A comprehensive analysis on development and transition of the solar thermal market in China with more than 70% market share worldwide

China is the second-largest economy country, and the largest country worldwide in total solar energy system capacity installed. More than 70% of total solar collector capacity worldwide is installed in China. The production of solar collector in China had decreased significantly from 64 million m² in 2012 to 37 million m² in 2017, corresponding to a reduction of around 40% of the market in 2012. There are very limited comprehensive studies in existing literature, which have investigated the reasons on the decline of Chinese solar thermal market. This study aims to identify the reasons from both the demand and the supply sides in details. Furthermore, with the rise of emerging markets, such as the rapid development of the “Clean Heating Initiative” for space heating in North China, solar heat industrial process, and the mandatory installation of solar domestic hot water system for residential buildings below 100m in urban area, the Chinese solar thermal market is expected to recover soon, called “U-shaped curve” in this study. The market share of flat plate collector and evacuated tube collector is predicted to change in the near future. The research and development of flat plate solar collectors will increase continually in the market other than evacuated tube solar collectors like the past 10 years. The main driver for the solar thermal market development in China in the near future will be the demand from the urban area.

A solar combi-system utilizing stable supercooling of sodium acetate trihydrate for heat storage: Numerical performance investigation

To reduce the energy consumption of buildings significantly, a novel solar combi-system with short and longterm heat storage has been developed. A system prototype with 22.4m² (aperture) evacuated tubular collectors, a 735 L water tank and 4 phase change material (PCM) units each containing 150 L sodium acetate trihydrate composite has been built. Experimental investigation has shown advantages of utilization of stable supercooling of sodium acetate trihydrate in spring and autumn. In this paper, a newly developed numerical model was used to investigate the performance potential of the system with combined utilization of the water tank and the PCM units, including on-demand crystallization of supercooled sodium acetate trihydrate composites. PCM units, the water tank and the collector circuit models were validated with measurement data from system demonstration. Space heating and hot water demand patterns of a Danish single-family Passive House with a yearly heat demand of 3723 kWh were applied. Results showed that a 56% annual solar fraction of heat supply was achieved with the prototype specifications. A 69% solar fraction could be achieved with an optimized scenario including a 15% increased hot water demand. Sensitivity analysis of component sizing showed that PCM units of 200 L can be more efficiently used with a 0.6m³ water tank. Optimal solar collector array tilt was 70°. Aperture areas between 12.8 and 22.4m² were found adequate for frequent utilization of a PCM volume up to 1m³. Thus, the PCM heat storage capacity could be utilized at least 5.5 times a year. With a 22.4m² collector area and 5 PCM units of 200 L each, a solar fraction of 71% was calculated for the annual heat supply. Assuming full charge of a 0.6m³ water tank and 2.8m³ of sodium acetate trihydrate composite by electricity at the beginning of the year, the system could run 18 days without need for auxiliary heating. Thus, in periods without solar collector power available, generation maxima of wind power could be utilized. In conclusion, building heat demand could be covered close to 100% by renewable energy resources.
Economic analysis and optimization of combined solar district heating technologies and systems

To find an optimal economic solution for solar district heating (SDH) in China, an evaluation model based on the levelized cost of heat (LCoH) is developed. A Python program is developed to calculate the LCoH of SDH systems using the quasi-dynamic test method. Based on these calculations, the trend of LCoH with solar collector area under different heating load intensities, heating terminal units, heated areas and land rents is discussed. The optimal solar collector area and the solar fraction are determined for combinations of solar thermal with four types of auxiliary heat sources, including air source heat pumps, ground source heat pumps, gas boilers and gas boilers with seasonal heat storage. The calculations show an economic optimal solar fraction of 11%-33% for a SDH system with heat pumps. High dependency of LCoH on network temperature is found for a SDH system with gas boilers. Seasonal heat storage minimizes LCoH of a SDH system with gas boilers at 100% solar fraction. The findings can be used as a reference for local authorities, consultants and engineers in the early energy planning to determine the optimal proportion of solar energy in a district heating system with the lowest operating cost.

Economic analysis and optimization of household solar heating technologies and systems

To find an optimal economic solution for single-family solar heating systems, an evaluation model based on the levelized cost of heat (LCoH) is developed. The initial investment and operating costs of typical single-family solar heating systems
are determined using case collection and literature study. These data are used to validate the evaluation model. A Python program is developed and used to calculate the LCoH of differently designed solar heating systems. Based on these calculations, the dependence of LCoH on the solar collector area under different heating load intensities, heating terminal units and heated areas are investigated. The optimal solar collector area and the solar fraction are determined for combinations of solar thermal (ST) with four different types of auxiliary heat source was discussed. The results show that LCoH does not necessarily decrease in a solar-assisted household heating system with an increase of solar fraction (SF) compared to a single conventional heat source system. The findings of this study are useful for designers, professionals and government officials to economically optimize the solar heating system for single-family houses.

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Experimental investigations on phase separation for different heights of sodium acetate water mixtures under different conditions
Phase separation is a key problem when using sodium acetate trihydrate (SAT) as phase change heat storage material. The formation of phase separation is highly correlated to the composition of SAT based heat storage material, the material height, operation method and environmental condition. This study focus on the phase separation investigation by means of measuring exact water proportions in different layers of SAT samples. The SAT samples were made with or without different amount of excess water or thickening agents at different heights. Then the samples were tested in supercooled state under different environmental conditions such as short or long term supercooling periods, standing still or shaking from time to time during supercooling, repeated heating and activating and low ambient temperature. The solidification of supercooled samples was activated from top or bottom in order to verify the influence of activation methods. The water proportions in different layers of SAT samples were measured and summarized for comparison. It can be concluded from the experiments that suitable amount of excess water or thickening agents and proper shaking are beneficial to reduce or avoid phase separation. On the other hand, SAT without any additives, repeated heating and activating and low ambient temperature are favourable to forming phase separation for supercooled SAT materials.

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Feasibility study on solar district heating in China
Solar thermal has contributed little for space heating in China. In 2014, although China shared 75.8% of the total solar collector installations in the world, only less than 0.3% of the solar collectors were used for space heating. To promote solar district heating (SDH) in China, based on Danish experiences and Chinese clean heating transformation practices, a PEST (policy, economics, social, and technology) analysis and a SWOT (strengths, weaknesses, opportunities, and threats) analysis on SDH development in China were conducted. An extensive survey and on-site investigation were carried out to identify the applicability of SDH in rural areas. SDH development strategies, roadmap, and decision-making process for a SDH project are summarized. SDH has a broad application prospect in China with abundant solar resources and favorable policies. The solar heated floor area can achieve 756 million m² with an assumption of 3% coverage of the total heat demand of buildings. Particular areas with low population density, scarce resources, and strict environmental requirements, e.g., Tibet, should be given a high priority for SDH. Rural villages and small towns with better infrastructure, e.g., district heating networks, are the best target market for SDH in the next five years. With the development of seasonal heat storage technologies and the accumulation of practical experience, SDH can be expanded to industrial parks, large residential communities in sparsely populated northwest China. Integration of solar heat with existing heating networks in big cities with central heating will be challenging in the long run.

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Large-scale solar district heating plants in Danish smart thermal grid: Developments and recent trends
Large solar collector fields are very popular in district heating system in Denmark, even though the solar radiation source is not favorable at high latitudes compared to many other regions. Business models for large solar heating plants in Denmark has attracted much attention worldwide. Denmark is not only the biggest country in both total installed capacities and numbers of large solar district heating plants, but also is the first and only country with commercial market-driven solar district heating plants. By the end of 2017, more than 1.3 million m² solar district heating plants are in operation in Denmark. Furthermore, more than 70% of the large solar district heating plants worldwide are constructed in Denmark. Based on the case of Denmark, this study reviews the development of large solar district heating plants in Denmark since 2006. Success factors for Danish experiences was summarized and discussed. Novel design concepts of large solar district heating plants are also addressed to clarify the future development trend. Potential integration of large solar district heating plants with other renewable energy technologies are discussed. This paper can provide references to potential countries that want to exploit the market for solar district heating plants. Policy-makers can evaluate the advantages and disadvantages of solar district heating systems in the national energy planning level based on the know-how and experiences from Denmark.
Optimization of the coefficient of performance of a heat pump with an integrated storage tank – A computational fluid dynamics study

The performance of a heating system consisting of a heat pump with an integrated storage tank was evaluated by means of Computational Fluid Dynamics (CFD) calculations. The aim of the investigations was to elucidate how thermal stratification in the tank would influence the COP of the system. Differently designed storage tanks were investigated under typical operation conditions. CFD models of heat storage tanks were developed and validated by experiments on a test tank. Calculations with the validated models were carried out in order to find the optimal tank design and system settings for achieving the highest possible COP. The investigated parameters were volume flow rate, tank geometry, diffuser design and tank wall material. Two different system COPs were defined: one based only on charge operation and the other on both charge and discharge operations. It was found that there is a direct connection between the thermal stratification inside the tank and the COP of the heating system. Higher degree of stratification leads to higher COP. For the ideal case where there is no mixing, no vertical thermal conduction in the tank and no heat loss from the tank, the system COP after a charge-discharge cycle is 3.69. When the effect of mixing is taken into account, the obtained COP of the system is decreased by approximately 9%. If heat transfer to the tank wall and vertical thermal conduction are also taken into account, the obtained system COP is lowered by another 5%. Moreover, the COP of a heating system with high flow rates can be significantly increased by a diffuser plate installed in the tank with a small distance to the inlet/outlet. The best performing system studied consisted of an insulated tall and slim tank with a h/d ratio of 3.64 and a perforated plate diffuser, giving a COP of 3.23 which was 32% higher compared to a case without a diffuser. The performance of the suggested system was not affected by variations of flow rates in the range from 0.12 to 0.24 kg/s.
Solar water heating systems applied to highrise buildings-lessons from experiences in China

High-rise buildings have a significant impact on the surrounding environment. Building-integrated solar water heating (SWH) systems are effective ways to use renewable energy in buildings. Impediments, such as security concerns, aesthetics and functionality, make it difficult to apply SWH systems in high-rise buildings. At present, only China uses SWH systems on a large scale in such buildings. What are China’s experiences and lessons learned in applying SWH systems in high-rises? Are these experiences scalable to other countries? This study used a combination of field investigation, literature review and case study to summarize 36 systems that had been in operation for 1–14 years. System types, collector types, installation methods, types of auxiliary heat sources, economic performance and various basic principles were summarized. The economic performance of SWH systems in high-rise buildings was analyzed and verified by a case study in Shanghai. The results show that the installation of SWH systems in high-rise buildings is feasible and reliable. Individual household systems (61%) were more popular than centralized systems (25%) and hybrid systems account (14%). The average area of solar collectors per household was 2.17 m²/household. The average design solar fraction was 52%. Flat plate solar collectors (53%) was the most commonly used collector, while electric heating elements (89%) were the most common auxiliary heat sources for SWH systems, followed by gas water heaters and air source heat pumps. The cost of SWH systems per m² of a building area was between 22 CNY/m² to 75 CNY/m². China’s unique practical experience gives a reference for other countries in their efforts to make high-rise buildings more sustainable.

Test method for evaluating and predicting thermal performance of thermosyphon solar domestic hot water system

A test method for evaluating and predicting the thermal performance of thermosyphon Solar Domestic Hot Water (SDHW) system was proposed. The evaluating mathematical model of SDHW system was developed based on the two-node theory – a SDHW system was divided into the solid part and the fluid part. By combining the dynamic energy conservation equations of the solid part and the fluid part, the evaluating mathematical model of SDHW system was derived. The model parameters have clear physical meaning which can be used to evaluate the SDHW systems. The evaluating mathematical model was further processed by using the Laplace transformation technique and the predicting mathematical model was then derived. The predicting model can be used to predict the thermal performance of SDHW system for short and long term period with flexible draw off load conditions. The experimental method was designed and experiments were carried out to validate the test method. The measured mean fluid temperature in the storage tank was compared to the predicted mean fluid temperature. The annual thermal performance prediction of the system with two draw off load conditions at different daily hot water consumptions was also carried out.
A comprehensive approach for modelling horizontal diffuse radiation, direct normal irradiance and total tilted solar radiation based on global radiation under Danish climate conditions

A novel combined solar heating plant with flat plate collectors (FPC) and parabolic trough collectors (PTC) was constructed and put into operation in Taastrup, 30 km north of Aalborg, Denmark in August 2015. To assess the thermal performance of the solar heating plant, global radiation, direct normal irradiance (DNI) and total radiation on the tilted collector plane of the flat plate collector field were measured. To determine the accuracy of the measurements, the calculated solar radiations, including horizontal diffuse radiation, DNI and total tilted solar radiation with seven empirical models, were compared each month based on an hourly time step. In addition, the split of measured global radiation into diffuse and beam radiation based on a model developed by DTU (Technical University of Denmark) and the Reduced Reindl correlation model was investigated. A new method of combining empirical models, only based on measured global radiation, was proposed for estimating hourly total radiation on tilted surfaces. The results showed that the DTU model could be used to calculate diffuse radiation on the horizontal surface, and that the anisotropic models (Perez I and Perez II) were the most accurate for calculation of total radiation on tilted collector surfaces based only on global radiation under Danish climate conditions. The proposed method was used to determine reliable horizontal diffuse radiation, DNI and total tilted radiation with only the measurement of global radiation. Only a small difference compared to measured data, was found. The proposed method was cost-effective and needed fewer measurements to obtain reliable DNI and total radiation on the tilted plane. This method may be extended to other Nordic areas that have similar weather.
Analysis and validation of a quasi-dynamic model for a solar collector field with flat plate collectors and parabolic trough collectors in series for district heating

A quasi-dynamic TRNSYS simulation model for a solar collector field with flat plate collectors and parabolic trough collectors in series was described and validated. A simplified method was implemented in TRNSYS in order to carry out long-term energy production analyses of the whole solar heating plant. The advantages of the model include faster computation with fewer resources, flexibility of different collector types in solar heating plant configuration and satisfactory accuracy in both dynamic and long-term analyses. In situ measurements were taken from a pilot solar heating plant with 5960 m² flat plate collectors and 4039 m² parabolic trough collectors in series in Taars, Denmark from Sep.2015 to Aug.2016. The simulated thermal performances of both the parabolic trough collector field and the flat plate collector field have a good agreement with the measured performances. The thermal performance of the hybrid solar district heating plants is also presented. The measured and simulated results show that the integration of parabolic trough collectors in solar district heating plants can guarantee that the system produces hot water with relatively constant outlet temperature. The daily energy output of the parabolic trough collector field can be more than 5 kWh/m², while the daily energy output of the flat plate collector field is less than 5 kWh/m² under Danish climate conditions. The simplified and validated TRNSYS model can be a useful tool to simulate and optimize thermal performance of solar heating plants with both flat plate and parabolic trough collectors.

