utilized for space heating of the house [2]. On the other side, heat leakage downwards can be treated as real loss.

V. Based on the results of the intermittent heating model with simplified geometry and the model with detailed geometry, it was stated that it is essential to set correct material properties and initial temperature field, to achieve proper quantitative modelling of thermal processes for TES system, and to be able to validate calculated data successfully [1]. Number and placement of thermocouples have to be planned carefully, and it is highly recommended to select such initial date and time for the beginning of the simulation when there exist only small gradients in temperature field.

VI. The three dimensional model with detailed geometry, which was built for this doctoral research, has a large number of spatial and material parameters, therefore it is capable for running several different simulations for optimization purposes. It can be used for planning TES systems similar to the experimental one at Ágfalva, but differing from it in sizing and/or materials chosen. The model is suitable for studying the thermal behaviour and mass transfer connected to the heating and withdrawal processes of such systems, too.

VII. Based on the results of two and three dimensional finite element modelling of the heat exchanger, it was stated that for the original (reference) geometry, the highly uneven velocity distribution of the airflow resulted in poor efficiency of the heat exchanger unit. In case of simulated variants of geometry, it was showed that the effectiveness could be improved by near 10% [3]. Thanks to the applied modification of experimental TES by inserting chimney brushes inside the heat exchanger, efficiency gain was almost 30%, as it was calculated from measurement data.

7. Publications and presentations related to the topics of the dissertation

Publications in peer-reviewed scientific journals written in foreign language:

[1] Horváth, T., Pásztory, Z., 2013. Modeling of seasonal heat container for wood frame residential homes. In: Jozef, K., Marian, B. (Szerk.), *Wood the Best Material for Mankind*. Arbora Publications, Zvolen, pp. 21–24.

[2] Horváth, T., Pásztory, Z., 2015. Heat stored in a solid block as source of heating energy. *International journal of smart grid and clean energy* 4(2), pp. 119–124.

[3] Horváth, T., Pásztory, Z., Horne, K., 2016. Performance comparison of heat exchanger designs for a seasonal heat storage system. *Energy and Buildings* 123, pp. 1–7. doi:10.1016/j.enbuild.2016.04.004

Publication in peer-reviewed scientific journal written in Hungarian:

[4] Horváth, T., Pásztory, Z., 2013. Szezonális hőtároló rendszer lehűlési folyamatának számítógépes modellezése. *Faipar* 61(3), pp. 6–11.

Publications in non-peer-reviewed journals written in Hungarian:

[5] Horváth, T., Pásztory, Z., 2013. Hogyan tárolhatjuk a napenergiát a téli időszakra? *Magyar Asztalos- és Faipar: az országos asztalos- és faipari szövetség hivatalos fóruma* 9, pp. 72–73.

[6] Horváth, T., Pásztory, Z., 2014. Szezonális hőtároló: Energiakonzerv télire. *Starfield magazin. Gerendaházak* 9(1), pp. 44–45.

Publication in online magazine written in Hungarian:

[7] Horváth, T., Pásztory, Z., 2013. Faépület fűtése szezonális hőtárolóval. *Fatáj-online*. [Online:] http://www.fataj.hu/2013/10/252/201310252_FahazFutesHotaroloval.php (megtekintve: 2016. július 30.).

Oral presentations:

[8] Horváth, T., 2012. Faházak szezonális hőtárolási lehetőségeinek modellezése. (Előadás). Doktorandusz konferencia 2012. NymE Cziráki József Faanyagtudomány és Technológiák Doktori Iskola, Sopron, 2012. június 1.

[9] Horváth, T., 2015. Szezonális hőtároló modellezése. (Előadás). Környezettudatos energiahatékony épület című projekt Záró konferencia (TÁMOP4.2.2.A-11/1/KONV-2012-0068), Sopron, 2015. február 20.

[10] Horváth, T., Pásztory, Z., 2012. Modeling of seasonal heat container for wood frame residential homes. (Előadás). Interaction of Wood with Various Forms of Energy, Zvolen, 2012. szeptember 26.

[11] Horváth, T., Pásztory, Z., 2015. Heat stored in a solid block as source of heating energy. (Előadás). 2015 5th International Conference on Future Environment and Energy, Taipei, 2015. január 24.

[12] Pásztory, Z., Ronyecz, I., Horváth, T., 2013. Development and Implementation of MIRRORPANEL Project. (Előadás). Academic workshop: Bridging research and Practice. (Researchers and Producers V-4: Development of cooperation in the field of passive and zero buildings.), Sopron, 2013. május 16.