Direct solar thermal systems with (thermosiphon) circulation frost protection using a Thermo-Differential Valve

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Abstract

This research involves a direct solar (combi-)system for use in cool climates, based on vacuum-tube collectors, that uses night-circulation for frost protection, which doesn't just rely on pumped circulation, but also provides frost protection through thermosiphon circulation as a back-up in case of power/control failures. Furthermore, this direct solar system does not use a collector sensor or storage tank sensor, but instead has both the temperature sensors integrated into the pumping station. These features are achieved by using a Thermo-Differential Valve (TDV), which is installed on the storage tank at the solar inlet, and which only opens when the solar supply temperature is higher than the storage tank temperature and bypasses the storage tank when the supply temperature is lower than the storage tank temperature. Novel strategies for operating the circulating pump have been developed and tested, that are designed to optimize the efficiency of the system using the TDV in low-intensity conditions, such as overcast conditions, and to create a system that can focus on generating high temperature heat, without significantly compromising efficiency, by using multiple collector passes to achieve the desired temperature, before directing the flow into the storage tank.

Keywords: Thermo-Differential Valve, Direct Solar System, Solar frost protection

1. Introduction

The use of the self-actuating Thermo-Differential Valve (TDV) has been previously reported for the application of promoting stratification in solar combi systems[1], where the TDV is used to direct the solar supply flow to the appropriate height in a (combi-)storage tank for solar systems. In this work the same valve is used, except that the valve is used to bypass the storage tank completely). The use of the TDV isolates the solar circuit from the storage tank when the temperature of the solar supply flow is lower than the temperature inside the storage tank (at the height where the TDV is installed) and allows circulation in the solar circuit without potential heat loss from the storage tank. This feature is used to position all the sensors for the controller inside the solar pumping station, using circulation to detect the temperature of the collector and the storage tank temperature. This periodic circulation will be referred to as 'sampling' in this article, and the waiting period between sampling is referred to as the 'rest'. The system switches to continuous pumping if at the end of the sampling period there is a significant temperature difference between the supply and return temperature (indicating that the TDV is in the open position), or if a maximum threshold temperature is reached during sampling. In continuous pumping operation, it is expected that in many circumstances the temperature increase in the collector, at minimum pumping speed, will not be sufficient to achieve a temperature high enough for the TDV to open, in which case multiple passed through the solar circuit will be made to achieve the necessary temperature for the TDV to open. At night, if the temperature in the solar circuit drops below a lower limit, a thermostatic frost protection valve opens, allowing a small amount of heat from the tank to flow into the solar circuit, just enough to maintain it at the preset minimum temperature, preventing frost damage. When there is a power failure and the periodic pumped circulation no longer takes place, thermosiphon flow starts circulating when the collector is cold and at risk of freezing (with the collector positioned at the highest point in the solar circuit), and in this case also the thermostatic frost protection valve adds heat to the solar circuit to maintain the preset minimum temperature.

In the research presented in this paper, supported by the EU's OP-Zuid program for regional development, the system arrangement shown in Figure 1 was used, which has the TDV positioned in the center of the storage tank, and the thermostatic frost protection valve connected to the upper section of the storage tank.