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Combined short- and long-term heat storage with Sodium Acetate Trihydrate for solar heat supply in buildings

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Combined short- and long-term heat storage with Sodium Acetate Trihydrate for solar heat supply in buildings

Because of its ability to preserve latent heat of fusion at room temperature in supercooled state, the phase change material (PCM) sodium acetate trihydrate (SAT) can be utilized for combined short and long-term heat storage in buildings. This was experimentally proved with a novel solar combisystem demonstrator including a segmented heat storage prototype, consisting of 4 flat units containing 200 kg of SAT composites each. A numerical model of the demonstrator was developed in TRNSYS environment. Ongoing system simulation indicates potential for more efficient domestic hot water and space heating supply. Further, based on experience with flat units, an inexpensive, cylindrical heat storage unit of the same PCM volume as one flat unit was designed and tested. Results showed that 27 kWh of heat can be stored. After cooling to room temperature, 11 kWh (long-term storage potential) were discharged during SAT composite solidification.

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Combined short and long term heat storage with Sodium Acetate Trihydrate in cylindrical tanks

A cylindrical heat storage prototype was designed to utilize Sodium Acetate Trihydrate (SAT) for combined short and long term heat storage. It was manufactured with inexpensive standard components of water stores. It contained 150 liter of SAT composite and 55 l of water. A heat storage test facility was used to investigate if the concept of stable supercooling of SAT can be applied and if thermal power during discharge is sufficient for domestic heat supply. Preliminary results showed that 27 kWh of heat can be stored during heat up to 90°C, which is significantly higher than water heat stores of the same volume. After a heat loss free storage period, 11 kWh (long term storage potential) were discharged during SAT composite solidification. Parallel application of heat storage units should be investigated to overcome heat transfer limitations.

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Crystallization by local cooling of supercooled sodium acetate trihydrate composites for long-term heat storage

Sodium acetate trihydrate (SAT) can be used for long-term heat storage in buildings by utilizing its ability to supercool stably to ambient temperatures while preserving its heat of fusion. Additives are used to stabilize the SAT and avoid phase separation. A reliable method for initializing the solidification of supercooled SAT composites is needed to operate a heat storage unit based on supercooled SAT. The crystallization temperatures of SAT composites during cooling were
therefore investigated and experiments carried out using methods applying local cooling in a small part of prototype heat storage units to initialize crystallization. To find the crystallization temperatures of SAT composites, supercooled samples were cooled down in a freezer. The influence of rusty metal parts submerged in melted SAT composite samples and various periods at rest in a supercooled state were investigated with regard to supercooling stability and crystallization temperature. Carboxymethyl cellulose, extra water, liquid polymer HD 310, metal-based graphite flakes, and silicone oil were applied as additives to form the different SAT compositions. Samples with 60 g SAT in glass jars were subject to repeated heating and cooling cycles. It was found that samples containing steel profiles crystallized in the range of −9 to −15 °C, while SA-water mixtures without steel profiles cooled down to −24 °C before crystallizing. Furthermore, samples with carboxymethyl cellulose and liquid polymer HD 310 showed a greater temperature rise during crystallization, which is in accordance with previous findings on heat contents. SA-water mixtures showed a second minor temperature peak at temperatures below −20 °C, when the sample was cooled down again after the first temperature rise. Devices were developed to initialize the crystallization of supercooled SAT composites in prototype heat storage units using rapid local cooling of the SAT composite. We successfully initialized crystallization by evaporating pressurized liquid carbon dioxide in a small chamber on one side of the PCM container and by using Peltier elements. Our experiments showed that the controlled initialization of crystallization by cooling is feasible for all the SAT composites investigated.

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**Design and functionality of a segmented heat-storage prototype utilizing stable supercooling of sodium acetate trihydrate in a solar heating system**
A solar heating system with 22.4 m² of solar collectors, a heat storage prototype consisting of four 200 kg phase-change material (PCM) storage units, and a 735 L water tank was designed to improve solar heat supply in single-family houses. The PCM storage utilized stable supercooling of sodium acetate trihydrate composites to conserve the latent heat of fusion for long-term heat storage. A control strategy directed heat from a solar collector array to either the PCM storage or a water buffer storage. Several PCM units had to be charged in parallel when the solar collector output peaked at 16 kW. A single unit was charged with 27.4 kWh of heat within four hours on a sunny day, and the PCM temperature increased from 20 °C to 80 °C. The sensible heat from a single PCM unit was transferred to the water tank starting with about 32 kJ of thermal power after it had fully melted at 80 °C. A mechanical seed crystal injection device was used to initialize the crystallisation of the sodium acetate trihydrate after it had supercooled to room temperature. The unit discharge during solidification peaked at 8 kW. Reliable supercooling was achieved in three of the four units. About 80% of latent heat of fusion was transferred from PCM units after solidification of supercooled sodium acetate trihydrate to the water tank within 5 h. Functionality tests with practical operation conditions on the novel, modular heat-storage configuration showed its applicability for domestic hot water supply and space heating.

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Long term measured and simulated performance of a combined solar district heating plant with flat plate collectors and parabolic trough collectors in series

Large scale solar heating plants develop fast in Europe, especially in Denmark. Most solar collectors used in previous solar heating plants are flat plate collectors. Flat plate collectors have relatively low efficiency at high temperature levels, such as 70 - 95 °C, which is the supply temperature of district heating networks. Parabolic trough collectors keep a high efficiency at the high temperature level. To maximize the advantages of flat plate collectors and parabolic trough collectors, a novel combined solar heating plant with flat plate collectors and parabolic trough collectors in series has been constructed in Taars, Denmark. The flat plate collectors preheat the return water from the district heating networks to about 75°C, then the parabolic trough collectors heat the preheated water from the flat plate collector field to the required supply temperature of the district heating network. The thermal performance of the combined plant was measured from September, 2015. More than 2 years’ thermal performance will be presented in this paper.

Modelling of a thermally activated building system (TABS) combined with free-hanging acoustic ceiling units using computational fluid dynamics (CFD)

Thermally Activated Building Systems (TABS) have proven to be an energy-efficient solution to achieve optimal indoor thermal environment in buildings. This solution uses the building mass to store heat and by means of water pipes embedded in the concrete slabs adjust the temperature in the premises. The active surfaces of TABS need to be as exposed as possible, but exposing bare concrete surfaces has a negative impact on the acoustic quality in the premises. Acoustic solutions capable of providing optimal acoustic comfort while allowing the heat exchange between the TABS and the room are desirable. This study focuses on the influence of two types of free-hanging ceiling absorbers (horizontal and vertical) on the cooling performance of the TABS. Different scenarios are investigated for each type of sound absorber. Computational Fluid Dynamics (CFD) simulations are used to illuminate the nature of the heat exchange between the TABS and the room and the occupants. The simulations are validated by comparison with full scale measurements in laboratory conditions. The study shows that for equivalent sound absorption levels, free-hanging vertical sound absorbers have a lower impact on the heat exchange between the room and the TABS compared to free-hanging horizontal sound absorbers. Cold air
stagnation between the sound absorber units and the TABS has been identified as the major cause of the cooling performance decrease of the TABS.

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**Thermal performance assessment and improvement of a solar domestic hot water tank with PCM in the mantle**
To develop an appropriate solar DHW (Domestic Hot Water) tank for residential dwellings and put it into the European solar thermal market for promotion, thermal performance tests of PCM (Phase Change Material) hot water storage tanks of both a prototype and an improved version with a water volume of 148 l and 35 kg PCM in the mantle has been carried out. The tank was designed to provide DHW for residential dwellings through a combination of solar and auxiliary heating, concurrently using PCM on the basis of cheap SAT (Sodium Acetate Trihydrate) as a thermal battery to shave off peak auxiliary power or to work under power outage. Heat transfer matching properties of the bottom and the top spirals separately for solar charge and auxiliary charge of the prototype DHW tank were ascertained in terms of heat exchanger capacity rate (HXCR) and the rule of thumb of boiler powers, respectively. Moreover, heat content of the PCM was estimated via a series of test cycles in order to infer its capacity and stability. It was found that there were some technical problems for the prototype tank module, such as mismatching property of the heat exchanger spirals, heat mixing phenomena during hot water draw-off. Thus, an improved tank was manufactured based on the test results of the prototype. Further tests indicated that the matching property of the top heat exchanger spiral was ameliorated for auxiliary charge and the heat mixing between hot water supply pipe and water tank was restrained during discharge, except that the length of the bottom spiral should be further reduced. Regarding the PCM in the mantle, it was inferred that the PCM heat content was somewhat lower than that of ideally working SAT. The PCM tended to perform stably under 16 test cycles with more than 3-month consecutive tests, implying no phase segregation occurred as that would degrade its performance.

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Thermo-economic optimization of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series

Large-scale solar heating plants for district heating networks have gained great success in Europe, particularly in Denmark. A hybrid solar district heating plant with 5960 m² flat plate collectors and 4039 m² parabolic trough collectors in series was built in Taars, Denmark in 2015. The solar heating plant was used as a reference case in this study. A validated TRNSYS-GenOpt model was set up to optimize the key design parameters of the plant, including areas of both collector types, storage size, orientation of the parabolic trough collectors and so on. This study introduces a generic method to optimize the hybrid solar district heating systems based on levelized cost of heat. It is found that the lowest net levelized cost of heat of hybrid solar heating plants could reach about 0.36 DKK/kWh. The system levelized cost of heat can be reduced by 5–9% by use of solar collectors in the district heating network in this study. The results also show that parabolic trough collectors are economically feasible for district heating networks in Denmark. The generic and multivariable levelized cost of heat method can guide engineers and designers on the design, construction and control of large-scale solar heating plants.

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Corresponding author: Tian, Z.
Contributors: Tian, Z., Perers, B., Furbo, S., Fan, J.
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Web of Science (2018): Indexed yes
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Analysis of measured and modeled solar radiation at the Tars solar heating plant in Denmark
A novel combined solar heating plant with tracking parabolic trough collectors (PTC) and flat plate collectors (FPC) has been constructed and put into operation in Tars, 30 km north of Aalborg, Denmark in August 2015. To assess the operation performance of the plant, detailed parameters, such as solar radiation, inlet and outlet temperature for the solar collector field, flow rate and pressure, ambient temperature, Wind speed and wind direction were measured. Global horizontal radiation, direct normal irradiation (DNI) and total radiation on the tilted collector plane of the flat plate collector field have been measured in Tars solar heating plant. To determine the accuracy of modeled and measured solar radiation in Tars solar heating plant, monthly comparisons of measured and calculated radiation using 6 empirical models have
been carried out. Comparisons of measured and modeled total radiation on the tilted surface with different methods were also studied. The results have shown that the DTU model could be used to calculate the diffuse radiation on horizontal surface and the anisotropic models (Perez 1988 model and Perez 1999 model) with only 1% and 2% disagreement with measured data respectively were the most accurate to be used for the calculation of total radiation on the tilted collector surface under Danish climate conditions only based on global horizontal radiation.

