INVESTIGATION OF SELECTED SOLAR PROCESS HEAT APPLICATIONS REGARDING THEIR TECHNICAL REQUIRMENTS FOR SYSTEM INTEGRATION

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1. Introduction

Many studies have been carried out for different countries or regions to estimate the potential for the utilization of solar heat for industrial processes (Vannoni et al., 2008). All studies arrive at the conclusion that the industrial sector is one of the most promising application areas for solar heating systems within the near future. This is based on the facts that the industry sector accounts for a large amount of consumed thermal energy with a relatively continuous demand over the year and a reasonable share at a temperature range below 150 °C. A recent potential study for Germany (Lauterbach et al., 2011a) showed the large number of industry sectors and processes that seem to be suitable for the integration of solar heating systems. Besides industry sectors in general that have with a significant heat demand below 150 °C, processes such as cleaning, washing, pre-heating, etc. were identified as promising application areas for the supply of solar process heat. Based on the research findings of the last years, Heß and Oliva (2010) tried to identify priority applications within a recently published planning guideline for solar process heat systems, to simplify the planning procedure for solar process heat systems with respect to dimensioning.

Although many industry sectors and processes have been classified as promising for the implementation of solar process heat systems, most considerations for the integration of solar heating systems are based on theoretical assumptions such as overall heat demand, temperature level and monthly production rates or on experiences of single demonstration plants. However, to estimate the feasibility for the supply of solar process heat, relevant boundary conditions of selected processes have to be identified and analyzed. These boundary conditions are important to estimate the future development and distribution of solar heating systems within the industry sector and can show the opportunities and constrains of this application area.

This paper gives an overview of technical requirements for the integration of solar heating systems in industrial applications. Since there are various possibilities for the integration of solar heating systems, it is reasonable to classify those possibilities to identify important boundary conditions. Therefore, a distinction is drawn between system integration on supply level and system integration on process level. After a definition and specification of those levels, the influence of boundary conditions on system integration is exemplified by selected applications.

2. Principles of system integration

There are different possibilities for the integration of solar heating systems to provide process heat. Basically, the integration on supply level can be distinguished from integration on process level. Industrial companies with a significant heat demand typically have a central boiler house, which supplies thermal energy for different processes. Mainly natural gas and heating oil are used within the boiler house to generate hot water or steam. Sometimes other fuels such as coal, biomass or organic residues are used. The heat generated by a boiler is usually fed into a central heat distribution network (mostly steam or hot water circuit). The steam or hot water circuit is able to supply all processes with the required thermal energy. Therefore, heat exchangers are connected to the heat distribution network.

Figure 1 illustrates the heat distribution network of a virtual company in a simplified way. In this example, all processes are heated by a steam circuit with a flow temperature of 165 °C (equivalent to 7 bar). Most processes have a heat exchanger and if necessary a pressure reducing valve to reduce the steam temperature. The condensed steam is collected and returned to the boiler house by an open condensate line with a mean temperature of 90 °C. Based on the respective boundary conditions it is also possible to heat a process without a heat exchanger e.g. for washing processes steam can be directly injected into cold water to reach the set temperature. In this case, not only the energy content of the steam is used, but also the mass, whereby no condensate can be returned to the boiler house (Process A).

