THEORETICAL INVESTIGATION ON A CONTROL - BASED APPROACH TO AVOID STAGNATION OF SOLAR HEATING SYSTEMS

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1. Introduction

During the periods of high sun insolation and minimal hot water consumption is the potential that a solar heating system goes into stagnation: the thermal store is full of hot water and the exceed heat cannot be removed from the collector any more. If exposed to high temperatures, the heat transfer fluid in the collector loop may rapidly degrade and excessive pressure may be produced that may damage the solar system components. The stagnation problem is even more harmful in climates with potential freezing periods where the propylene-glycol/water mixtures are typically used as the working fluid in the collector loop. Such mixtures are subject to deterioration at temperatures above 120°C and may become corrosive, resulting in damages to the solar system components.

It is a common practice to shut down the pump in the collector loop when the temperature in the thermal store is too high. This helps to prevent damage of the store but accelerates the degradation of the working fluid in the collector loop.

Sometimes stagnation can also happen on the sunny days in spring and fall if the mass flow in the collector loop is designed to be too low.

There are a plenty of approaches how to minimize the stagnation time of the solar heating systems. Most of them fall in one of the following three categories, see (Morhart, 2010):

- stagnation-proof system concepts (drain-back concept, water as a working fluid, heat-pipe collectors)
- control strategies (switching mode for solar pump control, night time cooling)
- stagnation cooler (passive and active cooling, heat transfer to swimming pool or ground)

In this study a control-based approach is presented and theoretically investigated in application to a solar combisystem, but the results can be applied to other solar heating systems as well.

2. A control-based approach

2.1. Description of the basic idea

A simple requirement must be fulfilled on a daily basis to prevent stagnation of a solar heating system: the energy delivered by the collector must fit into the store. As the stores are usually well-insulated, even for a large specific store volume (large ratio between store volume and collector area) the stagnation happens after several sunny days in a row with minimal heat consumption.

The control-based approach to avoid stagnation proposed in this paper starts with an attempt to minimize the energy produced by the collector during the day, that is, to get as little energy into the store as possible and thus have more space available for another hot day. In order to achieve this, the performance of the thermal collector should be lowered what happens, for example, when it is operated at high mean fluid temperatures. The fluid temperatures should be as high as possible, but still not damage any of the components in the solar heating system, including the heat carrier.

In the Figure 1, the mean fluid temperature T_{fluid} of the collector is shown for the two control strategies, the conventional ΔT strategy (dashed line) and the proposed anti-stagnation (constant 90°C) strategy (solid line).

The triangular dashed area built by these two lines gives a rough estimation of the potential of inefficient collector operation. The larger this area is, the less energy is produced by the collector comparing with the ΔT control strategy. It is also worth to mention that the quantity of energy produced by the collector when using the proposed anti-stagnation control strategy is constant and it does not depend on either the store size or its initial temperature.

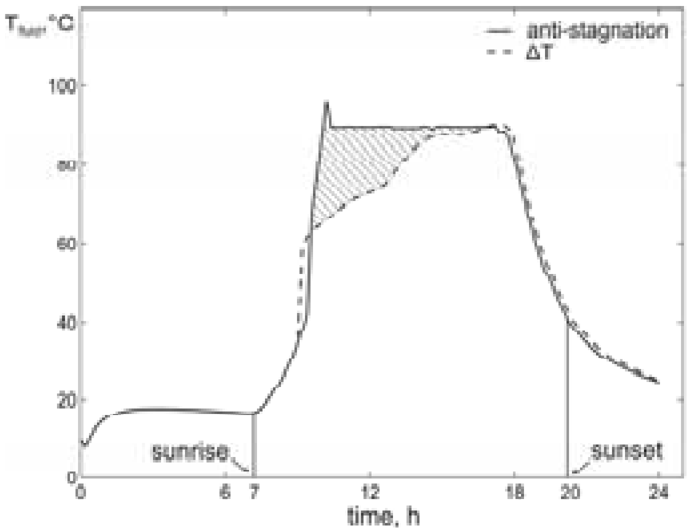

Fig. 1: Collector mean fluid temperature T_{fluid} for anti-stagnation and conventional control strategies

As it was already shown in (Scheuren, 2008), the inefficient collector operation alone is usually not enough to avoid the stagnation. The stagnation may still happen a few hours later and can then be even more dangerous due to higher irradiances. Thus, sufficient store space is needed for the incoming energy and it could be provided, for example, by a night cooling of the store. During the night, the collector is used as a heat sink. Hot water from the store is cooled down through the collector as the ambient temperature is much lower than the temperature in the store. The heat loss coefficient of the collector is a crucial factor for the performance of the night cooling and should be large enough. As shown below, the night cooling makes sense only for the solar thermal systems with not too good insulated flat plate collectors.

