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Drainback solar thermal systems: A review

R. Botpaev^{a,*}, Y. Louvet^a, B. Perers^b, S. Furbo^b, K. Vajen^a

^a*Institute of Thermal Engineering, University of Kassel, Kurt-Wolters Straße 3, 34125 Kassel, Germany*

^b*Department of Civil Engineering, Technical University of Denmark, Brovej, Building 118, 2800 Kgs. Lyngby, Denmark*

Abstract

Although solar drainback systems have been used for a long time, they are still generating questions regarding smooth functioning. This paper summarizes publications on drainback systems and compiles the current knowledge, experiences, and ideas on the technology. The collective research exhibits a lack of scientific publications dedicated to the drainback technology, however a significant number of patents have been published, detailing innovative technical solutions towards improvements and reliability. Based on the evaluation of drainback hydraulics, a detailed classification of this technology has been developed, with a brief description of each hydraulic typology. The operating modes have been split into three stages: filling, operation, and draining, which have been studied separately. A difference in the minimal filling velocities for a siphon development in the solar loop has been discovered in various reports. Specific features of the operation mode have been described. For the draining, existing mechanisms to initiate the emptying process have been identified and categorised. Finally, state-of-the-art hydraulic components for drainback systems have been established, with emphasis on their requirements. Based on those findings, the authors suggest potential future research paths in order to fill the knowledge gap and disseminate the drainback technology.

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Keywords: Solar drainback system; Drainback tank; Draindown system; Review

Abbreviations: ASHRAE, American society of heating, refrigerating and air-conditioning Engineers; CPVC, chlorinated polyvinyl chloride; CW, cold water; DB, drainback; DBS, drainback system; DD, draindown; DDS, draindown system; Downcomer, a pipe from collector to tank; DTU, Technical University of Denmark; ESTIF, European solar thermal industry federation; ETC, evacuated tubular collector; EPDM, ethylene propylene diene monomer; Flow pipe, a pipe from collector to tank; HE, heat exchanger; HTF, heat transfer fluid; HW, hot water; ICS, integral collector storage; ID, inner diameter; IEA, International Energy Agency; ISES, International Solar Energy Society; ISO, International Organization for Standardization; NPSH, net positive suction head; NREL, national renewable energy laboratory; OTTI, Ostbayerisches Technologie-Transfer-Institut e.V.; PB, polybutylene; PEX, cross-linked polyethylene; PMMA, poly(methyl methacrylate); PP, polypropylene; Return pipe, a pipe from tank to collector; Riser, a pipe from tank to collector; SDHW, solar domestic hot water; SERI, Solar Energy Research Institute; SHC, solar heating and cooling; SWH, solar water heating.

1. Introduction

In solar thermal applications, drainback systems (DBS) provide simple protection against overheating and freezing of the applied heat transfer fluid (HTF), guaranteeing the reliability of the system in general. For a safe operation, three repetitive operating stages are necessary, namely filling, operation mode and draining. DBS do not only offer reliable freeze and overheating protection, but also a low level of maintenance. Fewer hydraulic components render

* Corresponding author. Tel: +49 (0)561 804-3890; fax: +49 (0)561 804-3993

E-mail address: solar@uni-kassel.de

the system simpler and more economically feasible. DBS are not susceptible to failure due to air entrainment, whereas it is a typical problem for pressurised solar thermal systems. In spite of the numerous advantages, DBS are widespread only in a few countries yet. One of the reasons of poor spread is the necessity of a careful hydraulics design and a scrupulous installation process. In addition, a lack of educated installers can also be a barrier. Indeed, trivial mistakes made during the installation of the different hydraulic components may lead to the failure of the system.

The aim of this paper is to synthesise the accumulated knowledge, experiences and ideas on DBS in order to discuss the strengths, weaknesses and improvement potential of this technology. Publications related to the drainback field have been scanned in a wide range including accredited scientific journals, project reports, conference proceedings and patent databases. Investigations have been carried out in English, German, Danish and French, but relevant information has also been translated from e.g. Dutch and Chinese. All evaluated publications have been split into four categories, as presented in Fig. 1. The analysis shows that patents, with 2/3rd of the total, are the main sources of knowledge when considering DBS, while the least frequent sources are journal publications.

Fig. 1. Share of references by category specifically dedicated to DBS, from over 100 evaluated scientific documents. Conference Proceedings include all the Proceedings from ISES EuroSun Congresses, the Symposium “Thermische Solarenergie” (OTTI) and the ISES Solar World Congresses (from 1999). Project reports include among others research from SERI (US), NREL (US), DTU (DK) and AEE Intec (AT). The databases Depatisnet, Google patent and Espacenet have been used for patents research.

The review is split into four sections. In Section 2, the basic principles of DBS, their evolution with time, a classification of the systems and their hydraulic peculiarities are presented. Section 3 deals with the three different stages of DBS operation, i.e. operation mode, filling and draining processes. Section 4 is entirely dedicated to specific DB components and materials, as they appear to be one of the main issues with DBS. The review concludes with a short summary of the main results, and a discussion.

2. DB concept, evolution and classification

A *drainback system* corresponds to a “solar thermal system in which, as part of the normal working cycle, the heat transfer fluid is drained from the solar collector into a storage device when the pump is turned off, and refills the collector when the pump is turned on again” (ISO, 1999). This unique attribute to empty the collectors and to refill them again requires a careful design and the consideration of a number of DB specific rules. Different hydraulic configurations and multiple strategies for a successful draining have been developed over the last decades (Kutscher et al., 1984; Suter et al., 2003; Botpaev and Vajen, 2014a).

2.1. The DB concept

It has to be emphasized that not only drainback systems are capable of emptying the solar collectors. Besides drainback, there are two other types of solar thermal systems with “draining” attributes, namely: draindown and steam-back systems. Drainback systems refer to solar thermal systems in which the drained HTF is collected in a storage device, which is part of the solar collector loop hydraulics. On the contrary, a *draindown system* describes a “direct solar heating system in which the water can be drained from the collector and run to waste, usually to prevent freezing” (ISO, 1999). Draindown systems (DDS) are also sometimes called *drainout* (Kutscher et al., 1984), and require an additional HTF source (e.g. water net) for the refilling. DDS hydraulically isolate the storage tank by means of automatic valves in order to drain the rest of the solar collector loop (Jorgensen, 1984). A last technique is the so called *steam-back* concept, where the heat transfer fluid is pushed out of the collectors in an external reservoir during the stagnation phase, due to vaporisation (Harrison and Cruickshank, 2012). However the principles of the steam-back are beyond the scope of this paper.

The numerous advantages and drawbacks of DBS mentioned in the literature are summarized in Table 1 in alphabetical order. The most common ones such as a simple freezing protection or requirement for a careful installation of the piping, are given by most of the sources, while some more specific ones are more rarely discussed. It has to be emphasized that different sources can provide opposite statements for the same subject, e.g. cost considerations.

Table 1
Summary of the advantages and drawbacks of DBS.

Type	Short description
Cost considerations	Lower system costs can be achieved due to several advantages mentioned below (no overpressure, water as HTF, less components, use of plastic materials) (Burch et al., 2005; Haberl et al., 2008). This assertion has to be carefully considered, as economic comparisons (Kutscher et al., 1984; ESTIF, 2003; Burch et al., 2005) show that existing DBS are not necessarily the cheapest systems. Jack et al. (2014) even describe DBS as an expensive solution, unfortunately without further explanation.
Less components	Depending on the type of DBS some components such as the pressurized expansion vessel, the safety valve, the check valve, and the heat exchanger can be removed in the primary loop (Thiesen, 2009; Mugnier et al., 2011; Frank et al., 2014).
Lower and easier maintenance	No overheating, less components and water as HTF cause less maintenance. Moreover maintenance is facilitated, as the system is already drained when not active (Jorgensen, 1984; Kutscher, 1984; ESTIF, 2003; Suter et al., 2003; Mugnier et al., 2011).
No overpressure	For unpressurized DBS only. Ensures a better system safety and creates good preconditions for polymer application (Suter et al., 2003).
Not susceptible to failure due to air	Air in the solar collector loop is even mandatory for DBS, whereas it is often a typical problem for conventional pressurised solar thermal systems (Botpaev and Vajen, 2014b; Vögelin, 2014).
Performance improvement	The thermal performance of DBS is improved in comparison with conventional ones, in particular with water as HTF (increased heat exchange capacity rate) and in case of direct charging of the storage without a heat exchanger (increased collector efficiency) (Goumaz and Duff, 1981; Leibfried and Strok, 2005; Haberl and Vogelsanger, 2008).
Plastic materials compatible	As a direct consequence of an unpressurized system and automatic overheat protection; plastic materials can be used in the solar collector loop much easier (Kutscher et al., 1984; Burch et al.,

2005).

Protection against freezing	DBS are inherently freeze protected as the HTF drains from the collector(s) and outside piping when the solar collector loop is not in operation (most sources).
Protection against overheating	As for protection against freezing, DBS are intrinsically protected against overheating of the HTF. The collectors are drained when the temperature in the primary loop reaches a critical limit, e.g. if the tank is completely charged. The protection is also guaranteed in case of power failure (Suter et al., 2003; Kusyy and Vajen, 2011; Mugnier et al., 2011).
Specific use	Systems well suited for applications with discontinuous loads such as schools, sport centres, hotels, industries, etc., as long stagnation phases do not lead to mechanical stress and HTF degradation (Mugnier et al., 2011; Pott et al., 2013).
Start after stagnation	In case of stagnation, the system might be started again later during the day if conditions are reached, which is not the case for conventional systems (Pott et al., 2013).
Water as HTF	Present several advantages: - no HTF property changes which could lead to corrosion in the collector loop (Goumaz and Duff, 1981; Suter et al., 2003; Frank et al., 2014); - heat transfer properties of water are better than for other HTF (heat capacity and thermal conductivity are higher and viscosity is lower) (Suter et al., 2003; Eisenmann et al., 2003); - water is cheaper than other HTF, easily available and non-toxic (ESTIF, 2003; Suter et al., 2003).
Careful installation	All the components (collectors, piping, valves...) located in the freeze-prone zone have to be installed in a way that no water remains after draining, which could damage the system in case of freezing. This might be compensated using an HTF with antifreeze, thus losing some advantages of DBS (most sources).
Cavitation	Most DBS are unpressurized; the net positive suction head (NPSH) of the pump(s) must be taken into account to avoid cavitation (Tully, 1981a; Mugnier et al., 2011).
Choice of components	The assortment of applicable components for DBS (especially solar collectors and pumps) is limited, as their hydraulics does not always allow a complete draining (Suter et al., 2003).
Corrosion	In open systems, corrosion resistant components are required to avoid oxidization from ambient air. A closed solar circuit might be chosen, in this case the construction of an air tight system is an issue, as underpressure in the solar collector loop hydraulics favours ambient air to be sucked in (Helgesson et al., 2000; Bokhoven et al., 2001; Mugnier et al., 2011).
Flow balancing	The presence of air in the primary loop might complicate the balancing of the flow rates in parallel collector arrays with different pressure drop characteristics (Kratz and Van Dam, 1999; Mugnier et al., 2011).
Noise level	The splashing of water from the flow pipe in the DB vessel might result in undesirable noises. The design of the downcomer must take this issue into consideration (Andersen, 1988; Boye-Hansen and Furbo, 1995; Menicucci, 2011).
Organic matter formation	Open loop design can foster the growth of organic matter in the solar collector loop (Norbäck et al., 1984).