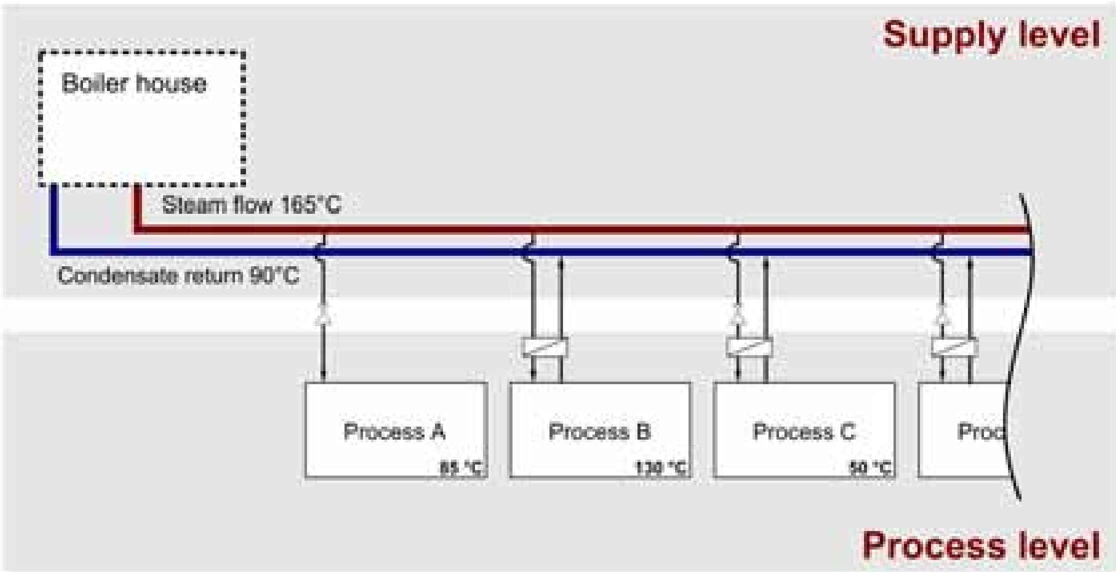

Fig. 1: Distinction between supply and process level

Depending on whether solar energy is used in the boiler house or directly to heat a specific process, the integration of the solar heating system is assigned to process or supply level. Both levels of system integration have different characteristics, advantages and disadvantages that will be explained within the next subchapters.

2.1. System integration on supply level

Referring to the integration of solar heating systems, the supply level includes the generation and distribution of thermal energy. Major differences within the supply level may arise through the utilization of different energy sources or heat distribution media. Oil or gas fired boilers are most commonly used to generate hot water or steam. Steam is usually used as heat distribution medium for temperature requirements above 100 °C. However, it is also possible to supply temperatures up to 240 °C with pressurized hot water circuits. Standard hot water cycles might be used if there are no processes that require temperatures above 100 °C.

The processes with the highest temperature demand determine the flow temperature provided by the boiler. The dimensions of the hot water or steam circuit also have a major impact, since long piping and large amount of armatures cause thermal losses that reduce the temperature of the heat distribution medium. Usually, the centralized heat generation in the boiler house also supplies heat for domestic hot water generation and space heating. However, it is also possible to find several heat supply systems with different technologies that provide heat at different temperature levels for the respective applications.

Regarding the integration of solar heating systems on supply level, a distinction can be drawn between (pressurized) hot water systems and steam circuits. A pressurized hot water system consists mainly of a boiler that heats the return of the water circuit. This circuit is usually closed and no water leaves the system. The solar heating system can either increase the return temperature right before the boiler by a serial connection or supply hot water with the required flow temperature that is fed into the flow parallel to the boiler.

Gas or oil fired steam systems are more widespread in industrial companies than (pressurized) hot water systems. The process of steam generation starts with the condensate return. The accumulated condensate can be returned to the boiler house with a pressure of 2..5 bar. In this case, the condensate equals the boiler feed water and enters the boiler directly to be heated and evaporated. This is comparable with the pressurized hot water cycle described before. However, 90 % of all condensate systems are not operated at overpressure (Sattler and Schibel 2011). Figure 2 shows all important installations that can be found in the boiler house for steam generation with open condensate systems. Since the condensate within those open systems gets in contact with the environment, it has to be treated before entering the steam boiler. This process is called degasification. The degasification takes place at ambient pressure with 95 °C or with slight overpressure at 105 °C. Therefore, a small amount of steam is used to heat the condensate to the required temperature to remove oxygen, carbon dioxide and other gases. After degasification the so-called feed water enters the boiler for steam generation.

A continuous loss of condensate is another important characteristic of open condensate systems. Flash vaporization occurs in different sections of the network due to ambient contact and causes mass losses in the range of 5..15 %. This depends on the respective pressure range (Sattler and Schibel 2011). Additional losses can occur if processes are heated directly by steam injection. These losses can vary from a few percent up to a large share of the overall amount of condensate and have to be compensated with so-called make-up water. This is raw water (surface-, well- or tap water) that passes through a softening process to remove alkaline earths before entering the degasification (Ernst 2009).