Annual measured and simulated thermal performance analysis of a hybrid solar district heating plant with flat plate collectors and parabolic trough collectors in series

Flat plate collectors have relatively low efficiency at the typical supply temperatures of district heating networks (70–95 °C). Parabolic trough collectors retain their high efficiency at these temperatures. To maximize the advantages of flat plate collectors and parabolic trough collectors in large solar heating plants for a district heating network, a hybrid solar collector field with 5960 m² flat plate collectors and 4039 m² parabolic trough collectors in series was constructed in Taars, Denmark. The design principle is that the flat plate collectors preheat the return water from the district heating network to about 70 °C and then the parabolic trough collectors would heat the preheated water to the required supply temperature of the district heating network. Annual measured and simulated thermal performances of both the parabolic trough collector field and the flat plate collector field are presented in this paper. The thermal performance of both collector fields with weather data of a Design Reference Year was simulated to have a whole understanding of the application of both collectors under Danish climate conditions as well. These results not only can provide a design basis for this type of hybrid solar district heating plants with flat plate collectors and parabolic trough collectors in the Nordic region, but also introduce a novel design concept of solar district heating plants to other high solar radiation areas.
Experimental and theoretic investigations of thermal behavior of a seasonal water pit heat storage

Seasonal heat storages are considered essential for district heating systems because they offer flexibility for the system to integrate different fluctuating renewable energy sources. Water pit thermal storages (PTES) have been successfully implemented in solar district heating plants in Denmark. Thermal behavior of a 75,000 m³ water pit heat storage in Marstal solar heating plant was investigated experimentally and numerically. Temperatures at different levels of the water pit storage and temperatures at different depths of the ground around the storage were monitored and analyzed. A simulation model of the water pit storage is built to investigate development of temperatures in and around the storage. The calculated temperatures are compared to the monitored temperatures with an aim to validate the simulation model. Thermal stratification in the water pit heat storage and its interaction with the ground are elucidated by calculations using the validated CFD model.

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Keywords: Solar heating plants, Seasonal water pit thermal storages (PTES), Experimental investigations, Computational fluid dynamics (CFD), Thermal stratification

Full Scale Measurements and CFD Investigations of a Wall Radiant Cooling System Based on Plastic Capillary Tubes in Thin Concrete Walls

Densely occupied spaces such as classrooms can very often have problems with overheating. It can be difficult to cool such spaces by means of a ventilation system without creating draughts and causing discomfort for occupants. The use of a wall radiant cooling system is a suitable option for spaces with a high occupant density. Radiant systems can remove most sensible heat loads resulting in a relatively small requirement for supply air for ventilation.

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Long-term PCM heat storage for a solar space heating and domestic hot water combisystem

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Organisations: Energy and Services, Department of Civil Engineering, Chinese Academy of Sciences
Contributors: Fan, J., Furbo, S., Wang, Z., Englmaier, G.
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Performance Evaluation of a Demonstration System with PCM for Seasonal Heat Storage: Charge with Evacuated Tubular Collectors
A seasonal heat storage with phase change material (PCM) for a solar space heating and domestic hot water combisystem was tested in automated operation during charge with solar collectors. A water tank was operating as buffer heat storage. Based on measurements during a representative day with sunshine, the storage system performance was evaluated regarding charge with solar heat. It shows the system behavior during typical operation resulting from the control strategy. Heat transfer rates from the solar collector array (22.4 m² aperture area) to the heat stores reached a peak of 19 kW, when PCM was melted. 30 kWh of heat was transferred to the 750 l water volume as it heated up. Afterwards 46 kWh of heat was transferred to the segmented PCM storage. In total 56 % of the total irradiation on the tilted collector plane was utilized to heat the storage units. During PCM charge heat transfer fluid temperatures were increasing with the state of charge. This is in contrast to maximization of solar yield. However, the energy conversion efficiency (65 %) of the collector array was satisfying. By considering pump electricity consumption, an overall performance ratio of 30.8 was obtained.

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Organisations: Department of Civil Engineering, Section for Building Energy, Chinese Academy of Sciences
Contributors: Englmaier, G., Furbo, S., Kong, W., Dannemand, M., Fan, J., Wang, Z.
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Thermal performance analysis of a solar heating plant
Detailed measurements were carried out on a large scale solar heating plant located in southern Denmark in order to evaluate thermal performances of the plant. Based on the measurements, energy flows of the plant were evaluated. A modified Trnsys model of the Marstal solar heating plant was developed to calculate thermal performances of the plant.

In the Trnsys model, three solar collector fields with a total solar collector area of 33,300 m², a seasonal water pit heat storage of 75,000 m³, a simplified CO2 HP, a simplified ORC unit and a simplified wood chip boiler were included. The energy consumption of the district heating net was modeled by volume flow rate and given forward and return temperatures of the district heating net. Weather data from a weather station at the site of the plant were used in the calculations. The Trnsys calculated yearly thermal performance of the solar heating plant was compared to the measurement results. Validity of the Trnsys model was analyzed. Recommendations are given with aim to develop a Trnsys model that can be used to optimize design of a solar heating plant under different scenarios.

General information
Development of a Performance Calculation Program for Solar Domestic Hot Water Systems with Improved Prediction of Thermal Stratification

The transient fluid flow and heat transfer in a hot water tank during cooling caused by standby heat loss were investigated by computational fluid dynamics (CFD) calculations and by thermal measurements in previous investigation. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank at different thermal conditions.

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Organisations: Department of Civil Engineering, Section for Building Energy , Beijing Computer Center
Contributors: Fan, J., Furbo, S., Li, Z.
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Experimental investigations on heat content of supercooled sodium acetate trihydrate by a simple heat loss method

Sodium acetate trihydrate is a phase change material that can be used for long term heat storage in solar heating systems because of its relatively high heat of fusion, a melting temperature of 58 °C and its ability to supercool stable. In practical applications sodium acetate trihydrate tend to suffer from phase separation which is the phenomenon where anhydrous salt settles to the bottom over time. This happens especially in supercooled state. The heat released from the crystallization of supercooled sodium acetate trihydrate with phase separation will be lower than the heat released from sodium acetate trihydrate without phase separation. Possible ways of avoiding or reducing the problem of phase separation were investigated. A wide variety of composites of sodium acetate trihydrate with additives including extra water, thickening agents, solid and liquid polymers have been experimentally investigated by a simple heat loss method. The aim was to find compositions of maximum heat released from the crystallization of supercooled sodium acetate trihydrate samples at ambient temperature. It was found that samples of sodium acetate trihydrate with 0.5–2% (wt.%) Carboxy-Methyl Cellulose, 0.3–0.5 % (wt.%) Xanthan Gum or 1–2% (wt.%) of some solid or liquid polymers as additives had significantly higher heat contents compared to samples of sodium acetate trihydrate suffering from phase separation.

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Contributors: Kong, W., Dannemand, M., Johansen, J. B., Fan, J., Dragsted, J., Englmaier, G., Furbo, S.
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Publication date: 2016
Experimental investigations on prototype heat storage units utilizing stable supercooling of sodium acetate trihydrate mixtures

Laboratory tests of two heat storage units based on the principle of stable supercooling of sodium acetate trihydrate (SAT) mixtures were carried out. One unit was filled with 199.5 kg of SAT with 9% extra water to avoid phase separation of the incongruently melting salt hydrate. The other unit was filled with 220 kg SAT mixture thickened with 1% carboxymethyl cellulose. The heat exchange capacity rate during the charging of the unit with the extra water was significantly higher than for the unit with the thickening agent due to the different levels of convection. The SAT mixtures in the units were stable and supercooled at indoor ambient temperatures for up to two months, after which the units were discharged. The energy discharged after solidification of the supercooled SAT and water mixture was 194 kJ/kg in the first test cycle, dropping to 179 kJ/kg after 20 test cycles. The energy discharged from the unit with SAT and the thickening agent after solidification was stable at 205 kJ/kg over 6 test cycles.
Laboratory Testing of Solar Combi System with Compact Long Term PCM Heat Storage

To enable the transition from fossil fuels as a primary heat source for domestic hot water preparation and space heating, solar thermal energy has great potential. The heat from the sun has the disadvantage that it is not always available when there is a demand. To solve this mismatch, a thermal seasonal storage can be used to store excess heat from the summer to the winter when the demand is higher than the supply. Installing a long-term thermal storage in a one family house it needs to be compact and sensible heat storages are not suitable. A latent heat storage with a phase change material (PCM) can provide a more compact way of storing heat. Sodium acetate trihydrate (SAT) is a good candidate material as it has a relatively high heat of fusion and in addition it has the ability to supercool to room temperature without solidifying. In this paper, results from the test of a solar combi system with a latent heat storage with SAT is presented. The SAT heat storage modules were heated to 80 °C by the solar collectors 53 times in the test period from June to November 2015 and this enabled the modules to supercool. Supercooling was achieved for 39 days for a SAT module after which 11 kWh of heat were discharged.

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Organisations: Section for Building Energy, Department of Civil Engineering
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Performance Analysis of a New Thermal Stratification Device for Hot Water Storage Tank Heated at the Bottom

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Organisations: Department of Civil Engineering, Section for Building Energy, Technical University of Denmark, Beijing Computing Center
Contributors: Fan, J., Ptacek, V., Furbo, S., Dragsted, J., Sun, P.
Number of pages: 11
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DOIs:
10.18086/swc.2015.02.14
URLs:
http://proceedings.ises.org/
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2017 › Research › peer-review
Simulation and optimization study on a solar space heating system combined with a low temperature ASHP for single family rural residential houses in Beijing

A pilot project of the solar water heating system combined with a low temperature air source heat pump (ASHP) unit was established in 2014 in a detached residential house in the rural region of Beijing, in order to investigate the system application prospect for single family houses via system optimization design and economic analysis. The established system was comprised of the glass heat-pipe based evacuated tube solar collectors with a gross area of 18.8 m² and an ASHP with a stated heating power of 8 kW for the space heating of a single family rural house of 81.4 m². The dynamic thermal performance of the pilot system was measured for continuous 20 days under typical cold climate conditions and the test data was used to validate the TRNSYS simulation model established. On the basis of model validation, system optimizations of both the existing pilot household and the typical rural house with good building insulation were undertaken to figure out the system economical efficiency in the rural regions of Beijing. The results show that the payback periods of the solar space heating system combined with the ASHP with the collector areas 15.04-22.56 m² are 17.3-22.4 years for the established pilot household on the current electricity price level of 0.5 RMB/kWh, comparing with the reference condition of the fully ASHP space heating. It is further found that the equivalent solar heat price per kWh is too high under the current solar market cost price and collector technology. To put forward the integrated solar space heating for reducing carbon emission, it is suggested that the Beijing municipal government should offer some financial subsidy to compensate the equivalent solar heat price per kWh.

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Research output: Contribution to journal – Journal article – Annual report year: 2016 – Research – peer-review

Tårs 10000 m² CSP + Flat Plate Solar Collector Plant - Cost-Performance Optimization of the Design

A novel solar heating plant with Concentrating Solar Power (CSP) collectors and Flat Plate (FP) collectors has been put into operation in Tårs since July 2015. To investigate economic performance of the plant, a TRNSYS-Genopt model, including a solar collector field and thermal storage tank, was established. The optimization showed that there was a synergy in combining CSP and FP collectors. Even though the present cost per m² of the CSP collectors is high, the total energy cost is minimized by installing a combination of collectors in such solar heating plant. It was also found that the CSP collectors could raise flexibility in the control strategy of the plant. The TRNSYS-Genopt model is based on individually validated component models and collector parameters from experiments. Optimization of the cost performance of the plant has been conducted in this paper. The simulation model remains to be validated with annual measured data from the plant.

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Organisations: Department of Civil Engineering, Section for Building Energy, Department of Buildings and Energy, Technical University of Denmark
Contributors: Perers, B., Furbo, S., Tian, Z., Egelwisse, J., Bava, F., Fan, J.
Pages: 312-316
Publication date: 2016
Testing of PCM Heat Storage Modules with Solar Collectors as Heat Source

A latent heat storage based on the phase change material Sodium Acetate Trihydrate (SAT) has been tested as part of a demonstration system. The full heat storage consisted of 4 individual modules each containing about 200 kg of sodium acetate trihydrate with different additives. The aim was to actively utilize the ability of the material to supercool to obtain long storage periods. The modules were charged with solar heat supplied by 22.4 m² evacuated tubular collectors. The investigation showed that it was possible to fully charge one module within a period of 270 minutes with clear skies. In long periods with high level of irradiance several modules were charged in parallel due to the limited heat exchange capacity of the integrated heat exchanger of the modules. After the modules were heated to more than 80 °C they were set to passively cool down. Modules reached 30 °C in a period of parallel cool down without the sodium acetate trihydrate solidified in 3 of the 4 modules. Further tests showed that stable supercooling at ambient temperature is possible.
Validation of a simple dynamic thermal performance characterization model based on the piston flow concept for flat-plate solar collectors

A simple dynamic characterization model of flat-plate solar collectors based on the piston flow concept is used both to identify the collector characteristic parameters and to predict the dynamic thermal performance. The heat transport time originally defined as \( (1 - e^{-1})^{-1} \tau_C \) by Amrizal et al. (2012) for the model turns out to be the collector static response time constant \( \tau_C \) by analytical derivation. The nonlinear least squares method is applied to determine the characteristic parameters of a flat-plate solar air collector previously tested by the authors. Then the obtained parameters are used to predict the dynamic behavior of the collector outlet temperature. The model coefficients particularly \( c_3 \) in the simple dynamic characterization model are examined by the collector dynamic prediction under variable meteorological conditions. Meanwhile, the prediction accuracy of the simple dynamic model based on the first-order difference method is compared to that of the numerical solution of the collector ordinary differential equation (ODE) model using the fourth-order Runge-Kutta method. The improved thermal inertia model (TIM) on the basis of closed-form solution presented by Deng et al. (2016a) is also considered. The results show that the prediction performance of the simple dynamic model is nearly as accurate as the ODE numerical solution and the TIM by Deng et al. (2016a) except some special conditions such as sharply changed solar irradiance and collector inlet temperature.

