DEVELOPMENT OF SOLAR DISTRICT HEATING SYSTEMS AND IMPLEMENTATION OF FLAT PLATE SOLAR COLLECTORS

ROZWÓJ CENTRALNYCH SŁONECZNYCH SYSTEMÓW GRZEWCZYCH I WDRAŻANIE PŁASKO-POWIERZCHNIOWYCH KOLEKTORÓW SŁONECZNYCH

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ABSTRACT

The paper deals with presentation of present state and development of flat plate solar collectors and solar district heating systems. The role of flat plate solar solar collectors in solar district heating systems is underlined. Different classification of such systems is given and analyzed. The main elements of these systems are presented. Focus has been put on the storage and auxiliary source of energy and their connections to solar collectors and modes of cooperation.
Implementation of solar district heating systems in Eurpe has been analyzed and the prospects for future deployment are given.

STRESZCZENIE

Artykuł prezentuje obecny stan i rozwój płaskich kolektorów słonecznych, i centralnych systemów ciepłowniczych. Rola płaskich kolektorów słonecznych w centralnych systemach ciepłowniczych jest podkreślona. Różne metody klasyfikacji takich systemów są przedstawione i przeanalizowane. Następnie główne elementy tych systemów są opisane. Nacisk został położony na magazyn ciepła i pomocnicze źródło energii, oraz ich połączenie z kolektorami słonecznymi i możliwym ich trybem pracy. Realizacje centralnych słonecznych systemów ciepłowniczych w Europie są przedstawione i perspektywy ich dalszego rozwoju są zaprezentowane.

INTRODUCTION

Flat plate solar collector technology used to dominate in the world solar thermal technologies market for years. The first solar thermal collectors – the flat plate type – were used for Domestic Hot Water, DHW heating. An example of such a system was preserved in a picture; on the roof of the single family house in Pamona Valley, USA, in 1911. Even earlier, in the year 1900, a kind of advertisement was published by the Climax Solar Company. It recommended its flat plate solar collector products. Thus, since the beginning of the XX century till 2008 flat plate solar collectors were the main solar thermal technology in the world. Nowadays, vacuum tube solar collectors dominate the world solar thermal market. This is because of their production and growing use in Asian countries and mainly in China, especially in a form of natural gravity (thermosiphon) solar thermal DHW systems.

PRESENT TYPES OF SOLAR THERMAL COLLECTORS

Nowadays, there are many solar collector technologies. Different classifications of solar collectors can be made. The first one is connected with concentration ratio. Generally there are non-concentrating and concentrating solar collectors. The concentration ratio can differ a lot, as can be seen in Table 1.

The second classification takes into account the working fluid temperature. Thus solar collectors can be classified as:

- low temperature, when temperature of working fluid is < 100 ^{0}C;
- medium temperature, when temperature of working fluid is between 100 ^{0}C - 200 ^{0}C,
- high temperature, when temperature of working fluid is > 200 ^{0}C.

The third type is connected with the motion of solar collectors. Generally solar collectors can be classified as stationary and non- stationary, i.e. tracking ones. Tracking can be on one or two axes.

Different types of solar collectors and their main parameters of operation are presented in Table 1.

Table 1. Types and main parameters of solar collectors (ref. Wang R.Z., Xu Z.Y., Ge T.S., 2016)

Collector	**Motion**	**Absorber type**	**Concentration ratio**	**Indicative temperaturę [^{0}C]**
Flat plate	Stationary	Flat	1	30 – 80
Evacuated tube	Stationary	Flat	1	50 - 200
CPC	Stationary	Flat	1-5	60 - 240
PTC	Single axis tracking	Tubular	15-45	60 - 300
LFR	Single axis tracking	Tubular	10-40	60 - 250
Parabolic dish	Two axes tracking	Point	100 - 1000	100 -500
Solar tower	Two axes tracking	Point	100 - 1500	150 - 2000

