Toward a smart control of Solar Domestic Hot Water (SDHW) systems

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Context

Energy savings is an on-going topic, which involves many different research activities. Despite recent efforts, a significant share of energy consumption worldwide is still devoted to buildings, mainly for heating, cooling and ventilation purposes, especially in developed countries (Pérez-Lombard et al., 2008). Among the numerous research subjects related to energy consumption, the one used for Domestic Hot Water (DHW) has some specificities. First, it meets a demand which is little influenced by the environmental conditions, meaning that the demand exists both for cold (Beausoleil-Morrison et al., 2019; Furbo et al., 2005), temperate (Haines et al., 2019; Pang and O'Neill, 2018) and hot (Artur et al., 2018; Cardemil et al., 2018) countries. Second, it is highly suitable with solar energy by using a water tank in order to mitigate the mismatch between the availability of the energy and the hot water demand. This system is known as Solar Domestic Hot Water (SDHW) and has been studied for decades (Berbash et al., 1995; Knudsen, 2002). It is mainly made of a solar collector, at least one pump and a thermal storage tank connected to the DHW circuit. Generally, an auxiliary heater is added at the top of the tank in order to heat up the water when the solar gains are insufficient. Two examples are provided in Figure 1, but it is acknowledged that other designs exist, such as thermosiphon systems where the water flow relies on buoyancy and no pump is needed.

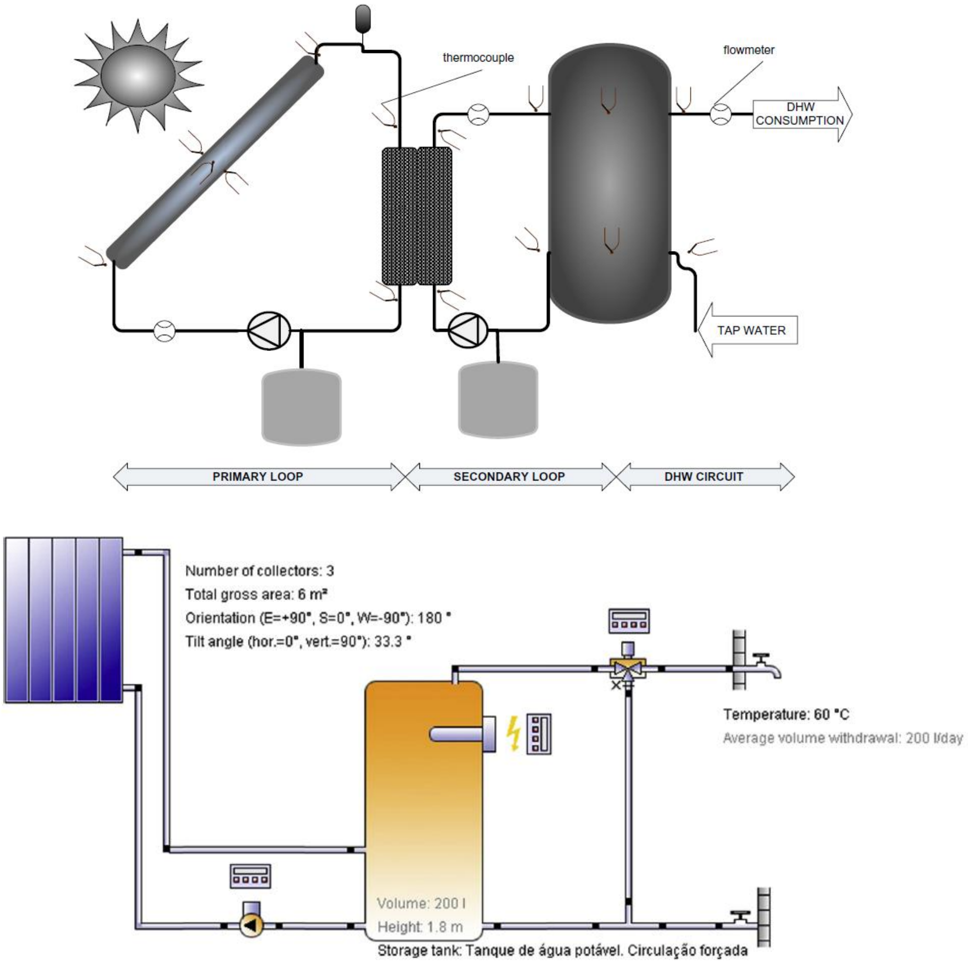

Figure 1: SDHW system with a secondary loop (Rodríguez-Hidalgo et al., 2012) at the top and SDHW system with an auxiliary heater (Artur et al., 2018) at the bottom.