2.2. Suitable hydraulics

The proposed control-based approach of an inefficient collector operation coupled with the night cooling of the store can be directly applied to the solar heating systems with an external heat exchanger. The inefficient collector operation is provided by adjusting the fluid mass flows in the collector and store (primary and secondary) loops in an appropriate way.

Application to the heating systems with an internal heat exchanger is more complicated as there is only one mass flow to adjust. Moreover, since the internal heat exchanger is usually placed in the lower one-third of the store, a high efficient night cooling requires additional pump for stirring the store a few times per night and thus making it possible to cool down the whole store.

3. Implementation of the approach

3.1. System description

The proposed control-based strategy is applied in this investigation to the reference solar combisystem of the IEA SHC Task 32 (Heimrath and Haller, 2007) with an external heat exchanger. The hydraulics of the investigated system is shown in the Figure 2. The system has 40 m^2 of the flat plate collectors. The 40% propylene-glycol/water mixture is used as the heat transfer fluid in the collector loop. The specific heat transfer coefficient of the collector heat exchanger is set to 125 W/Km^2_{col}. The auxiliary heating volume is 200 l.

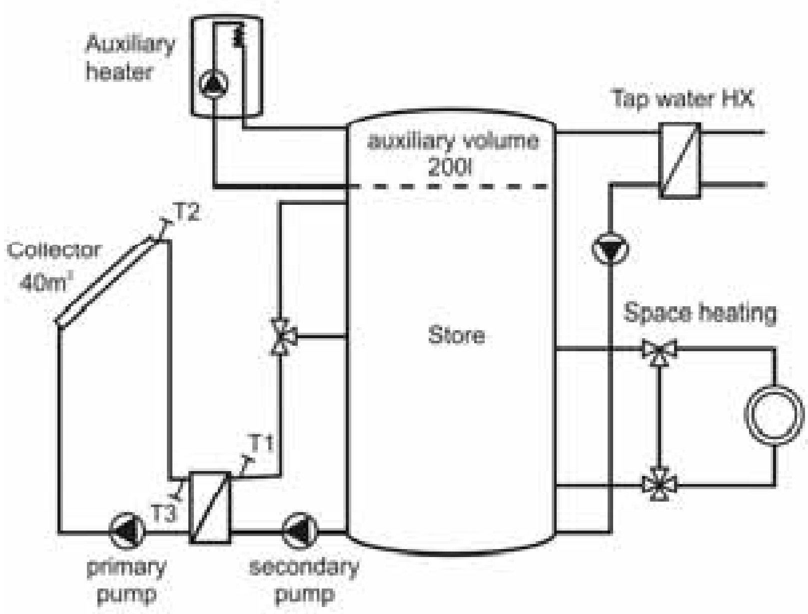

Fig. 2: Hydraulics of the reference solar combisystem of the IEA SHC Task 32

To safely operate the heating system near the stagnation point, the following two requirements are to be met by the anti-stagnation control strategy:

a. relatively high constant specific mass flow at 27 l/m^{2}h in the collector loop
b. the temperature T1 at the secondary HX output to the store does not exceed 95 °C

The first requirement provides that the fluid flows uniformly through the collector and there is no risk of partial stagnation. The second requirement prevents steam delivery to the store.

The pump in the collector loop (primary pump) starts when the temperature T2 at the collector output rises up to 70 °C in the morning and runs with the constant flow rate of 27 l/m^{2}h. The pump in the secondary loop (secondary pump) starts when the temperature T3 at the entrance of the heat exchanger from the collector side reaches 95 °C. It runs with a variable flow rate adjusted to keep the temperature T1 at the heat exchanger output to the store constant at 95 °C. Such control strategy prevents the collector from overheating (the collector output temperature T2 does not exceed 100 °C) and operates the collector at high mean fluid temperature.

The night cooling mode turns on in the evening around sunset. The two pumps run with a constant flow rate 27 l/m^{2}h and cool down the store through the collector as a heat sink. If the following day is expected to be very hot and probably with only little hot water consumption, then the night cooling can be continued till around sunrise. Otherwise, the pumps should be turned off earlier providing that enough energy is left in the store to cover the possible consumption for the following day.

4. Results and discussion

4.1. Modelled weather conditions

The reference solar combisystem was simulated with application of the proposed anti-stagnation control strategy using the TRNSYS 16 software. The extreme weather conditions were especially modeled for three different locations: Madrid (ES), Zurich (CH) and Stockholm (SE). The hottest summer day was picked up from the statistical year for each location and then the system was simulated for such ten days in a row without hot water consumption.

