CombiSol project

Solar Combisystems Promotion and Standardisation

Comparison of Expansion Vessel Calculation Tools for "Boil-Back" Stagnation Protection

Created by:

Chris Bales

Staff member of Solar Energy Research Center SERC, Högskolan Dalarna
(January, 2011)

With contributions from:
Alex Thür, AEE Intec
Thomas Letz, INES Education

This project is supported by Intelligent Energy Europe programme.

The sole responsibility for the content of this document lies with the authors. It does not necessarily reflect the opinion of the European Communities. The European Commission is not responsible for any use that may be made of the information contained therein.

Table of Contents

1 Background

In solar combisystems there is generally a higher capacity than load during some parts of the summer. This means that the store becomes fully charged and the collector circuit pump has to be turned off to prevent boiling in the store. The collector then goes into what is called stagnation and, during periods of high solar radiation, reaches high temperatures of up to 200°C and in the case of evacuated tube collectors, even higher. The normal freeze protection used in northern Europe is to add propylene glycol to water. However, propylene glycol breaks down with time at temperatures above 140°C. Thus if nothing is done to protect the glycol, this can result in solid residues that block filters, valves and pumps. There are several methods to protect the glycol from these high temperatures, but the most common one is the "boil-back" method that is described here. For this method, unusually large expansion vessels are required, and there have been a number of methods derived to calculate this volume. However, all calculation methods are dependent on what system pressures are chosen and also what pre-pressure the expansion vessel is set to before filling the circuit with the water-glycol mixture. They are also dependent on the static pressure.

Expansion vessel pre-pressure is the pressure in the gas part of the expansion vessel, when the other side (normally with fluid in) is open to the atmosphere. This is normally done just before the circuit is filled and is a value that the installer has to both know and apply. In practice at this stage the rubber membrane is forced to the end of the vessel so that the vessel is filled with gas. Nitrogen should be used.

System pressure is the pressure at the manometer when the collector is "cold". It is normally set so that the expansion vessel is not quite filled with gas at "normal" ambient temperatures, so that when it is cold outside during the winter, some small amount of fluid is still in the vessel. This means that it is slightly greater than the expansion vessel pre-pressure (assuming that the manometer and expansion vessel are at more or less the same height).

Static pressure is the pressure at the manometer due to the height difference between the top of the collector and the manometer.

1.1 "Boil-Back" Stagnation Protection

The "Boil-back" method for protecting the glycol is based on the fluid boiling at temperatures below 140°C and the vapour pressure pushing the fluid out of the collector so that only (water) vapour is left in the collector at the higher temperatures that can occur at stagnation. The temperature at which this boiling first occurs is dependent mainly on the system pressure, but also the size of the expansion vessel.

The stages of the stagnation process are well described by Hausner and Fink [2] as well as Scheuren [4]. The sequence of events during stagnation can be divided into five different phases on the basis of a simplified collector model by Hausner, et al. [5, 6].

Phase 1 – expansion of liquid. The collector temperatures rise until the evaporation process begins in the upper part of the collector array, somewhere in an absorber. The increase in the system pressure is small.

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.

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. The essential heat transport mechanism in this phase is the evaporation of the fluid in the collector and then condensation and heat loss through pipes and components. This carries on until all fluid has been boiled off. The magnitude of this heat transfer from collector to pipes, the steam production, is dependent on the efficiency of the collector and how well it empties, essentially how much fluid is left in the collector.

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.

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. 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.

1.2 Function of the Expansion Vessel

The functions of the expansion vessel can be split into the following:

- Take up the expansion of the fluid during normal operation of the collector circuit.
- Provide the correct pressure for the system so that the fluid in the collector boils at the desired temperature.
- Take up the fluid that is forced out of the collector by the “boil-back” process. Note that if there is significant steam production, some of the fluid in the pipes is also forced into the expansion vessel. In extreme cases the steam can reach the expansion vessel and thus all the fluid in pipes up to the vessel will be forced into the vessel.

The rubber membrane should be protected from high temperatures if it is to retain its full function. Thus the expansion vessel should be connected from the top to avoid unnecessary heat transfer within the connecting pipe to the vessel. Some expansion vessels are designed to be connected to the bottom or the side, and if this is the case, the manufacturers’ instructions should be followed.

It is not uncommon that the gas in the expansion vessel leaks. Thus this should be checked regularly.

1.3 Cooler for protection of expansion vessel

As explained in the previous section, in certain cases, the steam from the collector can penetrate as far as the expansion vessel if the steam production power is higher than the losses from the piping network. In such cases it is recommended to add a cooler for condensing the steam before it reaches the expansion vessel. An example of such a device is given in Fig. 1. As alternative bare pipes or a smaller vessel can be used.

