A SOLAR HIGH-TEMPERATURE HEAT ACCUMULATION SYSTEM WITH AN ORC GENERATOR

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1. Introduction

In recent years, a very rapid development of alternative energy applications can be seen, not only in the energy sector but also in the construction sector. Particularly noteworthy is the solar energy, which can be used in heating systems, either active or passive. In favour of its application speaks not only care about the environment, but also the cost-effectiveness in daily life, compared to buildings with conventional heating (Leckner and Zmeureanu, 2011).

Because of the possibility of adaptation to existing facilities, we often can meet installations with flat liquid collectors, which are used for space heating and domestic hot water preparation. There also are systems that thanks to the additional installation of absorption or adsorption produce cooling for residents in the summer (Zhai et al., 2008) when the solar radiation is the highest. Passive houses are also popular (Tan M., 1997) in which by the suitable insulating of external walls, seal, building design, glazing, ventilation system, and the use of solar installation the independence of energy is almost achieved.

Less popular in Poland are solar air heating systems, which in solutions in other countries are often integrated directly with the roof or a wall (Belusko et al., 2004). The main problem of this type of energy source is its existence only during the day and seasonality. This fact creates the need for accumulation systems. The simplest of these systems are well-insulated water tanks, which can even for a few days meet the heat needs of building users. Another solution, mentioned previously in solar air heating systems, is the accumulation of heat in the massive compartments of buildings or separate deposits of solid material, such as a concrete slab located in the basement (Chen et al., 2010) or in the deposit stone, which additionally compensates daily air temperature directed to other living quarters (Abbud et al., 1995; Joudi and Dhaidan, 2001). There are also year-long research on the accumulation of heat for the provision of thermal comfort in the winter due to the absorption system with a tank filled with different solutions, such as water and glycerol (Hui et al., 2011). There are also projects of entire housing estates, as in Sweden (Lundh and Dalenback, 2008) and Germany (Schmidt et al., 2004), where a great quantity of the solar heated liquid is pumped into underground spaces of accumulation.

Actually all of the above-mentioned systems can be classified as low temperature installations.

Research on high-temperature systems, which could be used as thermal systems in residential buildings, are not common. A lack of security is suggested as their main disadvantage; however, this presupposition ignores the fact that the conventional systems, such as coal-fired stoves or fireplaces produce very high temperatures as well and still are very common.

A further part of the article is devoted to the authors' idea of the high-temperature thermal system designed for a single-family home.

2. An autonomous solar home

2.1. General description

The authors of the article have spent the last few years on working on a novel concept of energy self-sufficient house that could work in climatic conditions of Poland. In general, a home heating system is based on the collaboration of a large solar concentrating collector with of a stone deposit accumulation.

Hot air, which in an absorber of the concentrating collector reaches temperature of hundred degrees of Celsius, is directed to a suitably insulated accumulation or deposit to the generating installation. Then, depending on the needs of the residents of the building, the heat stored in the reservoir can be used in a variety of micro-energy devices and converted into other useful forms of energy such as heat heating, domestic hot water, electricity and cold.

Dissertations on the interaction of the solar collector deposit parameters have been described in previous papers (Kasperski and Nemś, 2008a, 2008b, 2008c) of two authors. These works proved that the crushed granite should be the deposit fill material and that mineral wool with a thickness of about 1m would be the best insulation material.

