Stagnation behaviour of solar thermal systems

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Solar Combisystems

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by

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A technical report of Subtask A

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Contents

1 Introduction

Due to the large collector areas and small summertime loads, combisystems are more frequently exposed to an excess in solar heat production than are solar water heaters. Adequate protection against high temperatures in the system is therefore an important issue to make sure that these systems operate properly in the long term, with minimum maintenance. The behaviour of combisystems at stagnation has to be considered critically.

In the summer period, solar space heating systems often reach stagnation conditions since on a clear day the storage tank easily reaches the maximum temperature (e.g., 95 °C). In this case, the collector-loop pump is switched off by the controller. Then, the temperature of the absorber rises rapidly and reaches the so-called stagnation temperature, which is from 180 to 210 °C for selective coated absorbers of flat-plate collectors and from 220 to 300 °C for vacuum tube collectors.

Often evaporation of the collector fluid occurs even with flat-plate collectors (selective coated absorbers) and in collector loops with 6 bar maximum pressure. Usual design rules state that the membrane expansion vessel should exceed the volume of the expanded collector fluid plus the volume of the displaced fluid from the absorber. This design practice should prevent the activation of the collector loop safety valve and thus loss of fluid.

Nevertheless, there are sometimes problems with overheating of system components and loss of fluid during summer time:

- High-temperature exposure in parts of the collector loop including some sections in the heat storage room; malfunctions of system components and system leaks can result from this exposure.
- Opening of the collector loop safety valve even though the usual design guidelines have been followed with regard to size of the expansion vessel and pressure conditions.
- Condensation pressure shocks in the collector loop and in secondary circuits heated up by this loop.

In the framework of a European Craft project and an Austrian national project (Fink, et al., 2001) the stagnation behaviour of combisystems was investigated. In the following the results and recommendations of these projects are discussed.

2 Processes encountered during stagnation

The sequence of events during stagnation can be divided into five different phases on the basis of a simplified collector model [2, 7].
Slightly different system behaviour is observed if the arrangement of the check valve in the evaporation process does not allow the expansion vessel to be filled with liquid both from the return as well as from the flow line. The five phases are essentially the same, but with different quantitative aspects.

2.1 Phase 1 – Expansion of liquid.

The collector temperatures rise until the evaporation process begins somewhere in the upper part of the collector array. The increase in the system pressure is small.

2.2 Phase 2 – Pushing the liquid out of the collector

Large amounts of liquid are pushed into the expansion vessel by the formation of saturated steam within the collector. As a result, the system pressure rises rapidly as does the boiling point in the pipe sections filled with saturated steam. Liquid which is almost at the boiling temperature puts a high temperature stress on the system components. This phase lasts for only a few minutes and ends when there is a continuous path for steam from the collector inlet to the outlet. Residual liquid remains in the collector.

2.3 Phase 3 – Emptying of collector by boiling

The residual liquid in the collector evaporates and transports energy very effectively to other system components as steam. These other components are heated to the local boiling temperature by the condensing steam. The local temperature is determined by the system pressure and the local composition of the heat transfer medium. With the system pressures common in combisystems of around 1.5 to 3.5 bar, the boiling temperatures are around 130 °C to a maximum of around 155 °C. The energy transported out of the collector is released to components (connection lines and e. g. a heat exchanger) and ultimately to the environment via the formation of condensate. At the end of phase 3 the steam volume and the system pressure reaches their maximum values.

2.4 Phase 4 – Emptying of collector by superheated steam

The collector becomes increasingly dry and the steam is superheated resulting in a decrease in the effectiveness of energy removal. As a result the steam volume can fall and draw liquid back until the lower connection of the collector is reached despite the fact that solar irradiation continues. The superheating phase can take a few hours on cloudless days and ends when irradiance is on the decline. With collector designs where the fill lines are on top, slow saw-tooth like pressure fluctuations of moderate amplitude can occur.

2.5 Phase 5 – Refilling of collector.

The collector begins to refill when the collector temperature falls below the boiling temperature and condensation begins as a result of a reduction in the solar irradiation.