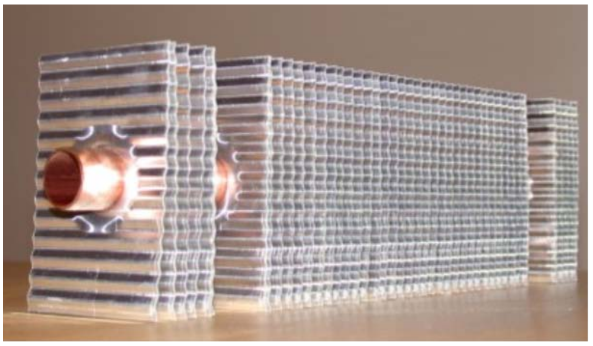

Fig. 1: Example of an active cooler for protecting the expansion vessel from steam. (source: AEE Intec)

2 Description of Calculation Tools

In this chapter the various calculation methods are described briefly, enough to give information for an inter-comparison between the methods. The method used by Viessman and AEE Intec as well ISFH and Fraunhofer ISE represents the latest research in the area, based on several projects over the last decade. This should be seen as the best method at the moment, which is why it is given in more detail here. It is possible to place the expansion vessel on the flow or the return side, but it is recommended to have it on the flow (cold) line and this is what it is assumed in the following comparison.

2.1 Common Features

For nearly all of the methods described here, the required volume of the expansion vessel is determined using the volume of fluid that has to be taken up in the vessel (V_{exp}) and a pressure factor (D_f) that essentially relates the maximum pressure (P_e) of the gas in the expansion vessel when V_{exp} has been pushed into it and the pre-pressure in the expansion vessel (P_0) and is determined by the gas laws for adiabatic compression of a gas.

$$V_{\exp} = V_{coll} + V_{pipe,steam} + V_{liq,\exp}$$

Where V_{coll} is the fluid volume in the collector, $V_{pipe,steam}$ is the volume of steam in the pipe network and $V_{liq,exp}$ is the liquid expansion of the heat transfer fluid.

Vcoll is treated in the same way in all cases. $V_{pipe,steam}$ is different in the different methods, and $V_{liq,exp}$ is calculated in the same way using the expansion coefficient for the fluid However, different methods use different assumptions for the temperatures used to calculate the expansion coefficient. Generally the coefficient varies between 0.09 and 0.13.

$$D_f = \frac{P_e + 1}{P_e - P_0}$$

The values used for P_e vary in the different methods, as does the recommended value for P_0. In the AEE Intec method the pressure factor also accounts for the difference in height between the expansion vessel and the safety valve and uses a factor of 0.9 for the pre-pressure in the expansion vessel (as an absolute pressure).

In nearly all cases, the pressure factor is used together with the volume pushed into the vessel to calculate the required expansion vessel volume, using:

$$V_{\exp.vessel} = V_{\exp} \cdot D_f$$

2.2 Viessmann & AEE Intec

Fig. 2 shows the calculation method reported by Scheuren and Kirchner [3] for determining the need for a cooler and the steam volume. The first stage is to estimate the boiling temperature based on the system pressure in the collector (p_{sys}) and the net heating rate (P_{stag}) based on this temperature, the ambient temperature together and the collector characteristic equation. The amount of energy transferred to the steam is dependent on the collector field design, where three different empirical equations for different emptying behaviour were derived based on extensive measurements on a number of different collector fields: A (good), B (moderate) and C (bad). This steam power is assumed to be transferred to the piping network where the steam is condensed and the heat is lost to ambient. The basic assumption is that the extent of the steam penetration is the length of pipe needed to have heat losses equal to the steam power (SPP). If the heat losses from the pipes is not as large as the steam power, then a cooler is required.