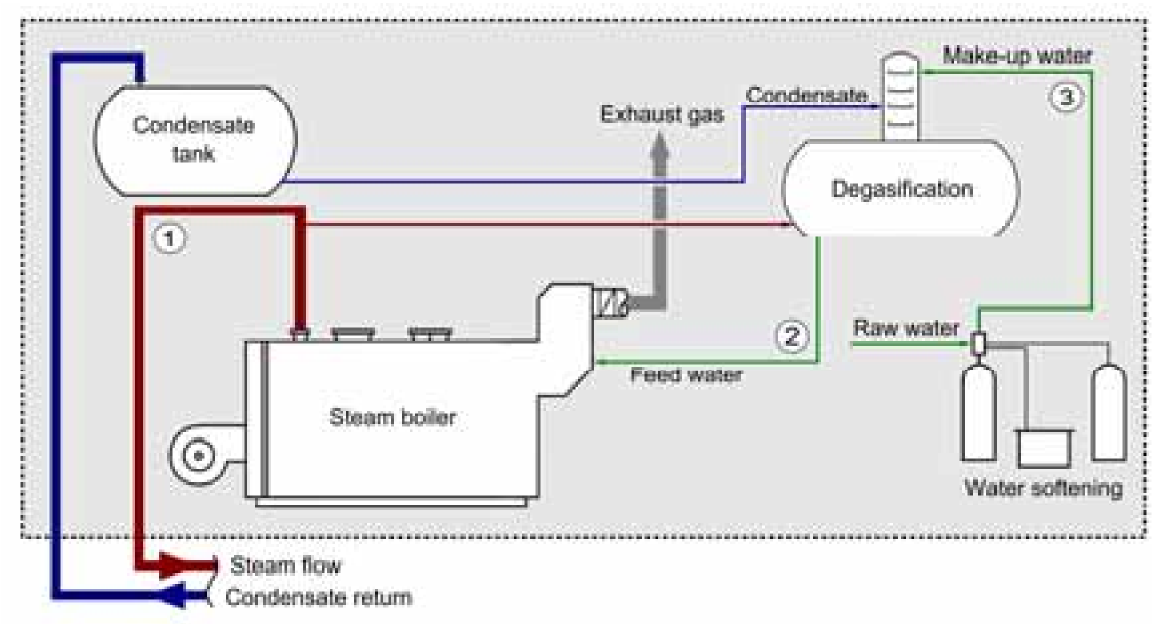

Fig. 2: Relevant components of a steam boiler house. Simplified illustration based on (Sattler and Schibel 2011)

According to Figure 2 there are three possibilities to integrate a solar heating system on supply level to assist the steam generation. The first possibility (number 1) is the parallel integration of a solar heating system to generate and feed-in steam. Secondly, the increase of the feed water temperature seems reasonable. After degasification the feed water can be heated from approx. 100 °C up to 150 °C, depending on the steam pressure that is produced within the boiler. If there is an appropriate amount of make-up water, the third possibility is the pre-heating of make-up water before it enters the degasification.

Besides the heating of make-up water, all integration alternatives on supply level come along with high set temperatures that have to be provided by the solar heating system. The minimum set temperature for the solar heating system is approximately 100 °C, and can easily exceed 200 °C, based on the respective system concept (parallel or serial integration) and the boundary conditions of the heat generation and supply system (hot water or steam circuit, open or closed condensate system, etc.) Therefore, the integration on supply level should only be realized in regions with very good irradiation.

2.2. System integration on process level

The integration of solar heating systems on process level can hardly be generalized, since there is a multitude of processes with varying installations and temperature demands. Solar energy can be used directly for one or more processes, at temperatures below the return temperature of the heat distribution network. Therefore, the supply of solar heat on process level generally comes along with lower temperatures compared to integration on supply level. Figure 3 shows exemplary three processes of a brewery that are fed by a steam circuit with a flow temperature of 165 °C. The accumulated condensate is returned to the boiler house with a mean temperature of 90 °C.