3 Critical phases

The hot liquid pushed out of the collector in the course of phase 2 can put a critical temperature strain on components other than the collector. The most critical aspect is the heat transport by saturated steam produced in the collector and condensed at high temperatures at all ‘cold’ locations in the loop, with potential degradations of components even though they are located far away from the collector, like e.g. the expansion vessel installed near the heat storage tank.

The course of phases 2 and 3 determines the maximum system temperatures. The liquid remaining at the end of phase 2 determines the length of phase 3. The evaporation of the remaining liquid keeps most of the collector at the boiling temperature with a comparatively high efficiency of energy removal. This leads to a large steam flow rate that reaches a maximum level at the end of phase 3. Once the evaporation of the liquid has been completed the whole collector reaches its maximum stagnation temperature and thus no longer transfers any energy to the remainder of the system (around the middle of phase 4).

The emptying properties of the collector and the collector loop during phase 2 are important in determining the stagnation behaviour of the plant. Figure 8.1 illustrates three different emptying behaviours, from poor to very good. The systems and collectors are the same – with the exception of the emptying behaviour. A high pressure also means that system components will have to bear the strain of the boiling. The stagnation phases are illustrated using a collector which has not been emptied effectively. In this example a pressure of around 3.2 bar corresponds to a steam volume which only encompasses the collector area. In the event of pressures higher than this the steam also reaches more distant parts of the system.

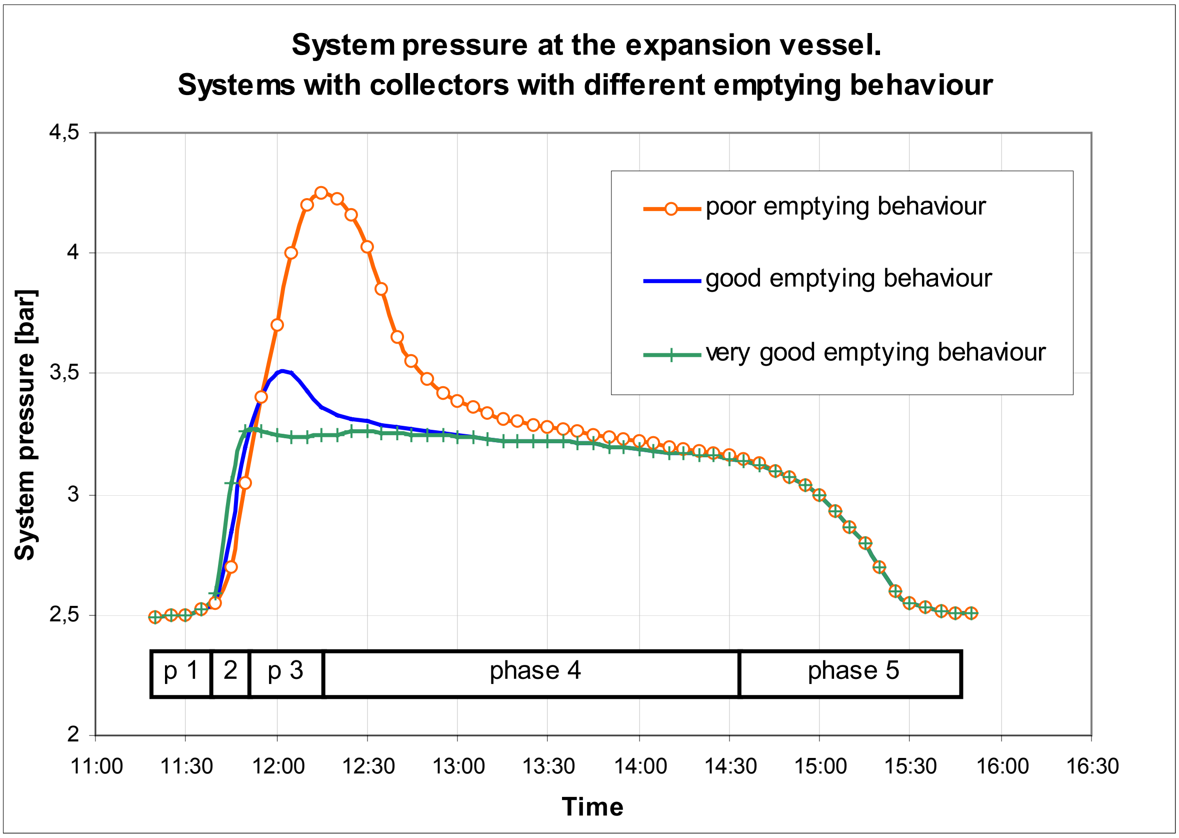

Figure 1: System pressure versus time for three different emptying behaviours.