A new Laplace transformation method for dynamic testing of solar collectors

A new dynamic method for solar collector testing is developed. It is characterized by using the Laplace transformation technique to solve the differential governing equation. The new method was inspired by the so called New Dynamic Method (NDM) (Amer E. et al (1999) [1]) but totally different. By integration of the Laplace transformation technique with the Quasi Dynamic Test (QDT) model (Fischer S. et al (2004) [2]), the Laplace – QDT (L-QDT) model is derived. Two experimental methods are then introduced. One is the shielding method which needs to shield and un-shield solar collector continuously during test period. The other is the natural test method which doesn't need any intervention. The new L-QDT model with the shielding method are tested by TRNSYS (Klein S. et al (1988) [3]) simulation. Experiments were carried out at Technical University of Denmark by using the L-QDT method and the natural experimental method. The identified collector parameters are then compared and analyzed with those obtained by the steady state test method and the QDT test method. The results comparison shows that the L-QDT method and the natural experimental method are also valid. It can be concluded that the new Laplace test method can obtain reasonable and accurate collector parameters under transient weather condition.
Behavior of a solar collector loop during stagnation

A mathematical model simulating the emptying behavior of a pressurized solar collector loop with solar collectors with a good emptying behavior is developed and validated with measured data. The calculated results are in good agreement with the measured results. The developed simulation model is therefore suitable to determine the behavior of a solar collector loop during stagnation. A volume ratio R, which is the ratio of the volume of the vapour in the upper pipes of the solar collector loop during stagnation and the fluid content of solar collectors, is introduced to determine the mass of the collector fluid pushed into the expansion vessel during stagnation, Min. A correlation function for the mass Min and the volume ratio R for solar collector loops is obtained. The function can be used to determine a suitable size of expansion vessels for solar collector loops.

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Contributors: Chen, Z., Dragsted, J., Furbo, S., Perers, B., Fan, J.
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Development of a hot water tank simulation program with improved prediction of thermal stratification in the tank

A simulation program SpiralSol was developed in previous investigations to calculate thermal performance of a solar domestic hot water (SDHW) system with a hot water tank with a built-in heat exchanger spiral [1]. The simulation program is improved in the paper in term of prediction of thermal stratification in the tank. The transient fluid flow and heat transfer in the hot water tank during cooling caused by standby heat loss are investigated by validated computational fluid dynamics (CFD) calculations. Detailed CFD investigations are carried out to determine the influence of thickness and material property of the tank wall on thermal stratification in the tank. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank at different thermal conditions. The existing equation of the heat loss removal factor used in SpiralSol is evaluated by means of the detailed CFD calculations. A generalized new equation for the heat loss removal factor is obtained by regression. The new equation calculates the heat loss removal factor for a given temperature gradient in the tank, taking into account the influences of tank volume, height to diameter ratio, tank insulation, thickness and material property of the tank and initial thermal conditions of the tank. The equation is validated for a tank volume between 150 l and 500 l, a tank height to tank diameter ratio of 1-5, a tank wall thickness of 1.5 mm to 3 mm for a stainless steel tank and a tank wall thickness of between 3 mm to 5 mm for a normal steel tank. Accuracy and reliability of the SpiralSol program with the improved prediction of heat loss removal factor will be examined in future investigations.

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Drain Back Systems in Laboratory and in Practice

Drain back systems with ETC collectors are tested and analyzed in a Danish - Chinese cooperation project. Experiences from early work at DTU, with drain back, low flow systems, was used to design two systems:
1) One laboratory system at DTU. 2) One demonstration system in a single family house in Sorø Denmark. Detailed monitoring and modelling/validation of the system in the DTU lab is done, to be able to generalize the results, to other climates and loads by simulation and to make design optimizations. The advantage with drain back, low flow systems, is that the system can be made more simple with less components and that the performance can be enhanced. Also problems with long term degradation of glycol collector loops are totally avoided. A combination of the drain back and system expansion vessel was tested successfully. It is very important to achieve a continuous slope for the pipes in the collector loop to have a safe reliable operation. The components should also be designed and marked so that only one correct mounting option is possible, like forward and return pipes to/from the collector of slightly different sizes or color. Adapted installer education and training is a very important step to have success with drain back systems. Practices used in glycol systems may give serious failures.
Key-words: Drain Back, Low Flow, Solar Combi System, ETC collectors.

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Organisations: Department of Civil Engineering, Section for Building Energy , Section for Building Physics and Services
Full Scale Measurements and CFD Simulations of Diffuse Ceiling Inlet for Ventilation and Cooling of Densely Occupied Rooms

Spaces with high occupant densities result in high heat gains and need for relatively high air change rate. By means of traditional mechanical ventilation diffusers it becomes a challenge to supply large amounts of fresh air into the space without creating a local discomfort for occupants. One solution to this problem is the use of a diffuse ceiling inlet supplying a fresh air into the room through a large area of perforated ceiling. The aim of this paper was to report the research conducted on a diffuse ceiling inlet installed in the full-scale test outdoor facility. The diffuse ceiling inlet is based on gypsum boards with airtight connections were created utilizing the full potential of diffuse layer without undesirable crack flow reported by other authors. The measured values were used to validate the detailed Large Eddy Simulation model of the test room created in CFD software with an aim to evaluate indoor comfort numerically.

Results of our investigations have shown that diffuse ceiling inlet is a suitable solution for the spaces with high density occupancy. The results have shown that transient calculations using Large Eddy Simulation models can predict well temperatures and velocity magnitude of air flow in the room.

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Web of Science (2015): Indexed yes
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Laboratory test of a prototype heat storage module based on stable supercooling of sodium acetate trihydrate

Laboratory test of a long term heat storage module utilizing the principle of stable supercooling of 199.5 kg of sodium acetate water mixture has been carried out. Avoiding phase separation of the incongruently melting salt hydrate by using the extra water principle increased the heat storage capacity. An external expansion vessel minimized the pressure built up in the module while heating and reduced the risk of instable supercooling. The module was stable supercooled at indoor ambient temperature for up to two months after which it was discharged. The energy discharged after activating the supercooled sodium acetate water mixture was 194 kJ/kg of sodium acetate water mixture in the first test cycles dropping to 179 kJ/kg in the later test cycles. Instability of the supercooling occurred when the charging periods were short and in the last test cycles where the tube connecting the module to the expansion vessel had been blocked by the salt hydrate.

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Potential Analysis On Solar District Heating in China
This paper analyzes the feasibility of developing solar district heating (SDH) in China from the perspective of incentive policy, selections of technical route, regional adaptability and economic feasibility for clean heating. Based on the analysis, this proposes a road map for the development of SDH in China, and predict the market potential.

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Side by side tests of two SDHW systems with solar collectors with and without antireflection treatment

Two low flow SDHW systems based on mantle tanks are tested side by side in a laboratory test facility for solar heating systems under the same weather and operation conditions. The systems are identical with the exception that one system is equipped with a solar collector with antireflection treated glass while the other system has a collector with a normal glass. Measurements of the thermal performance of the two systems have been carried out for a long measuring period. The thermal performances of the systems have also been calculated with a detailed simulation model. There is a good agreement between measured and calculated thermal performances for both systems. The extra thermal performance of the system with the solar collector with the anti reflection treated glass cover is a strong function of the solar fraction. In sunny periods with high solar fractions the percentage extra thermal performance gained by the antireflection treatment is low. In less sunny periods with low solar fractions the percentage extra thermal performance of the system with the antireflection treated cover glass is high, typically up to 8%.

Testing, development and demonstration of large scale solar district heating systems

In 2013-2014 the project “Testing, development and demonstration of large scale solar district heating systems” was carried out within the Sino-Danish Renewable Energy Development Programme, the so called RED programme jointly developed by the Chinese and Danish governments. In the project Danish know how on solar heating plants and solar heating test technology have been transferred from Denmark to China, large solar heating systems have been promoted in China, test capabilities on solar collectors and large scale solar heating systems have been improved in China and Danish-Chinese cooperation on solar heating has been improved.
Thermal conductivity enhancement of sodium acetate trihydrate by adding graphite powder and the effect on stability of supercooling

Sodium acetate trihydrate and graphite powder mixtures have been evaluated to investigate the influence of the graphite powder on the stability of supercooling. A sodium acetate and water mixture mixed with graphite powder was successfully supercooled at ambient indoor temperatures for five months. The graphite powder was stabilized using carboxymethyl cellulose and successfully tested in heating and supercooling cycles with no loss of performance. Thermal conductivity enhancing properties of graphite powder was shown in samples.

Since the experiments were conducted in small scale, at 200 g per sample, large scale experiments are required to validate graphite as a thermo conductivity enhancing agent, suitable for use in seasonal heat storage applications utilizing SAT.

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Drain Back, Low Flow Solar Combi Systems: Design, Monitoring and Simulation

Drain Back systems with ETC collectors are tested and analyzed in a Danish - Chinese cooperation project. Experiences from early work at DTU, with drain back, low flow systems, was used to design two systems:
1) One laboratory system at DTU and 2) One demonstration system in a single family house in Sorø Denmark. Detailed monitoring and modelling of the system in the DTU lab is done to be able to generalize the results, to other climates and loads and to make design optimizations.

The advantage with drain back, low flow systems, is that the system can be made more simple with less components and that the performance can be enhanced. A combination of the drain back- and system expansion vessel was tested successfully. Small initial problems with installation and proposals for design improvements to avoid these in practice are

Drain Back systems with ETC collectors are tested and analyzed in a Danish - Chinese cooperation project. Experiences from early work at DTU, with drain back, low flow systems, was used to design two systems:
1) One laboratory system at DTU and 2) One demonstration system in a single family house in Sorø Denmark. Detailed monitoring and modelling of the system in the DTU lab is done to be able to generalize the results, to other climates and loads and to make design optimizations.

The advantage with drain back, low flow systems, is that the system can be made more simple with less components and that the performance can be enhanced. A combination of the drain back- and system expansion vessel was tested successfully. Small initial problems with installation and proposals for design improvements to avoid these in practice are
Installer education and training is an important step to have success with drain back systems.

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Investigations of Intelligent Solar Heating Systems for Single Family House

Three differently designed intelligent solar heating systems are investigated experimentally in a test facility. The systems provide all the needed yearly heating demand in single family houses. The systems are based on highly stratified tanks with variable auxiliary heated volumes. The tank is a tank in tank heat storage with domestic hot water in the inner tank and space heating water in the outer tank. The total tank volume is 750 liters and the solar collector area is 9 m². The auxiliary energy supply system is based on electrical heating element(s)/heat pump and is different for all three systems. The system will be equipped with an intelligent control system where the control of the electrical heating element(s)/heat pump is based on forecasts of the variable electricity price, the heating demand and the solar energy production. By means of numerical models of the systems made in Trnsys, the control strategy of intelligent solar heating systems is investigated and the yearly auxiliary energy use of the systems and the electricity price for supplying the consumers with domestic hot water and space heating are calculated.

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Validation of a CFD model simulating charge and discharge of a small heat storage test module based on a sodium acetate water mixture

Experimental and theoretical investigations are carried out to study the heating of a 302 x 302 x 55 mm test box of steel containing a sodium acetate water mixture. A thermostatic bath has been set up to control the charging and discharging of the steel box. The charging and discharging has been investigated experimentally by measuring surface temperatures of the box as well as the internal temperature of the sodium acetate water mixture through a probe located in the center of the steel box. The temperature developments on the outer surfaces of the steel box are used as input parameters for a Computational Fluid Dynamics (CFD) model. The CFD calculated temperatures are compared to measured temperatures...
internally in the box to validate the CFD model. Four cases are investigated; heating the test module with the sodium acetate water mixture in solid phase from ambient temperature to 52°C; heating the module starting with the salt water mixture in liquid phase from 72°C to 95°C; heating up the module from ambient temperature with the salt water mixture in solid phase, going through melting, ending in liquid phase at 78°C/82°C; and discharging the test module from liquid phase at 82°C, going through the crystallization, ending at ambient temperature with the sodium acetate water mixture in solid phase. Comparisons have shown reasonable good agreement between experimental measurements and theoretical simulation results for the investigated scenarios.

Investigations on efficiencies of HT solar collectors for different flow rates and collector tilts
Two HT solar collectors for solar heating plants from Arcon Solvarme A/S are tested in a laboratory test facility for solar collectors at Technical University of Denmark (DTU). The collectors are designed in the same way. However, one solar collector is equipped with an ETFE foil between the absorber and the cover glass and the other is without ETFE foil. The efficiencies for the collectors are tested at different flow rates and tilt. On the basis of the measured efficiencies, the efficiencies for the collectors as functions of flow rates are obtained. The calculated efficiencies are in good agreement with the measured efficiencies.