CPC – Compound Parabolic Concentrator
PTC - Parabolic Trough Collector
LFR - Linear Fresnel Reflector

Table 1 presents types of solar collectors according to classification given by Wang (Wang R.Z., Xu Z.Y., Ge T.S., 2016). It should be mentioned that parabolic trough collectors, linear Fresnel reflectors and parabolic dish are very specific types of collector. Of course they collect solar radiation, but their main function is to concentrate solar radiation onto a tubular absorber or to a point in the case of the last type. In a solar tower it is even more complicated, because not only collection of concentrated solar radiation in a point takes place, but there is steam production at that place to drive turbine, that is located at the tower, to produce electricity. So only the receiver at the top of the tower plays the role of a solar collector.

Usually classification is made with regard to the two most typical types of solar collectors: flat plate and vacuum tube (Chwieduk D., 2012). The flat plate solar collectors are then classified according to the working fluid: liquid (water and anti-freezing mixture) and air. Then flat plate solar collectors are divided into glazed and unglazed.

At the end of 2013 the total installed capacity of solar collectors (flat plate and vacuum tubular) was equal to 375 GW, that corresponded to 535000000 m^2 of collector area worldwide (Mauthner F., Weiss W., Spoerk-Duerk M., 2015). The vacuum tubular solar collectors are nearly 70,5% of the total, due to the world's largest solar thermal market in China. Glazed liquid flat plate solar accounts for 22,4%, due to domination of this solar thermal technology in Europe. Then unglazed liquid solar collectors contribute with 6,7%. The rest is for unglazed and glazed air collectors, 0,3% and 0,1% respectively. It should be underlined that Germany represents nearly 40% of the European solar collector market, then Italy with 10%, Poland 9%, France and Greece 7% each (ESTIF, 2015).

As it has been mentioned, the flat plate solar collectors are the most prominent technology in Europe. They are the most mature technology, but it does not mean that this technology is not under improvement all the time. For example evacuated flat plate solar collectors have been under intensive studies for years. There is research on new materials for absorbers to make them cheaper without losing their high selectivity and heat conduction ability. Different configuration of tubing of absorbers have been analyzed and tested for many years. Under development are large size solar collectors (each module a few meters high and wide). Flat plate solar collectors are the only type of solar collectors that are used in central solar heating systems. With intensive implementation of the central solar heating systems the number of installed flat plate solar collectors should increase. There is a need for further research on effective operation of solar collectors in central solar heating systems, with regard to operation of the required number of solar collectors in one loop and many loops connected together, with focus on their thermal performance, stagnation temperature and reliability.

SOLAR CENTRAL HEATING SYSTEMS

Development of solar distric heating systems

Low-energy buildings are characterized by low energy demand. Low heating energy demand of buildings makes possible utilization of low temperature heat sources based on renewables:

- solar energy,
- energy of environment utilized via a heat pump.

When low temperature heat sources are used then low temperature district heating systems for low-energy buildings in new districts can be applied.

Utilization of solar energy in central/district heating systems is a kind of challenge for traditional district heating. The most important problems to be analyzed are:

- low temperature heating medium,
- short term storage with heat stratification,
- long-term (seasonal) storage,
- integration of different complementary low temperature heat sources,
- introduction into smart energy regions and smart cities.

Even if there are many challenges for quick implementation of solar district heating worldwide, there are many good examples of efficient operation of such systems in Europe, and especially in high latitude countries, with Denmark as a leader.

Main elements of solar heating systems

In general, solar central heating systems have the same components as regular micro and middle scale solar heating systems. Thus the main elements of a solar heating system are:

- solar collectors,
- storage tank/s,
- auxiliary conventional or unconventional heaters (devices or systems).

Other elements and devices necessary for operation of solar heating systems are following:

- pipelines,
- circulation pumps,
- heat exchangers,
- safety devices such as expansion vessels, safety valves, vents,
- instrumentation and control systems.

All components listed above are needed for different type of solar heating systems. Features of the main components, typical of district heating systems are described in the following paragraphs.