Figure 2 shows the frequencies of temperatures during a 5-months period measured at different points in a combisystem with a collector which does not empty well. The maximum temperatures of system components in the heating room were around 150°C in this period, around 210°C in the absorber strips and around 170°C in the collector header pipes.

These maximum values lasted for around 26 hours at the measuring point „flow line - basement", and around 10 hours at the measuring point „return line - basement". The formation of steam, which occurs frequently, has an effect even on the secondary side of the heat exchanger („heat exchanger sec. outlet"). The temperature which occurred at the inlet to the expansion vessel stayed above 100 °C for approximately 40 hours and the maximum value was around 150 °C. The maximum temperature of the liquid in the expansion vessel was around 105 °C, whereas the gas volume in the expansion vessel reaches about 45 °C. In this particular combisystem, the high liquid temperatures damaged the membrane of the expansion vessel. This system was successfully improved by measures shown in figure 7.

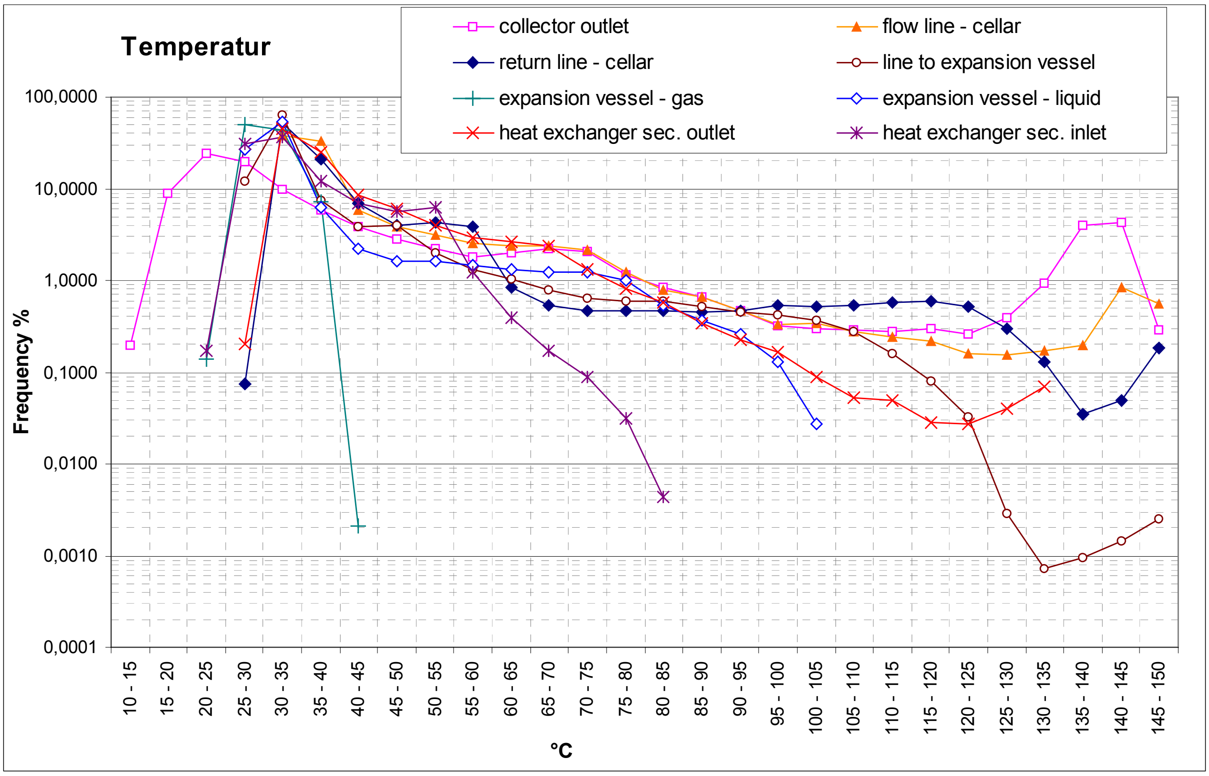

Figure 2: Measured example of frequencies of different system temperatures during a 5-monts period (May to September) of a combisystem with a collector with poor emptying behaviour. A frequency of 1% corresponds to 36.7 h, 0.01% corresponds to 22 min.

These results show clearly that the real temperature loads in commonly available solar systems in the event of stagnation can lie above the limits recommended by the component manufacturers and this can lead in turn to damage to components respectively to a reduction in the service life of the plant and in turn to unsatisfied customers.

4 Emptying behaviour of collectors