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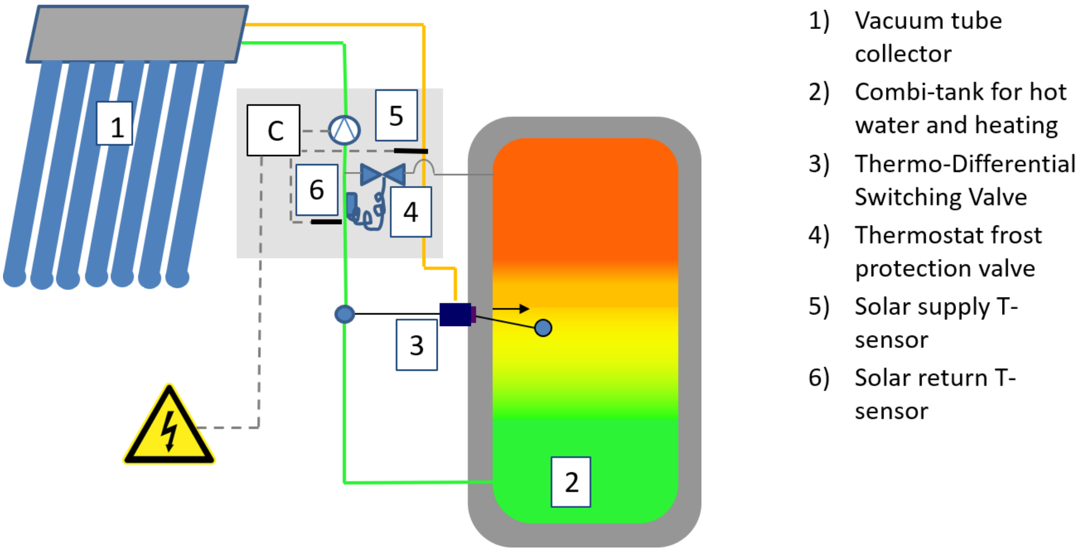

Fig. 1: System arrangement, only solar circuit depicted

The operation of the system in sampling mode, in low intensity conditions, is explained graphically in Figure 2.

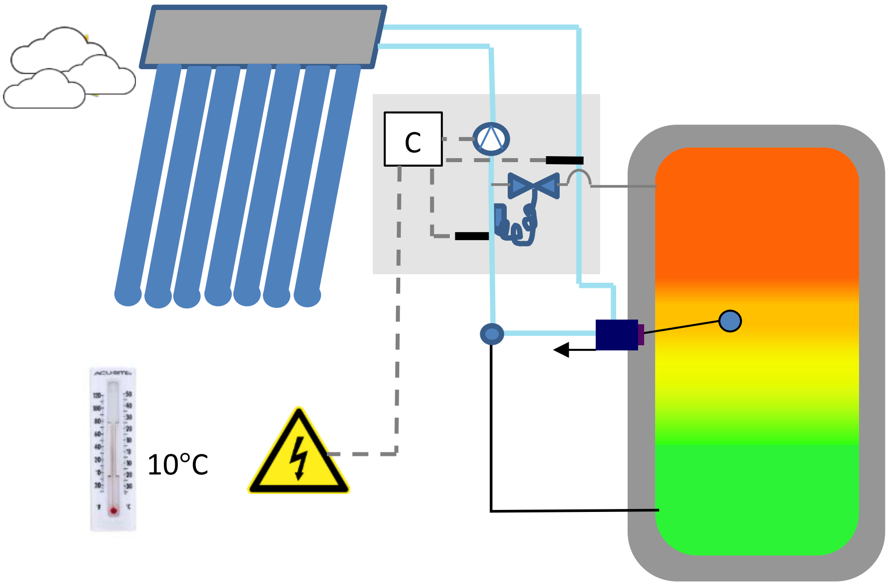

Fig. 2: Operation of the system arrangement in sampling mode, in low intensity conditions

In Figure 2 the solar collector does not generate enough heat for the TDV to switch to open position during sampling, so the TDV remains in the bypass position, and the system returns to the rest state after sampling

The expected operation of the system in continuous mode, in high intensity conditions, is depicted in Figure 3.

In the high intensity conditions of Figure 3, the vacuum tube collector can reach the high temperature of the center of the storage tank, and the controller switches to continuous mode. The system can achieve the necessary increase in temperature in one pass through the collector (as depicted), in which case the TDV stays in the open position, or in multiple passes, in which case the TDV switched between bypass and open position. The controller allows a post-run period in the continuous mode before switching back to sampling mode to allow the multiple passes.