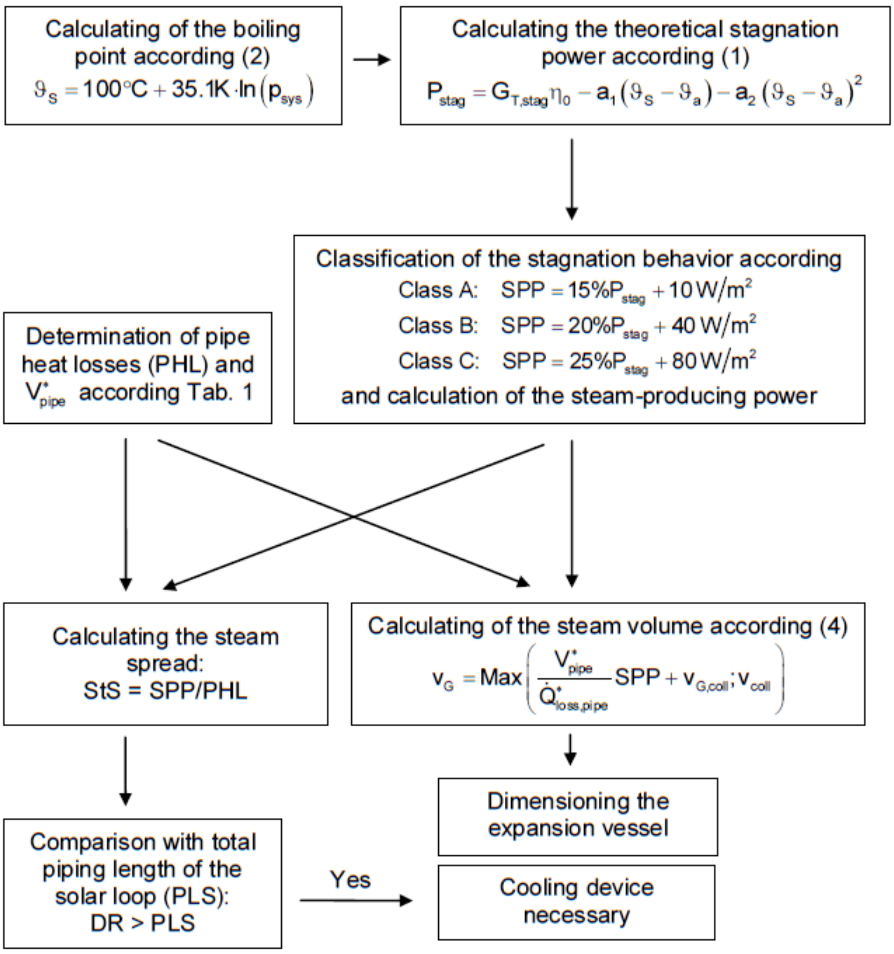

Fig. 2: Calculation flow chart for calculating the expansion vessel size and whether a cooling device is required in order to protect the expansion vessel.
(source: Scheuren and Kirchner [3])

Both the Viessmann and AEE Intec use essentially the same equations and methods but not in the same way. The calculation of the expansion volumes is the same in both case, the only difference being that AEE Intec use an expansion coefficient for the liquid of 0.09 while Viessmann use 0.13.

In the AEE Intec method the pre-pressure in the expansion vessel is recommended to be set to 2.0 bar for height differences up to 15 m. For greater heights, larger pre-pressure is recommended. The height of the collector above the expansion vessel is not an input to the model. The system pressure is to be set to 0.5 bar greater than the pre-pressure in the expansion vessel. P_e, the maximum allowed pressure, is set to 80% of the nominal release pressure of the safety valve, making it 4.8 bar for the normally used 6.0 bar safety valve. The pressures are corrected for differences in height between expansion vessel and safety valve. Additionally the method does not calculate the cooling capacity of an active cooler. Note that in the tool the volume of liquid in the collector is fixed to 0.5 l/m^2 and cannot be altered by the user. This fixed value was used for all the cases, even though it was smaller than the values specified for the comparison. This resulted in lower expansion vessel volumes than if the proper value had been used.

In the Viessmann method the pre-pressure is set to 0.7 bar greater than the static pressure caused by the height difference between the collector and expansion vessel, thus 1.7 bar for a height difference of 10 m and 1.2 bar for a height difference of 5 m. The system pressure is to be set to the expansion vessels pre-pressure plus 0.3 bar. These pressure values are outputs of the tool. P_e is set to 90% of the nominal release pressure of the safety valve, making it 5.4 bar for the normally used 6.0 bar safety valve. The tool is limited to the Viessmann collectors, and thus also the liquid volume in them. These were used for the comparison.

Thus there are some differences in application of the methodology here. An important difference, not clear from the above, is that the pre-pressure and system pressure are outputs of the calculation tool of Viessmann, while the pre-pressure is an input (ie open for the user to choose as he/she wants) in the AEE Intec tool. Similarly the Viessmann tool assumes a safety valve pressure of 6 bar while the user can enter what they want in the AEE Intec tool. The two tools produce different results, based on the different assumption while using the same methodology.

The Viessmann tool is more complete, as it also calculates whether there is a need for a cooler, and in addition what size this cooler has to be for: an uninsulated pipe, a small vessel, and a small radiator. It also calculates the expansion vessel size for these three different coolers. The tool is however, specific to the range of Viessmann collectors in terms of choosing collector size (and thus fluid volume).

