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SciVerse ScienceDirect
Energy Procedia 30 (2012) 715 – 722
Energy Procedia

SHC 2012

Application of the ESP-r / TRNSYS co-simulator to study solar heating with a single-house scale seasonal storage

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Abstract

Solar thermal systems have been identified as a viable solution to meeting domestic thermal energy needs due to their low temperature operating conditions. The complication of these systems is that solar availability and demand side loads are often mismatched. This is especially true for solar space heating systems, where demand is a maximum in winter when solar potential is the lowest. By using a long-term thermal storage, useful gains in the summer may be carried over to the heating season. There are numerous simulation tools capable of studying such solar thermal systems and building-side demands, however each tool possesses both strengths and shortcomings. This paper outlines the strengths of two modelling tools, TRNSYS and ESP–r, through a new co-simulator in order to evaluate the potential contributions of a seasonal solar thermal system at a single-house scale.

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Keywords: Thermal storage; solar thermal; solar energy; seasonal; simulation; ESP-r; TRNSYS

1. Introduction

1.1. Motivation

In 2008, the residential sector in Ontario, Canada accounted for 21.0% of the total secondary energy use in the province, with a large portion due to space heating and domestic hot water (DHW) [1]. Solar thermal systems have been identified as a viable solution to meeting domestic thermal energy needs due to their low temperature operating conditions [2], while reducing the energy demand from greenhouse gas intensive energy sources. Major Canadian cities are at latitudes that compare favourably to regions where

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1876-6102
Selection and/or peer-review under responsibility of PSE AG
doi:10.1016/j.egypro.2012.11.081

solar space heating is common, such as Austria and Switzerland. Heating loads in Canada, however, are generally higher [3]. The complication with using such systems is that, especially for latitudes above 40°, there is typically high solar availability in the summer season while space heating demand is a maximum during winter. This seasonal mismatch is illustrated in Fig 1. Additionally, at a diurnal scale, domestic thermal demands typically peak in the morning and evening, while solar availability is highest at midday, assuming clear skies. Cloud cover also contributes to intermittence of solar availability, where locations may experience several days with low insolation.

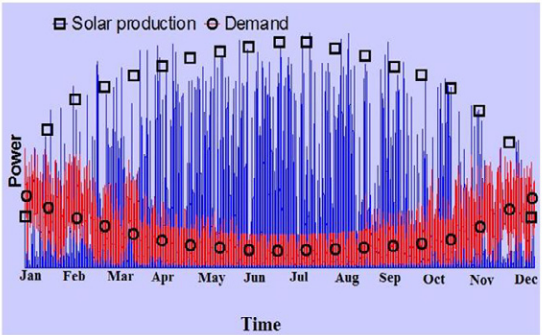

Fig. 1. Seasonal offset between production and demand

To address the supply–demand mismatch in solar thermal systems thermal energy storage (TES) is typically used, forming the link between periods of excess production and periods of high demand. Storage systems can be large to carry over summer production for use in winter (seasonal storage) or small to handle the diurnal mismatch and short periods of intermittence. Typically, large annual systems can contribute up to 100% of domestic thermal demands whereas smaller, diurnal systems rarely exceed a 60% contribution [4]. Annual systems are also less susceptible to long periods of inadequate sunshine and their decreased surface–to–volume ratio reduces heat loss on a unit of storage capacity basis [4]. Braun et al. [5] found that the required collector area for heating could be reduced by using a seasonal storage system at Northern latitudes. Hooper [6] came to similar conclusions, stating that a Canadian home equipped with seasonal storage producing a solar fraction of 100% used 75% less collector area compared to a system with short–term storage. With solar collectors tending to be expensive, there is potential for economical seasonal storage systems. The medium to store heat is discussed in the following subsection.

1.2. Storage media

Water is often used for thermal storage due to its relatively low cost, high availability, non-toxicity and the ability to use it as both storage and transport medium. When designing sensible systems using water, careful consideration needs to be taken to promote stratification and control heat losses. Stratification (temperature layering) of a water–based storage can be achieved with careful placement of inlets and outlets and proper tank geometric design. The layering of warmer fluid at the top and coldest at the bottom improves the usability of the storage by ensuring there is a warm zone to extract from when the tank is nearly fully discharged and a cooler region to inject to when the tank is nearly fully charged. For solar thermal systems, stratification can also improve the system performance by providing colder return temperatures which promote a large temperature difference across the collectors. Large sensible systems typically use heavy insulation to control heat loss to the environment and sometimes they are buried or bermed.