The emptying behaviour of collectors determines the frequency, area, magnitude and duration of the maximum temperature of the system and of its components. Collector piping networks should have a good emptying behaviour to avoid stagnation problems. Systems with good emptying behaviour minimise the amount of residual liquid and thus reduce the period of time and extent of the critical stagnation phase 3.

Collector examples with poor emptying behaviour are shown schematically in Figure 3. Arrangements to be avoided are: connection of the return and flow lines at the top of the collector with the absorber pipes laid ‘down and upwards’, horizontal absorber pipes and parallel U-tubes (e. g. vacuum tube collectors) respectively. These configurations do not lead to good emptying behaviour as a result of the liquid trapped in parts of the collector (illustrated in the last schematic) that cannot be expelled in liquid form but rather has to evaporate to be removed. This trapped liquid leads to a large amount of energy which is transported via steam in the event of stagnation throughout the system. The pressure develops in the way shown in Figure 1 which is described as ‘poor emptying behaviour’. In addition the probability of condensation pressure shocks increases [3].

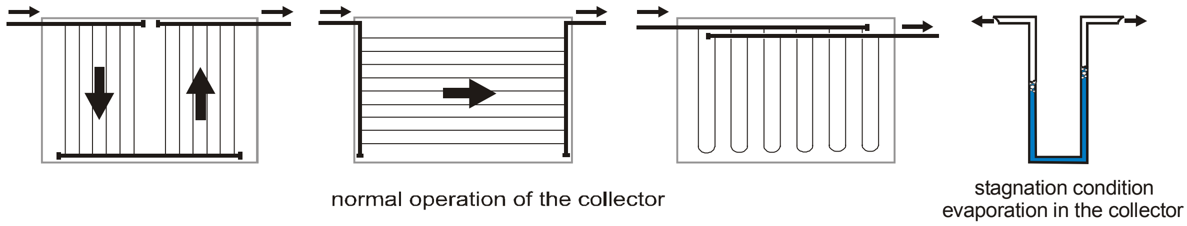

Figure 3: Schematic examples of common collector circuits with poor emptying behaviour (the three schematics on the left illustrate the normal function of the collectors, while the right-hand schematic shows in simplified terms the condition of steam formation in the collector).

The collector circuits shown schematically in Figure 4 provide for a much more favourable emptying behaviour. The return line (and/or flow line) is located at the bottom on the collector. With this or similar arrangements the liquid is driven out of the collector in phase 2. Consequently the duration and extent of the critical stagnation phase 3 is reduced so that the areas with saturated steam only reach to just below the bottom of the collector. These arrangements produce the pressure development described in Figure 1 as very good or good emptying behaviour.