2.3 INES

The method used by INES, and which is implemented in the excel tool that is available online at their home page [7], is one developed by the expansion vessel manufacturer Pneumatex from Switzerland. It assumes that there is a steam volume of 110% of the volume of the collector. Thus, in effect, the volume of steam in the pipes is assumed to be 10% of the volume of the collector. In addition to the normal expansion volume of the liquid in the whole collector circuit, the method also calculates and uses an initial fluid volume in the expansion vessel that should be at least 3 litres.

It calculates both the vessel pre-pressure and system pressure as an output. The pre-pressure is dependent on the “vaporisation” pressure in the collector, itself dependent on the maximum allowed temperature of the collector in normal operation specified by the user (default value 120°C), as well as the static pressure and the minimum pressure allowed in the collector (specified by the user, default value 0.5 bar). The system pressure is also an output of the method and is calculated based on the pre-pressure in the vessel as well as the total volume of the expansion vessel and the initial volume of fluid in it. However, it is normally around 0.3 bar higher than the pre-pressure of the vessel.

The pressure factor is calculated in the same way as for Viessmann, with P_e assumed to be 90% of the release pressure of the safety valve.

2.4 SP

This method assumes that the steam volume is twice that of the collector volume, ie the steam volume in the pipes is the same as the collector volume. The liquid expansion is calculated as being for the temperature interval 20 – 160°C for the volume of the collector and 20 – 95°C for the rest of the collector circuit. The maximum pressure P_e is assumed to be the release pressure of the safety valve. No definition of the pre-pressure in the expansion vessel is given in the handbook for installers [9], but in the courses they recommend 0.5 bar above the static pressure with the system pressure a further 0.5 above the pre-pressure of the vessel.

2.5 SERC

The method is based on the fact that the boiling should start at a fixed temperature, normally 130°C (defining the pre-pressure of the vessel) and that boiling should stop at another, higher temperature, normally 150°C (defining the maximum pressure allowed P_e). This is different to the other methods described previously, that calculated Pe based on the release pressure of the safety valve. The idea behind the method is to limit the temperature of the glycol: boiling starts at 130°C and stops at 150°C. The pressures are calculated directly based on the vapour pressures at these temperatures and the static pressure in the circuit. Thus the inputs to the method are in terms of temperatures and the pressures are outputs. The system pressure is set to the pre-pressure in the vessel plus 0.5 bar.

The method assumes that the volume of steam in the circuit is just the volume of the collector itself, ie no steam penetration into the pipes. The method gives relatively large expansion vessel volumes despite this fact, as the pressure factor is large due to the fact that there is a relatively small difference between P_e and the pre-pressure. The method is described by Bales et al. [8].

2.6 DTU

This method is based on many experiments at the Danish Technical University in Denmark that Dragsted et al. have reported [1]. The report includes the method of calculation described here. As the measurements were only made on one specific collector, the authors conclude that the method is only strictly valid for a collector with similar piping, and thus emptying behaviour, to the tested collector. In addition the expansion vessel in the tests had only 70% of the total volume available to the liquid. The equations for calculating the various points are not given in the report, but the background theory is as are several comparisons of the theory with the measurements. The authors have created an excel sheet that uses the method, and this has been used for this comparison.

This method is different compared to other methods in that it requires the input of piping near to the collector (Lmax – see Fig. 3). A value of 5 m was used for the small collector areas (5 and 10 m^2) while 10 m was used for the larger areas. Additionally it gives suggestions for the maximum allowed temperature for the glycol. This vlaue is used in the calculation of the expansion vessel volume. This is not the same as the boiling temperature of the liquid as used in other methods. The values given as guidelines are roughly 120 to 170°C. A value of 140°C, recommended by the authors was used in the comparison. The vessel pre-pressure and system pressure have also suggested limits, which are generally relatively low, but the user has to input the value himself/herself.