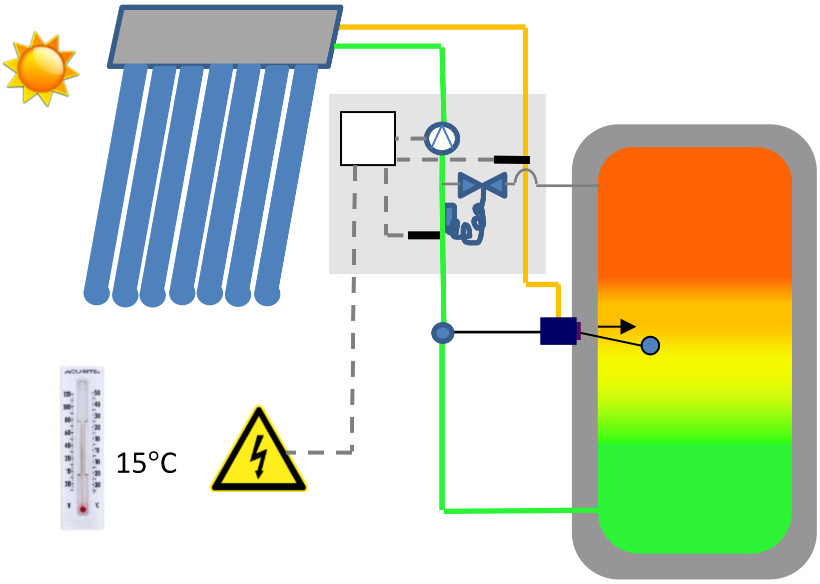

Fig. 3: Operation of the system in continuous mode, in high intensity conditions

The expected operation of the system during night-time is depicted in Figure 4.

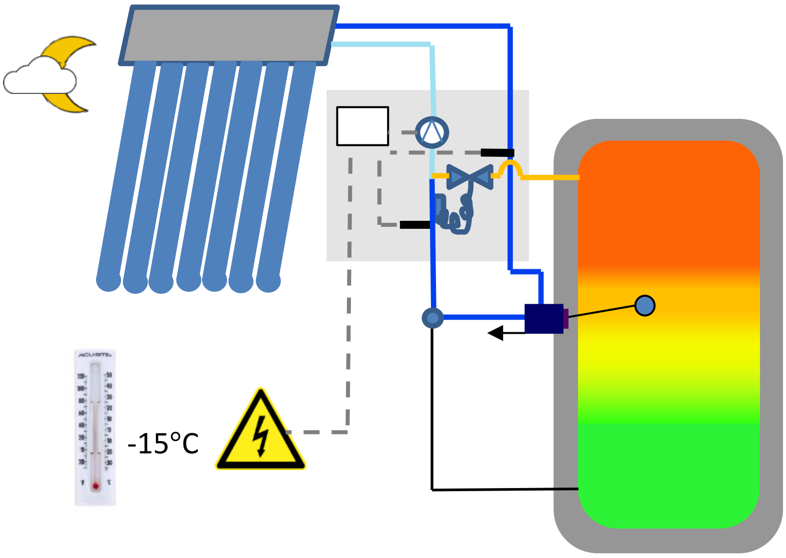

Fig. 4: Operation of the system in night-time mode, with periodic pumped circulation

At night the periodic circulation of the sampling mode continues. When the temperature in the circuit drops below a preset value, the frost protection valve opens and allows heat into the solar circuit, to prevent frost damage to the collector and/or the tubing.

The expected operation of the system during night-time, in case of a power black-out, is depicted in Figure 5.

Figure 5 depicts a power blackout during freezing conditions, in which case pumped circulation stops, and thermosiphon flow is allowed to take place, to prevent frost damage also during power outages (or pump/controller failure).