Solar collectors in district heating

Solar collectors are of course the main elements of any solar heating system. Their operation in a standard active heating system is based on a closed solar collector loop. A working fluid (water, anti-freezing mixture) circulates in a closed loop and exchanges heat with a storage medium through a heat exchanger.

Flow rate in a solar collector loop can be as follows:

- in high-flow systems approx. 50 l/ (h m^2 of collector area),
- in low-flow systems approx. 10–15 l / (h m^2 of collector area).

In solar district heating systems solar collectors are grouped into parallel flow and combined series–parallel flow. Parallel flow is the most frequently used, because:

- it is inherently balanced,
- it has low pressure drop,
- solar collectors can be drained easily, if required.

Figure 1 shows an array of solar collectors of district heating system in Graz, Austria. A few solar collectors connected together constitute a group of solar collectors (as can be seen in this figure).

Fig. 1. An array of solar collectors of district solar heating plant in Graz, Austria

The external and internal manifolds are the two most popular collector header designs. Internal manifolding is preferred for large systems, mainly because of better insulation, but is not always used.

The number of collectors connected together depends on the size of the header and the type of solar absorber of the collectors. Usually, if solar absorbers are the harp type, then 6 solar collectors are connected together (see Fig.1), but if solar absorbers are the meander type, then 8 solar collectors can be connected together in series. This is because of the necessity of reducing the pressue drop in a loop of connected solar collectors.

Very important and very basic rule of operation of the solar collectors in an array in a solar district heating system is to maintain the same flow through all collectors. The problem could occur with no flow or too small flow in some of the collectors, usually with the last one/ones in the row. Such a situation can cause the temperature to rise beyond the anticipated stagnation temperature limit of the solar collector. When the temperature of the working fluid rises above the limit then the solar collector can be destroyed (with too high a pressure, absorber tubes can crack).

A field of solar collectors (array) includes many individual groups of collectors. All collectors must be identical and all panels (group of solar collectors connected together) must contain the same number of solar collectors to maintain balanced flow.

There are two main types of solar collectors connections to create an array (a field of solar collectors):

- direct return – balancing valves are used to ensure uniform flow through panels of collectors, they are installed at the outlet of the panel of solar collectors (e.g. six collectors connected together) (to keep the flow resistance at the level necessary to ensure filling of all panels on pump start-up, if draining and filling is applied);
- reverse return –the array is self-balanced as all collectors (e.g. six collectors are connected together) operate with the same pressure drop.

An array of solar collectors should be designed in such a way to be able to drain. Piping to and from the solar collectors and collectors themselves must slope to drain with an inclination of 20 mm per linear meter (ASHRAE, 2004). It must be underlined, that different mounting and plumbing is required for the external and internal manifold collectors:

- external ones can be mounted with no inclination, but the lower header must be pitched and the upper header can be either pitched toward the collectors or not;
- internal ones must be tilted (the tilt angle equals to 3-5^0).

Apart from solar collectors next very important element of a solar district heating system, as of all solar heating systems, is storage.

Storage in a district heating system

It is characteristic that solar energy systems needs storage and no matter what size (scale) of a solar heating system is used: a Domestic Hot Water system and/or a space heating system in a single family house, or in a multi-family apartment building, or a big district heating system.

The intermittent nature of solar radiation and its periodical availability means that storage of solar energy is very important. There are significant daily and especially yearly variations of solar irradiance. Most energy needs and especially heating needs are also time dependent. Therefore storage is crucial for efficient operation of different types of solar thermal systems. When solar energy is used for space heating then distribution in time of heating load and its quantity is quite opposite to availability of solar radiation in time and its peak values.

Efficient storage of solar energy is the key issue for effective operation of solar active space heating systems. To assure the efficient storage of solar energy the heat stratification in a storage tank is necessary, whatever size of solar heating system it is. There are many different methods to improve stratification effect in stores, one of them is to utilize the PCM – Phase Change Materials. It is possible to apply the PCMs having melting point at different temperature level in the same storage tank, but at different height of the tank. The PCM of lower melting point is located at the bottom of the storage, and another PCM of higher melting point is located at the top of the storage (Chwieduk, 2016).