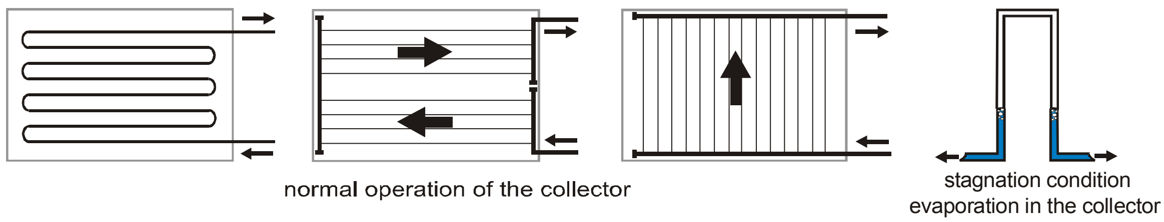

Figure 4: Schematic examples of common collector circuitries with good emptying behaviour (the three schematics on the left illustrate the normal function of the collectors, while the right-hand schematic shows in simplified terms the condition of steam formation in the collector).

5 Emptying behaviour of collector fields

Good emptying behaviour in individual collectors does not guarantee good emptying behaviour of collector fields. The basic principles for individual collectors also have to be observed for collector fields. If the connecting lines of the collectors are not arranged in a favourable manner, good emptying behaviour for a collector can become poor emptying behaviour for a collector field.

In the example shown on the left-hand side of Figure 5, the return line connection is arranged in such a way as to trap liquid. At the end of phase 2 this arrangement leads to one of the two collectors becoming filled with steam as a result of slight individual differences. The resulting steam-liquid circuit, which can last for a long time, supplies liquid to the collector not yet fully emptied by condensing the steam in the condensation stretch of pipe. This process also leads to a greater volume of steam in the remaining system. A simple solution to the problem is to ensure that the system will drain as shown on the right-hand side of Figure 5.

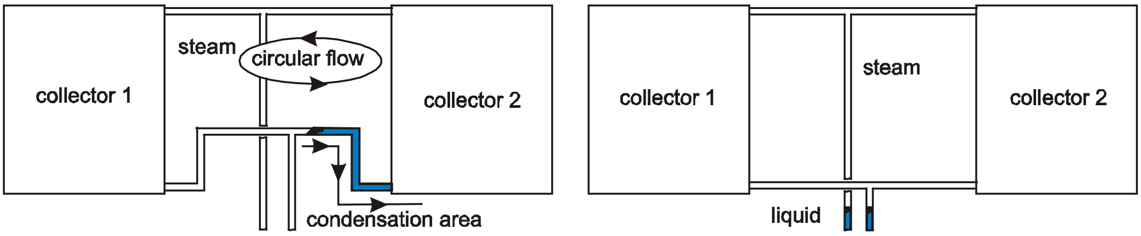

Figure 5: Examples of the interconnection of two collectors which empty well with poor emptying behaviour (left figure) and good emptying behaviour (right figure). The circular flow shown on the left-hand figure supplies liquid for a long period of time which leads to the further formation of steam in one of the collectors.

6 Influence of system hydraulics on the emptying behaviour of collectors

The emptying behaviour of collectors is considerably influenced by the position of the check valve in relation to the expansion vessel. If the arrangement of the components in the return group is as shown in the right-hand side of Figure 6 then emptying during stagnation conditions can only be performed through the collector outlet line (flow line of the system). This arrangement results in a lot of residual liquid in the collector. The resulting large volume of steam generated has only the flow line available for the release of heat so that steam can penetrate very far into the system. The collector inlet line (return line of the system) remains filled with liquid up to the entrance to the collector due to the position of the check valve.

The condition for good emptying behaviour of collectors in the event of stagnation can be achieved by the simple repositioning of the check valve in relation to the expansion vessel as shown in the left-hand side of Figure 6. In this arrangement the contents of the collector in the event of stagnation can be driven into the expansion vessel via both the return and flow lines whereby little residual fluid remains in the collector. In addition the volume of steam flow and the associated energy flow is divided between the two lines.