2.2. History of DBS

It is often mentioned that drainback systems were developed in the 1980s in the Netherlands (ESTIF, 2003; Visser and Peter, 2003). Governmental regulation towards drinking water quality played a crucial role in the development of DBS. According to this regulation, additives in circulating heat transfer mediums were allowed in the solar collector loop only once a double wall heat exchanger was installed or a second additional heat exchanger connected in series was applied. These preconditions fostered the development of the solar thermal branch in this country towards DBS, because water as circulation fluid without double walls heat exchanger in the solar loop was an economically feasible solution (Furbo, 2003). DBS “captured” the Dutch market and represented at the beginning of the 2000s 80% of the total solar thermal installations in the country (Hausner et al., 2003) despite modifications of the former governmental regulations (ESTIF, 2003). This widespread of DBS in the Netherlands became one of the successful milestones in the history of this technology. The DB principle is however an older approach already known before the massive penetration on the Dutch market in the 1980s. A century ago the solar collector loop was manually drained for the whole winter in order to prevent frost damages in the solar heater (Bailey, 1917; Gould, 1930). The idea to use full automatic draining and refilling processes in solar thermal systems appeared later in the 1940s. The research has revealed a US patent from 1949 (Christenson, 1949) which describes a solar thermal system with similar features to DB/DD systems. A special hydraulics was proposed to automatically drain the water out of the upper parts into a special tank “in cold climate at night”. Hastings (2005) claims that the first MIT solar house built in 1939 was designed with the DB concept. However further information on the hydraulics and operation principles of that system could not be found. According to the previously mentioned sources it can be concluded that the first ideas and implementation of DBS might have come from the US.

A real interest for solar thermal systems and in particular for DBS was awakened after the first Arab oil embargo in 1973. About 5,000 solar thermal systems were installed in US in 1974, whereas in 1980 the number of solar installations had increased to 160,000 (Hirshberg, 1981). A similar scenario is observed in other countries, as well as in Europe, where the oil crisis stimulated the interest for solar applications. The research pointed out that during this period (between 1976 and 1980) a significant number of DBS/DDS inventions were patented in the US and in Europe, showing the first strong interest for this technology (Cronin et al., 1977; Baardman, 1979; Busch et al., 1979; Cartland, 1979; Duval et al., 1981). The primary objective of DBS/DDS was to use water as circulating fluid and to “drain it back” to eliminate freezing issues. Additional operational peculiarities such as the unpressurised solar loop create a perfect compatibility with plastic components. Early attempts towards combination of DBS with polymers were proposed in the 1980s (Kutscher et al., 1984; Perers, 1988). DBS in combination with plastic collectors were further experimented in the mid-90s in Norway, but due to weaknesses in the collectors the manufacturing has been interrupted. Since then, similar concepts with plastic components appear regularly on the market, for instance in the mid-2000s DBS with unpressurised polypropylene (PP) storage (Consolar, 2014) or DBS with plastic collectors (Magen eco-Energy, 2014).

Meanwhile, there are at least 50 different DBS available on the global market (Botpaev and Vajen, 2014a). Each system has its own peculiarity in hydraulics and operation. DBS are widely used in a few countries such as Netherlands, Norway and Belgium. In the USA, Spain, Portugal, Italy, France and Switzerland DBS are also relatively popular, but represented on the market with a share below 20% (Botpaev and Vajen, 2014a). DBS size can vary from a couple of square meters up to several thousands. One of the largest DBS, with 2400 m² of collector area, has been constructed for industrial heat for a confectionery factory in Breda, Netherlands (Bokhoven et al., 2001).

Summarizing the previous paragraphs, four main driving forces in the development of DBS can be emphasized:

- Arab oil embargo in 1973: growing interest for alternative energies and first massive development of several configurations of DBS/DDS.
- Regulation towards water quality in the Netherlands (1980s), first country with high market penetration from DBS.
- Research in plastic components for solar thermal application.
- Economic competitiveness of DBS (see also Section 4).

2.3. *Hydraulic configurations and classification of DBS*

The ways to design DBS are multiple and there is a necessity to classify them according to their characteristics. One of the most common approaches to classify DBS is to make the distinction between open and closed systems, i.e. systems vented to the atmosphere or not (Kutscher, 1985; Suter et al., 2003; Botpaev and Vajen, 2014a). Open systems can be applied with plastic materials, due to low pressure in the solar collector loop; whereas in a closed loop between 110 and 150 kPa (Kaiser et al., 2013b; Schabbach and Leibbrandt, 2014) up to 300 kPa (Suter et al., 2003) can be expected as a maximum (absolute pressure). Another classification, which may apply to all solar heating systems, is to distinguish between direct and indirect systems, i.e. depending if the water delivered to the end user is directly circulated in the collectors or not (Kutscher et al., 1984). Nowadays the focus seems to be exclusively on indirect systems (Botpaev and Vajen, 2014a), among which the main distinction is to be made between collector-side heat exchanger (HE) and load-side heat exchanger (Kutscher, 1985). Botpaev and Vajen (2014a) proposed to classify currently existing DBS furthermore according to their DB volume, either an external DB tank, an oversized heat exchanger or the heat storage itself.

Fig. 2 summarizes those different classifications. Additional categories appear such as DD thermosiphon systems, described by Kutscher et al. (1984) but rarely addressed in the literature, and sub-divisions for direct systems also given by the same author. Moreover the distinction between open and closed loop systems does not appear on the figure as most categories described can use either one or the other. In the following sections, the different configurations are reviewed with further details.

Fig. 2. Classification of DBS, according to various parameters, adapted from Kutscher et al. (1984), Suter et al. (2003) and Botpaev and Vajen (2014a).

2.3.1. DB with air compressor

It consists of a constantly pressurized direct DBS, with an additional air compressor used to maintain the pressure in the system when it drops below a certain level, due to air leakage to the surroundings (Kutscher et al., 1984). Early patents came out with this concept, which is depicted in Fig. 3a. Cartland (1979) and Prieur (1980a) proposed different versions of the concept; one important part in the system is the device used to activate the compressor (respectively a float and a water level sensor).

One major drawback is that in case of long power disruption, the water level in the hydraulics cannot be controlled anymore, and freezing damage could occur (Kutscher et al., 1984). With such systems, the essence of the DB concept (safe draining in any situation) is therefore distorted. A pressurized DBS without additional compressor was first proposed by Prieur (1980b), before he noticed that losses of pressure had to be compensated (Prieur, 1980a). For that reason, the system does not seem to have raised a lot of attention as recent literature has not been found on the topic.

2.3.2. Direct DBS with unpressurized storage tank

Like for the previously mentioned system, references to direct unpressurized DBS are very limited. The DBS with water level control mentioned by Kutscher et al. (1984) is one option, which is presented in Fig. 3b. The water level in the tank is adjusted via a valve controlled by a floating device monitoring the water level. The system being unpressurised, a second pump is required for water distribution. More recently, Atkinson (2012) proposed the use of an additional header tank where the water level is controlled. This potentially enables a decrease of the static head to be overcome at startup of the system, but is not intrinsically different from the solution described by Kutscher et al. (1984).

2.3.3. Draindown

The draindown configuration is slightly different from all the others as explained in section 2.1, as the fluid is drained to the outside and therefore not reused. Kutscher et al. (1984) described two types of strategies for draining such systems, either when a frost danger occurs or simply each time the pump stops. The latter present the drawback of wasting a significant amount of water. Moreover studies have shown that the weakest point of

draindown systems is the use of automatic valves not being fully reliable and requiring maintenance in most cases (Kutscher, 1984). Jorgensen (1984) noted in his study that 85% of the draindown systems monitored were prone to problems, with an average of more than four problems per system. In addition, it has to be considered that automatic valves might increase parasitic energy consumption (Kutscher et al., 1984).

Several designs have been proposed, but the main aim is to isolate the storage tank thanks to automatic valves in order to drain the solar collector loop. A typical hydraulic scheme is described in Fig. 3c, derived from Cronin et al. (1977) and Scharf et al. (1980). Specific complex valves have been developed (Duval et al., 1981) but simpler solutions have also been proposed (Meucht, 1994). An advantage of the draindown configuration is the absence of the need to overcome the static head, the system being filled due to the network pressure. A further solution was also proposed by Baardman (1979) and by Oquidam (1980), in order to avoid the incoming of fresh water every time the system is filled up; which is potentially dangerous in regard to lime deposit and corrosion. In this case, an additional heat exchanger is required between the solar collector loop and the storage tank, resulting in a hybrid draindown system with collector-side heat exchanger, close to the systems described in section 2.3.5. More precisely, it consists in coupling the primary loop and the water network via a vessel composed of two chambers separated by an elastic diaphragm. The diaphragm transmits the pressure of the network to the HTF contained in the chamber connected to the solar collector loop, keeping the system filled. Disconnecting the second chamber from the water net and draining it to waste, leads to the emptying of the solar collector loop inside the first chamber.

Most literature found on draindown configurations date back from the late 70s, and it seems that currently this solution has lost interest, certainly because of the mentioned issues.

2.3.4. Draindown thermosiphon

This type is briefly mentioned by Kutscher et al. (1984) and is described in Fig. 3d. It simply consists of a thermosiphon system with the additional possibility to drain down the collector thanks to automatic valves. The same issues as the one described for the DDS may occur. Draindown thermosiphon systems are rarely mentioned in the literature, nevertheless Morrison et al. (1999) mention the widespread use of such systems in China. Indeed a large number of patents have been published in the last years, proposing complete hydraulics solutions (Dong, 2010; Hou, 2012), or specific devices and valves, such as Jichang (2007) and Fuxian (2013), aiming at automatically draining outside piping, to mention only few of them. The purpose of all those solutions is to prevent the freezing of the thermosiphon solar heating system in winter. Burch and Salasovich (2005) also studied freeze prevention valves in such configuration in the US, showing that the annual waste of water is highly impacted by the climate, from less than 380 l in the south of the country to more than 38 m³ for most of the northern part, for a typical solar domestic hot water (SDHW) system.