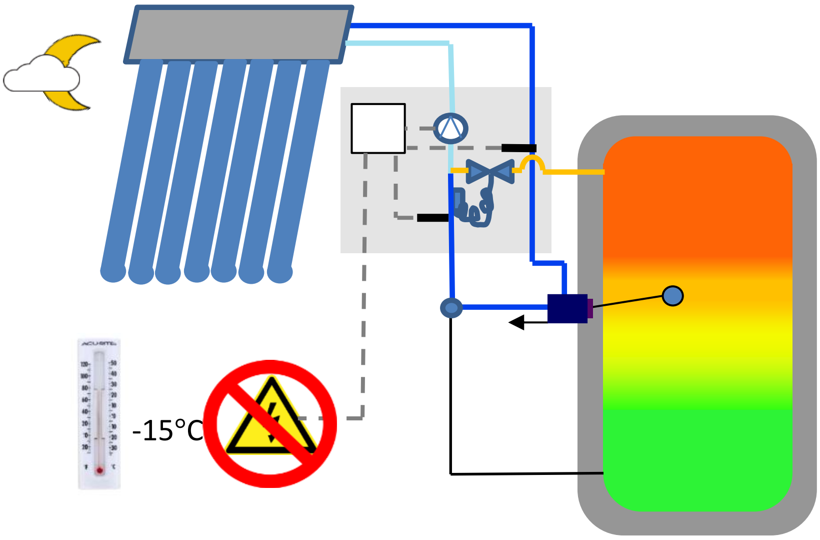

Fig. 5: Operation of the system during night-time, during a power black-out

2. Experimental

To test and further develop the direct solar system, a prototype was built at our location in Veldhoven, the Netherlands. Some basic details about this prototype are given in table 1:

Tab. 1: Selected details of direct solar system prototype

Collector array:	2 x TWL HLK-30, vacuum tube (Sydney), heat pipe
Orientation:	South, 45° inclination
Collector array area:	Gross: 9.98 m2, Aperture: 5.56 m2
Collector parameters:	$\eta_0 = 0.761$, $a_1 = 2.299$, $a_2 = 0.010$
Storage tank:	900 litre steel buffer-tank, height: 208 cm, diameter 79 cm
Tank connections:	TDV: 0.5 rel. height, Thermostat valve: 0.8 rel. height, return: 0 rel. height
Solar tubing:	2 x 15 meter DN16 corrugated stainless steel

The circulation pump used in the solar circuit is a Wilo Yonos Para ST15.0/7.0 PWM controlled pump, controlled by an Arduino-based controller, that uses the solar supply temperature and return temperature (measured close to the storage tank) in various algorithms to determine the PWM signal for the circulation pump. To study the thermosiphon behavior in different and realistic conditions, negative loops were introduced into the tubing (see also Figure 6). The first negative loop is on the flat roof, where the tubing runs along the roof floor, before rising 25 cm into the roof passage (also, the tubing on the roof was installed symmetrically – 2 x 2.5 meter of outside tubing – to create a worst-case-scenario for thermosiphon flow starting up), the second negative loop is indoors, and is variable, dipping up to 1 meter. The top of the collector is positioned 9.5 meters above bottom of the tank.

Fig. 6: Images of direct solar system with TDBV; collector array (left), adjustable negative loop (middle) and the storage tank (right) with TDV installed at 0.5 relative height, and thermostat valve at 0.8 relative height

The system is monitored using 18 T-type thermocouple temperature sensors connected to a datalogger, the temperatures that are measured and used in the results are:

Temperature measurement position	Line type/color used for graphs
Solar supply temperature, measured just before TDV	Bold line, Red
Solar return temperature, measured just after pump	Bold line, Blue
Collector outlet temperature	Fine line, Red
Collector inlet temperature	Fine line, blue
Temperature inside vacuum tube	Bold line, Green
Temperature of tubing just before thermostat frost protection valve	Long-dash line, Pink
Temperature of storage tank at frost protection valve connection	Short-dash, Grey
Temperature of storage tank at TDV	Long-dash, Grey
Outside ambient temperature	Fine line, Purple
Inside ambient temperature at storage tank	Fine-dash, Brown

Tab. 2: Details of temperature measurement positions, based on pumped flow direction

3. Results

To analyse the frost protection behavior, a measurement was performed on a cold night, where the power supply was interrupted for several hours, test the thermosiphon behavior. The results are presented in Figure 7.