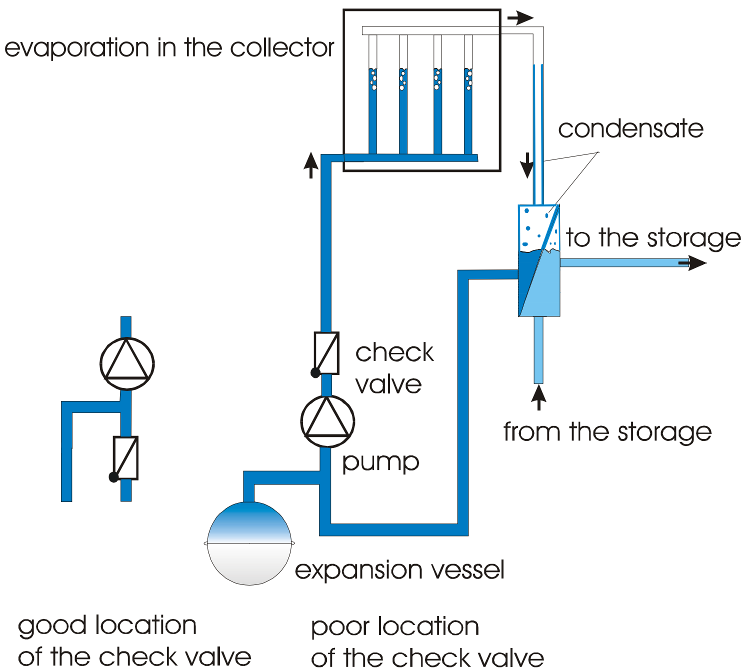

Figure 6: Good and poor arrangement of the components of the primary solar circuit..

7 Measures to improve the stagnation behaviour given an unfavourable emptying behaviour

In the event that unfavourable conditions (e. g. an unfavourable pipe layout as a result of unusual geometric conditions in the building) do not provide an opportunity to obtain optimum emptying behaviour different measures can bring about an improvement in the stagnation behaviour. Details are given in Fink, et al., 2000. These are as follows:

- avoidance of stagnation condition using night cooling
- avoidance of stagnation condition using an air cooler
- active removal of energy transported via the steam in the event of stagnation with
  - a small-volume heat sink with a large surface or
  - the controlled use of the external heat exchanger and the secondary circulating pump.

The last measures only protect system components from high temperature loads, the high temperature loads to the heat transfer medium is not reduced by this technique. With the first, second and last measure supplementary energy has to be used to remove excess energy, thus reducing the overall efficiency of the solar plant.

Examples of the use of a simple small-volume heat sink with a large surface which operates automatically in the case of stagnation and does not use supplementary energy are shown in Figure 7. The heat sink has to be positioned about 2 m or more above the level of the components to be protected (communicating vessels). A simple and inexpensive room heater (copper tube with aluminium fins) is a well-tried solution. A commercially available heat exchanger (18x1 mm tubes with 80x56x0.3 mm Al-sheets spaced at a distance of 5 mm) can dissipate about 750 W/m at the boiling temperature.

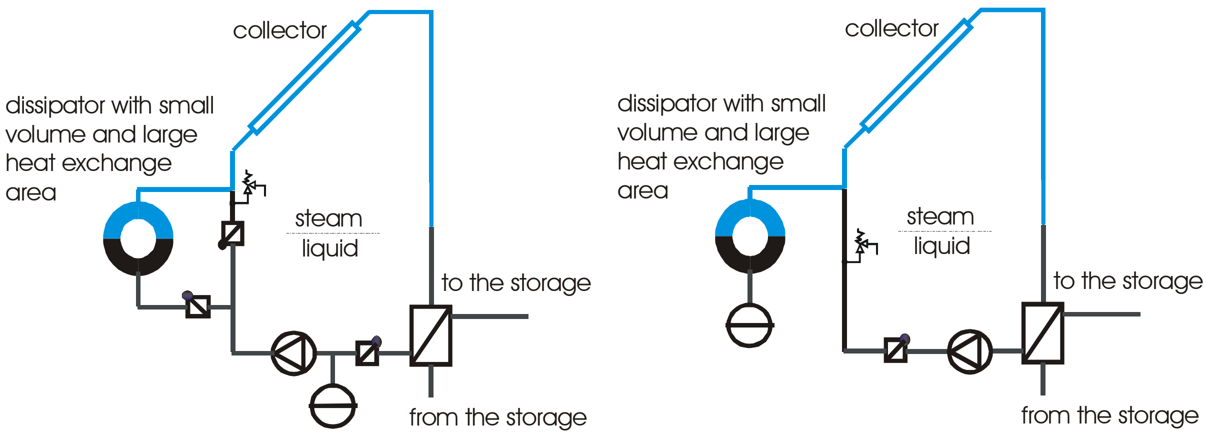

Figure 7: If the emptying behaviour of the collector cannot be improved, a simple automatically controlled air cooler in the primary solar circuit can limit the steam volume.