The aim of the simulation was to find minimal V_{store} /A_{col} ratio at which the system still does not go into stagnation. In the Table 1, the climate data and the $V_{store,min}$ /A_{col} are given for the three chosen locations. The results show that it is possible for flat plate collectors to completely avoid stagnation of the solar heating system with relatively low specific store volumes, even for such modeled extreme weather conditions.

Tab. 1: Minimal specific store volume $V_{store,min}$ / A_{col} for 3 climates (Madrid(ES), Zurich(CH) and Stockholm(SE))

Location	Collector slope, °	Irradiation, kWh/m^2day	Ambient temperature, °C, T_{max} ; T_{min}	$\frac{V_{store,min}}{A_{col}}$, l/m^2
ES	35	7.36 (Aug, 18)	35,5 ; 18,5	68
CH	45	7.48 (Aug, 17)	28.7; 15.9	50
SE	50	7,49 (Jul, 20)	28.3; 15.2	42,5

4.2. Dependency of $V_{store,min}$ from U_{col}: method applicability range

To determine the applicability range of the proposed anti-stagnation control strategy to solar heating systems with different collector types, the collector loss coefficient U_{col} was varied in the range from 2.0 W/m^2K (evacuated tube collectors) to 4.5 W/m^2K (poor isolated flat plate collectors). For U_{col} between 2.5 and 2.0 W/m^2K the mass flow rate of the primary pump during the day and that of both pumps in the night was gradually increased up to maximally 70 l/m^2h. The ratio $V_{store,min}$ /A_{col} versus U_{col} is shown in fig. 3 for Zurich (CH). As seen from the figure, the $V_{store,min}$ /A_{col} grows exponentially with U_{col} decreasing, what means that the applicability of the proposed anti-stagnation is restricted to the flat plate collectors with U_{col} not smaller than 3.0 W/m^2K. The evacuated tube collectors and well-insulated, e.g. double glazed, flat plate collectors have good efficiency at around 90 °C mean fluid temperature during the day. Therefore, their heat losses are too low to sufficiently cool down the store at night.

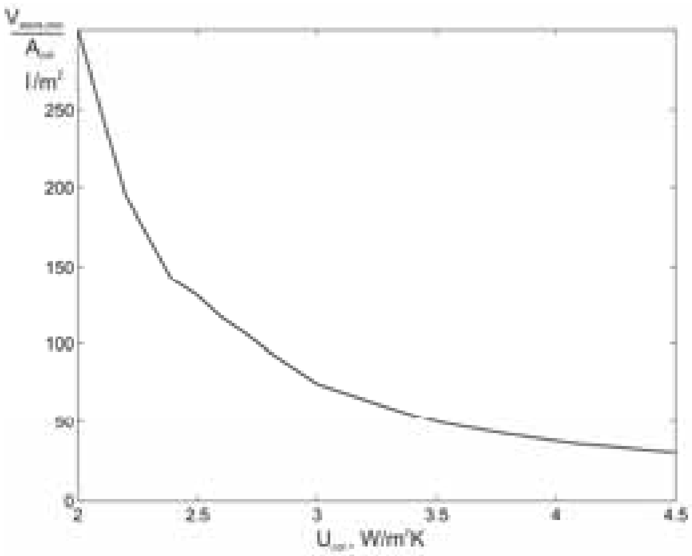

Fig. 3: Minimal specific store volume $V_{store,min}$ /A_{col} versus collector thermal losses U_{col}

4.3. Influence of the weather conditions on $V_{store,min}$ /A_{col}.

It is obvious that changes of weather conditions have influence on the minimal specific store volume. To estimate this influence, the variations of the global radiation H_t, the ambient day and night temperatures, ($T_{amb,day}$ and $T_{amb,night}$, respectively) were carried out for the modeled weather conditions in Madrid (ES). The Figure 4 shows nearly linear dependence of the $V_{store,min}$ /A_{col} from the radiation H_t. A 5% change of the radiation leads to approximately 20% change of the minimal specific store volume.