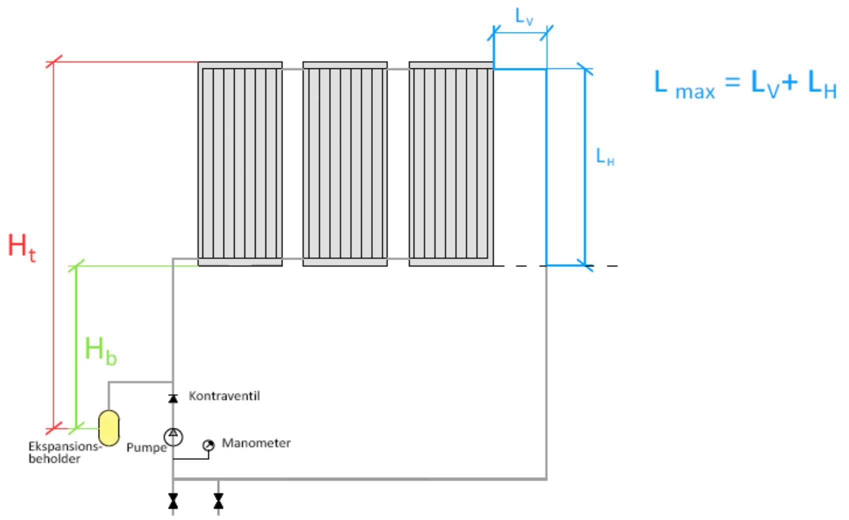

Fig. 3: Simplified diagram of collector circuit with relevant distances shown. (source: Dragsted et al., [1])

3 Comparison of Results

A set of different cases were used for all tools, with a variety of emptying behaviour for the collectors, types of collector, height differences between collector and expansion vessel (Ht) as well as maximum allowed temperature in the collector. These are defined in the next section. All the tools described in chapter 2 were used to calculate the expansion vessel volume as well as the pre-pressure and system pressure used in the calculation or output from the calculation.

3.1 Studied Cases

Table 1 defines the cases used in the comparison of the various calculation methods. The cases are paired such that there are two cases with the same conditions apart from the type of collector. The pairs have a flat plate collector with good emptying behaviour (FP) and evacuated tube collector with bad emptying behaviour (EC). There is a variation in collector size, height difference and maximum allowed collector temperatures.

Type of collector (vacuum tube or flat plate) - ETC/FP		FP	ETC	FP	ETC	FP	FP	FP	FP
Emtying behaviour (good or bad) - good/bad		good	bad	good	bad	good	bad	good	bad
Thickness of pipe insulation	mm	20	20	20	20	20	20	20	20
Antifreeze concentration	%	43	43	43	43	43	43	43	43
Specific volume of fluid in the solar collector	l/m²	0.7	0.7	0.7	0.7	1.0	1.0	1.0	1.0
Solar collector area	m²	10	10	10	10	20	20	30	30
Lengh of the solar loop (flow and return pipes in total)	m	25	25	20	20	30	30	30	30
Inside diameter of the pipes	mm	13	13	13	13	20	20	20	20
Fluid volume in the heat exchanger	l	4	4	4	4	6	6	6	6
Maximum temperature in the solar collector in operation (normal operation)	°C	130	130	110	110	130	130	130	130
Height diff. between exp. vessel and top of collector (H_t)	m	10	10	5	5	10	10	10	10
Minimum pressure at the top of solar collector	bar	1	1	1	1	1	1	1	1
Opening pressure of the safety valve	bar	6	6	6	6	6	6	6	6
Temperature when filling the solar loop (T_{re})	°C	20	20	20	20	20	20	20	20

Table 1: Conditions for the eight cases used in comparison. Several of the parameters are only used by the method from INES.

3.2 Expansion Vessel Pressure and System Pressure at Filling

Fig. 4 shows the comparison of the expansion vessel pre-pressures suggested by the different methods. When studying this, it has to be remembered that some of the methods have this value as an output while others have it as an input. For those methods having it as an input, we have used values suggested by either the authors. However, the (independent) user has the possibility to use what they want, giving the possibility of different results compared to the ones shown here. In some methods, such as the SERC and INES methods it is an output, but is calculated based on another input such as "maximum allowed temperature in the solar collector in operation", as it essentially defines the boiling temperature and thus pressure.

The Viessmann, SP and DTU methods have very much the same pre-pressure values. The INES method gives slightly less than one bar higher pressure than the SERC method for all cases. Similar trends are shown for the system pressure, as nearly all methods have some fixed, or at least very similar, difference between the expansion vessel pre-pressure and the system pressure when filling. See Fig. 5. The range of values is quite high.

