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

Contact:
Matthieu LABAT (m_labat@insa-toulouse.fr)
Stéphane Ginestet (sgineste@insa-toulouse.fr)

Keywords: Energy consumption, control, modelling, stochastic approach, optimization

Context

Energy savings is a persistent topic that encompasses various research activities. Despite recent efforts, buildings still account for a significant share of global energy consumption, particularly in developed countries, mainly for heating, cooling, and ventilation purposes (Pérez-Lombard et al., 2008). One of the many research subjects related to energy consumption is Domestic Hot Water (DHW), which has its own specificities. This demand exists in 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) climates. Also, this demand is not significantly influenced by environmental conditions. Additionally, the existing systems are highly compatible with solar energy, utilizing a water tank to mitigate the mismatch between energy availability and hot water demand.

The Solar Domestic Hot Water (SDHW) system, consisting of a solar collector, at least one pump, and a thermal storage tank connected to the DHW circuit, has been studied for decades (Berbash et al., 1995; Knudsen, 2002). An auxiliary heater is typically added at the top of the tank to heat the water when solar gains are insufficient. Figure 1 provides two examples, but it is acknowledged that other designs exist, such as thermosiphon systems where water flow relies on buoyancy and does not require a pump.

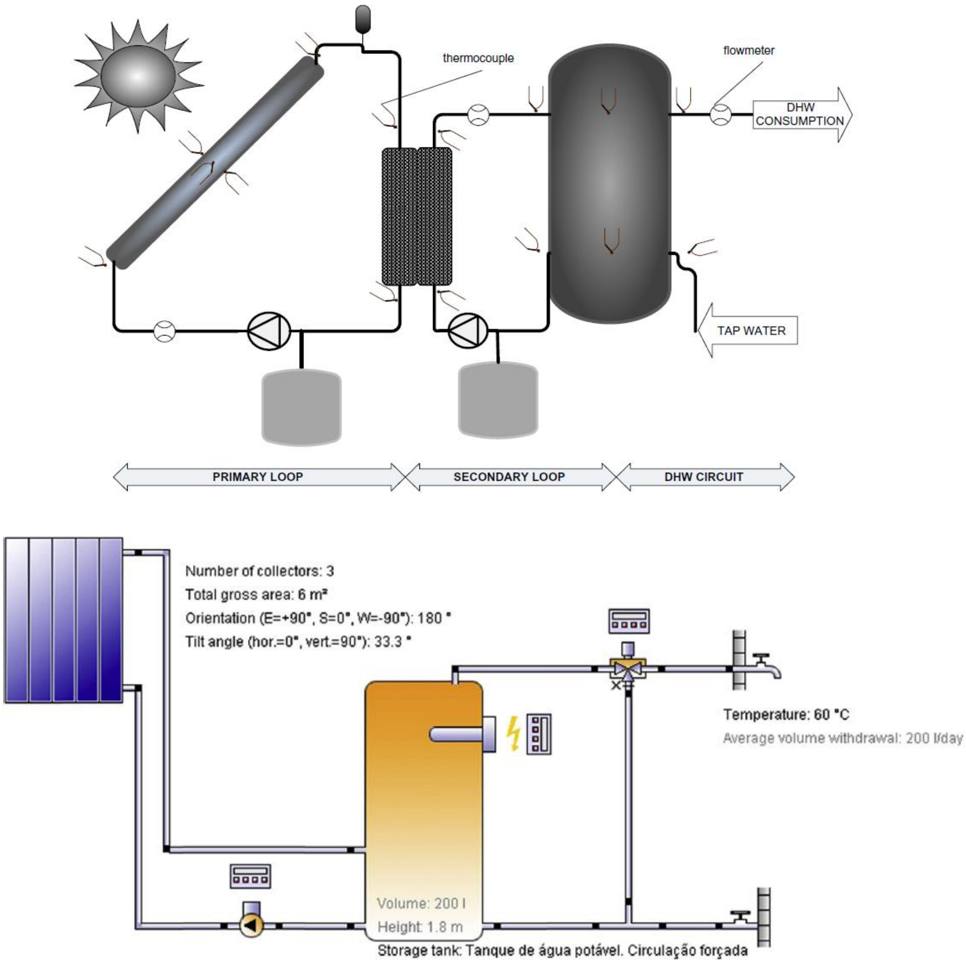

Figure 1: SDHW system with a secondary loop (Rodríguez-Hidalgo et al., 2012) at the top and SDHW system with an auxiliary heater (Artur et al., 2018) at the bottom.

The financial investment limits the size of the main components, namely the solar collector area and the volume of the thermal storage tank. The system must maintain a sufficient amount of water at a high temperature to cover the demand for hot water. The pump runs when solar gains are sufficient, and the auxiliary heater is used otherwise. To achieve the most economical outcome, it is recommended to refrain from using the auxiliary heater and to run the pump for the shortest possible duration. It is worth noting that while many authors acknowledge the need for an auxiliary heater, its design is not extensively discussed in the literature, with the exception of (Furbo et al., 2005) where its impact was emphasised.