2.3.5. DB with collector-side heat exchanger

Drainback systems with collector-side heat exchanger are the most commonly applied DBS on the market (Botpaev and Vajen, 2014a). In this configuration, an additional DB volume has to be added in order to gather the HTF when the system is not in operation. Two configurations exist for this system, which depends on the device used as DB reservoir (Botpaev and Vajen, 2014a). The first option and the most common one is the use of an external DB tank (Fig. 3e), while the second one consists in oversizing the heat exchanger and using it as DB volume (Fig. 3f). The latter was proposed by Fossum and Fossum (1996) and by Schabbach and Wagner (2003) with internal heat exchangers. Since then, the concept has been taken over by several companies (Botpaev and Vajen, 2014a). A simpler design, with a mantle heat exchanger is also described in Boye-Hansen and Furbo (1995).

The location of the DB volume is an important parameter as it determines the static head the pump has to overcome at the start of the system (Botpaev and Vajen, 2014a). Locating the reservoir as high as possible is often

recommended (Suter et al., 2003); however, in order to achieve a compact design, it was also proposed to integrate the DB reservoir inside the storage tank, at the bottom, only separated by a partition wall (Eurometaal N.V., 1983; Van Dam and Overman, 1994). This kind of compact design is typically used in the Netherlands (ESTIF, 2003). An alternative, others proposed to locate the DB reservoir just below the collector (Vögelin, 2005), or even to integrate it at the bottom of the collector (Patterson, 2005). This solution enables the use of smaller pumps but in return, a HTF with anti-freeze has to be applied in cold climates.

2.3.6. DB with load-side heat exchanger

As the previous system, a DB with load-side heat exchanger is an indirect system (Fig. 3g), which presents the advantage of having an unpressurized, or low-pressure solar collector loop and heat storage, depending if the system is open or closed.

Compared with the previous solution, the additional DB reservoir is avoided, however, Kutscher (1985) calculated that in order to achieve the same yearly performance as with a collector-side heat exchanger design, the heat exchanger in this case has to have a four times larger surface area. A tank-in-tank design is another option to cope with this issue (Kutscher, 1985; Perers et al., 2015). Some authors also proposed the use of an additional DB tank in this configuration, notably in the case of high buildings, in order to minimize the pump power at the start of the system (Pei, 1982; Perers et al., 2015). This solution might however hamper the installation of a low-pressure buffer heat store.

2.3.7. DB with heat store located higher than the collectors

This very specific case was described by Suter et al. (2003) and requires some additional parts to make the draining feasible. A possible option for the hydraulic is shown in Fig. 3h. Another possibility is to use an external heat exchanger between the DB tank and the heat storage. This second solution requires an additional pump. Previously, Prieur (1980a) proposed a more complex solution, in a pressurized DB circuit with air compressor; the pressure of the air being adequately set in order to empty the collectors when the pump is not in operation.

2.3.8. Low-flow DBS

DBS were designed for high flow or what was thought of as normal flow as mainly the collector performance was considered and a test flow of 1.2 l per minute and m² was the reference. Very soon around 1980 came the first publications about the merits of low-flow for the system as a whole, which can enhance the stratification in the storage and reduce the average collector temperature as seen over the whole day. This is true especially at the end of the day, when a high flow system stops quite early, as the tank bottom is already half warmed up, whereas it is still cold in a good low-flow system and the collector can continue to operate. An overview of the low-flow principle and performance merits are given by Hollands and Lightstone (1989). The performance advantage of a well-designed low-flow system was investigated in a side-by-side test of 3 systems at DTU (Furbo, 1987). This system test showed a 20% performance improvement of low-flow over a standard design high flow system. Boye-Hansen and Furbo (1995) compared the simulated yearly performance of a low-flow and a conventional flow DBS (resp. 0.15 and 1.0 l min⁻¹ m⁻²) and also found an improvement of around 10-15% in the low-flow case.

Fig. 3. Typical hydraulic configurations of existing DB/DD systems, adapted from Kutscher et al. (1984) and Suter et al. (2003).

3. Operating modes of DBS

A unique attribute of DBS is the repetitive three stages operating mode: filling, operation mode and draining of the HTF from the system. The main function of the filling is obviously to fill the solar collector loop. Simultaneously, the air should be usually completely removed from the upper part of the hydraulics and collected in a special DB volume. Once a single-phase flow is established in the loop the operation mode starts. It has almost the same purposes as a conventional pressurized solar thermal system, aiming to gain the solar energy yield. The only differences are other operation conditions and the control strategy of the pump. When the pump is stopped, a gravitational draining process occurs automatically. The draining has a protective function for drainback solar thermal systems. Empty collectors exclude both overheating problems during stagnation and frost damages in cold periods.

3.1. The filling process

Once an appropriate temperature difference between the collector and the lower part of the storage is achieved, the control unit activates the pump. The filling process is initiated and continued several minutes. During the filling the pump should overcome not only the frictional flow resistance through the hydraulic components, but also an elevation head. The elevation head is the height between the water level in the drainback tank when the system is not in operation and the top of the hydraulics. The elevation head is one of the decisive parameter in the choice of the pump(s). One of the distinctiveness of the filling process is a variable operating point of the pump(s) (Tully, 1981a), hence the system curve is continuously changing (Fig. 4). The HTF first fills the return pipes, then the collector(s), overcomes the highest point of the hydraulics and finally the flow pipe. Once the system is completely filled, a constant operating point is achieved ("after siphon" on the figure). This variable operating point is a real challenge for the operational efficiency of the pump(s) in DBS. When single speed pumps are used, they have to be oversized in order to be able to fill the loop completely. This causes a high electricity consumption, which is considered as one of the drawback of the DB technology (Tully, 1981a; Kutscher et al., 1984).

Fig. 4. Pump operating points during the filling process (Tully, 1981a).

Flow rate and pressure measurements of a DBS during the filling process are presented in Botpaev and Vajen (2014b) and transposed in Fig. 5. This drawing shows the hydraulics of the DBS, the positioning of the measurements sensors (Fig. 5, left) and the typical behaviour of DBS at start. For a better comprehension the X-axis (Fig. 5, right), that reflects the time in seconds, was additionally split into several stages and designated with capital letters. The stage AB corresponds to the non-operated system and the two serially connected pumps are started at time B. The spike of the flow rate at the beginning of the filling process (MID_return at $t = 22$ s) is typical for DBS. As the pumps should overcome not only the frictional resistance through the hydraulic components, but also the vertical lift head the operating point of the pumps moves to the left (Fig. 4) causing a continuous reduction of the flow rate (Tully, 1981a). At approx. $t = 25$ s, the HTF reaches the highest point of the hydraulics and flows further through the flow pipe. The magnetic-inductive flow meter (MID_flow) detects the flow and displays wrong fluctuating values, due to air bubbles. The air bubbles are pushed by the flow into the storage creating a siphon in the loop. The siphon in turn supports the pumps and cancels out the initial lift head. This is expressed by an increase of the flow rate in the return pipe and the appearance of an underpressure at the top. In C, the process is stabilized and the collector loop is fully filled with water.

Fig. 5. Filling stage and operation mode of a DBS (Botpaev and Vajen, 2014b).

Several schemes of successful/failed filling processes are presented in Fig. 6. From the left side is shown a failed filling process, as the chosen pump was not able to overcome the elevation head. The fluid reaches a certain height below the collector, afterward the circulation ceases. The graph on the right side presents the finished filling process with an established siphon, thus a full flow is observed in the downcomer. In the middle a double phase flow of air and water circulates in the flow pipe. Such regime occurs when the fluid velocity is not sufficient to remove the air from the loop, due to the small capacity of the pump or an oversized diameter of the downcomer.

Fig. 6. Different filling processes (HTF coloured red, air is depicted white).

Air is completely removed during the filling process, and the siphon established only if the HTF velocity exceeds a certain minimal value. Tully (1981a) and Seiler (1982) mentioned that the required velocity should be at least 0.3 m/s in order to fill the solar collector loop completely. In their report, Rühling et al. (2013) presented a comparison of different filling procedures for conventional pressurised solar heating systems. One of the investigated filling procedures, so-called “quick rising filling” is very similar to the filling process in DBS. The authors reported that a minimal “cleaning” velocity of 0.4 m/s is mandatory for a successful termination of this filling procedure. They also experimentally confirmed that this filling method is more appropriate for small size solar thermal systems with a restricted static height and small diameter of the piping.

One of the earliest attempts to experimentally figure out the minimal flow rate for siphon establishment in DBS was undertaken in the 1980s (Kutscher et al., 1984). They demonstrated the influence of the flow pipe diameter on the filling process. An experimental setup of a drainback system was constructed from copper pipes. The methodology of the experiments consisted in continuously increasing the flow rate and observing the established flow. Once a siphon was established, the flow rate was recorded. The results confirmed the development of a siphon in the downcomer with a diameter of 12.7 mm at a velocity of 0.21 m/s, whereas for a 19 mm tube the required velocity is less than half of the previous one, 0.09 m/s. Different hydraulics with the same piping diameters also showed a variation of approx. 7% of the minimal velocities, therefore suggesting the impact of the solar loop design on this minimal required velocity. However, it was not specified whether the piping arrangement or the height of the hydraulics was the reason for this deviation.

Boye-Hansen and Furbo (1995) presented a report on DBS, where the “critical” fluid velocity which guarantees a single flow for straight and bended pipes was summarised. These experimental results are taken from a previous work of Mikkelsen (1988). Kaiser et al. (2013a) also conducted similar experiments to derive the minimal flow rate for the “cleaning” of the air in the downcomer. The hydraulics of the DBS was constructed with transparent PMMA pipes for visual observations of the processes. Pipes with different diameters and bends were systematically filled with different flow rates. The minimal desired flow rate which eliminates the air from the loop was derived for vertical pipes alone and vertical in connection with 90 degrees elbows. Moreover, the filling process was also investigated with propylene glycol as HTF, which confirmed the requirement of lower velocities for siphon establishment in comparison with water.

The results of the above mentioned investigations are summarized in Fig. 7.. Particular emphasis should be on the non-homogeneity of the results, especially for the piping with a diameter around 20 mm. Moreover, trend curves show various correlations. While the minimal velocity is continuously increasing with the pipe diameter in Boye-Hansen and Furbo (1995) it is not the case in Kaiser et al. (2013a) where the velocity curve shows a minimum around 16 mm. Measurement uncertainty, methodology of experiments, boundary conditions might be a reason, as they certainly play a role, but were partly specified in all the studies.

Fig. 7. Required minimal velocity for siphon establishment in DBS according to different studies.

The filling behaviour above the minimal “velocity” has been investigated in (Botpaev and Vajen, 2014b). They measured a deterioration of the deaeration process with reduction of the filling velocity. An indicator for the assessment of this process was an integral of the flow rate curve within the duration of the filling process.