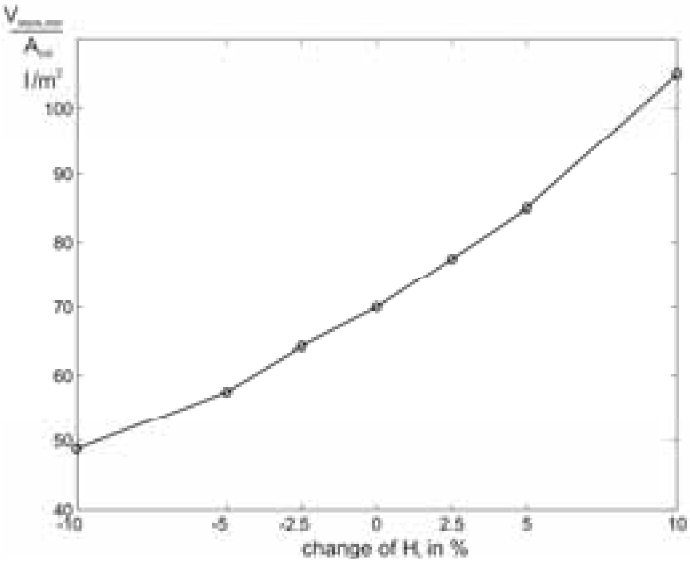

Fig. 4: Influence of global radiation H_t on minimal specific store volume $V_{store,min}/A_{col}$. ($U_{col} = 3.5\ W/m^2K$, $U_{store} = 5\ W/m^2K$)

To investigate the variation of the ambient day and night temperatures ($T_{amb,day}$ and $T_{amb,night}$), the real ambient temperature was approximated by the sine curve. The modeled curve was varied in four different ways. First, day and night temperatures were changed independently, to show the influence of the ambient temperature on the inefficient collector operation and the night cooling in separate. In two other variations the temperatures were changed simultaneously either in one direction (the sine curve was shifted up or down increasing or decreasing the average temperature) or in the opposite directions (the sine curve was deformed, contracted or stretched). The latter variation is probably most realistic. It models the ambient temperature for the climate types starting with the maritime-like climate (relatively small difference between day and night temperatures) and ending by the continental one (hot day and quite cool night).

The Figure 5 shows the results of all four variations of ambient temperature. As it was expected the shifting of the whole ambient temperature curve has the largest impact on the minimal specific store volume (solid line in Figure 5). Variation of only day temperature has approximately the same influence as that of the night temperature (dash-dotted and dotted lines, respectively). The least influential is the last variation that preserves the average temperature (dashed line).

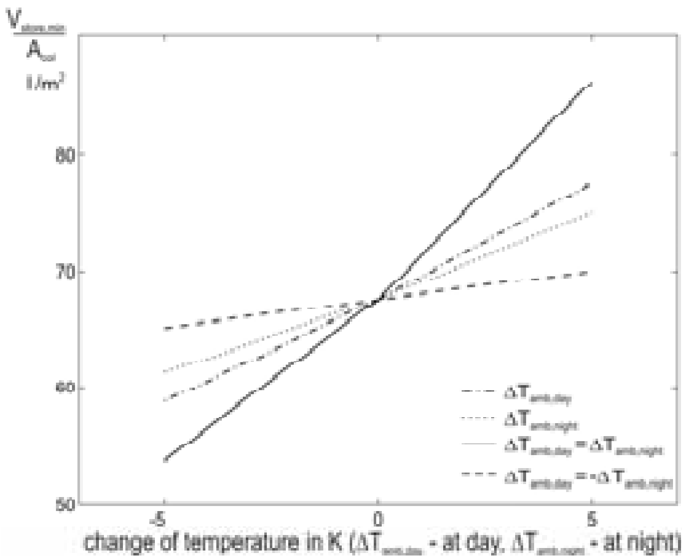

Fig. 5: Influence of ambient day and night temperatures on minimal specific store volume $V_{store,min}/A_{col}$

4.4. Influence of the duration of night cooling period on $V_{store,min}$

The duration of the night cooling period is another important factor for the proposed anti-stagnation strategy. In principle, the night cooling period can be as long as possible if no consumption is expected during the following day, starting in the early evening, when the sunbeams are parallel to the collector, and ending in the later morning when the rising sun comes on the collector again. For example, for the chosen Madrid weather condition the maximum night cooling period is 14.8 hours. But if the hot water demand, larger than the auxiliary volume in the store, is expected on the next day, especially in the early morning, the night cooling must be stopped earlier in the morning or started later in the evening, thus, providing that enough energy is left in the store. The similar is correct if the weather is expected not to be that sunny on the following day. The power consumed by the pumps could be then saved by making the night cooling period shorter.

In the Figure 6 the variations of the night cooling starting and ending times are presented for the modeled Madrid weather conditions and without hot water demand. It is easily seen that the night cooling in the morning saves much more storage space than that in the evening does. In order to save electricity it is better to start the night cooling as late in the evening as possible and to finish it just before the sun comes on the collector in the morning. The lower ambient temperature in the morning lead to a more efficient night cooling.