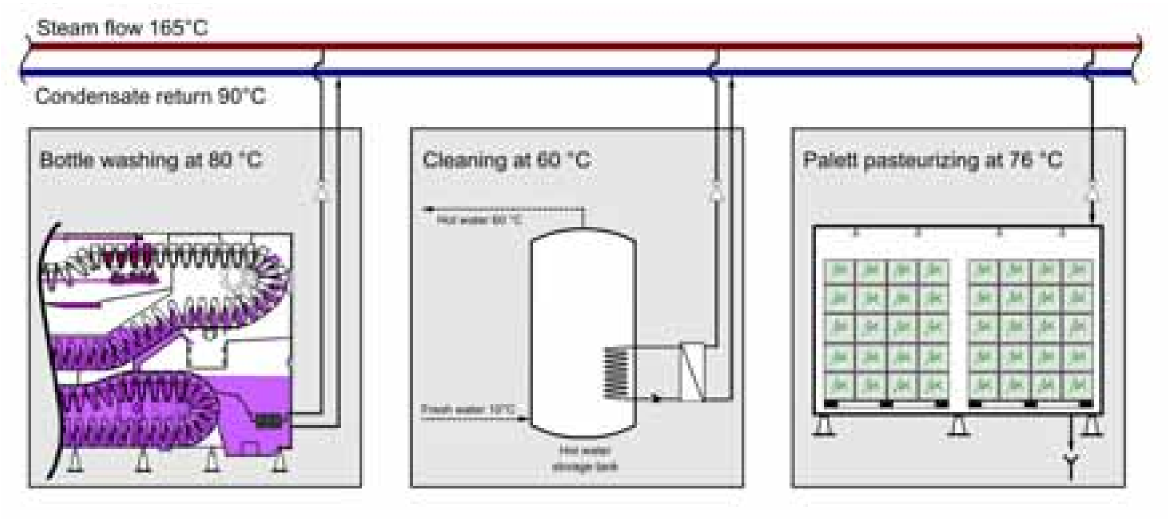

Fig. 3: Exemplary illustration of selected processes fed by steam circuit within a brewery

The first process illustrated in Figure 3 is washing of bottles that are filled with beer afterwards. Therefore, all bottles run through different cleaning sections of a bottle washing machine. The biggest section is an alkaline bath with several cubic meters and a set temperature of 80 °C during operation. Usually, a tube bundle heat exchanger is installed within the alkaline bath that is heated by the steam circuit. Before entering the heat exchanger the steam pressure has to be reduced to 2..5 bar due to technical reasons. The condensed steam is returned. All other baths within that washing machine are heated by internal heat recovery, as they usually have lower set temperatures. The integration of a solar heating system for this process is strongly influenced by the heat exchanger of the alkaline bath (internal or external). The necessary temperature that has to be supplied by the solar heating system during operation would be at least 90 °C, resulting in a return temperature in the range of 85 °C.

The second process illustrated in Figure 3 is supply of hot water for cleaning of production facilities. Lots of sections within a brewery have to be cleaned daily or weekly. All tanks and piping that are directly in contact with beer are usually cleaned automatically by so-called CIP-systems (Cleaning-in-Place). However, machineries and sections exist, which cannot be cleaned automatically, such as fillers, casings or floors. Therefore, fresh water is heated up to 60 °C or 80 °C within a storage or by a hot water preparation unit. Using steam as heat distribution medium, heating of water is typically realized with an additional water circuit that is heated by the steam circuit. Compared to the bottle washing, the integration of a solar heating system for this process seems much easier. An additional heat exchanger for the integration of solar energy can be connected to the storage. Alternatively, cold water can be heated by a solar heating system before entering the storage. In both cases, a solar heating system can assist the cleaning process even when the temperature of supplied heat is below the set temperature of the process.