Siphon establishment is however not always desired during the filling of DBS. Frissora (1981) focused on developing an evacuated tubular collector (ETC) with a double chamber, the overflow of the first chamber only partially filling the second one, connected to the flow pipe, thus ensuring a non-siphonic flow in the downcomer. One of the earliest comparisons between the oversized flow pipe or trickle-down design preventing siphon formation and systems with siphon return was presented in Tully (1981b). Kratz and Van Dam (1999) patented an invention, which aimed at optimizing the filling process of DBS with several parallel collector fields. In practice some collectors are located higher than others, which leads to a faster filling of the lower positioned collectors compared to the others. As water passes through the “lowest” rows, a siphon starts building up in those rows, disturbing the filling process of other collector rows, and leading to a decrease of energy production capacity. They suggested to oversize the diameter of the flow side pipes, preventing siphon establishment. In this case a two-phase flow is continuously observed in the flow side (Fig. 6, in the middle). The main disadvantage of such a solution is that the pump always has to overcome the static head, leading to increased power consumption (Goumaz and Duff, 1981).

For the filling of large collector fields, an alternative solution was proposed by Gößlinghoff (2010), where the siphon effect is conserved for complex hydraulics. Automatic valves are mounted at the inlet of each collector row. A successive opening and closing of the valves during the start of the system ensures the complete filling of each row separately. Thus, a successful filling of the entire DBS is achieved avoiding oversizing the pump capacity.

It is important to emphasize that investigations concerning the entry, control and release of air in/from pipelines are still relevant. The issue of air removal in pipelines is the focus of numerous researches (Lauchlan et al., 2005), where the minimal water flow rate for preventing air accumulation in pipelines is determined either experimentally or analytically. This knowledge can be partly derived for DBS, and new correlations (Pothof and Clemens, 2011) might be utilized for a better comprehension of air-water mixtures behaviour in DBS. The factors mentioned previously in this section make it clear that a correct filling process is essential for a smooth functioning of DBS. During this stage, the pump operating point is variable and the termination of the process happens either with or without establishment of a siphon flow. To achieve a single phase flow in the downcomer, a minimal flow velocity should be exceeded, which depends on the pipe diameter. Nevertheless further investigations should be carried out in this direction, as all impacting parameters have not been studied in detail so far.

3.2. The operation mode

The operation mode of DBS is similar to the one of conventional pressurised system, aiming at maximizing the solar energy yield. The HTF is heated up in the collectors and then the energy is delivered to the heat storage. Nevertheless, additional nuances have to be taken into consideration due to the specific operation conditions in DBS. An unpressurized solar collector loop is one of the main differences between DBS in comparison with conventional solar thermal systems. As a consequence, the pressure at the top of the hydraulics is often below atmospheric pressure, if a siphon is established in the loop (Tully, 1981b).

A stationary operation mode is seen in Fig. 5 on the right side of point C, as detailed in Botpaev and Vajen (2014b). The water completely fills the flow pipe and an underpressure is established at the top (about 60 kPa in this case). This vacuum pressure at the top can be calculated using Bernoulli's equation (Botpaev et al., 2014):

$$P_1 + \rho gh_1 + \frac{\rho v_1^2}{2} = P_2 + \rho gh_2 + \frac{\rho v_2^2}{2} = \text{constant} \quad (1)$$

P_1 , P_2 being the static pressure respectively at the top and the lowest point of the flow pipe, ρgh the hydrostatic pressure and $\rho v^2/2$ the dynamic pressure. The dynamic pressure is, in a normal operation mode, equal in both parts of the equation, assuming that flow rates and piping diameters are identical. Thus, the static pressure at the top is:

$$P_1 = P_2 - \rho g(h_1 - h_2) \quad (2)$$

From equation (2) appears that the reduction of the pressure at the top is proportional to the water head in the flow pipe, i.e. the height from the air gap at the end of the downcomer to the upper point in the flow side. It has to be noticed that this is the theoretical maximal value of the underpressure, as the pressure drop between 1 and 2 is not considered.

The underpressure influences the operation of DBS. First of all the water tightness of piping connections at the top is not easy to detect. Water droplets do not appear at the pipe surface, but instead air is sucked inside. Furthermore, even if the fittings are sealed against the circulating fluid, they hardly prevent the penetration of air molecules inside (Mikkelsen, 1988). Another significant influence of the underpressure is a lower boiling point of the HTF. A comprehensive example of this physical phenomenon was presented by Kutscher et al. (1984) and is summarized in Table 2. For instance at 1500 m above sea level, with a water head of 6.4 m in the DBS, they state that the boiling temperature could reach 60 °C. Boiling has a negative influence and should be avoided. According to Kutscher et al. (1984) two methods can be applied for this purpose: a periodic pressurization of the entire collector loop or the usage of a vacuum breaker. Positioning the valve below the collectors allows to eliminate the underpressure at the top. Haberl and Vogelsanger (2008) suggested to avoid this underpressure by means of an appropriate pump and a pressure sustaining valve at the end of the downcomer. By reducing the flow pipe size and having an extra adjustable flow resistance/throttle valve, close to the inlet of the drain back volume a slight overpressure can be maintained in the whole collector loop (Tully, 1981b; Rühling et al., 2013). For a low-flow system the loop has to be designed with smaller pipe diameters and a flow restrictor.

Table 2
Boiling point of water at various pressures (Kutscher et al., 1984).

Pressure at the top, kPa	11.7	19.9	32.7	51.8	101.3
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Boiling point of water, °C	48.9	60.0	71.1	82.2	100
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The water level in the heat storage/DB reservoir is another important aspect for the operation, which has to be regularly observed. The drainback tank should be between 3/4 and 7/8 full when the system is off, and between 1/8 and 1/2 while in operation (ASHRAE, 1990). “Levels outside these ranges signify potential problems” warns the ASHRAE. Botpaev and Vajen (2014b) investigated the phenomena at stakes and showed that the water flowing downward in the DB tank causes air entrainment due to vortex and splashing effects (Fig. 8). The investigations concluded that the depth of the air entrainment depends on many parameters such as the shape of the drainback tank, the water level, the velocity of the HTF, and the height of the air layer inside. The depth of air entrainment can exceed 20 cm due to splashing, therefore it is desired to avoid it “by transforming the falling fluid energy into something else”. As alternative the inlet pipe can be submerged. Such kind of measures can reduce both noise and air entrainment.

Fig. 8. The DB tank under various operation conditions (Botpaev and Vajen, 2014b).

Corrosion is another concern that has to be considered especially for open DBS, where fresh air with oxygen is permanently penetrating into the solar loop. Tully (1981a) reported that cast iron body pumps installed in a large open DBS, showed little or no signs of rust after two years of operation. Bokhoven et al. (2001) described on the contrary, a large close system with plain-steel materials which was clogged after six months of operation. Unavoidable air penetration in the system led to the creation of magnetite (Fe_3O_4) particles, blocking absorber pipes. Filters were first installed to solve the clogging problem, but the final solution was to maintain overpressure with nitrogen injection (Frank et al., 2014). Helgesson et al. (2000) noted that in their open DBS, the oxygen content stabilized after one month at a level (1 mg/l) they considered reasonable with regards to corrosion. Another long-term issue which is rarely mentioned is organic matter formation in open systems. An early large open direct DBS with up to 2500 m^2 collector area and 10,000 m^3 storage had to be rebuilt due to algae formation after short operation (Norbäck et al., 1984). Another large system (120 m^2 of collectors and 600 m^3 storage) built at the same period with a closed direct loop design did not on the contrary encounter any algae or corrosion problems (Roseen and Perers, 1980).

An additional issue is the comprehension of the freezing threat, which is especially important for DBS with water as HTF, in particular in cold climates. Honikman (1979) proposed a redundant freeze protection including primary and secondary measures. The primary measure is the draining of the circulating fluid from the collectors, once their temperature drops below a certain value. The secondary measure is activated only if the primary measure fails. In this case the circulation fluid circulates through the heat storage and then heats up the collectors. More recently, Van Dam (2009) proposed to use after the stop of the pump(s) a series of short startup of the pump(s) aiming at draining water potentially trapped in the solar collector loop. Another example is a special computer algorithm for DBS, which eliminates the freezing problem at start (Kosok, 2013). A control unit adjusts the filling process by running successively several short filling - draining processes. The temperature of the drained fluid is measured after each cycle. If this temperature is below a lower threshold value, the filling process is interrupted. The risk of

HTF freezing during the filling of a cold pipe was also theoretically investigated by Boye-Hansen and Furbo (1995). They showed that this effect depends on several parameters, such as the pipe cross-section, the HTF flow rate and obviously the inlet and outside temperatures. According to their results, water at 10 °C would freeze after approx. 32 m with a flow rate of 5 l/min and an ambient temperature of -10 °C, if a 28/25.6 mm copper pipe is assumed. The freezing threat is one of the crucial factors, which can not only cause technical and financial problems, but generate “smear campaigns” against DBS. Therefore a lot of DBS on the market are available with antifreeze, which is another simple solution to avoid the freezing (Botpaev and Vajen, 2014a).

Finally, the performance improvement of DBS over standard glycol systems was studied by a few authors. TRNSYS simulations validated against measurements showed a solar fraction improvement of 17% for a combi-system located in the Colorado climate, mainly due to the absence of heat exchanger (Goumaz and Duff, 1981). Leibfried and Strok (2005) found with their DB combi-system an overall solar yield improvement of 11% with simulations. Taken one by one, the absence of heat exchanger was the most impacting parameter (7%), then came the use of water instead of glycol (3%) and the avoided heat losses due to the draining in the evening (3%). Concerning the advantage of water against glycol, Eisenmann et al. (2003) also noted a better performance of DBS due to a higher heat exchange capacity rate. Finally, in their simulations, Haberl and Vogelsanger (2008) calculated that DBS would increase the fractional extended energy savings by almost 5%, also because of heat exchanger removal and the use of water as HTF.

3.3. The draining process

Once the solar controller turns off the pump(s) or in case of power failure, the draining process occurs automatically. It has a protective function for the DBS, and implies the draining of the HTF from the upper part of the hydraulics into the drainback volume. Empty collectors and hydraulics prevent both HTF overheating during stagnation and frost damages in cold periods.

One of the earliest investigations of the draining process was conducted in the 1980s. Some simple experiments were carried out by Kutscher et al. (1984) in order to determine the range of pipe diameters, which would support a vertical water column of 1 m within a pipe with open cap at the bottom and closed at the top. From those results they proposed to find out whether a vacuum breaker is needed for the draining or if the water can run out by itself due to gravity. They demonstrated that pipes with inner diameter (ID) equal or smaller than 10 mm will not drain, whereas pipes with diameters of 14 and 19 mm empty easily. Further experiments and analytical results showed that stable menisci can form in pipes up to 14 mm ID but not larger than approx. 16 mm. In order to break the menisci either the end of the pipe can be angled cut or a hole drilled a few centimetres above its outlet (Fig. 9).