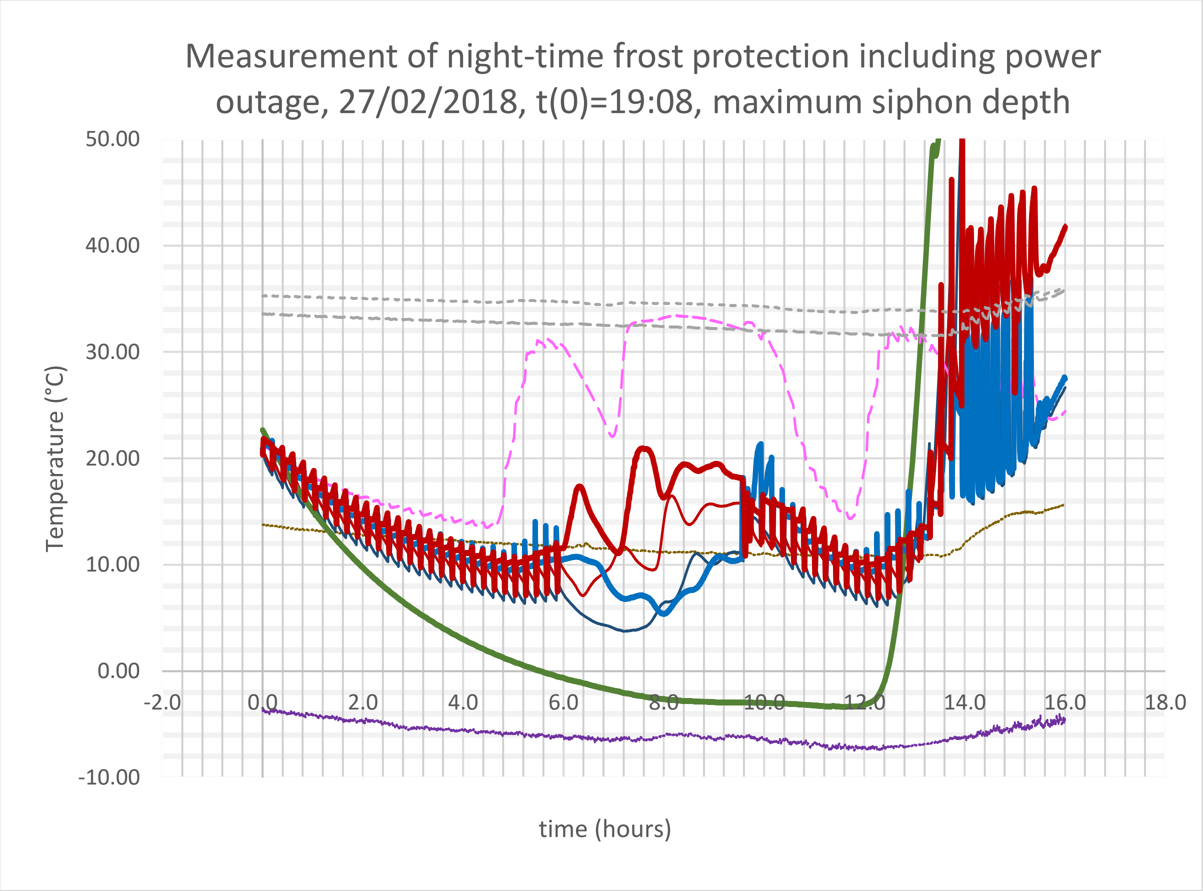

Fig. 7: Results obtained from the prototype solar system from 7 p.m. February 27th 2018 to 11 a.m. February 28th

