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Simulation-based Estimation of the Optimization Potential of Dynamic Controller Settings for Solar Thermal Combisystems

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Review Paper

Before improving the control settings of solar heating systems with the help of sophisticated predictive algorithms, it is reasonable first to determine or at least estimate the theoretical potential of these improvements and then to decide if they are worthy of implementation. An approach is proposed in this paper which enables the estimation of the theoretical potential of the dynamic control settings optimization for solar heating combisystems. Dynamic optimization was carried out for a solar combisystem with a solar fraction of approximately 35% for the period of an entire year. The theoretical potential of the optimization of the boiler controller settings as well as the fluid mass flow in the collector loop and, consequently, in store loop, was estimated. The solar thermal combisystem was simulated in TRNSYS and optimization was carried out by the binary (n-ary) search algorithm programmed in GenOpt (Generic optimization software). The results showed that the extended fractional savings for the considered combisystem with dynamically optimized mass flow in the collector loop was only 0.3 percent points larger than that for the system with an optimized, but fixed mass flow. The optimization potential of the boiler controller settings turned out to be more promising, showing an improvement of 4.4 percentage points in thermal fractional savings for the system with two instant electrical heaters versus the initial system with a heated volume in the store.

Procjena optimizacijskog potencijala postavki dinamičke kontrole solarnih kombi-sustava pomoću računalnih simulacija

Pregledni rad

Prije poboljšanja kontrolnih postavki solarnog toplinskog sustava pomoću sofisticiranih prediktivnih algoritama, potrebno je prije odrediti ili procijeniti teoretski potencijal tih poboljšanja. U ovom radu je prikazan pristup koji omogućava procjenu teoretskog potencijala optimizacije postavki dinamičke kontrole za solarne kombi-sustave. Dinamička optimizacija je vršena za solarni kombi-sustav sa solarnim udjelom od 35% tokom cijele godine. Teoretski potencijal optimizacije postavki kontrole spremnika, kao i protok radnog fluida u kolektorskom krugu. Solarni toplinski kombi-sustav je simuliran u programu TRNSYS i optimizacija je vršena binarnim pretraživačkim algoritmom programiranom u GenOpt programu (Generic optimization software). Rezultati pokazuju da je ušteda na promatranom kombi-sustavu sa dinamički optimiziranim masenim protokom u solarnom krugu tek 0.3% veća nego kod istoga sustava sa optimiziranim, ali fiksnim masenim protokom radnog fluida. Optimizacijski potencijal postavki kontrole spremnika je pokazao bolje rezultate, postigavši 4.4% posto veću uštedu toplinske energije za sustav sa dva električna grijača.

1. Introduction

Simulation-based optimization of solar thermal systems usually consists of two stages: optimization of the system during the planning process when main design parameters such as collector area, store volume, mass flows, etc., are determined, and optimization of the system in operation, when control parameters have to be adjusted, for example, on a seasonal or daily basis. As it was shown before [1, 2], the numerical optimization during the planning process can bring an additional > 10% benefit in terms of the fractional savings to a system already appropriately designed by experienced engineers. It seemed that further optimization of this system in operation did not have much potential [2]. Before developing a predictive control algorithm, its potential to improve system efficiency should be known. Therefore, an approach is proposed in this paper which enables estimating the maximal potential of operational optimization for an ideal case of precisely known weather data and load profile.

The main challenge for optimization algorithms are the large number of optimization parameters which runs into the thousands already when only one control parameter is being adjusted on an hourly basis. But even if the algorithm could cope with this number of parameters, the optimization process would be unacceptably long. For example, if five minutes are required per single simulation (which is usually the case for precise TRNSYS simulations with a short time step), then the optimization would take weeks or even months. The approach presented in this paper divides a yearly optimization into many short ones (up to 4 days and on average with 15 parameters per optimization) and thus enables the whole optimization in a reasonable amount of time. Such a splitting is justified only if changing a single optimization parameter affects the system performance (mainly the store temperature profile) for a time horizon not longer than a couple of days.

The theoretical potential of adjusting the boiler control settings, however, is estimated in a different way, by modifying the system hydraulics and then using a correlation between the set temperature of the heater and the ambient temperature.