Fig. 9. Observations of menisci (Kutscher et al., 1984).

Different possibilities to initiate the draining process have been proposed and are summarized in Fig. 10. The presented hydraulics are simplified as the heat storage is always presented as DB volume. The HTF is coloured red and the air white. Fig. 10a represents the crucial “mechanism” of the draining process. The driving force of the draining process is a difference of hydrostatic pressure between the flow and return pipes, designated with H (Botpaev et al., 2014). The same authors noticed that the profile of the flow rate over the draining process has a parabolic shape, as the hydrostatic pressure difference has the same tendency. The draining process occurs in opposite direction to the circulation as mentioned in Hapgood (1978) and Seiler (1982). The drained HTF flowing down in the return side pulls up the water column in the flow side, emptying the system. Therefore almost the whole water amount is drained over the return side due to siphon effect.

Fig. 10. Draining processes from literature and industry.

The first hydraulics considered (Fig. 10a) leads however to splashing of the circulating fluid during the operation mode (Beasley, 1982). Besides noise creation, it leads to air bubbles penetration into the DB volume, which might be damageable if then sucked through the pump (Botpaev and Vajen, 2014b). Therefore, the downward piping is sometimes submerged under the water level in the DB volume as shown in Fig. 10b and c. This solution requires however an additional mechanism to initiate the draining process. One possibility is a drilled hole in the downcomer pipe (Fig. 10b), whereas applying a motor, solenoid, or check valve is another alternative (Fig. 10c). Independently from the configuration considered, the device initiating the draining should never be obstructed. Boye-Hansen and Furbo (1995) and Perers et al. (2015) noticed during their experiments that the downcomer was connected too low, close to the HTF level in the drain back volume. As a result, rising water blocked the connection in the middle of the draining phase, creating two air volumes – one in the DB volume and one in the collectors. During cold periods, water could be sucked up in outdoor hydraulics, thus endangering the system.

Bliss (1958) was the first to mention a hole as draining “initiator” in a patent from the end of the 1950s (Fig. 11a). Later, Embree (1981) considered it as an interesting solution to initiate the draining process without moving parts (Fig. 11b). This hole enables a partial emptying of the downcomer from the hole down to the water level in the storage, when the pump stops. This partial emptying creates the hydrostatic pressure difference, which initiates the siphon draining described above. Bony and Renault (1999) reported that several drilled holes combined with a bypass piping parallel to the pump accelerates the draining process, reducing the draining time by a factor two. A detail of the flow pipe entering the heat storage is shown in Fig. 11c, where at least one hole has to be positioned above the fluctuating water level in the storage. Buderus Heiztechnik GmbH (2001) patented a similar solution (Fig. 11d, left), the hole being drilled with the shape of a vertical slot. Furthermore, the end of the piping in the DB tank is proposed to be bent just below the hole as detailed in the two right schemes of Fig. 11d. This shape should reduce the noise due to splashing and vortex in the DB tank. A comparable hydraulics concept is also mentioned in Schalajda and Leibfried (2002). Menicucci (2011) revealed that a few holes seem to be the most effective approach to eliminate the problem of noise and to foster the draining of DBS. The original drawings of some of these inventions are presented in Fig. 11.

Fig. 11. Schemes of different hydraulics with hole(s) in the flow pipe indicated with a dark arrow, adapted from (a) Bliss (1958), (b) Embree (1981), (c) Bony and Renault (1999) and (d) Buderus Heiztechnik GmbH (2001). Abbreviations applied in this figure: C - collector(s), F - flow pipe, R - return pipe and S - heat storage.

A branched pipe (also called bleeder or vacuum breaker) mounted in the downcomer with sometimes an additional valve (Fig. 10c) is another old approach to initiate the draining process in DBS. In operation mode the motor or solenoid valve is permanently closed, and opens once the pump is stopped. The branched pipe should be dimensioned in a way which allows air to freely pass through anytime when the pump is stopped but should avoid HTF circulation during operation. Bliss (1958), Embree (1980) and Beasley (1982) proposals are based on inverted U-formed piping without any additional mechanical or electrical devices (resp. Fig. 12a, b and c). Haberl and Vogelsanger (2008) use the same shape with an additional check valve (Fig. 12d), while Bunksolar (2014) proposes a motor valve (Fig. 12e).

Fig. 12. Schemes of different hydraulics with a branched pipe indicated with a dark arrow, adapted from (a) Bliss (1958), (b) Embree (1980), (c) Beasley (1982), (d) Haberl and Vogelsanger (2008) and (e) Bunksolar (2014). Abbreviations applied in this figure: C - collector(s), F - flow pipe, R - return pipe, S - heat storage and V - additional DB volume.

Another possibility to initiate the draining process is to utilize an air vent (or vacuum breaker) at the top of the hydraulics. The highest point of the vent allows a splitting of the circulating fluid during the draining into two water columns (Fig. 10d). Splitting the flow makes the draining process easier and faster (Botpaev and Vajen, 2014b). There is no siphon draining anymore and each water column is drained separately. The vent can be connected either to the ambient or through a vent line to the air volume in the DB volume. Hayes and Shikasho (1977) applied the latter to closed DBS (Fig. 13a). There was at the end of the 1970s a real boom of patented inventions with vacuum breaker at the top for the fostering of the draining process. Different devices were applied for this purposes, such as a solenoid valve (Krumpe, 1978) (Fig. 13b), a vacuum relief valve (Honikman, 1979) (Fig. 13c), a floating valve (Baardman, 1979) (Fig. 13d) and (Prieur, 1980a), an air pipe (Busch et al., 1979), an air vent (Scharf et al., 1980) or a membrane device (Oquidam, 1980) for DDS. Preventing a siphon formation during the filling process by means of oversized flow pipe diameter will cause a similar “two columns draining”, speeding up the emptying process (Kratz and Van Dam, 1999).

Fig. 13. Schemes of different hydraulics with a vacuum breaker at the top indicated with a dark arrow, adapted from (a) Hayes and Shikasho (1977), (b) Krumpe (1978), (c) Honikman (1979) and (d) Baardman (1979). Abbreviations applied in this figure: C - collector(s), F - flow pipe, R - return pipe, S - heat storage and V - additional DB volume.

A plenty of technical solutions towards initiation and fostering of the draining process have been described in this section. Many issues concerning optimal DB system design were extracted from patents, but there is a lack of scientific publications on this topic. A comparison of different draining methods, the influence of HTF properties and pipe parameters still have to be clarified; indicators to quantify the quality of the draining behaviour should also be developed.

4. Components and materials for DBS

The economic competitiveness of DBS has from the beginning attracted manufacturers and scientists to undertake further development of this technology. In his search for a low-cost solar water heating (SWH) system, Kutscher (1985) selected the DB configuration, for its high reliability (lower needs for maintenance), fewer components (solenoid and check valves are not necessary) and the potential use of cheaper components due to the low pressure in the solar collector loop. In the 2000s, DBS were still a way to achieve low-cost systems, using cheap materials, avoiding components like the pressurized expansion vessel or resorting to water as HTF (Stork and Siegemund, 2001; Haberl et al., 2008; Thiesen, 2009). If the potential for cost reductions with DBS is high, as it was highlighted in a study from Burch et al. (2005) due to the possibilities described above, they are not always the ultimate solution selected to drop down system costs (Hudon et al., 2012). Section 4 focuses on presenting the current state-of-the-art of hydraulic components for DBS and the specific requirements they have to fulfil. The use

of new or cheaper materials for DB applications is closely tied to this research area. Indeed due to their intrinsic qualities, DBS are for instance particularly favourable towards polymer materials (Suter et al., 2003).

4.1. Collectors

The assortment of applicable collectors for DBS is limited, as they are not always designed to be drained (Suter et al., 2003). For flat plate collectors, a downward pitch of the absorber channels is required. A meander flow pattern with safe slope (zig-zag) all the way is a solution (Hapgood, 1978; Hasenmaier, 2002; Leibfried, 2004) or a harp design with pitched header pipes (Hapgood, 1978; Hasenmaier, 2002). Double plate (Sandler, 2004; Rekstad, 2012; Leibbrandt et al., 2014) or roll bond (Wagner & Co. Solartechnik GmbH, 2006; Hermann, 2008) absorber flow patterns can easily be designed and manufactured for a safe draining. This also helps air venting in a glycol system and might be standard for all collectors in the near future. ETC may also be utilized in DB systems, with heat pipes (Perers et al., 2015) or with the manifold located at the bottom in case of direct flow (Frissora, 1981). Perers et al. (2015) also reported that monitored ETC did not show signs of degradation after hundreds of “dry” stagnation cycles.

The mounting is also an important issue, as a wrong slope direction causes water to stay in some parts of the collector and may lead to freeze damages. Remaining water can also create high steam pressures for some period, if it starts to boil during stagnation. This may push water out of the system via the safety valve and new water has to be refilled again (Andersen, 1988). Connecting several collectors together requires a specific attention to ensure a smooth functioning of the system. Collectors with outlet and/or return pipe located at the back are not suited for series connection. For parallel connection, it is preferable to minimize the length of the pipes connecting the collectors to the main pipe (Suter et al., 2003). Kaiser et al. (2013a) investigated several configurations with flat plate collectors and concluded that meander collectors connected in parallel is the most favourable option with regards to draining behaviour.

Furthermore the development of plastic collectors is often associated with DBS. The low pressure in the solar collector loop is indeed a strong advantage for the durability of polymer materials (Kahlen et al., 2010; Kaiser et al., 2013b). EPDM collectors have been tested in combination with the DB concept for a long time (Perers, 1988; Bertram et al., 2006). More recently, so-called engineering or high performance polymers have also been proposed (Kahlen et al., 2010; Rekstad, 2012).

4.2. Heat storage

Conventional heat storages are often used with DBS. However, the configuration with a load side heat exchanger offers the possibility to directly circulate the HTF from the storage in the solar collector loop. When open to the ambient, such systems are closely related to polymeric heat storage application, as most of them are pressureless tanks (Fischer et al., 2012). Materials such as PP (Brunold et al., 2012), EPDM rubber (Perers, 1988) or fibreglass (Bachmann et al., 2007) have already been tested in combination with DBS for storage. One of their main advantages pointed out by the authors, is their ease of installation in existing buildings, where large conventional stainless steel tanks can hardly be applied due to their non-flexible dimensions.