As it has been mentioned, in central solar district heating systems the solar collectors are divided in many loops, which are integrated together to supply heat to a storage system. In centralized solar heating plant storage of heat gained can be accomplished through:

- one big store, usually with water as a storage medium (see Fig.2),
- or through many smaller tanks connected in series and parallel.

Fig.2. Main storage tank at district heating plant in Graz, Austria

Depending on solar energy availability all smaller tanks can be connected together or only some of them can be used. Some of them can operate as buffer storage, some as main storage and some as peak storage.

Auxiliary heating

Depending on a type of the solar heating system different types of auxiliary source are used.

In a case of decentralized systems, i.e. in a micro and small scale systems the auxiliary heating source, as well as collectors and storage, are placed in the heating building. In Domestic Hot Water, DHW systems electricity is mainly used as auxiliary heat source. In solar combi heating systems, i.e. DHW + space heating, fossil (gas/ oil/ coal) or biomass boilers or heat pumps are used as auxiliary heat sources. Heat demand of a building can be covered in 100% by renewable energy. Nowadays, solar heating systems are coupled with heat pumps.

Centralized solar systems with decentralized solar collectors are mainly applied in a middle scale. In case of hot water systems and combi systems, hot water + space heating, gas/oil or biomass boilers, or heat pumps are used as auxiliary heat sources. Figure 3 shows a “boiler room” (however, there is no boiler there) with a group of heat pumps (coupled with the solar system) at a modern public building.

Fig.3. Heat pumps used as auxiliary heat sources in a heating plant in Katowice, Poland

In case of a big scale, i.e. a centralized solar heating plant a gas or biomass boilers are mainly used as auxiliary heat sources.

Taking into account integration of solar energy with another auxiliary energy source the solar heating systems operation can be classified as:

- monovalent mode, when only solar energy is used as an energy source;
- bivalent (hybrid) mode, when two energy sources are used.

In case of a solar central heating system the monovalent mode of operation is rarely used. It is possible when the solar heating system is applied to heat water for the use in summer only. A traditional (based on fossil fuels) central heating system can be switched off in summer and the hot water demand is supplied by the solar central heating system.

A bivalent mode of the solar heating system operation is commonly used. There are two main options:

- bivalent – alternative,
- bivalent – parallel.

In a bivalent – alternative mode two energy sources: solar and alternative – auxiliary are used. They are used separately, i.e. when the solar energy is used then no supplementary heating source is applied. When alternative – auxiliary source is used, it is the only one heating source. In a bivalent – parallel mode two energy sources are applied. Solar energy can be used as one main source of energy but usually solar energy is used as preliminary heat source. An auxiliary heat source is applied as a main base or peak source of energy.

Other features and elements of a solar district heating system

Major approach to increase the overall energy efficiency of existing district heating systems in urban areas can be:

- refurbishment of existing systems;
- introduction of new systems in existing or new building establishments.

The second one can be done through introduction of a solar heating system. Different countries develop different concepts for solar district heating. Most of them clasify the systems refering to the connection of solar plants to the net, i.e. distributed vs centralized, what has been already mentioned. There is also classification based on the size of the heating network:

- small – to supply a few buildings,
- middle – to supply new construction areas or villages,
- large – to supply large cities.

It should be mentioned that during refurbishment of existing district heating plants the new distributed solar collector system is constructed and it uses the district heating network as a store.

Central solar thermal systems use usually two-pipe networks. Two-pipe networks show in practice a high solar district plant efficiency and a high share of utilization of solar energy. Two-pipe networks operates in combination with:

- decentralized heat exchangers in buildings and centralized main storage tank/s and a centralized auxiliary heat source/s in the plant;
- decentralized heat storage tanks in buildings and decentralized auxiliary heat sources in buildings, and centralized main storage tank/s in a heating plant,
- main centralized storage tank in a plant and decentralized auxiliary sources (boilers) in buildings.