Symbols/Oznake

F_{target}	- target function, kWh - funkcija cilja, kWh	Q_{aux}	- auxiliary energy consumption of the solar combisystem, kWh - potrošnja pomoćne energije solarnog kombi-sustava, kWh
Q_{sol}	- solar gains, kWh - solarni dobici energije, kWh	Q_{ref}	- auxiliary energy consumption of the reference system without solar part, kWh - potrošnja pomoćne energije referentnog sustava bez solarnog dijela, kWh
W_{pumps}	- electrical energy consumption of primary and secondary pumps, kWh - potrošnja električne energije primarnih i sekundarnih crpki, kWh	$F_{\text{save, therm}}$	- fractional thermal energy savings, % - ušteda toplinske energije, %
E_{aux}	- auxiliary final energy consumption of the solar combisystem, kWh - potrošnja ukupne pomoćne energije solarnog kombi-sustava, kWh	$F_{\text{save, ext}}$	- extended fractional energy savings, % - proširena uštedas energije, %
E_{ref}	- final energy consumption of the reference system, kWh - potrošnja energije referetnog sustava, kWh		

2. System description and methodology

2.1. System description

The dynamic optimization potential of the reference solar combisystem of IEA SHC Task 32 [3] was estimated in this paper (see Figure 1). The combisystem was planned for a one family house located in Zurich (Switzerland) with an average consumption of approximately 200 l of domestic hot water at 45°C per day. The system was previously optimized for the best price/performance ratio with the help of a genetic algorithm (see [1]). Besides the collector and storage tank, the system has an auxiliary heating loop with a heated volume inside the tank. The storage tank is charged by the collector through an external heat exchanger. The time resolution of the calculations was set to 6 minutes.

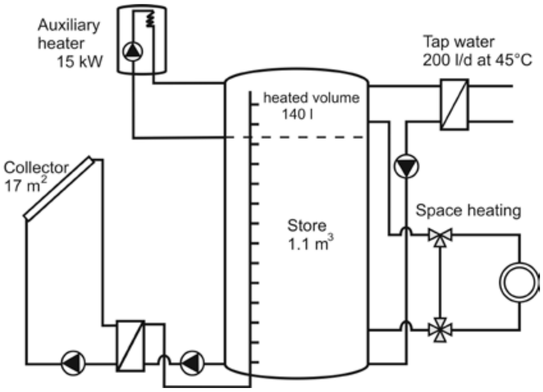

Figure 1. Simplified hydraulic scheme of the reference solar combisystem [3] with auxiliary heating loop.

Slika 1. Pojednostavljena hidraulička shema referentnog solarnog kombi-sustava [3] sa pomoćnim grijaćim krugom (15 kW).

2.2. Dynamical optimization of fluid mass flow

The solar combisystem (Figure 1) was dynamically optimized in order to get as much energy as possible from the collector into the storage tank and minimize the energy consumed by the pumps. The target function was defined as follows:

$$F_{\mathrm{target}} = Q_{\mathrm{sol}} - 3 \cdot W_{\mathrm{pumps}} \,. \tag{1}$$

Actually, the following function

$$F_{\mathrm{target}} = Q_{\mathrm{aux}} + 3 \cdot W_{\mathrm{pumps}} \tag{2}$$

should have been minimized, but it does not work in the optimization approach presented below. To maximize the defined target function (1), the fluid mass flow in the collector loop was adjusted on an hourly basis but only for hours when the specific solar insulation was high enough (> 200 W/m^2). The specific mass flow was varied in the range from 10 to 30 l/hm^2. The mass flow in the storage charging loop was calculated in such a way that the capacity flow rates in the collector and storage loops were equal.

As the choice of the collector mass flow for a selected day (or hour) has almost no impact on the performance of the system (more precisely: on the temperature profile of the storage tank) even a couple of days later, there is no reason to perform the whole year simulation of the system each time when the mass flow changes only during selected hours. Thus, it was suggested to split up the whole year optimization into many short ones with a duration of up to four days. After each short optimization, the temperature profile of the storage tank, temperature of the air zone of the building, temperatures of the walls and fluxes through the walls were saved at the end of the first day being optimized and taken as the initial condition for the next optimization (see Figure 2). Such a splitting allows the dynamic optimization saving a huge amount of computational time.