Combining DB and plain-carbon (mild) steel tanks is in any case not recommended (Frank et al., 2014), the inevitable presence of oxygen discussed before corroding the material (Bokhoven et al., 2001). Nevertheless resorting to such low cost materials is possible, in combination with an additional thin-film polymeric liner (Burch et al., 2005). With this solution, Kutscher et al. (1984) even proposed a wooden-based storage. A low-cost 2 m³ design with outer wooden board plates and 10 cm rigid polyurethane insulation with an EPDM rubber liner inside was successfully demonstrated in a DB system (Perers, 1988).

4.3. Drainback tank

The application of an external DB tank in collector-side heat exchanger configuration is a specificity of DBS hydraulics. Botpaev and Vajen (2014a) identified a significant plurality of designs for the reservoir on the market, where stainless steel and polymers are the most commonly used materials. The location of this tank is rather important as it was explained in section 2.3.5 as it determines the static head to be overcome by the pump (Vögelin, 2005; Mugnier et al., 2011). Seiler (1982) suggested mounting the DB tank parallel to the flow side, therefore there is no flow through this tank during operation mode. Van Dam and Overman (1994) integrated the DB tank at the bottom of the heat storage.

The DB tank must be able to store the total volume of HTF contained in the collectors and outside piping. In practice it needs to be over-dimensioned (Suter et al., 2003; Mugnier et al., 2011). Indeed, the water level in the DB tank plays an important role as it was highlighted in section 3.2 according to the works of ASHRAE (1990) and Botpaev and Vajen (2014b). The water level inside the tank should be regularly observed and maintained in the recommended range. For this purposes a sight glass is usually installed (Botpaev and Vajen, 2014a).

4.4. Pumps

Pump dimensioning and electric consumption has always been a special concern in DBS, due to the presence of the elevation head. The pump needs to overcome this static head at the start and during operation in case of a non-siphonic flow. A primary solution consisted in oversizing single speed centrifugal pumps, in order to overcome the elevation head and successfully accomplish the filling process; the pump is thus not always running at its optimum operating point (Tully, 1981a). One can also notice that for low-flow DBS the elevation head is an even sharper issue as the pump might at the same time enable a high lift head but with a low-flow operation range. No research has been found in this direction. On the contrary, DBS with water as HTF contribute to reduce the pump energy consumption during operation, due to a lower viscosity of water compared to glycol mixtures (Eisenmann et al., 2003; Suter et al., 2003). Detailed comparisons on this issue still need to be carried out.

Kutscher et al. (1984) analysed the pump efficiency, the operating conditions and the strategies to decrease parasitic energy consumption. The authors reported several ways to reduce operating costs, either by using more efficient pumps, applying a two-speed pump, two pumps in series or by modulating the speed of the pump with a controller. Tully (1981a) uses also several identical pumps in series and turns one off when the filling phase is terminated. Circulating a fluid through a shut-off pump might however lead to faster degradation, which has to be clarified. The ratio of the solar energy yields to the electricity consumption of the pumps was experimentally calculated by Muntwyler (2006) in a system with a start “booster” pump and a circulation pump in series. The evaluated DBS with collector area between 5 and 15 m² produced between 10.4 and 24.8 times more energy than the energy consumption of the pumps, depending if the booster pump was stopped or not after the filling process. In the former case, the booster pump was running only 2.5% of the time. Some authors also emphasized the necessity to respect the NPSH of the pump to avoid cavitation, as most DBS are unpressurized (Suter et al., 2003). This height is given by the water level in the DB volume (Mugnier et al., 2011).

Positive displacement pumps could be an alternative to conventional centrifugal pumps. They provide a nearly constant flow rate at fixed speed, regardless of the system pressure or head. Buderus Heiztechnik GmbH (2000) presented such a solution but added a particles filter to avoid the blocking of the pump. The filter additionally reduces the noise level, which is one of the drawbacks of these pumps. A further drawback is that they do not allow back-flow in comparison with conventional centrifugal pumps. A by-pass with a check valve is a solution in such case (Suter et al., 2003). Finally Mugnier et al. (2011) proposed as alternative to the two pump types described above the use of air cooled pumps.

4.5. Heat transfer fluid

As detailed in section 2.1, one of the interests of DBS is the possibility to use water as HTF even in cold climates. Corrosion being an important issue with DBS, the use of inhibited or distilled water might be a solution (Kutscher, 1985).

Nevertheless, there is a tendency to employ glycol/water mixture also for DBS, in order to prevent costly damages caused by installation mistakes (Thiesen, 2009; Mugnier et al., 2011; Frank et al., 2014). Experience shows that glycol does not noticeably deteriorate in DBS (Frank et al., 2014). Glycol decomposition at high temperature in non-DB systems leads to the formation of corrosive products, requiring its replacement (Goumaz and Duff, 1981).

4.6. Piping

4.6.1. Materials

The large majority of SWH systems are currently built with copper pipes (Hudon et al., 2012). For DBS, the use of plastic material for piping has also been presented as advantageous notably in order to achieve cost reductions. Polybutylene (PB), chlorinated polyvinyl chloride (CPVC) (Kutscher et al., 1984) and more recently cross-linked polyethylene (PEX) (NABCEP, 2012) have been proposed for use in combination with DBS. One of the main issues with these polymers is their maximum continuous temperature withstanding capacity, in the range of 82-99 °C depending on the materials (Kutscher et al., 1984; Hudon et al., 2012; NABCEP, 2012). Other drawbacks mentioned by these authors are the low UV stability, the higher risk of sagging (depending on mechanical properties) and the performance of the fittings, not always made in an appropriate material. Corrugated stainless steel pipes might be used too; however their flexibility also increases the risk of water pockets creation and therefore problems with draining and filling of the system (Perers et al., 2015). As with plastic, the risk of sagging can be reduced by decreasing the spacing between the supports (Kutscher et al., 1984), obviously increasing the costs. Another solution is to develop frost withstanding materials. Recent research showed that some PEX pipes are able to resist at least 500 freezing cycles (Hudon et al., 2012). Further investigations to understand the real causes of freeze damages could help developing safe prevention methods in this direction.

With plastic pipes, there is the necessity of a metallic transition pipe between the collectors and the main piping to avoid damages during collector stagnation. The Solar Rating & Certification Corporation (SRCC) recommends a minimum of 0.9 m of uninsulated copper pipe (NABCEP, 2012) as transition with PEX, while detailed heat balances from (Kutscher et al., 1984) showed that for a stagnation temperature of 200 °C, 0.33 m of uninsulated copper pipe, or 0.78 m of insulated copper pipe are enough to avoid critical temperatures along the plastic pipe. The latter solution is preferable to limit heat losses.

4.6.2. Slope

The recommended minimal slope of the piping in order to favour the draining was summarized by Botpaev and Vajen (2014a). Based on the values given, one can notice that the proposed range is wide, from 1 cm/m (Bokhoven et al., 2001; Suter et al., 2003) to 10 cm/m as given by an Australian company (Rheem, 2012). Boye-Hansen and Furbo (1995) and Botpaev et al. (2014) even noticed that horizontal pipes would not hamper the draining. They also highlighted that a small amount of water always remains in the hydraulics.

This necessity to build systems with continuous slope is certainly one of the main barriers for DBS, as installers are not always aware of the specific issues at stakes with DBS (Suter et al., 2003; Frank et al., 2014).

4.6.3. Dimensioning

The strategies for dimensioning the pipes are very important for the filling and draining processes as described in section 3. They can widely differ depending on the authors. The critical part in the system is the flow pipe, which

should not be too small, or it would hinder the draining but also not too large so that the HTF flow is able to completely remove the air at the start (Suter et al., 2003). The same authors note that in practice a good compromise is a flow pipe with a diameter one size smaller than the return pipe.

On the contrary, for large systems with several rows connected in parallel, the siphon effect has to be prevented for faster draining and equal flow distribution in the different rows. Kratz and Van Dam (1999) recommend therefore to oversize the flow pipe in order to maintain a mixed air-water flow in the downcomer.

4.7. Control units

Similarly to SWH systems, DBS can be controlled in different manners. Some are based on pure temperature measurements (Tully, 1981a; Boye-Hansen and Furbo, 1995) while other prefer a combination of irradiation and temperature data (Mugnier et al., 2011). In all cases, the control of the pump(s) is based on a hysteresis function, the temperature (or irradiation) difference (or threshold value) at start being higher than for shut-off. Boye-Hansen and Furbo (1995) recommend for instance a start temperature difference of 10 K and turn the system off when it falls down to 2 K.

Due to the peculiarity of DBS and the necessity to overcome the static head at the start, it is common that the pump(s) is (are) started at a high speed, which is then decreased. The length of the start phase varies depending on the system, but is usually rather short, 30 s (Boye-Hansen and Furbo, 1995) or 3 min as revealed in Muntwyler (2006). In order to optimally control DBS at start, Dietz (2006) came up with a control based on the measurement of the filling time with a temperature sensor in the flow side, potentially enabling to adapt the length of the start phase for any system.

Qin (1997) reported that for a system where it was not possible to get completely rid of air in the collectors a control strategy consisting in stopping the pump 20 s every 15 min was applied. The efficiency of this method was however not further documented.

5. Conclusions

This review showed the availability of a limited number of studies concerning DBS. Findings of appropriate literature in scientific journals have not been satisfactory as only few papers on DBS are published. Patents, on the contrary, have been found to be the largest source of useful publications on DB. Numerous designs of DB/DD systems have been proposed during the last decades. All are active systems with the exception of the DD thermosiphon system. Currently, there are at least 50 different configurations of DBS available on the global market and most of them are indirect systems with a preference for collector-side heat exchangers.

The nature of the DB concept renders its operation quite different from standard pressurised solar heating systems. Three operating modes: filling, operation and draining, are key features of a DBS. Whereas the complete filling of the entire hydraulics ensures a proper system operation, a failsafe draining guarantees the safety of the system. From the filling side, air “cleaning” velocities for siphon establishment were investigated several times in the literature, showing non-homogeneous results. However, siphonic filling can be problematic for large systems with many parallel loops. Therefore, a filling without siphon formation has been proposed in this respect. The operation itself also requires careful attention, especially because of the typical underpressure at the top of the hydraulics, and in order to avoid air entrainment through the pump(s), valves and pipe joints. Concerning the draining, several technical solutions have been developed such as the presence of a hole in the flow pipe, the use of a branched pipe, or a vacuum breaker. In addition to theory, these processes are highly influenced by parameters such as the pressure drop, the piping design and the reliable air venting of the collector loop. The mounting with continuous slope and

close enough fixing that avoid sagging over time are also suggested as important. This requires specific learning and training packages for installers and designers.

The review revealed that research on DBS is often linked with the development of new components or solar heating systems as a whole. The unpressurised solar collector loop and the use of water as HTF offer unique opportunities. Simpler hydraulic designs are notably enabled as well as the utilization of cheap materials such as polymers. It was however also highlighted that all standard solar components are not compatible with the DB design as they might hamper a proper draining.