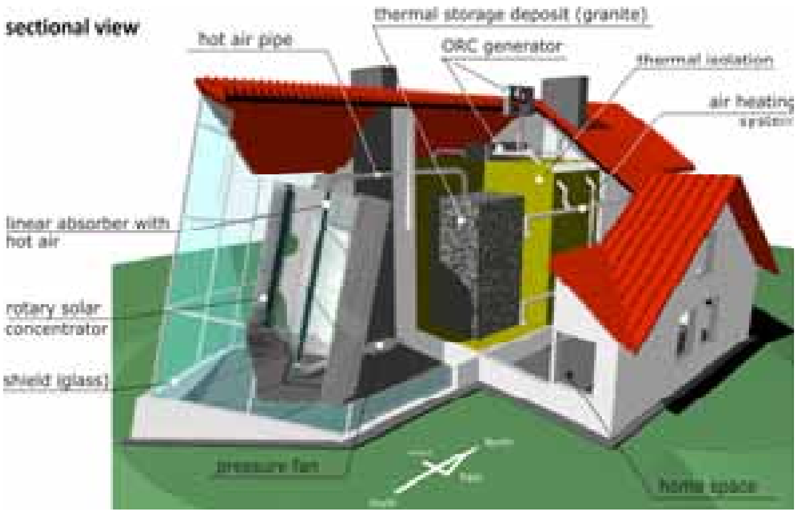

Fig. 1: House with the conceptual system

Possible schematic directions of the heat use from the bed, together with facilities which enable an energy conversion process are shown on Figure 1.

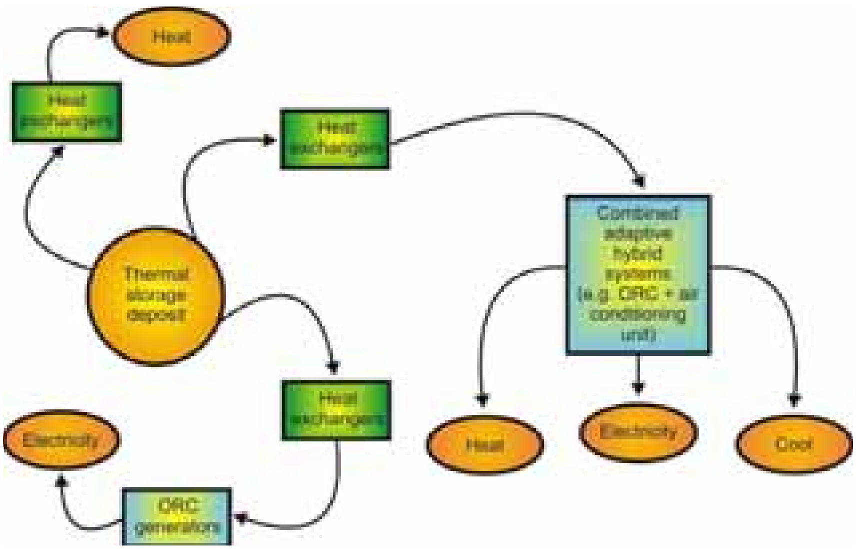

Fig. 2 Possible directions of the heat use from the deposit

2.2. Variants of the system

Home heating system is composed and allows for many variations of work. Choosing the right option depends on the density of solar radiation, the charge state (temperature) deposits accumulation, building demands for thermal energy and electricity. Depending on these parameters the basic variants of the system are possible (Fig. 2):