Performance analysis of a new design of office diffuse ceiling ventilation system
This paper aims to document and analyse performance of a new design of diffuse ceiling ventilation system in a typical office room. A full scale measurement is carried out in a climate chamber with an office setup at the Technical University of Denmark. Indoor air temperatures, air speeds, wall surface temperatures, pressure loss of the ceiling and ventilation effectiveness are measured for an air change rate of 3.5 h-1 and 5.1 h -1 respectively. A computational fluid dynamics
model of the office with the diffuse ceiling ventilation system is built and validated by the full scale measurement. The measurements of pressure loss across the ceiling show a low pressure drop between the plenum and the occupied zone. Ventilation effectiveness is measured to be close to 1 on average under the tested conditions. It is shown that the diffuse ceiling ventilation system is able to remove indoor pollutant in an efficient way. The draught risk is found to be insignificant by both experimental and theoretical investigations. A design chart based on "flow element" method is created for the diffuse ceiling ventilation system by calculations with the validated CFD model. The design chart serves as a guideline for design and dimension of the investigated diffuse ceiling terminals as an air distribution system. © 2013 Elsevier B.V.

Solar/electric heating systems for the future energy system
The project “Solar/electric heating systems in the future energy system” was carried out in the period 2008-2013. The project partners were DTU Byg, DTU Informatics (now DTU Compute), DMI, ENFOR A/S and COWI A/S. The companies Ajva ApS, Ohmatex ApS and Innogie ApS worked together with the project partners in two connected projects in order to develop solar/electric heating systems for laboratory tests. The project was financed by the Danish Agency for Science, Technology and Innovation under the Danish Council for Strategic Research in the program Sustainable Energy and Environment. The DSF number of the project is 2104-07-0021/09-063201/DSF. This report is the final report of the project. The aim of the project is to elucidate how individual heating units for single family houses are best designed in order to fit into the future energy system. The units are based on solar energy, electrical heating elements/heat pump, advanced heat storage tanks and advanced control systems.
Heat is produced by solar collectors in sunny periods and by electrical heating elements/heat pump. The electrical heating elements/heat pump will be in operation in periods where the heat demand cannot be covered by solar energy. The aim is to use the auxiliary heating units when the electricity price is low, e.g. due to large electricity production by wind turbines.
The unit is equipped with an advanced control system where the control of the auxiliary heating is based on forecasts of the electricity price, the heat demand and the solar energy production. Consequently, the control is based on weather forecasts.
Three differently designed heating units are tested in a laboratory test facility. The systems are compared on the basis of:
- energy consumption for the auxiliary heating
- energy cost for the auxiliary heating
- net utilized solar energy

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An improved dynamic test method for solar collectors

A comprehensive improvement of the mathematical model for the so called transfer function method is presented in this study. This improved transfer function method can estimate the traditional solar collector parameters such as zero loss coefficient and heat loss coefficient. Two new collector parameters \( t \) and \( mfCf \) are obtained. \( t \) is a time scale parameter which can indicate the heat transfer ability of the solar collector. \( mfCf \) can be used to calculate the fluid volume content in the solar collector or to validate the regression process by comparing it to the physical fluid volume content if known.

Experiments were carried out under dynamic test conditions and then test data were processed using multi-linear regression method to get collector parameters with statistic analysis. A comparison of the collector parameters obtained from the improved transfer function (ITF) method and the quasi-dynamic test (QDT) method is carried out. The results show that the improved transfer function method can accurately obtain reasonable collector parameters. The influence of different averaging time intervals is investigated. Based on the investigation it is recommended to use on line calculation if applicable for the second-order differential term with 6–9min as the best averaging time interval. The measured and predicted collector power output of the solar collector are compared during a test of 13days continuously both for the ITF method and the QDT method. The maximum and averaging error is 53.87W/m² and 5.22W/m² respectively of the ITF method while 64.13W/m² and 6.22W/m² of the QDT method. Scatter and relative error distribution of the measured power output versus the predicted power output is also plotted for the two methods. No matter in either error analysis or scatter distribution, the ITF method is more accurate than the QDT method in predicting the power output of a solar collector. In conclusion, all the results show that the improved transfer function method can accurately and robustly estimate solar collector parameters and predict solar collector thermal performance under dynamic test conditions.
Buoyancy driven flow in a hot water tank due to standby heat loss

Results of experimental and numerical investigations of thermal behavior in a vertical cylindrical hot water tank due to standby heat loss of the tank are presented. The effect of standby heat loss on temperature distribution in the tank is investigated experimentally on a slim 150l tank with a height to diameter ratio of 5. A tank with uniform temperatures and with thermal stratification is studied. A detailed computational fluid dynamics (CFD) model of the tank is developed to calculate the natural convection flow in the tank. The distribution of the heat loss coefficient for the different parts of the tank is measured by experiments and used as input to the CFD model. Water temperatures at different levels of the tank are measured and compared to CFD calculated temperatures. The investigations focus on validation of the CFD model and on understanding of the CFD calculations. The results show that the CFD model predicts satisfactorily water temperatures at different levels of the tank during cooling by standby heat loss. It is elucidated how the downward buoyancy driven flow along the tank wall is established by the heat loss from the tank sides and how the natural convection flow is influenced by water temperatures in the tank. When the temperature gradient in the tank is smaller than 2K/m, there is a downward fluid velocity of 0.003–0.015m/s. With the presence of thermal stratification the buoyancy driven flow is significantly reduced. The dependence of the velocity magnitude of the downward flow on temperature gradient is not influenced by the tank volume and is only slightly influenced by the tank height to tank diameter ratio. Based on results of the CFD calculations, an equation is determined to calculate the magnitude of the buoyancy driven flow along the tank wall for a given temperature gradient in the tank.

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Development of seasonal heat storage based on stable supercooling of a sodium acetate water mixture

A number of heat storage modules for seasonal heat storages based on stable supercooling of a sodium acetate water mixture have been tested by means of experiments in a heat storage test facility. The modules had different volumes and designs. Further, different methods were used to transfer heat to and from the sodium acetate water mixture in the modules.

By means of the experiments:
• The heat exchange capacity rates to and from the sodium acetate water mixture in the heat storage modules were determined for different volume flow rates.
• The heat content of the heat storage modules were determined.
• The reliability of the supercooling was elucidated for the heat storage modules for different operation conditions.
• The reliability of a cooling method used to start solidification of the supercooled sodium acetate water mixture was elucidated. The method is making use of boiling CO2 in a small tank in good thermal contact with the outer surface of the heat storage module.
• Experience on operation of the heat storage modules was gained.

Based on the investigations recommendations for future development of a seasonal heat storage based on stable supercooling of a sodium acetate water mixture are given.
Efficiencies of flat plate solar collectors at different flow rates

Two flat plate solar collectors for solar heating plants from Arcon Solvarme A/S are tested in a laboratory test facility for solar collectors at Technical University of Denmark (DTU). The collectors are designed in the same way. However, one collector is equipped with an ETFE foil between the absorber and the cover glass and the other is without ETFE foil. The efficiencies for the collectors are tested at different flow rates. On the basis of the measured efficiencies, the efficiencies for the collectors as functions of flow rate are obtained. The calculated efficiencies are in good agreement with the measured efficiencies.

Heat storage based on a NaCH₃COO water mixture for solar heating systems

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Investigation of Thermal Performance of Flat Plate and Evacuated Tubular Solar Collectors According to a New Dynamic Test Method

A new dynamic test method is introduced. This so called improved transfer function method features on two new collector parameters. One is time term which can indicate solar collector's inner heat transfer ability and the other is a second order term of collector mean fluid temperature which can obtain fluid thermal capacitance in data processing. Then theoretical analysis and experimental verification are carried out to investigate influencing factors of obtaining accurate and stable second order term. A flat plate and ETC solar collector are compared using both the new dynamic method and a standard method. The results show that the improved function method can accurately and robustly estimate these two kinds of solar collectors.

Thermal behavior of a heat exchanger module for seasonal heat storage

Experimental and theoretic investigations are carried out to study the heat transfer capacity rate of a heat exchanger module for seasonal heat storage with sodium acetate trihydrate (SAT) supercooling in a stable way. A sandwich heat storage test module has been built with the phase change material (PCM) storage box in between two plate heat exchangers. Charge of the PCM storage is investigated experimentally with solid phase SAT as initial condition. Discharge of the PCM storage with the presence of crystallization is studied experimentally. Fluid flow and heat transfer in the PCM module are theoretically investigated by Computational Fluid Dynamics (CFD) calculations. The heat transfer rates between the PCM storage and the heating fluid/cooling fluid in the plate heat exchangers are determined. The CFD calculated temperatures are compared to measured temperatures. Based on the studies, recommendations on how best to transfer heat to and from the seasonal heat storage module are given.
Thermal performance of marketed SDHW systems under laboratory conditions

A test facility for solar domestic hot water systems, SDHW systems was established at the Technical University of Denmark in 1992. During the period 1992-2012 21 marketed SDHW systems, 16 systems from Danish manufacturers and 5 systems from manufacturers from abroad, have been tested in the test facility under the same realistic test conditions. The systems had different designs and sizes. Each system was tested during a long test period consisting of both a summer and winter period.

Detailed simulation models for each system were developed. The simulation models were modified and the input to the models were fitted in such a way, that the calculated thermal performance is in good agreement with the measured thermal performance, both for a typical winter period and for a typical summer period. In this way it is possible to use the simulation models to calculate the yearly thermal performance of the tested systems with weather data from the Danish Test Reference Year and with the same hot water consumption.

The tests showed that the designs of the heat storage and that the system concepts are of vital importance for the thermal performances of the systems and that neither the solar collector efficiency nor the solar collector area is influencing the thermal performance as much as the heat storage design and the system concept. The tests also showed that all the tested systems can be improved with relative simple design changes.

Based on the tests it is concluded that high thermal performances of SDHW systems are achieved by reducing the heat loss from the upper part of the heat stores to a minimum by having no pipes connected to the upper part of the tank, reducing the auxiliary volume at the top of the heat stores as much as possible, of course with consideration of the required hot water comfort, avoiding simple errors, using the low flow principle and heat stores with a high degree of thermal stratification and by using components with good thermal characteristics.

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Thermal stratification in a hot water tank established by heat loss from the tank

This paper presents numerical investigations of thermal stratification in a vertical cylindrical hot water tank established by standby heat loss from the tank. The transient fluid flow and heat transfer in the tank during cooling caused by standby heat loss are calculated by means of validated computational fluid dynamics (CFD) models. The measured heat loss coefficient for the different parts of the tank is used as input to the CFD model. Parametric studies are carried out using the validated models to investigate the influence on thermal stratification of the tank by the downward flow and the corresponding upward flow in the central parts of the tank. Tank design parameters such as tank volume, height to diameter ratio and insulation and different initial conditions of the tank are investigated. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank at different thermal conditions. The results show that 20–55% of the side heat loss drops to layers below in the part of the tank without the presence of thermal stratification. A heat loss removal factor is introduced to characterize the effect of the buoyancy driven flow on exchange of heat loss between tank layers by natural convection. Based on results of the parametric studies, a generalized equation for the heat loss removal factor is obtained by
regression which takes into account the influences of tank volume, height to diameter ratio, tank insulation and initial conditions of the tank. The equation is validated for a 150–500l tank insulated with 0–7cm mineral wool and a tank height to diameter ratio of 1–5. The equation will be implemented in an existing tank optimization and design program for calculation of thermal performance of a hot water tank.

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Energy savings for solar heating systems in one family houses

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Experimental studies on seasonal heat storage based on stable supercooling of a sodium acetate water mixture

Laboratory tests of a 230 l seasonal heat storage module with a sodium acetate water mixture have been carried out. The aim of the tests is to elucidate how best to design a seasonal heat storage based on the salt water mixture, which supercools in a stable way. The module can be a part of a seasonal heat storage, that will be suitable for solar heating systems which can fully cover the yearly heat demand of Danish low energy buildings. The tested module has approximately the dimensions 2020 mm x 1285 mm x 80 mm. The module material is steel and the wall thickness is 2 mm. Different methods to transfer heat to and from the module have been tested. Further, a solidification start method, based on a strong cooling of a small part of the salt water mixture in the module by boiling CO2 in a small brass tank in good thermal contact to the outer side of the module wall, has been tested. Tests of the long term durability of small scale seasonal heat storage modules with different heights have been carried out in order to elucidate the maximum height of a module resulting in a stable heat storage. Based on the studies, recommendations for the design of a seasonal heat storage based on modules with a sodium acetate water mixture will be given.

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Heat transfer capacity of a heat exchanger module for seasonal heat storage

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Solar combisystems with forecast control to increase the solar fraction and lower the auxiliary energy cost

Solar Combi systems still need quite a lot of auxiliary energy especially in small systems without seasonal storage possibilities. The control of the auxiliary energy input both in time and power is important to utilize as much as possible of the solar energy available from the collectors and also to use low backup energy prices during the day if electricity is used. The storage function and both stratified charging and extraction of heat, are very important, to separate different temperature zones in the storage. This paper describes a step towards forecast control for electricity based auxiliary energy sources. It can be either direct electric heating elements or a heat pump upgrading ambient energy in the air, ground, solar collector or waste heat from the house. The paper describes system modeling and simulation results. Advanced laboratory experiments are also starting now with three different combisystems, operating in parallel. These systems will be briefly described too.