The measurement was performed with a maximum dip in the negative loop (maximum siphon depth). Going through the results presented in Figure 7 chronologically; the system is in regular sampling mode in the evening, with a rest period of 10 minutes. As the solar circuit cools down, after roughly 4.5 hours the temperature reaches the preset temperature at which the frost protection valve starts opening, being 10°C, which is evident from the sudden increase in the temperature of the piping before the frost protection valve, and from the gradual increase of the solar circuit supply and return temperature after the 4.5 hours point. At 6.0 hours into the measurement, the power is switched off for 3.5 hours, to simulate a black-out. For the first 25 minutes after the power is switched off, there is no thermosiphon flow, which is evident from both the collector inlet and outlet temperature decreasing at the same rate. After 25 minutes thermosiphon flow starts up, noticeable from the sudden decreasing of the solar supply temperature and increasing of the collector outlet temperature, which is taking place in the opposite direction of the pumped flow direction. At this point the flow through the frost protection valve is almost zero; it opened during the pumped circulation, but only slightly, just enough to allow enough flow through under pumped conditions, but with the very low pressure-differences in the case of thermosiphon flow this slight opening does not let through a significant flow. The thermosiphon flow causes the return temperature of the solar circuit to start decreasing at around t=7 hrs, and this decrease leads to the further opening of the frost protection valve at t=7.5 hrs, which causes the thermosiphon flow to accelerate, and which also causes the collector inlet temperature to start increasing. The observed minimum temperature in the collector is 4°C, which is still safely above frost damage risk The thermosiphon stabilizes around t=8.5-9 hrs, with a temperature difference of around 10 K between supply and return temperatures. At t=9.5 hrs the pumped sampling starts again as power is restored, and this leads to an increase in supply and return temperatures, as the frost protection valve has opened to a relatively large extent during thermosiphoning. This increase leads to the frost protection valve closing, which causes temperatures in the solar circuit to cool down again, until t=11.7 hrs, when the frost protection valve opens again, as temperatures in the solar circuit have fallen back to the 10°C preset limit again. From t=12 hrs the sun comes up, as can be observed from the sudden increase of the measured temperature inside the vacuum tube. From just before t=14 hrs onwards heat is collected by the storage tank, first while in sampling mode, in which case the TDV switches to open and back to bypass within the sampling period, and from t=15.5 hrs in continuous circulation mode.

4. Conclusions & Discussion

From the results it appears that with the frost protection valve set to start dosing heat from the tank at 10°C, the collector temperature stays above 6°C, with an ambient temperature of -5°C and a rest period of 10 minutes between sampling. With an assumed scenario of ambient temperatures of -20°C, the heat loss of the collector during the rest period will be twice a large, so the collector can be expected to cool down to 2°C during the rest period. It also appears that the frost protection valve only needs to open slightly during the tested conditions, even with the top of tank at very moderate temperature levels of around 35°C, so it can be concluded that providing sufficient heat for frost protection is not a problem using this configuration.

From the results with the power switched off, it appears the critical aspect of the thermosiphon frost protection circulation is the start-up. Once the thermosiphon has established and stabilized, it achieves sufficient flow to maintain the collector at 10°C, far above critical levels, with a temperature difference between supply and return of 10 K. Since this temperature difference could rise a lot further if necessary, and the collector temperature is allowed to fall well below 10°C it can be concluded that the thermosiphon can provide enough heat also in conditions of ambient temperatures of -20°C.

One of the important questions that remain is whether the thermosiphon will always start up quickly enough to prevent freezing before sufficient flow is established. The start-up of the thermosiphon depends, to a great extent, on the level of symmetry in the temperature profiles of the supply and return lines. During the sampling in this experiment the circuit fluid was circulated exactly once around, and after sampling it was observed that temperature differences between the supply and return tubing were small, which presents the worse case for the thermosiphon starting up. Creating a situation where there is an a-symmetry between supply and return tubing during the rest period will likely improve the start-up behavior of the thermosiphon flow.

References:

1) Van Ruth, N.J.L., 2016. New Type of Valve for Solar Thermal Storage Tank Stratification. Energy Procedia https://www.sciencedirect.com/science/article/pii/S1876610216303101