The third exemplary process is pasteurization. This can be done in continuous or batch mode by various installations before or after the filling process. The displayed pallet pasteurization is a discontinuous process for pasteurizing bottled beer. This process is usually applied for smaller amounts of beer, when larger continuous installations are not affordable. Therefore, it is commonly used in small-sized breweries that produce smaller amounts of beer-based mixed drinks or non-alcoholic beer that have to be pasteurized after filling. For the pasteurization process, complete pallets of bottled beer are put into a chamber in which steam is directly injected, increasing the core temperature of the bottles to a set temperature of 76 °C. After injection, the steam condenses and is usually drained. A condensate recovery is usually not feasible due to few operating hours and soiling of condensate. Direct steam production is the only way to supply this type of pasteurization with solar energy, since hot water cannot be used for this process. However, it might be reasonable to produce low pressurized steam by a solar heating system that is used for this process so high pressure steam can be saved.

The processes described before are representative for the large number of alternatives that exist in industry. In addition to the actual process temperatures, there are large variations in the load profiles and the heating of the process. It can be distinguished between open and closed processes, batch and continuous operation, direct or indirect heat transfer and so on. Therefore, a generalization on process level is not easily possible. However, there are often processes, e.g. the heating of cold water, where solar heat can be integrated with relatively low temperatures compared to the heat supply system.

3. Analysis of selected applications

As pointed out in the previous chapter, a generalization of integration possibilities of solar heating systems in the industrial sector is very difficult. The processes listed in chapter 2.2. show that the integration of a solar heating system is different for each process, which is valid for various processes within the industrial sector. Hence, not only the temperature level of a process or heat distribution network is important for the integration of a solar heating system, but also the technical installations and mode of operation. Therefore, it is necessary to investigate the specific characteristics of a potential integration point comprehensively. Following aspects play an important role: the hydraulic integration into the heat distribution network and the required hardware and changes in control strategy of the conventional system. These characteristics will be analyzed for selected applications in the following subchapters.

3.1. Selected applications on supply level

As mentioned in chapter 2.1. two possibilities to integrate a solar heating system on supply level exist: A serial integration prior to the boiler for increasing the return temperature or an integration parallel to the boiler to provide steam or hot water with the required flow temperature. However, the serial integration differs between steam and hot water circuits. A serial integration into a hot water circuit results in an increase of return temperature before entering the boiler. A serial integration into a steam cycle includes the heating of boiler feed- and/or make-up water.

Parallel integration

The feasibility of integrating a solar heating system in parallel to the conventional heat supply system is strongly influenced by the used heat distribution medium. Using steam as a heat distribution medium, the parallel integration is relatively easy. On the one hand there is a buffer available due to the condensate tank and degasification and on the other hand there are different state of aggregations within the flow and return. Hence, steam supplied by a solar heating system can be easily fed into the existing network. The impact on the boiler is similar to a reduced heat demand so power of the boiler is reduced and less steam is produced. This kind of integration is illustrated in Figure 4. A fraction of boiler feed water is heated by concentrating collector loop and fed into a steam drum where the water steam mixture is separated. The feed water that remains in the steam drum is recirculated for evaporation within the collector loop. The solar steam is fed into the steam line as soon as the pressure is sufficient. Based on the amount of evaporated water, new boiler feed water from degasification enters the solar loop. This way of system integration was realized in Germany within the framework of the research project “P3 – Pilot plant for solar process heat generation with parabolic trough collectors”. Anthrakidis et al. (2011) have recently shown that this parallel integration on supply level is relatively uncomplicated regarding the required hardware and changes in control strategy of the conventional system. However, a continuous steam production during daytime and an economic operation of the system is strongly affected by high irradiation. Therefore, this application should be favored at locations with very good irradiation and high ration of direct irradiation.

Although flow temperatures of hot water circuits can be similar to steam lines, the parallel integration of a solar heating system into a pressurized hot water circuit is more complicated, since these circuits are often closed systems. Similar to steam circuits, the set temperature provided by the solar heating system has to be at least as high as the temperature of the pressurized hot water circuit, e.g. 150 °C (approx. 7 bar). Due to the closed and pressurized circuit, solar heated water with 150 °C can only be fed into the circuit, if the same amount of water leaves the return simultaneous. This increases the complexity of the hydraulic integration, because an appropriate buffer store or bypass is needed. For closed pressurized water circuits, a serial integration would be preferred instead of a parallel integration. In this case, the return temperature can be increased by an additional heat exchanger that is fed by a solar heating system.