The size of the main components (that is, the solar collector area and the volume of the thermal storage tank) is limited by the financial investment while this system has to maintain a sufficient amount of water at a high temperature in order to cover the demand for hot water. To do so, the pump is running when solar gains are sufficient, and the auxiliary heater is used otherwise. The best option on the economical point of view is to avoid using the auxiliary heater and to run the pump for the shortest period of time. Note that most authors agree on the necessity of an auxiliary heater. Its design is however sparsely discussed in the literature, except in (Furbo et al., 2005) where its influence was highlighted.

However, the thermal losses at the tank are unavoidable, leading the pump and the auxiliary heater of an oversized system to run for a longer period in order to maintain a constant temperature. This was suggested by (Fraisse et al., 2009), as it would benefit to use a smaller tank and a larger solar collector to optimize the system. A similar conclusion was obtained in (Rodríguez-Hidalgo et al., 2012). Besides, control has a significant influence on the energy consumption, especially for forced-circulation systems (compared to thermosiphons). Here, control refers to the selection of the components for the hydronic network such as valves and variable speed pumps (Nhut and Park, 2013). One of the reason is that the control strategy considerably influences the formation and maintenance of the thermal stratification in the tank (Fernández-Seara et al., 2013), which in turn affects the energy efficiency of the system. For large systems, (Rahmatmand et al., 2020) demonstrated that the use of Electronic Mixing Valves exhibited superior performances compared to traditional Thermostatic valves. Overall, even if SDHW is a widespread system, its design did not sound straightforward and attention should be paid to the sizing of the main components.

Second, SDHW has to deal with two major uncertain parameters : the weather conditions and the hot water demand that is, the amount of hot water required at a given period of the day (Araújo and Pereira, 2017). While the weather conditions can be dealt with by using measured outdoor conditions, including variable solar gains, the energy demand varies strongly according to the user's lifestyle and to its own engagement with regard to energy (Haines et al., 2019). Earliest studies relied on "realistic profiles", also called deterministic profiles. By this, we mean that one or a few typical hourly averaged energy demand profiles were repeated daily to test and design a SDHW system. Nowadays however, it is acknowledged that realistic tests should consider the stochastic nature of hot water demand and multiple advances were made recently on this topic (Li et al., 2019). For example, (Fischer et al., 2016) proposed a model adapted to Germany that combined behavioral and energy balance models with a stochastic approach. The Karhunen Loève expansion was used in (O'Neill and Niu, 2017; Pang and O'Neill, 2018) to sample time-dependent inputs, that is the schedules for using hot water. Recently, (Rouleau et al., 2019) developed a code with Matlab to unify different models for generating schedules of active occupancy, including the DHW demand. Still, we can observe that these improvements were made recently and that the application to the design of SDHW systems is still scarce.

Finally, smart control is an emerging trend in the building sector (Sovacool and Furszyfer Del Rio, 2020). When dealing with energy saving purposes, "smart control" can refer to a technology that is more sophisticated than a simple On/Off control. In (Lomas et al., 2018), the distinction was made between advanced controls (such as the use of a Time Proportional control, a weather or a load compensator) and smart technologies (learning algorithms, occupancy sensors, remote control for example). In most cases however, the authors concluded that there was no strong evidence of the energy savings provided by smart or even some of the advanced technologies. One of the reason for such poor results comes from the scientific methodology that does not provide high quality evidences. Besides, the behavior of the end user and his expectations might also reduce the simulated performance of an advanced system. This was underlined by (Haines et al., 2019), who specified that any technological advancements should be considered alongside energy related behavior for a successful adoption. Still, the hardly predictable nature of the hot water demand and the time-varying outdoor conditions harden the design of a robust SDHW system, and it sounds relevant to seek for a control system that could adapt to the season and to the demand, at least within reasonable proportions.