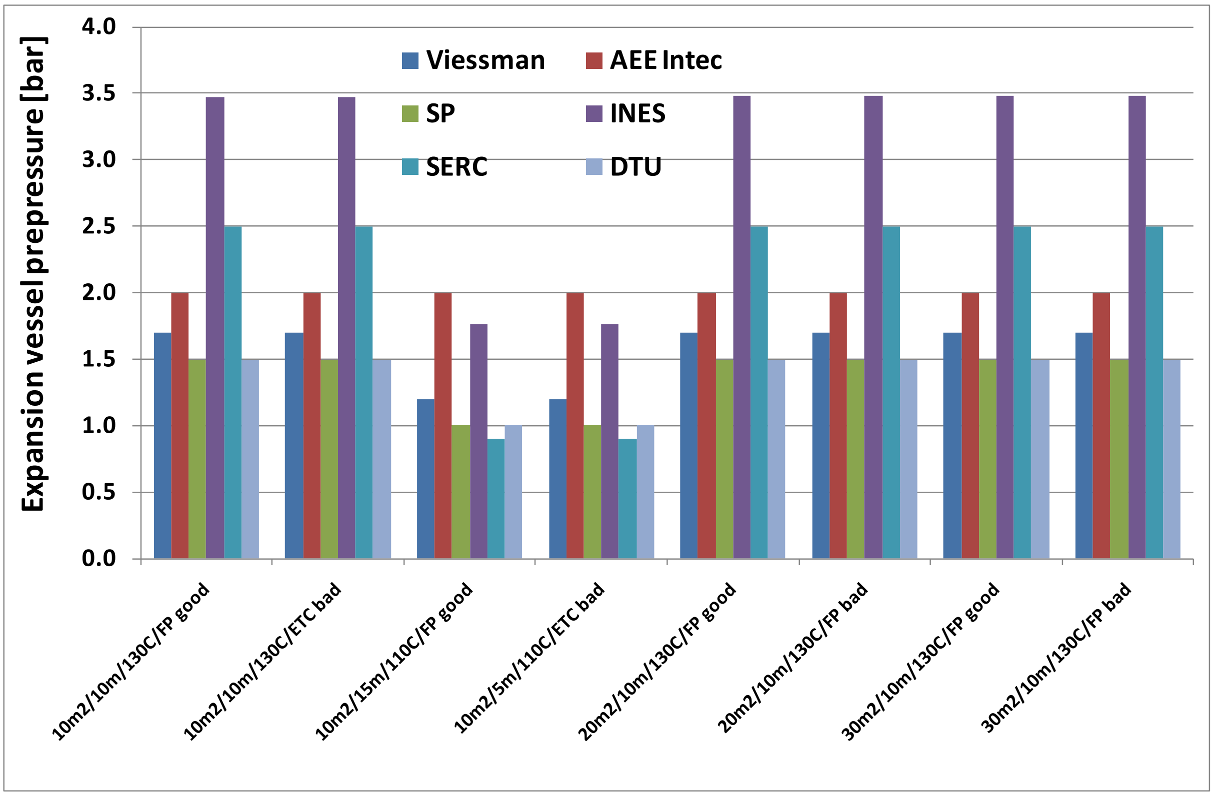

Fig. 4: Comparison of suggested expansion vessel pre-pressure from the different methods, for the cases defined in table 1.