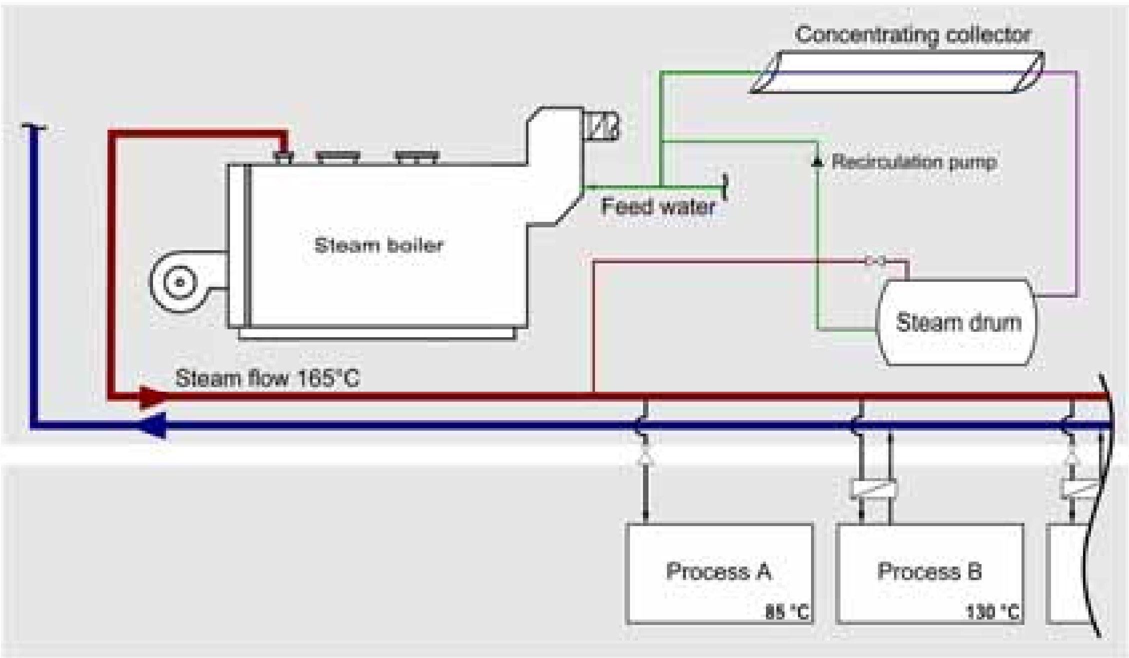

Fig. 4: Parallel integration of concentrating collector for direct steam production

Increase of return temperature

For steam circuits the increase of return temperature includes the heating of boiler feed- and make-up water. Basically, these applications (number two and three in Figure 2) seem feasible due to the continuous demand and in case of make-up water the relatively low temperature level. However, for both applications there are boundary conditions that reduce the potential impact of solar heating systems. Typically, steam boilers have an economizer which is a special heat exchanger for the exhaust gas. This economizer is usually used to heat the **boiler feed water** from degasification temperature (95..110 °C) up to 130..140 °C. The actual temperature lift that can be achieved depends on the exhaust gas temperature which is typically 60..80 K above steam temperature. If an economizer is installed, solar heating of feed water is usually not reasonable, since this is done by heat recovery. However, if the utilization of an economizer is not possible, or it is used to heat a different stream, the increase of feed water temperature by solar heating system can be considered. For the hydraulic integration of a solar heating system a buffer storage is required, since the feed water is pumped discontinuous into the steam boiler. During operation at full load, a solar buffer store is not necessary. The share of full-load operation and turndown strongly depends on the specific boundary conditions of the company (sector, processes, annual production, production time, etc.). For this application the solar buffer store must be designed for high pressures that go along with the required temperatures. The integration of a solar heating system to heat the feed water has no major effect on control and operation of conventional steam generation system.