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Solvarmælægs energibesparelser
Energy savings for a number of new solar heating systems in one family houses have been determined by means of information on the energy consumption of the houses before and after installation of the solar heating systems. The investigated solar heating systems are marketed by Velux Danmark A/S, Sonnenkraft Scandinavia A/S and Batec Solvarme A/S. Solar domestic hot water systems as well as solar combi systems are included in the investigations. The houses have different auxiliary energy supply systems: Natural gas boilers, oil fired burners, electrical heating and district heating. Some of the houses have a second auxiliary energy supply system. The collector areas vary from 1.83 m² to 9.28 m². Some of the solar heating systems are based on energy units with a new integrated natural gas boiler and a heat storage for the solar heating system. The existing energy systems in the houses are for most of the houses used as the
auxiliary energy systems for the solar heating systems. The yearly energy savings for the houses where the only change is the installation of the solar heating system vary from 300 kWh per m² solar collector to 1300 kWh per m² solar collector. The average yearly energy savings is about 670 kWh per m² solar collector for these solar heating systems. The energy savings per m² solar collector are not influenced by the solar heating system type, the company marketing the system, the auxiliary energy supply system, the collector area, the collector tilt, the collector azimuth, the energy consumption of the house or the location of the house. The yearly energy savings for the houses with solar heating systems based on energy units including a new natural gas boiler vary from 790 kWh per m² solar collector to 2090 kWh per m² solar collector. The average yearly energy savings is about 1520 kWh per m² solar collector for these solar heating systems. The energy savings per m² solar collector for these systems are also not influenced by the solar heating system type, the company marketing the system, the auxiliary energy supply system, the collector area, the collector tilt, the collector azimuth, the energy consumption of the house or the location of the house. That is, yearly energy savings for new solar heating systems in one family houses are high, ranging from 300 kWh per m² solar collector to 2090 kWh per m² solar collector. If the existing energy system is used as the back up energy system for the solar heating system typical yearly energy savings vary from 500 kWh per m² solar collector to 800 kWh per m² solar collector. For solar heating systems with a new energy unit including a new natural gas boiler typical yearly energy savings vary from 1000 kWh per m² solar collector to 2000 kWh per m² solar collector.
DETAILED MODELLING OF CHARGING BEHAVIOUR OF SMART SOLAR TANKS

The charging behaviour of smart solar tanks for solar combisystems for one-family houses is investigated with detailed Computational Fluid Dynamics (CFD) modelling and Particle Image Velocimetry (PIV) measurements. The smart solar tank can be charged with a variable auxiliary volume fitted to the expected future energy demand. Therefore the heat loss from the tank is decreased and the thermal performance of the solar heating system is increased compared to a traditional system with a fixed auxiliary volume. The solar tank can be charged either by an electric heating element situated in the tank or by an electric heating element in a side-arm mounted on the side of the tank. Detailed CFD models of the smart tanks are built with different mesh densities in the tank and in the side-arm. The thermal conditions of the tank during charging are calculated with the CFD models. The fluid flow and temperature calculations are compared to PIV (Particle Image Velocimetry) measurements of fluid flows and temperature measurements. The aim is to elucidate the temperature distribution and thermal stratification of the tank during charging. It is elucidated how the calculated temperatures in the tank are influenced by the mesh densities, the distribution of computational cells, the physical model and time steps used in the simulations. The findings of the investigations will be used as guidance for creation of CFD models for optimal design of smart solar tanks.

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Research output: Contribution to conference › Poster – Annual report year: 2010 › Research › peer-review

DETAILED MODELLING OF CHARGING BEHAVIOUR OF SMART SOLAR TANKS

The charging behaviour of smart solar tanks for solar combisystems for one-family houses is investigated with detailed Computational Fluid Dynamics (CFD) modelling and Particle Image Velocimetry (PIV) measurements. The smart solar tank can be charged with a variable auxiliary volume fitted to the expected future energy demand. Therefore the heat loss from the tank is decreased and the thermal performance of the solar heating system is increased compared to a traditional system with a fixed auxiliary volume. The solar tank can be charged either by an electric heating element situated in the tank or by an electric heating element in a side-arm mounted on the side of the tank. Detailed CFD models of the smart tanks are built with different mesh densities in the tank and in the side-arm. The thermal conditions of the tank during charging are calculated with the CFD models. The fluid flow and temperature calculations are compared to PIV (Particle Image Velocimetry) measurements of fluid flows and temperature measurements. The aim is to elucidate the temperature distribution and thermal stratification of the tank during charging. It is elucidated how the calculated temperatures in the tank are influenced by the mesh densities, the distribution of computational cells, the physical model and time steps used in the simulations. The findings of the investigations will be used as guidance for creation of CFD models for optimal design of smart solar tanks.

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Fan, J., Andersen, E., Furbo, S., Perers, B.
Publication date: 2010

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ISBN (Print): 978-3-901425-13-4
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Electronic versions:
Jianhua_Fan_SmartSolarTank.pdf
Source: orbit
Source ID: 272327
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research › peer-review
Investigations on small low flow SDHW systems with different solar pumps and solar collector loops

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Furbo, S., Fan, J.
Publication date: 2010

Publication information
Place of publication: Department of Civil Engineering, Technical University of Denmark
Original language: English
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Research output: Book/Report › Report – Annual report year: 2010 › Research

Solar Electric heating systems using smart solar tanks and variable electricity costs

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Perers, B., Furbo, S., Andersen, E., Fan, J.
Publication date: 2010

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Title of host publication: Eurosun 2010
ISBN (Print): 978-3-901425-13-4
Source: orbit
Source ID: 272820
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research › peer-review

Thermal advantage of tracking solar collectors under Danish weather conditions
Theoretical investigations have been carried out with the aim to elucidate the thermal advantage of tracking solar collectors for different weather conditions in Kgs. Lyngby, Denmark (55.8°N), and for the weather conditions in Sisimiut, Greenland (66.9°N), just north of the arctic circle. The investigations are based on calculations with a newly developed program. Measured weather data from a solar radiation measurement station at Technical University of Denmark in Kgs. Lyngby Denmark in the period 1990 to 2002 and the Danish Design Reference Year, DRY data file are used in the investigations. The weather data used for Sisimiut are based on a Test Reference Year, TRY weather data file. The thermal advantages of different tracking strategies is investigated for two flat plate solar collectors with different efficiencies, operated at different temperature levels. The investigations show that the advantage of full tracking is in the range 40% – 90% depending on the solar collector and the operation conditions. The advantage is higher for a low efficient solar collector than for a high efficient solar collector and higher for high solar collector temperatures than for low solar collector temperatures. Further, design reference years are not suitable to elucidate the advantage by tracking.

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Andersen, E., Dragsted, J., Furbo, S., Perers, B., Fan, J.
Publication date: 2010

Host publication information
Title of host publication: Thermal advantage of tracking solar collectors under Danish weather conditions
Place of publication: Graz, Austria
ISBN (Print): 978-3-901425-13-4
Source: orbit
Source ID: 272468
Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2010 › Research › peer-review

Towards seasonal heat storage based on stable super cooling of sodium acetate trihydrate
The 12.5 m² flat plate solar collector HT, today marketed by Arcon Solvarme A/S, has been used in solar heating plants in Scandinavia since 1983. The collector is designed to operate in a temperature interval between 40°C and 90°C. The efficiency of the collector has been strongly improved since it was introduced on the market. The paper will present the increase of the efficiency of the collector due to technical improvements since 1983. Further, measurements from the spring of 2009 of the efficiency of two HT collectors, which have been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate, will be presented. The efficiencies will be compared to the efficiencies of the collectors when they were first installed in the solar heating plants. The measurements are supplied with inspections of the collectors inclusive investigations of possible corrosion of the copper pipes of the absorbers of the collectors. It is shown that from 2002 to 2007 the thermal performance of solar collector has been increased by 29%, 39%, 55% and 80% for a mean solar collector fluid temperature of 40°C, 60°C, 80°C and 100°C respectively due to improvement of the collector design. The test of the two collectors shows that due to aging the Ottrupgaard collector has a yearly thermal performance which is 4% lower than the collector tested in 1991 for a solar collector fluid temperature of 45°C, while the Marstal collector has a yearly thermal performance which is 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgaard collector and the Marstal collector is respectively 11% and 10% lower than the collector tested in 1991. Keywords: Flat plate solar collector, Collector efficiency, Efficiency test, Lifetime, Solar heating plants.

EFFICIENCY AND LIFETIME OF SOLAR COLLECTORS FOR SOLAR HEATING PLANTS

The 12.5 m² flat plate solar collector HT, today marketed by Arcon Solvarme A/S, has been used in solar heating plants in Scandinavia since 1983. The collector is designed to operate in a temperature interval between 40°C and 90°C. The efficiency of the collector has been strongly improved since it was introduced on the market. The paper will present the increase of the efficiency of the collector due to technical improvements since 1983. Further, measurements from the spring of 2009 of the efficiency of two HT collectors, which have been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate, will be presented. The efficiencies will be compared to the efficiencies of the collectors when they were first installed in the solar heating plants. The measurements are supplied with inspections of the collectors inclusive investigations of possible corrosion of the copper pipes of the absorbers of the collectors. It is shown that from 2002 to 2007 the thermal performance of solar collector has been increased by 29%, 39%, 55% and 80% for a mean solar collector fluid temperature of 40°C, 60°C, 80°C and 100°C respectively due to improvement of the collector design. The test of the two collectors shows that due to aging the Ottrupgaard collector has a yearly thermal performance which is 4% lower than the collector tested in 1991 for a solar collector fluid temperature of 45°C, while the Marstal collector has a yearly thermal performance which is 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgaard collector and the Marstal collector is respectively 11% and 10% lower than the collector tested in 1991. Keywords: Flat plate solar collector, Collector efficiency, Efficiency test, Lifetime, Solar heating plants.
lower than for the collector tested in 1991 for a solar collector fluid temperature of 45°C, while the Marstal collector has a yearly thermal performance which is 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgård collector and the Marstal collector is respectively 11% and 10% lower than the collector tested in 1991.

General information
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Organisations: Section for Building Physics and Services, Department of Civil Engineering, Lund University
Contributors: Fan, J., Chen, Z., Furbo, S., Perers, B., Karlsson, B.
Publication date: 2009

Event Information
Event: 29th Biennial Solar World Congress of the International Solar Energy Society
Location: Johannesburg, South Africa
Keywords: Flat plate solar collector, Collector efficiency, Efficiency test, Lifetime, Solar heating plants
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Research output: Non-textual form › Sound/Visual production (digital) – Annual report year: 2009 › Research

Levetid for solfangere i solvarmecentraler

General information
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Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Chen, Z., Fan, J., Perers, B., Furbo, S.
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Research output: Book/Report › Report – Annual report year: 2009 › Research

Long term investigations of thermal performance and energy savings for a solar combi system

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering, AEE INTEC
Contributors: Furbo, S., Fan, J., Thür, A.
Publication date: 2009

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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2009 › Research › peer-review

Solar Electric Heating for the future Energy System

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Perers, B., Furbo, S., Andersen, E., Fan, J.
Publication date: 2009

Host publication information
Solar transmittances for glass covers with and without antireflection treatment under real climatic conditions

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Furbo, S., Chen, Z., Fan, J., Schultz, J. M.
Publication date: 2009

Host publication information
Title of host publication: ISES Solar World Congress 2009 Proceedings
Source: orbit
Source ID: 255029

Thermal stratification in a hot water tank established by heat loss from the tank
Results of experimental and numerical investigations of thermal stratification and natural convection in a vertical cylindrical hot water tank during standby periods are presented. The transient fluid flow and heat transfer in the tank during cooling caused by heat loss are investigated by computational fluid dynamics (CFD) calculations and by thermal measurements. A tank with uniform temperatures and thermal stratification is studied. The distribution of the heat loss coefficient for the different parts of the tank is measured by tests and used as input to the CFD model. The investigations focus on the natural buoyancy resulting in downward flow along the tank side walls due to heat loss of the tank and the influence on thermal stratification of the tank by the downward flow and the corresponding upward flow in the central parts of the tank. Water temperatures at different levels of the tank are measured and compared to CFD calculated temperatures. The investigations will gain insight into the natural buoyancy driven flow in the tank. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank for different thermal conditions.

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Fan, J., Furbo, S.
Publication date: 2009

Event information
Event: 29th Biennial Solar World Congress of the International Solar Energy Society
Location: Johannesburg, South Africa
Source: orbit
Source ID: 255009
Research output: Non-textual form – Sound/Visual production (digital) – Annual report year: 2009 – Research

Thermal stratification in a hot water tank established by heat loss from the tank
Results of experimental and numerical investigations of thermal stratification and natural convection in a vertical cylindrical hot water tank during standby periods are presented. The transient fluid flow and heat transfer in the tank during cooling caused by heat loss are investigated by computational fluid dynamics (CFD) calculations and by thermal measurements. A tank with uniform temperatures and thermal stratification is studied. The distribution of the heat loss coefficient for the different parts of the tank is measured by tests and used as input to the CFD model. The investigations focus on the natural buoyancy resulting in downward flow along the tank side walls due to heat loss of the tank and the influence on thermal stratification of the tank by the downward flow and the corresponding upward flow in the central parts of the tank. Water temperatures at different levels of the tank are measured and compared to CFD calculated temperatures. The investigations will gain insight into the natural buoyancy driven flow in the tank. It is elucidated how thermal stratification in the tank is influenced by the natural convection and how the heat loss from the tank sides will be distributed at different levels of the tank for different thermal conditions.