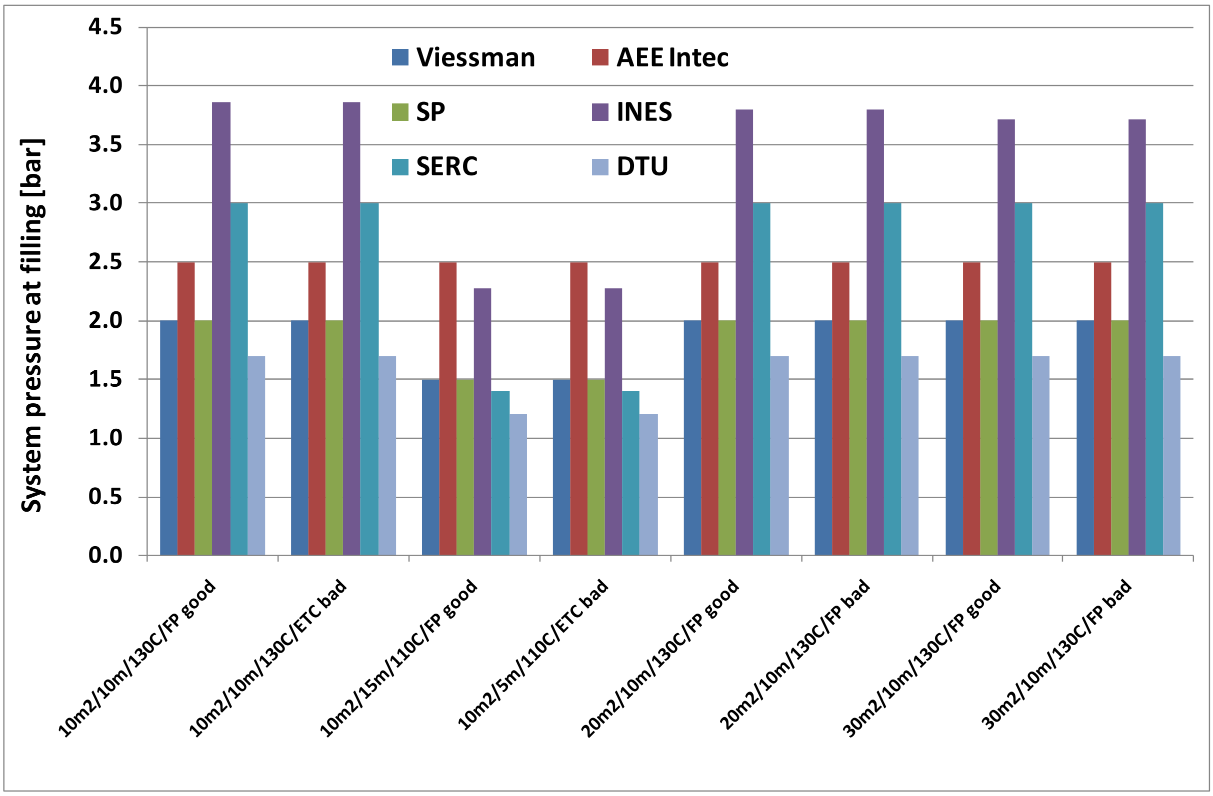

Fig. 5: Comparison of suggested system pressure from the different methods, for the cases defined in table 1.

3.3 Expansion Vessel Size

Fig. 6 shows the comparison of suggested expansion vessel sizes from the various methods. Here it can be noted that only the Viessmann and AEE Intec method give different values for the good (FP) and bad (EC) emptying behaviours and types of collector. The values differ more for the Viessmann method as this also determines the required size of the cooler if the steam power is greater than the heat losses in the piping network. As this also has a volume of liquid that is pushed into the expansion vessel, this affects the vessel size. The Viessmann method calculates the volume for three types of cooler: extra vessel, uninsulated tube, and small radiator. The values shown here are for uninsulated tubes. The lengths of these tubes can be quite long (unrealistically so in the last cases) but have been used for consistency. Using a small vessel instead of cooling tube results in larger vessel sizes. Using a radiator results in larger sizes for small collector areas (small cooling power) but smaller vessel sizes for larger cooling powers. For both the Viessmann and AEE Intec tools, the specific liquid volume in the collector is fixed and may be different from that defined in table 1.

The results show that the SP method constantly suggests significantly smaller expansion vessels than the other methods. The methods suggest more similar volumes for collectors with good emptying behaviour than with bad emptying behaviour, which is not surprising as most do not take into account different amounts of steam power and make simplified assumptions on how much steam goes into the pipes. The spread in results is large in nearly all cases.