However, thermal losses at the tank are unavoidable, which causes the pump and auxiliary heater of an oversized system to run for longer periods to maintain a constant temperature. This suggestion was made by (Fraisse et al., 2009) and supports the use of a smaller tank and a larger solar collector to optimize the system. A similar conclusion was reached in (Rodríguez-Hidalgo et al., 2012). Control has a significant influence on energy consumption, particularly for forced-circulation systems when compared to thermosiphons. In this context, control refers to the selection of components for the hydronic network, such as valves and variable speed pumps (Nhut and Park, 2013). One reason is that the control strategy significantly influences the formation and maintenance of thermal stratification in the tank (Fernández-Seara et al., 2013). This, 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 performance compared to traditional thermostatic valves. Overall, although SDHW is a widely used system, its design is not straightforward. Therefore, it is important to pay attention to the sizing of the main components.

Secondly, SDHW systems must account for two major uncertain parameters: weather conditions and hot water demand, which refers to the amount of hot water required at a given time of day (Araújo and Pereira, 2017). While weather conditions can be addressed by using forecasted outdoor conditions, including variable solar gains, energy demand varies greatly depending on the user's lifestyle and their engagement with energy (Haines et al., 2019). Early studies relied on 'realistic profiles', also known as deterministic profiles. This means that one or a few typical hourly averaged energy demand profiles were repeated daily to test and design a solar domestic hot water (SDHW) system. However, it is now acknowledged that realistic tests should consider the stochastic nature of hot water demand. Multiple advances have been made recently on this topic (Li et al., 2019). For instance, (Fischer et al., 2016) proposed a model that combined behavioural and energy balance models with a stochastic approach, adapted to Germany. (O'Neill and Niu, 2017; Pang and O'Neill, 2018) used the Karhunen Loève expansion to sample time-dependent inputs, specifically the schedules for using hot water. (Rouleau et al., 2019) developed a Matlab code to unify different models for generating schedules of active occupancy, including the DHW demand. However, these improvements have only been made recently and that their application to the design of SDHW systems is still limited.

Smart control is an emerging trend in the building sector, particularly for energy-saving purposes (Sovacool and Furszyfer Del Rio, 2020). It refers to a technology that is more sophisticated than a simple on/off control. Advanced controls, such as Time Proportional control, weather or load compensators, and smart technologies like learning algorithms, occupancy sensors, and remote control, should been distinguished as mentioned in (Lomas et al., 2018). However, these authors found no strong evidence supporting the energy-saving benefits of smart or advanced technologies. This may be due to limitations in the scientific methodology, which fails to provide high-quality evidence. Additionally, the behaviour and expectations of end-users may reduce the simulated performance of advanced systems. (Haines et al., 2019) highlighted the importance of considering energy-related behaviour alongside technological advancements for successful adoption. As a conclusion, designing a robust solar domestic hot water (SDHW) system is challenging due to the unpredictable nature of hot water demand and time-varying outdoor conditions. Therefore, it is relevant to seek a control system that can adapt to seasonal changes and demand, within reasonable proportions.

Research project

This research project aims to investigate the potential for enhancing the control of SDHW and its impact on system sizing. The study will primarily utilise numerical analysis, supplemented by experimentation using the lab's test-rig.

Figure 2: Picture of the lab's test rig.

TRNSYS software, a widely-used tool for solving heat and mass transfer in dynamic thermal systems, will be employed. The text discusses the suitability of the proposed method for parametric studies (Beausoleil-Morrison et al., 2019), sensitivity analysis (Pang and O'Neill, 2018), and multi-objective optimisation (Cardemil et al., 2018; Labat and Hazyuk, 2023).

The main objective is to develop a robust design for an SDHW system that can meet the hot water demand while minimizing capital and operational costs. The latter allows for the inclusion of economic considerations in the design process. The proposed steps for achieving this objective are as follows:

1. To conduct a bibliography survey on the application of smart control technologies to SDHW systems;
2. To propose, develop, and validate a TRNSYS model based on the experimental results obtained from the lab's test rig;
3. To incorporate a stochastic hot water demand, based on previously published research in this area and our own experience in a different field (Bui et al., 2019);
4. To conduct a sensitivity analysis that identifies the most influential input parameters and increases confidence in the model.
5. To propose and test smart control techniques, starting with simple techniques and progressing to more advanced ones.
6. To apply the obtained methodology on a larger scale and under different operating conditions, such as swimming pools, hotels, and hospitals.

Applicant

The applicant should be master graduated in the field of Mechanical Engineering or Energy and possess advanced skills in heat transfer and fluid dynamics. Basic knowledge of control and modelling is also required, with additional skills in energy systems being highly valued. Fluency in spoken and written English is 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., Hazyuk, I., 2023. Numerical comparison of an office cooled with and without a ventilated slab using a model predictive controller. Appl. Therm. Eng. 228, 120500. https://doi.org/10.1016/j.applthermaleng.2023.120500

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