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
A Long Term Test of Differently Designed Evacuated Tubular Collectors

During three years seven differently designed evacuated tubular collectors (ETCs) utilizing solar radiation from all directions have been investigated experimentally. The evacuated tubular solar collectors investigated include one SLL all-glass ETC from Tshinghua Solar Co. Ltd, four heat pipe ETCs and one direct flow ETC from Sunda Technology Co. Ltd and one all-glass ETC with heat pipe from Exoheat AB. The collectors have been investigated side-by-side in an outdoor test facility for a long period. During the measurements, the operating conditions – such as weather conditions and temperature of the inlet fluid to the collectors have been the same for all collectors. The volume flow rate through each of the collectors is adjusted so that the mean solar collector fluid temperature has been the same for all collectors. Thus a direct performance comparison is possible. The side-by-side tests were carried out with different mean solar collector fluid temperatures and in different seasons of the year. The results of the measurements are presented in this paper. The influence of the mean solar collector fluid temperature on the thermal performance of the different collector designs will be discussed. Further, the collector performances are compared for different times of the year and it is illustrated how the performance of the different collector types depends on weather conditions.

General information

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Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Fan, J., Dragsted, J., Furbo, S.
Publication date: 2008

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Buoyancy effects on thermal behavior of a flat-plate solar collector

Theoretical and experimental investigations of the flow and temperature distribution in a 12.53 m(2) solar collector panel with an absorber consisting of two vertical manifolds interconnected by 16 parallel horizontal fins have been carried out. The investigations are focused on overheating and boiling problems in the collector panel. Single-phase liquid flow and heat transfer in the collector panel are studied by means of computational fluid dynamics (CFD) calculations. Differently designed collectors are investigated with different collector fluid volume flow rates. The effect of friction and the influence of the buoyancy effects are considered in the investigations. Further experimental investigations of the solar collector panel are carried out. The flow distribution through the absorber is evaluated by means of temperature measurements on the back of the absorber tubes. The measured temperatures are compared to the temperatures determined by the CFD model and there is a good agreement between the measured and calculated temperatures. Calculations with the CFD model elucidate the flow and temperature distribution in the collector. The influences of collector fluid flow rate and inlet temperature on the flow and temperature distribution are shown. The flow distribution through the absorber tubes is uniform if a high flow rate of 10.01/min is used. By decreased collector fluid flow rate and by increased collector fluid inlet temperature, the flow distribution gets less uniform due to the influence of buoyancy force. If the collector fluid flow rate is small and the collector fluid inlet temperature is high enough, severe nonuniform flow distribution may happen with a small flow rate or even zero or reverse flow in the upper horizontal strips, resulting in overheating or boiling problems in the strips. The CFD calculations elucidate the flow and temperature distribution in the collector panels of different designs. Based on the investigations, recommendations are given in order to avoid overheating or boiling problems in the solar collector panel.
CFD Study of Fluid Flow in an All-glass Evacuated Tube Solar Water Heater

Abstract: The all-glass evacuated tube solar water heater is one of the most widely used solar thermal technologies. The aim of the paper is to investigate fluid flow in the solar water heater by means of computational fluid dynamics (CFD). The investigation was carried out with a focus on the convective heat transfer in the tube. The buoyancy induced flow circulation in different parts of the tube was analyzed. It is shown that fluid flow becomes stochastic and turbulent if fluid temperature is high enough. The flow instability leads to mixing of the warm uprising flow and the cold downward flow, which decreases efficiency of the heat exchange process. A baffle in the tube can prevent the flow instability and secure the flow circulation in the tube. The results of the investigation provide a helpful guidance for further investigation of the mechanism of heat transfer processes and a reference for future system optimization.

Consumer Unit for Low Energy District Heating Net

A low energy/low temperature consumer installation is designed and analyzed. The consumer type is a low energy single family house 145 m² with annual energy consumption in the range of 7000 kWh, incl. domestic hot water in a 2800 degree day climate. The network is an extreme low temperature system to reduce heat loss in the network. The consumer’s installation is a unit type with an accumulation tank for smoothing the heat load related to the domestic hot water. The building heat load is delivered by an under-floor heating system. The heavy under-floor heating system is assumed to
smooth the room heat load on a daily basis, having a flow temperature control based on outdoor climate. The unit is designed for a near constant district heating water flow. The paper describes two concepts. The analyses are based on TRNSYS (Klein et al., 2006) simulation, supplied with laboratory verification of the critical accumulator.

General information
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Organisations: Section for Building Physics and Services, Department of Civil Engineering, Danish Technological Institute, Danfoss AS
Contributors: Paulsen, O., Fan, J., Furbo, S., Thorsen, J. E.
Publication date: 2008

Experimental investigations on small low flow SDHW systems with different solar pumps

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Furbo, S., Fan, J.
Publication date: 2008

Performance investigations of differently designed heat-pipe evacuated tubular collectors in the Arctic climate

General information
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Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Dragsted, J., Fan, J., Furbo, S.
Publication date: 2008

Solar heating systems in the Arctic

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Dragsted, J., Furbo, S., Fan, J.
Publication date: 2008
TRNSYS simulation of the consumer unit for low energy district heating net

General information
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Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Fan, J., Furbo, S., Svendsen, S.
Publication date: 2008

An overview of CFD and PIV application in investigation of solar thermal systems

Abstract: Solar thermal system is one of the most widely used technologies of renewable energy presently. In order to further improve the system design and to increase its performance, a deep understanding of the complicated fluid flow and heat transfer in the system components is necessary. The most promising solution to this challenge is the use of computational fluid dynamics (CFD) in combination with particle image velocimetry (PIV), which will be the future trend in the investigation of solar thermal systems. The aim of this work is to give an overview of the status of the CFD-PIV application in solar thermal systems. Key words: Solar thermal system, CFD, PIV

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering, Zhejiang University
Contributors: Ai, N., Fan, J., Ji, J.
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Peer-reviewed: Yes

Experimental investigations on small low flow SDHW systems based on mantle tanks

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Furbo, S., Fan, J.
Publication date: 2007

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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2007 › Research › peer-review
FLOW DISTRIBUTION IN A SOLAR COLLECTOR PANEL WITH HORIZONTAL ABSORBER STRIPS

The objective of this work is to theoretically and experimentally investigate the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontal strips. Fluid flow and heat transfer in the collector panel are studied by means of computational fluid dynamics (CFD) calculations. Further, experimental investigations of a 12.5 m² solar collector panel with 16 parallel connected horizontal fins are carried out. The flow distribution through the absorber is evaluated by means of temperature measurements on the backside of the absorber tubes. The measured temperatures are compared to the temperatures determined by the CFD model and there is a good similarity between the measured and calculated results. Calculations with the CFD model elucidate the flow and temperature distribution in the collector. The influences of different operating conditions such as flow rate, properties of solar collector fluid, solar collector fluid inlet temperature and collector tilt angle are shown. The flow distribution through the absorber fins is uniform if high flow rates are used. By decreased flow rate and decreased content of glycol in the glycol/water mixture used as solar collector fluid, and by increased collector tilt and inlet temperature, the flow distribution gets worse resulting in a decreased collector efficiency and an increased risk of boiling in the upper part of the collector panel.

Keywords: Solar collector; Flow distribution; Computational Fluid Dynamics (CFD); Buoyancy effects

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Contributors: Fan, J., Shah, L. J., Furbo, S.
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Web of Science (2007): Indexed yes
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Preprint version of paper is uploaded
Source: orbit
Source ID: 194782
Research output: Contribution to journal › Journal article – Annual report year: 2007 › Research › peer-review

Flow distribution in a solar collector panel with horizontally inclined absorber strips

The objective of this work is to theoretically and experimentally investigate the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontally inclined strips. Fluid flow and heat transfer in the collector panel are studied by means of computational fluid dynamics (CFD) calculations. Further, experimental investigations of a 12.5 m² solar collector panel with 16 parallel connected horizontal fins are carried out. The flow distribution through the absorber is evaluated by means of temperature measurements on the backside of the absorber tubes. The measured temperatures are compared to the temperatures determined by the CFD model and there is a good similarity between the measured and calculated results. Calculations with the CFD model elucidate the flow and temperature distribution in the collector. The influences of different operating conditions such as flow rate, properties of solar collector fluid, solar collector fluid inlet temperature and collector tilt angle are shown. The flow distribution through the absorber fins is uniform if high flow rates are used. By decreased flow rate and decreased content of glycol in the glycol/water mixture used as solar collector fluid, and by increased collector tilt and inlet temperature, the flow distribution gets worse resulting in an increased risk of boiling in the upper part of the collector panel.

General information
Publication status: Published
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Contributors: Fan, J., Shah, L. J., Furbo, S.
Pages: 1501-1511
Publication date: 2007
Peer-reviewed: Yes

Publication information
Heat losses through pipe connections in hot water stores
The heat loss from pipe connections at the top of hot water storage tanks with and without a heat trap is investigated theoretically and compared to similar experimental investigations. Computational Fluid Dynamics (CFD) is used for the theoretical analysis. The investigations show that the heat loss from an ideally insulated pipe connected to the top of a hot water tank is mainly due to a natural convection flow in the pipe, that the heat loss coefficient of pipes connected to the top of a hot water tank is high, and that a heat trap can reduce the heat loss coefficient significantly. Further, calculations show that the yearly thermal performance of solar domestic hot water systems is strongly reduced if the hot water tank has a thermal bridge located at the top of the tank.
Large eddy simulations of flow instabilities in a stirred tank generate by a Rushton turbine

The aim of this paper is to investigate the flow instabilities in a baffled, stirred tank generated by a single Rushton turbine by means of large eddy simulation (LES) and simulation using the k-ε turbulent model. A sliding mesh method was used for the coupling between the rotating and the stationary frame of reference. The calculations were conducted on the “Shengcao-21C” supercomputer using CFD code CFX5. The flow fields predicted by the LES simulation and the simulation using k-ε model were compared to the results from digital particle image velocimetry (DPIV) measurement. It was shown that CFD simulations using k-ε model and LES approach agreed well with the DPIV measurement. Fluctuations of the radial and axial velocity were well predicted at different frequencies by the LES simulation. Velocity fluctuations of high frequencies were observed in the impeller region, while low frequencies velocity fluctuations were observed in the bulk flow. Flow circulation patterns predicted by the LES simulation were asymmetric, stochastic and complex, spanning a large portion of the tanks and varying with time, while circulation patterns obtained by the simulation using k-ε model were symmetric and simple. This shows that the LES simulation performs better than simulation using k-ε model for the investigation of flow instabilities in stirred tanks since large turbulent scales were directly calculated and a finer grid was used in the LES simulation, although the LES simulation demanded much more computational time and computer memories. The results of the present work give better understanding to the mixing mechanisms in the mechanically agitated tank.
The thermal performance of solar heating systems is strongly influenced by the thermal stratification in the heat storage. The higher the degree of thermal stratification is, the higher the thermal performance of the solar heating systems. Thermal stratification in water storages can for instance be achieved by use of inlet stratifiers combined with low flow operation in the solar collector loop. In this paper, investigations of a number of different fabric stratification pipes are presented and compared to a non flexible inlet stratifier. Additional, detailed investigations of the flow structure close to two fabric stratification pipes are presented for one set of operating conditions by means of the optical PIV (Particle Image Velocimetry) method.

Optimering og afprøvning af solfanger til solvarmecentraler

SIDE-BY-SIDE TESTS OF DIFFERENTLY DESIGNED EVACUATED TUBULAR COLLECTORS

Six differently designed evacuated tubular collectors, ETCs, utilizing solar radiation from all directions, have been investigated experimentally. The evacuated tubular solar collectors investigated include one SLL all-glass ETC from Tshinghua Solar Co., four heat pipe ETCs from Sunda Technolgy Co. and one all-glass ETC with heat pipe from Exoheat AB. The collectors have been investigated side-by-side in an outdoor test facility for a long period. During the measurements, the operating conditions – such as weather conditions, inlet and mean solar collector fluid temperatures...
have been the same. Thus a direct performance comparison is possible. The results of the measurements will be presented in this paper. Among other things, the influence on the thermal performance of the absorber design will be explained. Further, it will be illustrated how the thermal performances of the different collector types depend on the operating conditions and the time of the year and the collector performances will be compared.

**General information**

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Contributors: Fan, J., Dragsted, J., Furbo, S.  
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Research output: Chapter in Book/Report/Conference proceeding › Article in proceedings – Annual report year: 2007 › Research › peer-review

**Små ændringer af kappebeholder kan øge ydelsen af solvarmeanlæg**

**General information**

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Organisations: Section for Building Physics and Services, Department of Civil Engineering  
Contributors: Furbo, S., Fan, J.  
Pages: 108-109  
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Volume: 4  
Issue number: April 2007  
ISSN (Print): 1603-6913  
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Source ID: 209843  
Research output: Contribution to journal › Journal article – Annual report year: 2007 › Communication

**VALIDATION OF SIMULATION MODELS FOR DIFFERENTLY DESIGNED HEAT-PIPE EVACUATED TUBULAR COLLECTORS**

Differently designed heat-pipe evacuated tubular collectors have been investigated theoretically and experimentally. The theoretical work has included development of two TRNSYS [1] simulation models for heat-pipe evacuated tubular collectors utilizing solar radiation from all directions. One model is developed for heat-pipe evacuated tubular collectors with flat fins and one model is developed for heat-pipe evacuated tubular collectors with curved fins. The models are characterized by detailed calculations of the heat transfer processes in the fins, by detailed shadow modeling and by fins with selective coating on both sides. The input to the models is thus not a simple collector efficiency expression but the actual collector geometry. In this study, the TRNSYS models are validated with measurements for four differently designed heat-pipe evacuated tubular collectors. The collectors are produced by the Chinese collector manufacturer SUNDA Technology Co. The collectors have either flat or curved fins inside the evacuated tubes, the tubes have different diameters and the fins have selective coating on both sides. The collectors’ thermal performances have been measured side-by-side under the same operation conditions in an outdoor test facility. For periods with different operation conditions – such as weather conditions and inlet temperatures – measured and calculated thermal performances are compared for the four collectors. Further, the measured and calculated dynamic behaviors are compared. In all four cases, a good degree of similarity between measured and calculated results is found. With these validated models detailed parameter analyses and collector design optimization are now possible. Key words: Evacuated tubular collector, Heat pipe, Thermal performance, TRNSYS simulation.