8 Steam power

Measurements of the maximum steam power emerging from the collector at the end of phase 3 quantified the different emptying behaviour of different collector types [5]: Collectors of the type shown in Figure 4 (i.e., collectors with good emptying behaviour) exhibit short lasting maximum steam power values of around 20 W for each m² of collector area. Collectors of the type shown in Figure 3 (i.e., collectors with poor emptying behaviour) exhibit long-lasting maximum steam power values of up to 120 W for each m² of collector area.

The specific heat loss of common insulated return and flow lines at saturated steam temperature is around 25 W/m. Consequently, in small plants using collectors with good emptying behaviour the steam does not penetrate more than a few meters into the system and thus does not represent a problem. On the other hand collectors with poor emptying behaviour can enter the critical range even with small domestic hot water plants (e. g. 6 m² of collector area) since 20 – 30 m of pipe is necessary to dissipate the steam power. When steam reaches this far into the system temperature-sensitive system components can be affected. In combisystems, which have very large collector areas excess steam problems can be severe.

9 Dimensioning of membrane expansion vessel

The sizing of the membrane expansion vessel is important to ensure that heat transfer fluid is not lost through the pressure relief valve in the event of stagnation conditions. The following suggests a way to calculate the minimum expansion vessel volume for safe operation.

Estimate the maximum steam power depending on the type of emptying behaviour of the collector and the system according to the discussion above. For good emptying collectors/systems an estimate of the steam power is about 50 W/m² whilst for poor emptying collectors/systems an estimate of the steam power is about 120 W/m². These values are on the safe side and with experience with specific systems, these values can be lowered - e.g. increasing the system pressure can, depending on collector types, lower these values [5].

Calculate the energy removal capability of the return and flow lines. Often the horizontal parts of interconnections between collectors remain filled with liquid, so only the vertical sections should be taken into account. For pipes where the insulation thickness equals the outer tube diameter the specific heat losses will be approximately 25 W/m for a low preset pressure in the expansion vessel, (e. g. 1.5 bar) up to 31 W/m with a high preset pressure, (e. g. 3.5 bar) at the boiling point. If this length appears to be critical such that steam will reach temperature sensitive components, then measures have to be made to limit the steam volume (see chapter 1.7)

On the basis of these calculations, calculate the volume of the pipes and components outside the collector which can be filled with steam. This volume together with the collector volume gives the maximum volume of steam V_S. The common procedure to calculate the nominal volume of the expansion vessel V_N [1] has to be modified to:

equ. 1: $$V_N \geq \frac{V_M * n + V_V + V_S}{N}$$

equ. 2: $$n = \frac{\rho_{cold}}{\rho_{hot}} - 1 \approx 0.09$$

equ. 3: $$N = \frac{P_m - P_{diff} + 1 - (P_0 + 1)/0.9}{P_m - P_{diff} + 1} \leq 0.5$$

equ. 4: $$P_{diff} \approx H_{diff} * \rho_{cold} / 10000$$

Pressures are above atmospheric.

V_N	nominal volume of the expansion vessel [l]
V_M	entire volume of the heat transfer medium [l]
V_V	spare liquid in the expansion vessel [l]
V_S	maximum steam volume [l]
n	expansion factor (approx. 0.09 to ~120 °C for 40% propylene glycol)
N	maximum operational capacitance of the expansion vessel [-]
ρ	density of the heat transfer medium [kg/m³]
P_m	maximum allowable pressure = opening pressure of the safety valve – 20% [bar]
P_0	preset pressure in the expansion vessel [bar]. The factor 0.9 in the term (P_0+1)/0.9 allows for temperature changes in the gas volume due to hot liquid [7] (figure 2)
H_{diff}	if the safety valve and the expansion vessel are mounted at very different heights, this should be corrected for. H_{diff} = altitude of expansion vessel – altitude of safety valve [m]
P_{diff}	pressure difference corresponding to H_{diff} [bar].