1.3. Modelling of innovative systems

Simulation tools are sometimes used to guide the design of solar thermal systems and sizing of components. Building performance simulation (BPS) software can be used to model space heating loads and some BPS is equipped with resources to model typical or innovative HVAC systems like a seasonal solar thermal system. The challenge identified by Trčka et al. [7] with using BPS tools is that they have had fragmented development and often lack facets of the coupled interaction between building physics and plant–side energy performance. Trčka et al. [7] suggested that in order to further the use of BPS for new buildings and systems, tools need the flexibility to allow users to implement new plant component models, and need the ability to couple or integrate complimentary tools. Such pairing between tools has already occurred (see [7]), such as the merging of TRNSYS types into ESP–r [8] or process model co–operation between TRNSYS and MATLAB [9]. Recently, there has been work undertaken to develop a co–simulator between ESP–r and TRNSYS [10] to exploit both the robust building envelope modelling capabilities of ESP–r and the flexibility of TRNSYS system modelling. This new middleware coupler, aptly named *Harmonizer*, shows potential as a viable candidate to explore solar thermal and its interaction with building–side phenomena.

1.4. Objectives and outline of paper

This paper focuses on the methods used to develop a simulation model for the Carleton Innovation in Renewable and Sustainable Energy (C–RISE) house, an experimental 1424 ft^2 single–family detached dwelling to be built at Carleton University. The C–RISE house will be equipped with two seasonal storage systems: a buried water tank and a soil–based storage. Through the use of the Harmonizer, the integrated performance of the building envelope and the solar thermal systems of the C–RISE house may be accomplished to guide the final design of the house.

The approach used to model the C-RISE house and the solar thermal systems is discussed in Section 3. In addition, the solution method for both simulation tools, ESP-r and TRNSYS, is described. Further, an overview of the Harmonizer is provided and preliminary test results of the co–simulation are shown. Finally the paper concludes with future work that will be conducted involving a small–scale annual solar thermal system.

2. System concept

The solar thermal system, shown in Fig. 2, was selected for analysis. This system uses a small short-term tank for DHW loads and a second, larger seasonal tank for space heating. It has been stated in the literature that the use of a two–tank annual system may perform better at meeting a combined space and hot water load compared to a single tank system [11].

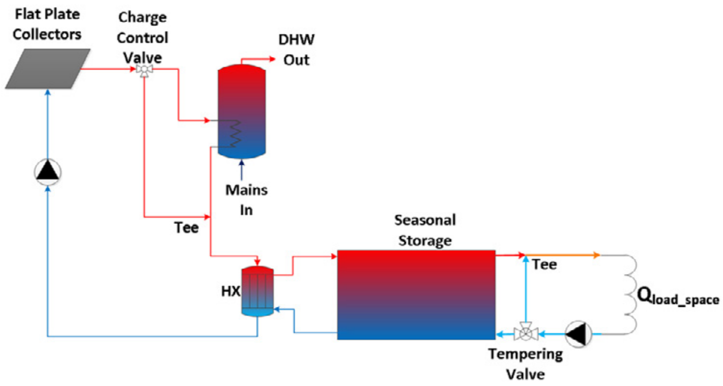

Fig. 2. Two-tank seasonal solar thermal system

During solar collection periods for the two-tank annual system shown in Fig. 2, the fluid in the collector loop charges the small DHW tank first and any remaining charge (heat) is sent to the large annual storage before returning to the collector field. By allowing the charge to go through the annual storage prior to returning to the collector field, the return temperature to the collectors remains low promoting a large temperature difference across the collectors and thereby increasing the efficiency of the system. Once the DHW tank is fully charged, the collector fluid bypasses the DHW tank and continues to charge the annual storage during times of sufficient solar availability.

3. Modelling methods

3.1. Building performance simulation in ESP-r

Development of the building envelope model for the C–RISE house, Fig. 3, was done in ESP–r. ESP–r is an open source BPS tool that uses a partitioned solution approach where custom solvers are applied to different parts of the building domain; thermal, air flow, electrical, plant systems, etc. Interaction or handshaking of the different solvers occurs at each timestep, generally only once (see [12] for details). The thermal domain in ESP–r takes a finite difference control volume approach, where a building is discretized into finite difference nodes representing air zones, solid constructions and solid–fluid interfaces. Each node is described with an energy balance, cast in an algebraic and discrete form using the Crank–Nicolson method. The energy balances for all nodes are then placed in a matrix and solved for simultaneously [13].