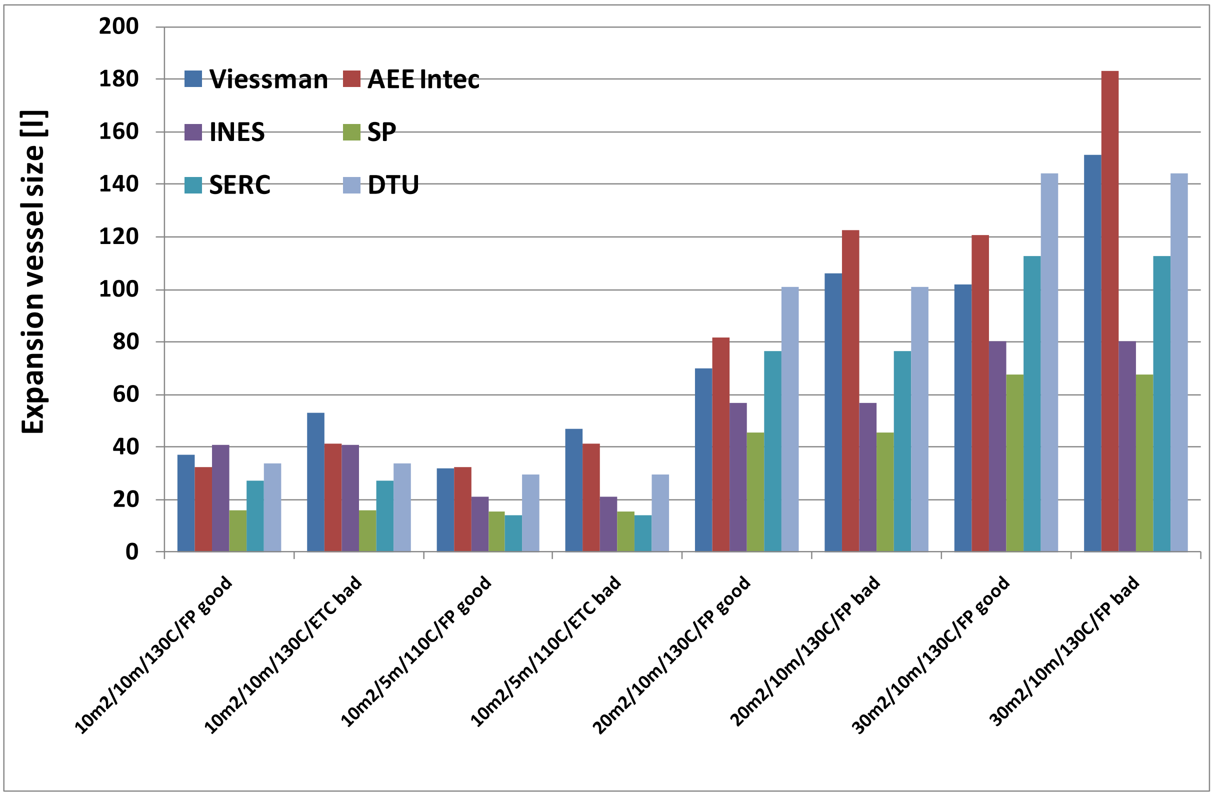

Fig. 6: Comparison of suggested minimum expansion vessel sizes from the different methods, for the cases defined in table 1.

4 Conclusions

Six different methods for determining the size of expansion vessel suitable for the “boil-back” method for stagnation protection of the heat transfer fluid have been described and compared for similar boundary conditions. Due to limitations and differences in the software, the exact boundary conditions were not exactly the same. Only two of the tools differentiate between good and poor emptying behaviour of the collector, the methods from Viessmann and AEE Intec, while only the Viessmann method determines the size of active coolers required to prevent steam reaching the expansion vessel.

The comparison shows that the methods suggest widely different expansion vessel sizes. The methods also suggest a variety of different pre-pressures in the expansion vessel, although the variation is smaller for these pressures.

The basic method used by Viessmann and AEE Intec is the same, but applied slightly differently. It is based on a lot of research on many different collector field configurations and can be considered state of the art. The Viessmann tool implements the method to the full extent, but is limited to the Viessmann collectors. It is suggested that this tool be adapted to be suitable for general use. However this was not possible within the time frame of the Combisol project.

5 References

[1] Dragsted, J., S. Furbo, B. Perers and Z. Chen, DTU Byg-Sagsrapport SR-10-04 (DK): *Solfangerkreds med stor ekspansionsbeholder og fordampning i solfanger ved faretruende høje temperaturer til sikring af solfangervæske og anlæg*, DTU, Institut for Byggeri og Anlæg, Lyngby, Denmark. 2010.

[2] Hausner, R. and C. Fink, Technical report: *Stagnation Behaviour of Solar Thermal Systems*, IEA-SHC Task 26 Solar Combisystems, Paris, France.http://www.iea-shc.org/task26. 2003.

[3] Scheuren, J. and M. Kirchner, Analysis and Prediction of the Steam-Producing Power in Large-Scale Collector Arrays under Stagnation Conditions. In *Proceedings Eurosun 2008*, Lisbon. 2008.

[4] Scheuren, J. and W. Eisenmann, ISFH Project Report 0329268A: *Stagnationsuntersuchungen in den Kollektorkreisen hochdimensionierter großer thermischer Solaranlagen*, ISFH, Hameln, Germany. 2007.

[5] Hausner, R., Fink, C., 'Stagnation Behaviour of Thermal Solar Systems', EUROSUN, Bologna,Italy, 2002.

[6] Hausner, R., Fink, C.., 'Stagnation Behaviour of Thermal Solar Systems', EUROSUN, Copenhagen, Denmark, 2000.

[7] INES education. Excel expansion vessel sizing tool, http://www.ines-solaire.com/vesth/Calcul%20vase%20d'expansion.htm. 2008. Accessed 2010-11-23.

[8] Bales, C., T. Persson, et al., ESES solar heating and storage compendium, Högskolan Dalarna, SERC, Sweden. 2010.

[9] Kovacs, P., *Solvärmesystem för småhus - kursmaterial för installatörer*. 1997, Stockholm, Sweden: FORMAS. ISBN: 91-540-5909-7.