Research project

In this research project, we propose to explore the possibilities of improving the control of SDHW, and to highlight its impact on the sizing of the system. This study will rely on a numerical work mostly. While some simplified techniques are available to estimate the energy performance of a SDHW system, and some of them being accurate (Araújo and Pereira, 2017), the use of dynamic model is now common and allow more flexibility and accuracy (Artur et al., 2018).

We propose to rely on TRNSYS software in order to take advantage of the experience in our lab (Labat and Attonaty, 2017). TRNSYS software is a widespread tool used to solve heat and mass transfer in dynamic thermal systems. It is suitable with parametric studies (Beausoleil-Morrison et al., 2019), sensitivity analysis (Pang and O'Neill, 2018) and multi-objective optimization (Cardemil et al., 2018), the latter making it possible to include economic considerations in the design process.

The main objective is to develop a robust design of a SDHW system, which is a system that is able to address the hot water demand for minimum capital and operational costs. To do so, we propose to follow the following steps:

1. To achieve an extensive literature review to determine the hydronic system used for SDHW, in order to select the most relevant ;
2. To include a stochastic hot water demand based on already published work on this topic and on our own experience in another domain (Bui et al., 2019) ;
3. Achieve a sensitivity analysis to identify the most influencing input parameters and gain confidence in the model.
4. Propose and test smart control techniques, moving progressively from simple to advanced techniques.

Applicant

The applicant should be master graduated in the field of Mechanical Engineering, Energy or Architecture. The applicant should be skilled in advanced heat transfer and fluid dynamics. Basic knowledge of control and modelling are also required. Additional skills in energy systems will be appreciated. Finally, written and spoken English are mandatory.

Laboratory

LMDC (Material and Durable Constructions Laboratory) is a French laboratory located in Toulouse. It is specialized in Civil Engineering and addresses, through the Energy axis, the design of efficient energy equipment for buildings. The laboratory gathers more than 52 permanent searchers and approximately 53 PhD students.

References

Araújo, A., Pereira, V., 2017. Solar thermal modeling for rapid estimation of auxiliary energy requirements in domestic hot water production: On-off flow rate control. Energy 119, 637–651. https://doi.org/10.1016/j.energy.2016.11.025

Artur, C., Neves, D., Cuamba, B.C., Leão, A.J., 2018. Comparison of two dynamic approaches to modelling solar thermal systems for domestic hot water. Sustain. Energy Technol. Assess. 30, 292–303. https://doi.org/10.1016/j.seta.2018.10.012

Beausoleil-Morrison, I., Kemery, B., Wills, A.D., Meister, C., 2019. Design and simulated performance of a solar-thermal system employing seasonal storage for providing the majority of space heating and domestic hot water heating needs to a single-family house in a cold climate. Sol. Energy 191, 57–69. https://doi.org/10.1016/j.solener.2019.08.034

Berbash, Y., Chandrashekar, M., Calamai, P., 1995. Technology for sustainable development: A case study of solar domestic hot water heating in Ontario. Energy 20, 495–510. https://doi.org/10.1016/0360-5442(94)00095-K

Bui, R., Labat, M., Lorente, S., 2019. Impact of the occupancy scenario on the hygrothermal performance of a room. Build. Environ. 160, 106178. https://doi.org/10.1016/j.buildenv.2019.106178

Cardemil, J.M., Starke, A.R., Colle, S., 2018. Multi-objective optimization for reducing the auxiliary electric energy peak in low cost solar domestic hot-water heating systems in Brazil. Sol. Energy 163, 486–496. https://doi.org/10.1016/j.solener.2018.01.008

Fernández-Seara, J., Uhía, F.J., Pardiñas, Á.Á., Bastos, S., 2013. Experimental analysis of an on demand external domestic hot water production system using four control strategies. Appl. Energy 103, 85–96. https://doi.org/10.1016/j.apenergy.2012.10.030

Fischer, D., Wolf, T., Scherer, J., Wille-Haussmann, B., 2016. A stochastic bottom-up model for space heating and domestic hot water load profiles for German households. Energy Build. 124, 120–128. https://doi.org/10.1016/j.enbuild.2016.04.069