Going through this in-depth review, several issues which have barely or insufficiently been addressed were identified. The development of components specifically designed for DB applications is necessary if the technology wishes to become more widely adopted. In this regard, drainable collectors (especially for large systems) as well as appropriate pumps require more attention. Another field concerns the physical phenomena at stakes during the filling, operation, and draining stages of a DBS. Further research should be carried out for a deeper understanding of their features. It would also benefit DBS to develop methods to evaluate the draining behaviour of the system - both after commissioning and during maintenance. It is to emphasize that no specific study has been found concerning the durability of DBS. The impact of long stagnation periods on the collectors remains one aspect that could be investigated. More specifically for open systems, the risks of corrosion or organic matter formation should be further explored.

Cost reduction and durability enhancement of solar heating systems through hydraulics and the application of new components and materials have been and remain the main “driving force” of research interest in DB. The few publications focusing on the actual cost reductions enabled by DBS suggest that the potential for cost performance improvement is significant. As this topic is vital for the solar thermal field, there should be an enhanced interest in this technology, which might gain market shares in the future.

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References

- Andersen, N.B., 1988. Solvarmeanlæg til rumopvarming og varmt brugsvand - Demonstrationsanlægget i Ejby. Thermal Insulation Laboratory, Technical University of Denmark. Report 189, Lyngby, Denmark.
- ASHRAE, 1990. Guide for Preparing Active Solar Heating Systems Operation and Maintenance Manuals. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc., Atlanta, Georgia, USA.
- Atkinson, E., 2012. Simplified drain back system for solar water heating. GB2491568 (A).
- Baardman, M., 1979. Solar energy system. EP0000803 (A1).
- Bachmann, S., Drück, H., Müller-Steinhagen, H., 2007. Vorstellung und Untersuchung eines neuen Konzepts für große Warmwasserspeicher. 17. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Bailey, W.J., 1917. Solar Heater. US1242511 (A).
- Beasley, R.J.E., 1982. Solar powered heating apparatus. GB2090963 (A).
- Bertram, E., Eisenmann, W., Hofmann, F., 2006. Metalldach-Sonnenkollektoren nach den EMA-Prinzip: Messergebnisse aus der Pilotanlage Freibad Nordstemmen. 16. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Bliss, J.R.W., 1958. Solar water heating system. US2838043 (A).

- Bokhoven, T.P., Van Dam, J., Kratz, P., 2001. Recent experience with large solar thermal systems in The Netherlands. *Sol. Energy* 71, 347–352. doi:10.1016/S0038-092X(00)00124-9
- Bony, J., Renoult, O., 1999. Installations solaires combinées pour villas : optimisation eau chaude, chauffage et climatisation. Haute École Spécialisée de Suisse Occidentale - École d'ingénieurs du Canton de Vaud, Yverdon-les-Bains, Switzerland.
- Botpaev, R., Orozaliev, J., Vajen, K., 2014. Experimental Investigation of the Filling and Draining Processes of the Drainback System (Part 1). *Energy Procedia*, 2013 ISES Solar World Congress 57, 2467–2476. doi:10.1016/j.egypro.2014.10.256
- Botpaev, R., Vajen, K., 2014a. Drainback systems: market overview. 11. Internationale Konferenz für solares Heizen und Kühlen, Gleisdorf, Austria.
- Botpaev, R., Vajen, K., 2014b. Experimental investigation of the filling and draining processes of the drainback system (Part 2). *Proceedings of the EuroSun 2014 Conference*, Aix-les-Bains, France.
- Boye-Hansen, L., Furbo, S., 1995. Solvarmeanlæg med tømning. Thermal Insulation Laboratory, Technical University of Denmark. Report 275, Lyngby, Denmark.
- Brunold, S., Papillon, P., Plaschkes, M., Rekstad, J., Wilhelms, C., 2012. Collectors and Heat Stores, in: Köhl, M., Meir, M.G., Papillon, P., Wallner, G.M., Saile, S. (Eds.), *Polymeric Materials for Solar Thermal Applications*. Wiley-VCH, Weinheim, Germany, pp. 301–317.
- Buderus Heiztechnik GmbH, 2001. Anlage zur Gewinnung von Wärme aus Sonnenenergie. DE20015689 (U1).
- Buderus Heiztechnik GmbH, 2000. Einer Zahnradpumpe vorgeschalteter Feststoffabscheider. DE20009140 (U1).
- Bunksolar, 2014. Bunksolar [WWW Document]. URL <http://bunksolar.com/> (accessed 12.30.14).
- Burch, J., Salasovich, J., 2005. Water consumption from freeze protection valves for solar water heating systems. *Proceedings of the 2005 Solar World Congress Bringing Water to the World*, Orlando, Florida, USA.
- Burch, J., Salasovich, J., Hillman, T., 2005. Cold-climate solar domestic water heating systems: life-cycle analyses and opportunities for cost reduction. *Proceedings of the 2005 Solar World Congress Bringing Water to the World*, Orlando, Florida, USA.
- Busch, D., Mitlacher, W., Schöpfer, H., 1979. Solarheizungsanlage als offenes System mit Entleer- und Ausdehnungsgefäß. DE2753756 (A1).
- Cartland, W.H., 1979. Solar heater freeze protection system. US4138996 (A).
- Christenson, B.O., 1949. Condition control system. US2469496 (A).
- Consolar, 2014. Consolar - High Efficiency Solar Systems [WWW Document]. URL <http://www.consolar.de/en/> (accessed 12.10.14).
- Cronin, P.W., Ottmar, P.H., Root, E.F., Simmons, H.M., 1977. Solar collector automatic freeze protection system. US4044754 (A).
- Dietz, E., 2006. Drain-Back-Solaranlage. DE102004042866 (A1).
- Dong, D., 2010. Anti-freezing intelligent drainage system for solar pipe in winter. CN101858654 (A).
- Duval, E.F., Bagshaw, D.P., Kast, M.A., Masters, G.M., Whitehouse, H.T., 1981. Freeze protection apparatus for solar collectors. US4280478 (A).
- Eisenmann, W., Vajen, K., Ackermann, H., 2003. Optimization of the material content of parallel flow flat-plate solar collector absorbers using a nomograph representation. *Proceedings of the ISES Solar World Congress 2003*, Göteborg, Sweden.
- Embree, J.M., 1981. Closed pressurized solar heating system with automatic valveless solar collector drain-back. US4269167 (A).
- Embree, J.M., 1980. Closed pressurized solar heating system with automatic solar collector drain-down. US4237862 (A).
- ESTIF, 2003. Sun in Action II – A Solar Thermal Strategy for Europe (Volume 2: The Solar Thermal Sector Country by Country - 21 National Reports). Uwe Brechlin, Ole Pilgaard, Raffaele Piria, Brussels, Belgium.
- Eurometaal N.V., 1983. Warmteaccumulator met expansievat. NL8102798 (A).
- Fischer, S., Drück, H., Bachmann, S., Streicher, E., Ullmann, J., Traub, B., 2012. Conventional Collectors, Heat Stores, and Coatings, in: Köhl, M., Meir, M.G., Papillon, P., Wallner, G.M., Saile, S. (Eds.), *Polymeric Materials for Solar Thermal Applications*. Wiley-VCH, Weinheim, Germany, pp. 73–106.
- Fossum, R.L., Fossum, M.J., 1996. Solar thermal water heating system. US5575276 (A).

- Frank, E., Mauthner, F., Fischer, S., 2014. Overheating prevention and stagnation handling in solar process heat applications. IEA SHC Task 49 - Solar Process Heat for Production and Advanced Applications, Institut für Solartechnik SPF, Rapperswil, Switzerland.
- Frissora, J.R., 1981. Drainable solar collector apparatus. US4262658 (A).
- Furbo, S., 2003. European Regulations and Recommendations for Separation between Solar Collector Fluids and Domestic Water. Byg. DTU, Lyngby, Denmark.
- Furbo, S., 1987. Fordele ved små volumenstrømme i solvarmeanlæg. Måling på tre små brugsvandsanlæg. Thermal Insulation Laboratory, Technical University of Denmark. Report 188, Lyngby, Denmark.
- Fuxian, S., 2013. Solar water heater pipeline emptying device. CN203249416 (U).
- Gößlinghoff, C.-H., 2010. Solaranlage mit Drain-Back-System und ein Verfahren zum Betreiben einer solchen. EP2246643 (A2).
- Gould, J.A., 1930. Solar water heater. US1747826 (A).
- Goumaz, J.Y., Duff, W.S., 1981. Comparison of drain-back and dual liquid solar heating and domestic hot water systems. David O. Hall, June Morton, Proceedings of the International Solar Energy Society Congress, Brighton, England, pp. 372–379.
- Haberl, R., Frank, E., Vogelsanger, P., 2008. Cost/Benefit Ratio Analysis of a Maximum Lean Solar Combisystem. Proceedings of the EuroSun 2008 Conference, Lisbon, Portugal.
- Haberl, R., Vogelsanger, P., 2008. Simulation and Optimization Report – MaxLean Concept. IEA-SHC-Task 32.
- Hapgood, W.H., 1978. Solar heating system. US4122830 (A).
- Harrison, S., Cruickshank, C.A., 2012. A review of strategies for the control of high temperature stagnation in solar collectors and systems. Energy Procedia, 1st International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2012) 30, 793–804. doi:10.1016/j.egypro.2012.11.090
- Hasenmaier, J., 2002. Absorber für Sonnenkollektor. DE10047823 (A1).
- Hastings, R., 2005. Zeitreise durch die Solararchitektur. 15. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Hausner, R., Fink, C., Wagner, W., Riva, R., Hillerns, F., 2003. Entwicklung von thermischen Solarsystemen mit unproblematischem Stagnationsverhalten. AEE Intec, Tyforop Chemie GmbH, Gleisdorf, Austria.
- Hayes, W.R., Shikasho, S., 1977. Solar heating/cooling system. US4027821 (A).
- Helgeson, A., Krohn, P., Larsson, S., Perers, B., 2000. Evaluation of three solar heating systems. Proceedings of the third ISES Europe Solar Congress EuroSun 2000, Copenhagen, Denmark.
- Hermann, M., 2008. Development of solar collectors with FracTherm® aluminium roll-bond absorber. Proceedings of the EuroSun 2008 Conference, Lisbon, Portugal.
- Hirshberg, A.S., 1981. Cost reduction opportunities: Residential Solar Systems. Booz-Allen and Hamilton Inc., Bethesda, Maryland, USA.
- Hollands, K.G.T., Lightstone, M.F., 1989. A review of low-flow, stratified-tank solar water heating systems. Sol. Energy 43, 97–105. doi:10.1016/0038-092X(89)90151-5
- Honikman, T.C., 1979. Freeze protection for solar heating systems. US4133338 (A).
- Hou, X., 2012. Solar freeze-proofing water saver and solar energy equipment. CN202371915 (U).
- Hudon, K., Merrigan, T., Burch, J., Maguire, J., 2012. Low-Cost Solar Water Heating Research and Development Roadmap. National Renewable Energy Laboratory (NREL), Golden, Colorado, USA.
- ISO, 1999. ISO 9488:1999 (E/F) Solar energy - Vocabulary. International Organization for Standardization (ISO), Genève, Switzerland.
- Jack, S., Föste, S., Schiebler, B., Giovannetti, F., 2014. Neuartige Kollektoren mit Wärmerohren zur Begrenzung der Stagnationstemperatur und Reduzierung der Systemkosten. 24. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Jichang, K., 2007. Solar water-heater drainage device. CN2896138 (Y).
- Jorgensen, G.J., 1984. A Summary and Assessment of Historical Reliability and Maintainability Data for Active Solar Hot Water and Space Conditioning Systems. Solar Energy Research Institute (SERI), Golden, Colorado, USA.
- Kahlen, S., Wallner, G.M., Lang, R.W., 2010. Aging behavior of polymeric solar absorber materials – Part 1: Engineering plastics. Sol. Energy 84, 1567–1576. doi:10.1016/j.solener.2010.03.021