The distribution network of a system with individual storage tanks can operate at different temperature levels, depending on the function of heating:

- for space heating the low temperature network is required – 40 °C
- for hot water preparation the high temperature is required – 60–70 °C.

Heat losses in the low temperature network are smaller. The distribution network of a system with individual heat exchangers operates at the highest temperature all the time – 60–70 °C. Heat losses in these networks are bigger. However, investment costs are lower than for systems with decentralized storage. Very often the investment costs decide on configuration of the systems, their components and modes of operation.

PRESENT STATE OF IMPLEMENTATION OF SOLAR CENTRAL HEATING SYSTEMS

Implementation of solar district heating systems started at the beginning of the 80-thies of the XX century. In 2007 in Europe there were 130 large-scale plant - collectors arrays (with collector array surface of ≥ 500 m²). The total installed capacity was equal to 137 MW_{th}, and the total collector area was of 240 000 m², that corresponded to 1% of the total installations of 60 000 SDHW systems. In those days the biggest plant was in Denmark, in Marstal, (construction year – 1996) with installed capacity of 12,8 MW_{th} equal to the total solar collector area of 18365 m². The next biggest one was in Sweden, in Kunglav (construction year – 2000), with installed capacity of 7 MWth equal to the total solar collector area of 10000 m².

Dynamic development of the solar district heating systems has been seen since 2007. However, all the time the solar central heating systems represent 1% of the total installed capacity in solar thermal systems. This is due to the fact that the whole solar thermal market has been developing very quickly. Nowadys, in the EU countries the total number of solar central heating systems is equal to 252, with a total installed capacity of 750 MW. Annual progress is 30 % per year, mainly in Denmark, Germany, Sweden, Austria (http://solar-district-heating.eu).

Denmark is the world leader with 50 SDH systems with average solor collector area of DSH systems of 7800 m^2. Annually the installed area of solar collectors surface in this country in recent years was: 2011 - 40000 m^2, 2012 - 76000 m^2, 2013 - 96000 m^2. Nowadays, five biggest SCDH – Solar Central District Heating systems are located in Denmark. They are listed in Table 2.

Table 2. The biggest SCDH – Solar Central District Heating systems in the world

Town	Installed capacity [kW_{th}]	Solar collectors area [m^2]	Year of construction
Vojens	49000	70000	2012 – 2014 extension
Gram	31385	44836	2009
Dronninglund	26300	37573	2014
Marstal	23300	33300	1996
Ringkøbing	21000	30000	2010 - 2014 extension

In last years 2010 – 2015, in Denmark there were 237 plants installed of the total capacity of 1500 MW. Most of the plants is coupled with the CHP plants. All of them was realized without incentives.

The biggest SDHS in the world was constructed in Vojens (see Table 2) by the Arcon-Sunmak company. Total capacity of the plant is equal to 12,25 MW_{th} (construction in 2012) + 49 MW_{Th} (construction in 2014). The total solar collector surface area is equal to 70 000 m^2. The opening of the system after the last extension of the system took place in 12.06.2015. Total volume of the storage, i.e. the water tank equals to 203 000 m^3. Heat is supplied to 2000 households, 10 schools and industrial buildings. Solar energy gained accounts for 400 kWh/m^2, that gives the solar energy share in heating demand of 45%. Temperature of the heat distribution network depends on the season and is equal to:

- 75°C/37°C in summer,
- 77°C/40°C in winter.

It is very interesting to compare the storage energy costs of solar district heating system and the conventional one. Thus the costs of energy storage of solar district heating system are equal to 47 EUR/MWh, while the costs of the natural gas are higher and equal to 57 EUR/MWh. It is expected that progress in deployment of solar district heating system could arise in 2020 by 4%, and in 2030 by 15%.

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