**General information**

Publication status: Published  
Organisations: Section for Building Physics and Services, Department of Civil Engineering
Evaluation of Test Method for Solar Collector Efficiency

The test method of the standard EN12975-2 (European Committee for Standardization, 2004) is used by European test laboratories to determine the efficiency of solar collectors. In the test methods the mean solar collector fluid temperature in the solar collector, $T_m$ is determined by the approximated equation where $T_{in}$ is the inlet temperature to the collector and $T_{out}$ is the outlet temperature from the collector. The specific heat of the solar collector fluid is in the test method as an approximation determined as a constant equal to the specific heat of the solar collector fluid at the temperature $T_m$. The power produced by the solar collector during a test period is determined by the product of the specific heat, the mass flow rate and the temperature increase of the solar collector fluid. The solar collector efficiency is in the standard determined by measurements at different temperature levels. Based on these efficiencies, an efficiency equation is determined by regression analysis. In the test method, there are no requirements on the ambient air temperature and the sky temperature. The paper will present an evaluation of the test method for a 12.5 m² flat plate solar collector panel from Arcon Solvarme A/S. The solar collector panel investigated has 16 parallel connected horizontal absorber fins. CFD (Computational Fluid Dynamics) simulations, calculations with a solar collector simulation program SOLEFF (Rasmussen
and Svendsen, 1996) and thermal experiments are carried out in the investigation. The investigations elucidate: •How the mean solar collector fluid temperature $T_m$ is underestimated by the approximated equation in the test standard and how the collector efficiency equation is influenced by the underestimation of $T_m$. The dependence of the volume flow rate is shown; •How the use of the approximated specific heat of the solar collector fluid is influencing the collector efficiency expression; •How the temperature levels used is influencing the collector efficiency expression; •How the measured collector efficiency is influenced by the weather conditions such as the ambient air temperature and the sky temperature. Based on the investigations, recommendations for change of the test methods and test conditions are considered. The investigations are carried out within the NEGST (New Generation of Solar Thermal Systems) project financed by EU.

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The Effect of the Volume Flow rate on the Efficiency of a Solar Collector
The flow distribution inside a collector panel with an area of 12.5 m² and with 16 parallel connected horizontal fins and the effect of the flow nonuniformity on the risk of boiling and on the collector efficiency have been theoretically and experimentally investigated for different volume flow rates. Theoretically, a simplified model of the solar collector panel is built by means of the CFD (Computational Fluid Dynamics) code Fluent, where the geometry of the collector panel except the casing is fully modeled. Both lateral and longitudinal heat conduction in the absorber fins, the heat transfer from the absorber to the solar collector fluid and the heat loss from the absorber are considered. Flow and temperature distribution in the collector panel are investigated with buoyancy effect. Measurements are carried out with the solar collector panel.
Collector efficiencies are measured for different flow rates, temperature levels and solar irradiances. The measured efficiencies are compared to the results of the CFD calculations. There is a good agreement between the measured and calculated results. Further, calculations with the CFD model elucidate the flow and temperature distribution in the collector. The collector efficiencies are calculated by means of CFD calculations and efficiency expressions are determined based on the results of the calculations. The influence of flow nonuniformity on the efficiencies of the solar collector is elucidated for different volume flow rates and weather conditions.

FLOW DISTRIBUTION IN A SOLAR COLLECTOR PANEL WITH HORIZONTAL FINS
The objective of this work is to theoretically and experimentally investigate the flow and temperature distribution in a solar collector panel with an absorber consisting of horizontal fins. Fluid flow and heat transfer in the collector panel are studied by means of computational fluid dynamics (CFD) calculations. Further, experimental investigations of a 12.5 m² solar collector panel with 16 parallel connected horizontal fins are carried out. The flow distribution through the absorber is evaluated by means of temperature measurements on the backside of the absorber tubes. The measured temperatures are compared to the temperatures determined by the CFD model and there is a good similarity between the measured and calculated results. Calculations with the CFD model elucidate the flow and temperature distribution in the collector. The influences of operating conditions such as flow rate, temperature of inlet flow and collector tilt angle are shown. Based on the investigations preliminary recommendations for the operation of the investigated collector are given. For instance, minimum flow rate in order to avoid boiling in the horizontal strips is recommended.

Investigations of fabric stratifiers for solar tanks
The thermal performance of solar heating systems is strongly influenced by the thermal stratification in the heat storage. The higher the degree of thermal stratification is, the higher the thermal performance of the solar heating systems. Thermal stratification in water storages can be achieved in different ways. For instance, water heated by the solar collectors or water returning from the heating system can enter the water storage through stratification inlet devices in such a way that the water enters the tank in a level, where the tank temperature is the same as the temperature of the entering water. In this paper investigations of a number of different fabric stratification pipes are presented and compared.
to a non flexible inlet stratifier. Additional, detailed investigations of the flow structure close to two fabric stratification pipes are presented for one set of operating conditions by means of the optical PIV (Particle Image Velocimetry) method.

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**LARGE EDDY SIMULATIONS OF THE TURBULENT FLOW IN A STIRRED TANK**

Computational fluid dynamics (CFD) simulations of the fluid flow in a baffled, stirred tank with a single Rushton turbine are performed. The simulations are carried out on the “Shengcao-21C” supercomputer via commercial CFD software CFX5, using k-ε and large eddy simulation (LES) turbulence model respectively. Results show that CFD simulations using k-ε and LES model agree well with DPIV measurements. From the LES simulation, the velocity fluctuation is shown to occur with the development of vortices and eddies. This shows that LES simulation is better than k-ε simulation, although it demands a lot more computational time and computer memory. The results of the present work help to give deep understanding to the mixing mechanisms of the mechanically agitated tank, and can be used as guidance for future development of engineering tools for the design and scale-up of the stirred tank.

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**A DPIV MEASUREMENT AND CFD SIMULATION OF VISCOUS FLUID FLOW IN A STIRRED TANK AGITATED BY A RUSHTON TURBINE**

Mixing, achieved mostly by mechanically stirring, is one of the most important unit operation processes in chemical and allied industries. The problem of designing and scaling-up stirred tanks has been tackled mainly by means of semi-empirical methods. Measurement and numerical simulation of viscous fluid in a stirred tank is still unsufficient and further development is needed. In this paper, computational fluid dynamics (CFD) simulation and digital particle image velocimetry (DPIV) measurement have been carried out to study the flow filed of viscous fluid in a stirred tank agitated by a four-blade Ruston turbine. The working medium is the mixtures of water and glycerine with various concentrations. The results show mean velocity, turbulent energy and vorticity of the fluids as well as the flow patterns change with the fluid viscosity. CFD code of CFX with sliding grids was used to simulate the flow field. The k-ε model was selected as the turbulent models of simulation. The CFD simulations were compared with the experimental DPIV data. The result shows that the CFD simulations reflect the flow of the viscous fluid in a stirred tank. Keywords stirred tank, DPIV, CFD, viscous fluid, turbulence model

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Digital PIV Measurement of Flow Fields in a Stirred Reactor Generated by Rushton Turbine
The velocity fields in mechanically agitated vessels were investigated using digital particle image velocimetry (DPIV) to measure the flow field within a baffled tank stirred by a Rushton turbine impeller with a large impeller to tank diameter ratio. The measurement errors due to the random fluctuations of the near-instantaneous velocity field obtained from the DPIV were minimized by using time-averaged velocity measurements with an optimum sample number. The time-averaged velocity fields were used to calculate the pumping number, vorticity, and dimension one turbulent kinetic energy. The effects of rotational speed and measuring plane position on the velocity field were also investigated. The results show that the kinetic energy in the impeller region is higher than in the bulk flow. The kinetic energy is distributed asymmetrically in the axial direction, and the asymmetry variation is a function of the rotational speed due to the influence of the free surface. Key words: stirred tank; Rushton turbine; digital particle image velocimetry (DPIV); flow field

LARGE EDDY SIMULATIONS OF THE TURBULENT FLOW IN A STIRRED TANK
Computational fluid dynamics (CFD) simulations of the fluid flow in a baffled, stirred tank with a single Rushton turbine are performed. The simulations are carried out on the “Shengcao-21C” supercomputer via commercial CFD software CFX5, using k-ε and large eddy simulation (LES) turbulence model respectively. Results show that CFD simulations using k-ε and LES model agree well with DPIV measurements. From the LES simulation, the velocity fluctuation is shown to occur with the development of vortices and eddies. This shows that LES simulation is better than k-ε simulation, although it demands a lot more computational time and computer memory. The results of the present work help to give deep understanding to the mixing mechanisms of the mechanically agitated tank, and can be used as guidance for future development of engineering tools for the design and scale-up of the stirred tank.

Spatio-temporal Analysis of Macro-instability in a Stirred Tank Reactor via Digital Particle Image Velocimetry (DPIV)
To characterize the flow instability in mechanically agitated vessels, digital particle image velocimetry (DPIV) was used to measure the near-instantaneous flow fields in a baffled, stirred vessel, equipped with a Rushton turbine impeller of large impeller and vessel diameter ratio. From the measured near-instantaneous flow fields, distinct large-scale flow patterns were identified and the formation mechanisms of the patterns were explored via multi-scale analysis. Further investigations show that the flow patterns are rather complex and unsteady. Macro-instability (MI) appears as a switch among those flow patterns. Spectra distribution function P(f), equivalent to probability distribution function from a purely
mathematical point of view, was introduced to extract information on MI from the time series of the vorticity of the fluctuating velocity field. The two-dimensional distribution of MI and its dependence on Reynolds number and measuring plane were studied. Results show that probability analysis via spectra distribution function can be successfully used to quantify the relative intensity of macro-instabilities. Low-frequency, large-scale fluctuations of flow patterns were much intensive in the lower and upper corner of the vessel than in the rest parts of the vessel. The fluctuations of flow patterns also had an offset to the core of the vessel due to the influence of baffles. Compared with visual observation technique, this new analysis method via DPIV is more objective and can be used to give much understanding to the spatio-temporal properties of macro-instability. Keywords: Stirred vessel; Macro-instability (MI); Spatio-temporal analysis; Probability distribution function; Digital particle image velocimetry (DPIV); Multi-scale complex system

**Spectral Analysis of the Velocity Fluctuations in a Mechanically Stirred Tank**

To characterize the flow instabilities in mechanically agitated vessels, digital particle image velocimetry (DPIV) was used to measure the flow fields within baffled, stirred tank, equipped with a Ruston turbine impeller of large impeller and tank diameter ratio. The near-instantaneous flow fields obtained was rather complex and stochastic, so spatially averaged vorticity was introduced to identify the change of flow patterns and Fast Fourier Transform method (FFT) was used to analyze the obtained time series of the spatially averaged vorticity. Results show that the flow fields are not steady; rather, they are subject to macro instability (MI) with period ranging from 100 to 200 blade passage period; The dominant frequency of MI increases linearly with that of the impeller revolution; At lower impeller rotational speed (30 ~ 60 min-1), apparent MI phenomenon can be observed; With the increase of rotational speed (120 ~ 180 min-1), MI tends to weaken while random velocity fluctuations tend to strengthen.

**Undersøgelse af HT solfangere med og uden teflonfolie**

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Experiments were conducted in three swirl mist separators, with the internal diameters being 340, 480, and 700 mm, respectively. The separators were equipped with 18 sets of swirl vanes. The effects of superficial gas velocity and geometrical parameters, such as the elevation and the radial angle of the swirl vane, vane number, the ratio of separator body height to diameter on mist separation efficiency and pressure drop were tested. Results showed that the separation efficiency and pressure drop increased as elevation, radial angle and vane number were increased. An optimal superficial gas velocity exists in the range from 5 to 9 m/s and it decreases slightly with scale-up. The optimal distance between the swirl vane and inner exiting tube is 32%~73% of the separator diameter. The mist separator should be designed to make the separation efficiency as high as possible, with the pressure drop less than 2 kPa. The structure of the swirl vane is one of the most important parameters by which pressure drop is determined. A pressure drop correlation was established based on experimental data and theoretic analysis. A scale-up procedure was suggested for the design of industrial mist separators. Pressure drops measured from two industrial scale separators (1.52 m and 1.90 m) were found in good agreement with the predicted values, and the separation efficiency of greater than 95% was achieved. Key words: mist separator; swirl vane; separation efficiency; pressure drop