Usually, there are also possibilities for heating **make-up water** by heat recovery before entering degasification. These alternatives have to be checked before the integration of a solar heating system is considered. If the condensate is fully degassed at slight overpressure, make-up water can be heated by condensing the occurring vapors of degasification in an additional heat exchanger. For small to medium amounts of make-up water this kind of heat recovery should always be considered. In a partial degassing, this is usually not possible, due to the lack of overpressure. If an industrial company has lots of processes that are heated by direct steam injection and therefore no or only a very small amount of condensate is returned, the condensing boiler technology is usually the best alternative for heating make-up water. Therefore, the economizer is followed by an additional heat exchanger in which make-up water is heated by condensation of water in the exhaust gas. If the verification of possible heat recovery options shows that a solar heating system can be used for heating make-up water, the hydraulic connection is relatively simple. In this case, a solar buffer store is necessary too, since the replenishment of degasification is done in batch mode. Also this type of system integration has no noteworthy effects on control and operation of the conventional system.

3.2. Selected applications on process level

As an example of the relevant parameters for integration on process level, the bottle washing will be described in more detail. For this application, both the existing hardware and the load profile of the process affect the feasibility of integrating a solar heating system. Bottle washing machines can be operated in two states. In addition to the regular operation during the cleaning of bottles, there is the heating mode, in which the entire machine is heated to the operating temperature of about 80 °C. The initial temperature for the heating mode and the frequency within a week are largely determined by the production time of the brewery (single or multi-shift operations and bottling days per week). On average 1.5 hours are required for the heating mode before bottle cleaning can start. In reality, the heating mode often starts a few hours before cleaning, leading to a higher heat demand by keeping the machine at operating temperature. Under normal conditions, the heat demand for cleaning is about 8..30 kWh per hour for 1,000 bottles. The heat required for regular heating mode from ambient to operating temperature is in the range of 50 kWh per 1,000 bottles (Grossmann and Buhler 2010). These values are strongly dependent on the particular capacity of the bottle washing machines that can range from 2,000 to 170,000 bottles per hour.

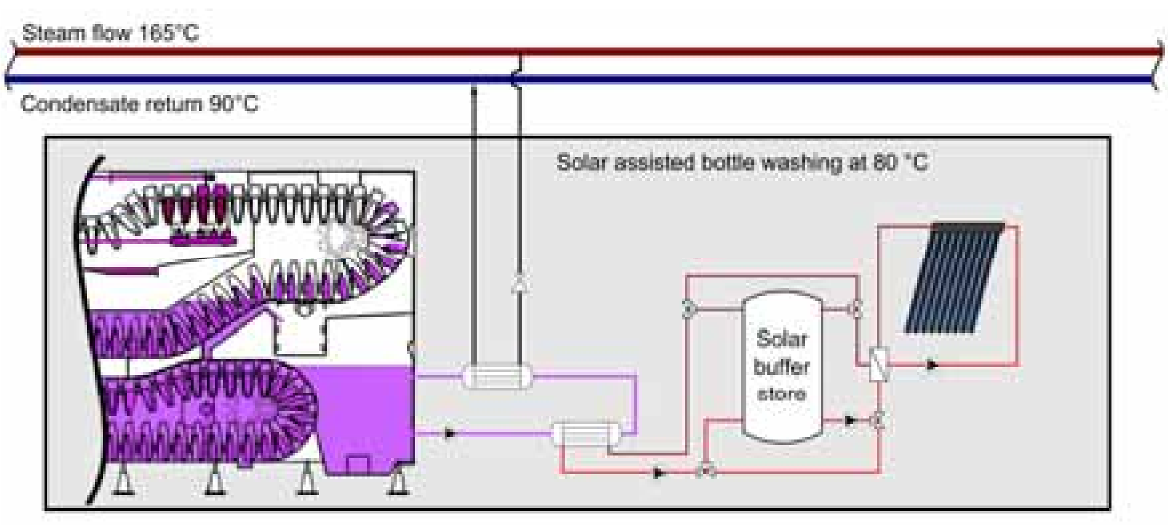

Fig. 4: Integration of solar heating system for heating of bottle washing machine