Figure 2. Schematic presentation of two four-day optimizations.

Slika 2. Shematski prikaz dvaju četverodnevnih optimizacija.

In Figure 2, two four-day optimizations are schematically presented. The hours with solar insulation > 200 W/m2 for which the mass flow is optimized are shown in grey color. In optimization 1, the optimal mass flow for days 1 – 4 is identified by the evaluation of the target function at the end of day 4. After optimization 1 is finished, the optimal mass flows during day 1 are stored and the temperature profile of the store, temperature of the air zone of the building, temperatures of the walls and fluxes are saved at the end of day 1. They are used to initialize the system at the beginning of day 2 in each simulation of optimization 2.

At each short optimization the target function (1) calculated over the time interval of four days, is maximized. As it was already mentioned above, minimization of the function (2) would be more appropriate since it represents the final energy consumption of the system, but it doesn't work in the approach represented here. The backup-heating may switch on by chance at the end of the fourth day, or just at the beginning of the fifth day. The evaluation of a target function is misleading in these cases. Thus, it was decided to maximize the solar gains, assuming that the more energy gets into the storage tank, the better the system performance is.

Choice of duration for each short optimization and the number of days of the shift between two consequent optimizations are the questions which should be cleared up in advance. If the optimization parameters are strongly correlated with respect to the chosen target function, then the duration should be longer and the shift should be short (one day). In the investigated case, the parameters (values of mass flow for specific hours) seem to be uncorrelated; even short optimizations with one day duration and with one day shift (next optimization starts from the following day) provide almost the same results as presented here.

2.3. Estimation of potential of boiler set temperature optimization

It can be assumed that the system performance is best if the boiler delivers to the store exactly the amount of energy needed by the consumer at a specific moment. Hot water, heated up by fossil fuels and stored, causes thermal losses. To optimize the boiler control settings such as set temperature and control dead bands, one could proceed as above by adjusting these settings on an hourly basis. Here, however, another way is chosen.

The hydraulics of the investigated combisystem was modified to determine the theoretical optimization potential of the boiler control settings. The boiler, heating up the auxiliary volume inside the storage tank, was replaced by two electric instant heaters placed in a tap water preparation and space heating loop, respectively (Figure 3). Such modification is expected to have several positive effects on the system performance. The store losses should decrease due to the lower temperatures, especially in the upper part of the tank. In the summer, when stagnation of the system may occur, more store space is available for a possible anti-stagnation control strategy [4] or, alternatively, the store can be made smaller and cheaper.

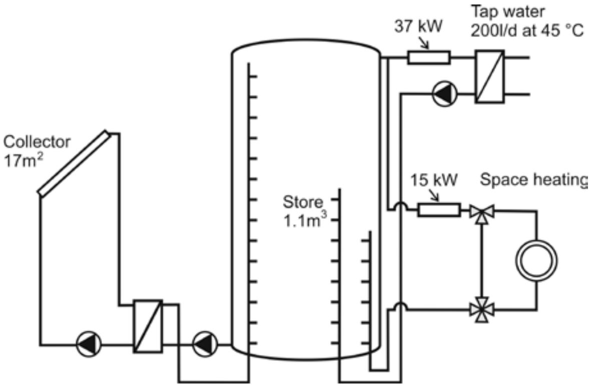

Figure 3. Modified combisystem with two electrical instant heaters in tap water and space heating loops.

Slika 3. Modificirani kombi-sustav sa dva električna grijača u krugovima grijanja PTV i grijanja prostora.

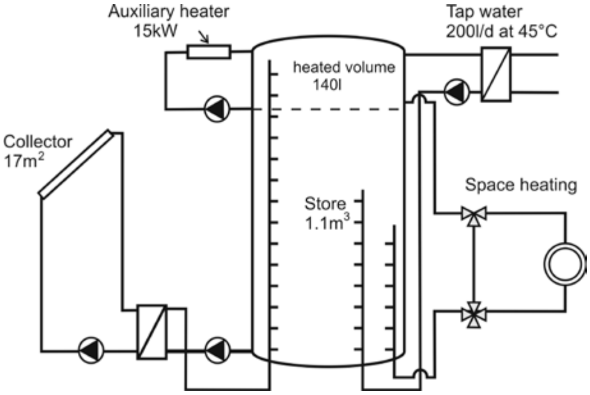

Figure 4. Reference combisystem with electrical heater in the auxiliary heating loop.