Fraisse, G., Bai, Y., Le Pierrès, N., Letz, T., 2009. Comparative study of various optimization criteria for SDHWS and a suggestion for a new global evaluation. Sol. Energy 83, 232–245. https://doi.org/10.1016/j.solener.2008.07.021

Furbo, S., Andersen, E., Knudsen, S., Vejen, N.K., Shah, L.J., 2005. Smart solar tanks for small solar domestic hot water systems. Sol. Energy 78, 269–279. https://doi.org/10.1016/j.solener.2004.08.022

Haines, V., Kyriakopoulou, K., Lawton, C., 2019. End user engagement with domestic hot water heating systems: Design implications for future thermal storage technologies. Energy Res. Soc. Sci. 49, 74–81. https://doi.org/10.1016/j.erss.2018.10.009

Knudsen, Sø., 2002. Consumers' influence on the thermal performance of small SDHW systems—Theoretical investigations. Sol. Energy 73, 33–42. https://doi.org/10.1016/S0038-092X(02)00018-X

Labat, M., Attonaty, K., 2017. Numerical estimation and sensitivity analysis of the energy demand for six industrial buildings in France. J. Build. Perform. Simul. 1–18. https://doi.org/10.1080/19401493.2017.1322637

Li, J., Yu, Z. (Jerry), Haghighat, F., Zhang, G., 2019. Development and improvement of occupant behavior models towards realistic building performance simulation: A review. Sustain. Cities Soc. 50, 101685. https://doi.org/10.1016/j.scs.2019.101685

Lomas, K.J., Oliveira, S., Warren, P., Haines, V.J., Chatterton, T., Beizaee, A., Prestwood, E., Gething, B., 2018. Do domestic heating controls save energy? A review of the evidence. Renew. Sustain. Energy Rev. 93, 52–75. https://doi.org/10.1016/j.rser.2018.05.002

Nhut, L.M., Park, Y.C., 2013. A study on automatic optimal operation of a pump for solar domestic hot water system. Sol. Energy 98, 448–457. https://doi.org/10.1016/j.solener.2013.08.040

O'Neill, Z., Niu, F., 2017. Uncertainty and sensitivity analysis of spatio-temporal occupant behaviors on residential building energy usage utilizing Karhunen-Loève expansion. Build. Environ. 115, 157–172. https://doi.org/10.1016/j.buildenv.2017.01.025

Pang, Z., O'Neill, Z., 2018. Uncertainty quantification and sensitivity analysis of the domestic hot water usage in hotels. Appl. Energy 232, 424–442. https://doi.org/10.1016/j.apenergy.2018.09.221

Pérez-Lombard, L., Ortiz, J., Pout, C., 2008. A review on buildings energy consumption information. Energy Build. 40, 394–398. https://doi.org/10.1016/j.enbuild.2007.03.007

Rahmatmand, A., Vratonjic, M., Sullivan, P.E., 2020. Energy and thermal comfort performance evaluation of thermostatic and electronic mixing valves used to provide domestic hot water of buildings. Energy Build. 212, 109830. https://doi.org/10.1016/j.enbuild.2020.109830

Rodríguez-Hidalgo, M.C., Rodríguez-Aumente, P.A., Lecuona, A., Legrand, M., Ventas, R., 2012. Domestic hot water consumption vs. solar thermal energy storage: The optimum size of the storage tank. Appl. Energy 97, 897–906. https://doi.org/10.1016/j.apenergy.2011.12.088

Rouleau, J., Ramallo-González, A.P., Gosselin, L., Blanchet, P., Natarajan, S., 2019. A unified probabilistic model for predicting occupancy, domestic hot water use and electricity use in residential buildings. Energy Build. 202, 109375. https://doi.org/10.1016/j.enbuild.2019.109375

Sovacool, B.K., Furszyfer Del Rio, D.D., 2020. Smart home technologies in Europe: A critical review of concepts, benefits, risks and policies. Renew. Sustain. Energy Rev. 120, 109663. https://doi.org/10.1016/j.rser.2019.109663