Typically, tube bundle heat exchangers are used for heating bottle washing machines, since the heated alkaline solution is contaminated with particles. Depending on the specific type of bottle washing machine, one or more of these heat exchangers exist, which are placed inside or outside the alkaline bath. The flow temperature of the heating medium (steam or hot water) is typically in the range of 120..150 °C. Based on the hardware of the bottle washing machine, the integration of a solar heating system is influenced by the arrangement of the tube bundle heat exchanger. If the heat exchanger is placed directly in alkaline bath, an additional heating by solar heating system is difficult to realize. In case of external arrangement of heat exchangers it is easier, since an additional heat exchanger fed by solar heat can be installed prior to the conventional one. Retrofitting existing bottle washing machines with a solar heating system is mostly very complex and costly due to the piping design and packing density. For new installations it would be possible to integrate an additional heat exchanger. As shown in Figure 5, the first heat exchanger is fed by solar energy, the second by the conventional heat distribution medium.

The flow temperature that has to be provided by the solar heating system during operation is strongly determined by the used heat exchangers. Flow temperatures below 90 °C can only be applied with plate heat exchangers or with relatively large sized tube bundle heat exchangers. However, the utilization of plate heat exchangers requires a filtration of alkaline solution. Lauterbach et al. (2011b) figured out that CPC collectors should be used for this application due to the relatively high flow temperature that is required. Additionally, it was found that in regions with moderate irradiation such as Central Europe relatively low specific system yields can be expected. Therefore, this type of process integration should be favored in climates with high irradiation. Besides the regular operation during the cleaning of bottles, at certain times also lower flow temperatures provided by the solar heating system can be used. After bottle washing, the temperature of alkaline solution slowly decreases to ambient temperature, so it has to be heated up before the next cleaning cycle. The required energy for heating mode can be provided by a solar heating system, which needs a relatively large buffer store. So far, many studies have concluded that processes with internal storage capacities are very well suited for the integration of solar heating systems because there is no need for a solar buffer store. Related to the bottle washing machine, this means that the solar heating system could feed in heat into the alkaline bath during off-times. Another advantage of this way of integration would be that no or a smaller amount of energy is required to heat the bottle washing machine at operating temperature. However, a detailed analysis shows that it is not conducive to keep the alkaline bath permanently at a high temperature. During off-times the alkaline bath should not be kept over 50..60 °C, since the forced and self-adjusting flows within the alkaline solution have negative effect on the desired sedimentation (GM 2011). Therefore, the volume of alkaline bath is not available as solar buffer at any time. Moreover, not every kilowatt hour that is fed into the alkaline bath by the solar heating system can be assigned to the system yield. During longer off-times of the bottle washing machine higher heat losses occur due to the increased temperature. A cool down to ambient temperature and following heating to operating temperature would be more reasonable based on energetic considerations. This makes it difficult to determine the economic efficiency of the solar heating system.

In summary, solar heating of bottle washing machines should be favored in regions with high irradiation, if the technical boundary conditions allow an appropriate integration. Additionally, a constant and long operation of the washing machine over the week should be given. Especially for smaller breweries with two or three cleaning days per week, solar heating of bottle washing machine is not recommended for economic reasons, in particular if there is no other heat sink during off-times.

4. Summary and outlook

The industry sector is one of the most promising application areas for solar heating systems within the near future due to the large amount of consumed thermal energy and continuous demand. Several potential studies identified numerous processes that seem promising for integration of solar heating systems based on the respective temperature level and spreading within the industry sector. However, detailed analysis showed that not only the process temperature is relevant for the feasibility to integrate a solar heating system. Therefore, also processes that were identified as promising in the first instance can be excluded for the integration of a solar heating system. Besides possibilities of heat recovery, hydraulic integration into the heat distribution network and the mode of operation of the process can lead to the conclusion that the integration of s solar heating system is not feasible due to technical or economical reasons. Therefore, these aspects should be considered while assessing the feasibility of solar process heat generation. For detailed conclusion, more processes have to be analyzed regarding the aspects described above. Additionally, different types of load profiles that can be found for those processes should be analyzed by simulations to estimate operating time and energetic contribution of an integrated solar heating system.

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