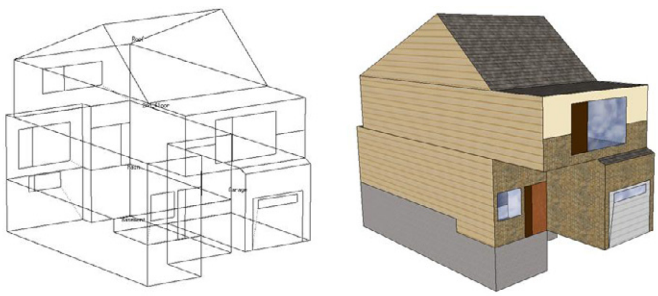

Fig. 3. ESP-r and rendered house model

The explicit plant network in ESP–r also employs control volume methods, where each plant component is represented by one or several control volumes. Each node contains equations for energy and mass balance, which are also cast into a matrix and solved for iteratively. Adding new components in ESP–r is a non–trivial task, since the user is required to have a good understanding of the software's solver and coding practices. This demonstrates ESP–r's weakness in keeping pace with simulating new and emerging sustainable building technologies.

The C–RISE house was described as five zones in ESP–r: basement, first floor, second floor, attic and garage. In addition to the thermal model, ESP–r's facilities were used to simulate air infiltration, solar gains, thermal gains from occupants, non–HVAC gains and a radiant floor heating system in the 1st floor. The radiant floor model, developed by Laouadi [14], uses a semi–analytical approach for a serpentine floor piping system in a slab. At each timestep, a two–dimensional analytical method determines a net flux delivered by the radiant system which is then passed to a user selected node in the one–dimensional floor model in ESP–r. For this test, a slab on subfloor system was modelled using poured gypsum with concrete tile flooring. Design of the radiant floor was guided by conventions provided in the ASHRAE HVAC Systems and Equipment handbook [15]. Major radiant floor parameters are listed in Table 1.

Table 1. Radiant floor parameters

Radiant Floor Parameters	
Number of Circuits	2
Length per Circuit [*m*]	115
Radiant floor area [m^2]	46
Nominal PEX Pipe Dia. [*mm*]	12.7
Pipe Space [*m*]	0.2
Slab Thickness [*mm*]	31.75

3.2. Plant simulation in TRNSYS

TRNSYS uses a different modelling approach than ESP–r. Plant networks are created by linking inputs and outputs of several components, referred to as Types. Each Type can represent something as simple as a flow diverter to something as complex as an absorption chiller using either simple analytical algorithms, numerical methods, empirical correlations, etc. The TRNSYS kernel treats each component as a "black box", mapping the output of one component to the input of others. At each iteration, if the inputs to a Type have changed then it is called by the kernel until convergence is achieved for the system and the simulation can move forward in time.

The TRNSYS software package comes pre–equipped with facilities and documentation for users to create custom components. By using these facilities, users can with relative ease implement new Types representing new and innovative plant components. This software flexibility enables users to keep pace with developments in sustainable technologies and this presents an advantage over the plant modelling abilities in ESP–r.

TRNSYS is ideal for study solar thermal systems like the one shown in Fig. 2 since the software contains a large library of hydronic, thermal storage and solar thermal Types. There is also an established set of controllers and the flexibility to add additional controls to meet specific needs.

3.3. Co-simulation

The *Harmonizer* [10] is a middleware software which couples the strength of ESP–r's building envelope modelling and TRNSYS's flexible plant network simulation. The *Harmonizer* acts as a mediator between ESP–r and TRNSYS, passing data between each software at run–time. The simulation of a coupled model begins by the *Harmonizer* invoking both tools and setting initial conditions. Pre–simulation checks are conducted to ensure timestep and simulation periods are synchronized between ESP–r and TRNSYS.