- Kaiser, A., Fink, C., Hausner, R., Altenburger, F., Buchinger, R., Riva, R., Schubert, M., 2013a. Selbstentleerende Kollektorsysteme zur Vermeidung von Stagnationsproblemen in großen solarthermischen Anlagen. 23. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Kaiser, A., Fink, C., Hausner, R., Ramschak, T., Streicher, W., Lang, R., Wallner, G., 2013b. Leistungsanforderungen an Polymermaterialien in solarthermischen Systemen. 23. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Kosok, J., 2013. Method for operating a fluid-conducting device. WO2013076203 (A1).
- Kratz, P., Van Dam, J., 1999. Method for starting a system of multiple solar collectors. EP0959309 (A1).
- Krumpe, A., 1978. Automatisches Füllen und Entleeren bei Sonnenkollektoren. DE2614142 (A1).
- Kusyy, O., Vajen, K., 2011. Theoretical investigation on a control-based approach to avoid stagnation of solar heating systems. Proceedings of the ISES Solar World Congress 2011, Kassel, Germany.
- Kutscher, C., 1985. Low Cost Solar Water and Space Heating Systems. Solar Energy Research Institute (SERI), Golden, Colorado, USA.
- Kutscher, C., 1984. Survey of Failure Modes from 122 Residential Solar Water Heaters. Solar Energy Research Institute (SERI), Golden, Colorado, USA.
- Kutscher, C., Davenport, R., Farrington, R., Jorgensen, G., Lewandowski, A., Vineyard, C., 1984. Low-Cost Collectors / Systems Development Progress Report. Solar Energy Research Institute (SERI), Golden, Colorado, USA.
- Lauchlan, C.S., Escameia, M., May, R.W.P., Burrows, R., Gahan, C., 2005. Air in Pipelines, A Literature Review. HR Wallingford.
- Leibbrandt, P., Schabbach, T., Weber, K., 2014. Flachkollektoren aus Glas - Erste Untersuchungsergebnisse. 24. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Leibfried, U., 2004. Leerlaufender Sonnenkollektor. EP1413835 (A2).
- Leibfried, U., Strok, H., 2005. SOLAR PUR: Solare Heizungsunterstützung mit reinem Wasser. 15. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Magen eco-Energy, 2014. Magen eco-Energy [WWW Document]. URL <http://www.magen-ecoenergy.com/> (accessed 12.29.14).
- Menicucci, D., 2011. Report on the Analysis of Field Data Relating to the Reliability of Solar Hot Water Systems. Sandia National Laboratories, Albuquerque, New Mexico and Livermore, California, USA.
- Meucht, B., 1994. Thermostatischer Frostschutz für Solaranlagen. DE4318480 (A1).
- Mikkelsen, S.E., 1988. Projektering af større Solfangeranlæg - Systemudformninger og diagrammer til beregning af ydelse og tab. Thermal Insulation Laboratory, Technical University of Denmark. Report 194, Lyngby, Denmark.
- Morrison, G.L., Rosengarten, G., Behnia, M., 1999. Modelling Thermosyphon Solar Water Heaters with Mantle Collector-Loop Heat Exchangers. Proceedings of the ISES Solar World Congress 1999, Vol. III, Jerusalem, Israel, pp. 236–244.
- Mugnier, D., Casals, L., Siré, R., Denn, A.L., 2011. Drainback systems as an efficient and safe solution for solar DHW installations: practical experience. Proceedings of the ISES Solar World Congress 2011, Kassel, Germany, pp. 621–632.
- Muntwyler, U.W., 2006. Projekt Drain-Back-Kompaktanlagen. Muntwyler Energietechnik AG, Zollikofen, Switzerland.
- NABCEP, 2012. Solar Heating Installer Resource Guide. North American Board of Certified Energy Practitioners, Clifton Park, New York, USA.
- Norbäck, K., Holst, P., Kjaerboe, P., Svensson, J., 1984. Utvärdering av solvärmecentraler i Lambohov. Statens råd för byggnadsforskning: Sv. byggtjänst (distr.), Stockholm, Sweden.
- Oquidam, B., 1980. Procédé et dispositif perfectionnés pour la préparation d'eau chaude à partir de l'énergie solaire. FR2432688 (A1).
- Patterson, J., 2005. Solar collector with integral drain back reservoir. US2005217664 (A1).
- Pei, Y.K., 1982. Solar energy collector assembly. US4319561 (A).
- Perers, B., 1988. Solvärt tappvatten för Rosvalla idrottsplats - Utvärderingsresultat 1987. Byggeforskningsrådet, Nyköping, Sweden.

- Perers, B., Furbo, S., Fan, J., Kong, W., Chen, Z., 2015. Drain Back Systems in Laboratory and in Practice. *Energy Procedia*, International Conference on Solar Heating and Cooling for Buildings and Industry, SHC 2014 70, 300–310. doi:10.1016/j.egypro.2015.02.127
- Pothof, I.W.M., Clemens, F.H.L.R., 2011. Experimental study of air–water flow in downward sloping pipes. *Int. J. Multiph. Flow* 37, 278–292. doi:10.1016/j.ijmultiphaseflow.2010.10.006
- Pott, M., Schicke, S., Severin, S., Wieringen, B. van, 2013. auroFlow plus - Stagnationsvermeidung bei Solarsystemen. 23. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Prieur, J.-P., 1980a. Procédé et installation de chauffage d’eau utilisant un capteur solaire. FR2435006 (A2).
- Prieur, J.-P., 1980b. Procédé et installation de chauffage d’eau utilisant un capteur solaire. FR2443029 (A1).
- Qin, L., 1997. Test and simulation of drain-back solar DHW system from SolarNor AS, Norway. Department of Buildings and Energy, Technical University of Denmark. Report SR-9724, Lyngby, Denmark.
- Rekstad, J., 2012. Arrangement for a Solar Collector Plate, Solar Collector Plate, Solar Collector Module, and Solar Collector System. WO2012067515 (A1).
- Rheem, 2012. Owners Guide and Installation Instructions - Rheem Heat Store Series 2 Commercial Drain Back Solar [WWW Document]. URL <http://www.rheem.com.au/Assets/1596/1/RheemHeatStore2OwnersGuide-Body36-7019RevA-May2012.pdf> (accessed 8.5.14).
- Roseen, R., Perers, B., 1980. A solar heating plant in Studsvik - Design and first-year operational performance. Swedish Council for Building Research, Stockholm, Sweden.
- Rühling, K., Heymann, M., Panitz, F., Rosemann, T., Wagner, M., 2013. Entgasung von Solarkreisläufen und Bestimmung der zur Auslegung erforderlichen Stoffdaten. Institut für Energietechnik, Dresden, Germany.
- Sandler, M., 2004. Vollflächig durchströmter Solarabsorber mit Schlitzeströmung und integrierten Sammelleitungen. 14. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Schabbach, T., Leibbrandt, P., 2014. Solarthermie: wie Sonne zu Wärme wird, Technik im Fokus. Springer Vieweg, Berlin.
- Schabbach, T., Wagner, A., 2003. Solaranlage. EP1363081 (A2).
- Schalajda, P., Leibfried, U., 2002. Luftabscheider und Leerlaufhilfe für Solaranlagen ohne Frostschutzmittel. DE20206564 (U1).
- Scharf, F., Kehl, A., Abele, H., Hahne, J., Peter, E., Reicherter, P., Schmidt, E., 1980. Einrichtung zum Bereiten von warmem Brauchwasser. DE2837565 (A1).
- Seiler, E.N., 1982. Solar heating freeze protection system. US4336792 (A).
- Stork, H., Siegemund, A., 2001. Solar Pur - Ein Solarsystem ohne Frostschutz für die solare Heizung. 11. Symposium Thermische Solarenergie, Bad Staffelstein, Germany.
- Suter, J.-M., Kovács, P., Hausner, R., Visser, H., Peter, M., 2003. Durability and reliability of solar combisystems, in: Weiss, W. (Ed.), *Solar Heating Systems for Houses - A Design Handbook for Solar Combisystems*. Solar Heating and Cooling Executive Committee of the International Energy Agency (IEA), London, UK, pp. 163–190.
- Thiesen, S., 2009. Simple and Safe Solar Heating: A Whole Systems Approach. *Pac. J. Sci. Technol.* 10, 117–122.
- Tully, G., 1981a. Drainback space heating systems: simple, reliable and easy to repair 16–19, 44.
- Tully, G., 1981b. Solar heating systems: analysis and design with the Sun-Pulse method, *An Energy learning systems book*. McGraw-Hill, New York.
- Van Dam, J., 2009. Device for Exchanging Energy, Methods for Use Thereof, Control for Such a Device, and Methods for Improving Devices for Exchanging Energy. WO2009122289 (A2).
- Van Dam, J., Overman, P.T.J., 1994. A device for storing solar energy. EP0616174 (A1).
- Visser, H., Peter, M., 2003. Drainback technology. *Ind.-Newsl. IEA SHC - Task 26* 11–13.
- Vögelin, D., 2014. <http://www.voegelin.ch/> [WWW Document]. URL <http://www.voegelin.ch/kontakt-voegelin.html> (accessed 8.5.14).
- Vögelin, D., 2005. Solar installation. WO2005059445 (A1).
- Wagner & Co. Solartechnik GmbH, 2006. Solarkollektorsystem. DE202006016100 (U1).