Slika 4. Referentni kombi-sustav sa električnim grijačem u pomoćnom grijaćem krugu.

For a more consistent comparison, the performance of the modified combisystem was compared to that of the initial combisystem having the boiler replaced by an electric instant heater controlled in the same way as the boiler (Figure 4). The heater turns on when temperature at the bottom of the auxiliary heated volume drops down to 48 °C and turns off when it reaches 56 °C. In the modified combisystem, the electric instant heaters in the tap water preparation and space heating loops have set temperatures of 54 °C and 48 °C, respectively. It should be noticed that the maximal heating rate of the electric heater in the tap water preparation loop was increased to 37 kW in order to fully meet the consumption demand. Both systems have stratification devices built into return flows of the tap water and space heating loops.

3. Results and discussion

3.1. Potential of the fluid mass flow optimization

The dynamic optimization of the fluid mass flow in the collector and storage loops was carried out by the binary (n-ary) search algorithm programmed in GenOpt (Generic optimization software). It is not as reliable in finding the global optimum as, for example, the genetic algorithm, but it is much faster and is believed to be an appropriate choice for the investigated case.

The results show that the extended fractional savings of the combisystem with hourly optimized varying fluid mass flow, defined as

$$F_{\mathrm{save,ext}} = \left(1 - \frac{E_{\mathrm{aux}}}{E_{\mathrm{ref}}}\right) \cdot 100\% \qquad (3)$$

are only 0.3 percent points larger than that of the reference combisystem (Figure 1) with a constant specific mass flow rate of 10 l/hm^2 (35.92% versus 35.59%). It should be noted, however, that for the reference combisystem operated with high flow (constant specific mass flow rate of 30 l/hm^2), the $F_{\text{save, ext}}$ equals 34.49%. Thus, for this particular system, one could not expect much optimization potential by dynamically adjusting only the mass flow rate.

3.2. Boiler control optimization potential

The reference combisystem (Figure 4) and the modified combisystem with electric instant heaters built into domestic water preparation and space heating loops (Figure 3) were simulated in TRNSYS software. The results in Table 1 show the auxiliary energy Q_{aux} and thermal fractional savings defined as

$$F_{\text{save,therm}} = \left(1 - \frac{Q_{\text{aux}}}{Q_{\text{ref}}}\right) \cdot 100\% \qquad (4)$$

for both of the investigated combisystems.

It is easily seen that the combisystem with electrical instant heaters in tap water and space heating loops needs around 7% less auxiliary energy for covering the hot water demand than the reference combisystem. In terms of the thermal fractional savings, an improvement of about 4.4 percent points could be reached. However, it must be noted that the maximal heating rate of the instant electrical heater in the tap water preparation loop is more than twice as large as that of the heater heating up the auxiliary volume in the reference system. Thus, the higher investment costs must be taken into account.

Table 1. Optimization potential of boiler control settings.
Tablica 1. Optimizacijski potencijal postavki kontrole spremnika.

	Auxiliary energy Q_{aux} in kWh	Thermal fractional savings, $F_{\text{save, therm}}$ in %
1. Reference system, Fig. 4	7107	37.0
2. Modified system, Fig. 3	6615	41.4

4. Conclusion

Before improving the control settings of solar heating systems with the help of sophisticated predictive algorithms, it is reasonable first to estimate the theoretical potential of these improvements and then to decide if they are worth implementing or not. In this paper, an approach is proposed which enables estimation of the theoretical potential of the dynamic control settings optimization for solar heating combisystems.

Application of this approach to optimization of the fluid mass flow in the collector and store loops of a solar combisystem on an hourly basis shows only 0.3 percent points of theoretically possible improvement in terms of the extended fractional savings $F_{\text{save, ext}}$. On the other hand, optimization of the control settings of the auxiliary heater is shown to have significantly more potential, but the investment costs for a more powerful boiler needed in this case, will be higher.

5. References

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