At each timestep, TRNSYS and ESP–r use their iterative solution method to resolve their individual systems. The Harmonizer then checks for global convergence across the two tools and if the convergence criteria is satisfied, the Harmonizer permits a marching forward in time. If the *Harmonizer* is not satisfied, ESP–r and TRNSYS is notified of the non–convergence and both tools re-run at the same timestep. More details of the Harmonizer can be found in the literature [10].

In order to couple TRNSYS with ESP–r, a portion of the plant system needs to be defined in ESP–r to facilitate the plant/zone heat flux interaction. The *Harmonizer* is designed so that the amount of the plant system described in each simulation tool is at the discretion of the user. For example, in the system shown in Fig. 2, the $\mathbf{Q}_{\mathbf{load}}$ was modelled as a radiant slab in ESP–r and the remainder of the system was described in TRNSYS. The system could also have been described with the space heating pump, flow diverter and tee piece in ESP–r and the seasonal storage tank and the remainder of the system modelled in ESP–r.

The data exchange capabilities of the *Harmonizer* include air and water flow rate and temperature, ESP–r zone air temperatures and flux gains from TRNSYS to ESP–r (e.g., to pass standby losses of a storage tank to the zone air in ESP–r). While this data can cover most situations, there are limitations. For the radiant floor system, ASHRAE HVAC and Systems Equipment [15] states that the radiant floor temperature should be controlled so as not to exceed 27 or 29 °C. There is currently no way for the *Harmonizer* to pass surface temperatures in ESP–r to TRNSYS for control. However, the flexibility of the *Harmonizer* to allow users to define how much of the plant is modelled in each software permits the modelling of the space heating pump in ESP–r and the radiant slab. In this way the pump may be controlled by built in ESP–r controllers that have access to more data in the building model.

4. Preliminary co-simulation test

To test the functionality of the *Harmonizer*, a simple TRNSYS plant was connected to the ESP–r radiant floor contained in the C–RISE model. The TRNSYS network consisted of a pump with a constant temperature heat source of 50 °C, a heating aquastat controller and Type 130 to pass hydronic flow data between ESP–r and TRNSYS. Type 130 also passes the 1st floor zone temperature from the ESP–r for use as the sensed condition of the heating aquastat. The controller is set to hold the room temperature at 21 °C with a 3°C deadband by cycling the pump on and off. The results of a 9 day simulation for January in Ottawa is shown in Fig. 4.

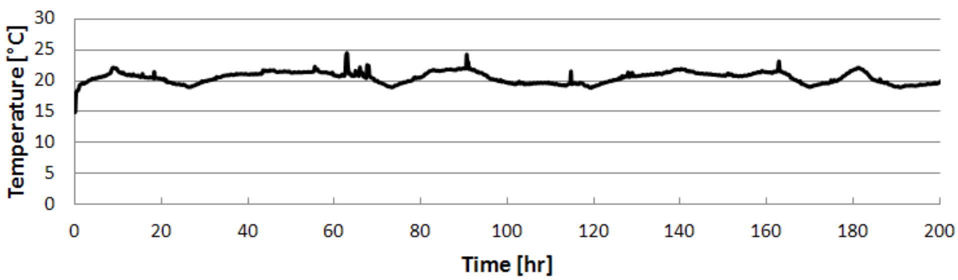

Fig. 4. Preliminary test of hydronic coupling between ESP-r and TRNSYS

The 1st floor zone temperature was held approximately within the deadband, with some periods of over and undershoot. This drifting beyond the deadband is likely the result of inadequate radiant floor control. The aquastat shut off the pump when the zone temperature reached the upper limit of the deadband, but the large thermal capacitance of the radiant slab generated a thermal lag. To ensure that the *Harmonizer* was functioning properly, a similar test was conducted where the TRNSYS network from the first test was replicated into the ESP–r model. When the simple radiant floor system was simulated in ESP–r only, there was no significant difference to results from the co–simulation.

5. Future work

With the functionality of the *Harmonizer* demonstrated with the simple case in Section 4, future work will include the co–simulation of the full seasonal storage system. The coupled model will be used to investigate collector–storage volume ratios for the system, the significance of insulation on the seasonal storage system and the achievable solar fraction for the Ottawa, Canada climate. There will also be work undertaken to examine different radiant floor control schemes when coupled to solar thermal systems.

Acknowledgement

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada (NSERC) and the NSERC Smart Net–zero Energy Buildings Strategic Research Network (SNEBRN) for supporting this work.

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