10 Thermal loads on heat transfer medium

The glycol component in the heat transfer medium and the inhibitor additives become unstable at high temperatures and can degrade due to flocculation and the formation of solid residues. The normal function of the system represents no essential load for the heat transfer medium. However, long lasting high temperatures, which might occur in the event of stagnation, are to be avoided as far as possible to prevent the premature ageing of the heat transfer medium [6]. Collectors with a good emptying behaviour largely comply with this requirement. With the system pressures common in solar plants, boiling temperatures of around 130 °C to a maximum of around 155 °C are reached but only have a short-term influence on a small amount of the liquid heat transfer content given good emptying behaviour.

With poor emptying behaviour the residual liquid can be exposed to boiling temperature for a long period of time. This boiling results in the preferred evaporation of water (fractional distillation) with corresponding increases in the concentration of glycol and inhibitor components in the residual liquid. This increased concentration leads to a local increase in the boiling temperature. The process continues until the highly concentrated residual liquid no longer evaporates resulting in extremely long-lasting and high temperatures with corresponding significant ageing (for the pure glycol components the boiling point exceeds 210 °C with the usual pressures at stagnation conditions).

The high temperatures of the steam phase within the collector at stagnation temperature should not represent any serious problem since this steam mainly contains water (fractional distillation) and only affects very small amounts of glycol.

11 Condensation pressure shocks

The arrangement of the pipes inside and outside of the collector has a great influence on the formation of condensation pressure shocks. Not all of the causes are known, but some known causes are long horizontal pipes or sags in horizontal pipes, where steam could be enclosed from liquid (condensate). As this trapped steam condenses, liquid columns hit together or against the walls of the pipes.

Collectors with good emptying behaviour do not have a great potential to generate condensation pressure shocks but collectors with poor emptying behaviour have a much greater potential. Because of pressure fluctuations residual liquid can be pushed to-and-fro and can enclose steam pockets.

All of these pressure shocks can give uncomfortable acoustic emissions. However, measured pressure peaks are moderate (~0.1 bar and the safety valves usually do not react). On the other hand, at the point of origin the pressure peaks could be higher and failures cannot completely be excluded.

To avoid pressure shocks a good emptying behaviour of the whole system is recommended and long horizontal lines, lines with sags or lines which slope towards the collector should be avoided.

12 References

[1] Terschüren K-H., et. al., 'Anlagenkomponenten, Inbetriebnahme und Betriebssicherheit', seminar 'Thermische Solarenergienutzung an Gebäuden', FhG ISE, Freiburg, 1994

[2] Hausner R., et. al., 'Stagnation Behaviour of Thermal Solar Systems', EUROSUN, Copenhagen, Denmark, 2000

[3] Streicher W., 'Minimising the risk of water hammer and other problems at the beginning of stagnation of solar thermal plants – a theoretical approach', EUROSUN, Copenhagen, Denmark, 2000

[4] Fink C., et. al., 'Strategien zur Vermeidung von unzulässigen Temperaturbelastungen an Anlagenkomponenten im Stagnationsfall', conference 'Materialien und Komponenten in Solaranlagen', Salzburg, 2000

[5] Fink C., et. al., 2. interim report to the project 'Entwicklung von thermischen Solarsystemen mit unproblematischem Stagnationsverhalten', program line 'Haus der Zukunft', federal ministry for traffic, innovation and technology, Vienna, Austria, 2001

[6] Hillerns F., 'Untersuchungen zur thermischen Dauerbelastbarkeit von Solarflüssigkeiten', Elftes Symposium Thermische Solarenergie, OTTI, Kloster Banz, Staffelstein, Germany, 2001

[7] Hausner R., et. al., Stagnation Behaviour of Thermal Solar Systems, EUROSUN, Bologna, Italy, 2002