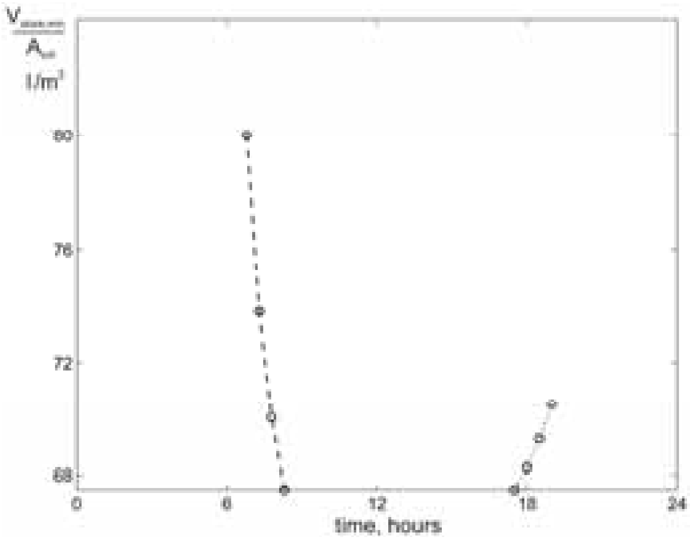

Fig. 6: Influence of duration of night cooling period on minimal specific store volume $V_{store,min}$ /A_{col}

4.5. Electricity consumption of the pumps (night cooling)

In comparison with the usual ΔT control strategy, the proposed anti-stagnation strategy has larger power consumption of the pumps due to the night cooling of the store. For the hottest day in Madrid (ES) the collector and store pump will consume 2.14 kWh and 0.71 kWh per night, respectively. During the night cooling the mass flows and thus the power consumption can be lowered by 50% resulting in only 10% increase of the minimal specific store volume. The pump power consumption during a day can be hardly compared with the usual ΔT control strategy as the solar heating system controlled by ΔT strategy leads early to stagnation. If there were quite large hot water consumption and the ΔT strategy hold a day without stagnation, then the power consumption by the collector pumps would be almost equal at 1.22 kWh/day for both strategies and the consumption by the store pumps would be 0.40 kWh for the ΔT strategy and 0.15 kWh for the anti-stagnation strategy. This difference is explained by significantly lower mass flow in the store loop during a day for the anti-stagnation strategy.

4.6. Discussion questions

An important question to answer before the practical implementation of the proposed anti-stagnation control strategy is when to use this strategy and how to couple it with the usual ΔT control strategy. In the case when the house owners go on vacation for a couple of weeks in the summer it could be switched on manually (the so-called vacation modus of the controller). The automatic switching between the control strategies or automatic adjustment of the duration of night cooling period for the anti-stagnation strategy requires rough prediction of the weather and consumption distribution on the following day. In other words, the controller should roughly know how much energy will come into the store next day, what part of it will be used and when the consumption will take place. The weather conditions could be approximately estimated as average worst case conditions for the chosen location and season. The more precise weather forecast for the following day can be provided online by the nearby meteorological station. This feature must be programmed in the controller and the data transmission line must be very reliable. The hot water consumption should be predicted or set fixed by the consumer. Basing on these two predicted values, the weather conditions and consumption, it is possible to control the heating system in such a way that no stagnation will take place in the summer and the hot water demand will be covered to the 100 per cent.

5. Conclusions

In this paper an anti-stagnation control strategy for solar heating systems was proposed and theoretically investigated. The minimal specific storage volume needed to completely avoid stagnation by the solar heating system without consumption, was calculated for specially modeled extreme weather conditions in three locations. The influence of irradiation and ambient temperature was estimated. It was shown that the proposed anti-stagnation control strategy can only be applied to the heating systems with moderate-insulated flat plate collectors.

6. References

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Scheuren, J., 2008. Untersuchungen zum Stagnationsverhalten solarthermischer Kollektorfelder (Investigation of stagnation behavior of solar thermal collector fields). Phd-Thesis, Kassel University, Germany.

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Appendix: NOMENCLATURE

Quantity	Symbol	Unit
Collector area	A_{col}	m^2
Store volume	V_{store}	m^3
Minimal store volume	$V_{store,min}$	m^3
Collector thermal loss coefficient	U_{col}	W/m^2K
Global radiation	H_t	kWh/m^2day
Mean fluid temperature in collector	T_{fluid}	°C
Day ambient temperature	$T_{amb,day}$	°C
Night ambient temperature	$T_{amb,night}$	°C