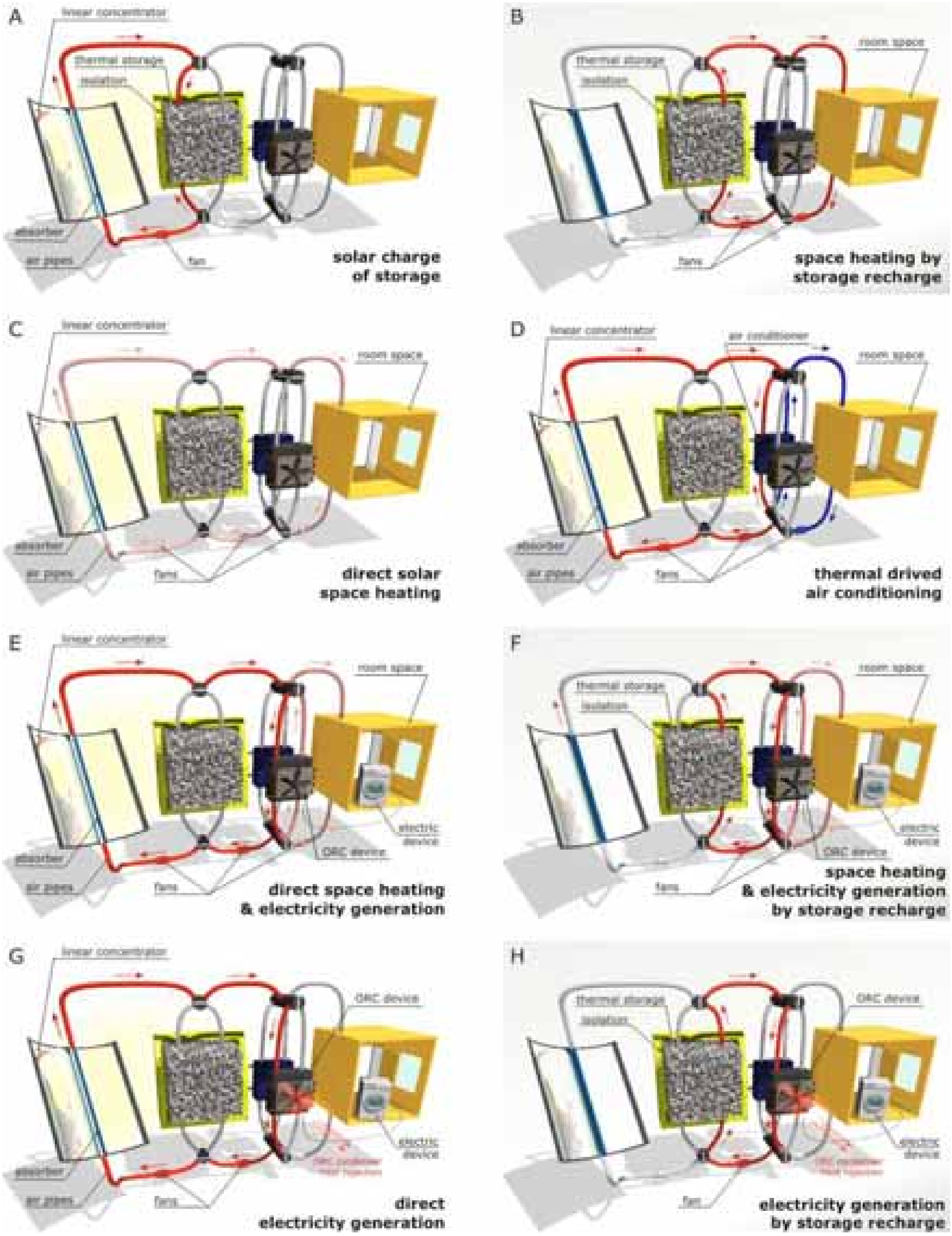

Fig. 3: Variants of the system

A – a direct charging of deposits accumulator with thermal energy obtained in the solar collector. The density of solar radiation must produce temperatures higher than the temperature of accumulative deposits. This occurs mainly during the daytime from spring to autumn.

B – a residential space heating from the heat produced by the accumulation deposit. The amount of heat stored in the deposit is decreasing during a discharging process thus the deposit temperature is also lowering. This occurs mainly during the night and during overcast days in the period from autumn to spring.

C – a direct heating of residential space with heat energy drawn from the solar collector. This situation occurs when the density of solar radiation is low and the temperature generated in the collector is lower than the temperature of accumulation deposits but still is high enough to enable space heating. This occurs mainly during the day during autumn and winter.

D – air conditioning of the living space during periods of excessive ambient temperatures. Air conditioning unit is powered directly by heat extracted from the solar collector. This occurs mainly during the day from spring to autumn.

E – a generation of electricity through the device of ORC directly powered by thermal energy drawn from the solar collector. Heat condensation from ORC unit is not wasted because it is used to heat the living space. This occurs during the day in the period from autumn to spring.

F – a generation of electricity using devices powered by ORC heat energy stored in the accumulation deposit. The temperature level device driver for ORC depends on the temperature of the deposit. Condensation of heat from ORC unit is not wasted, because it is used to heat the living space. This occurs mainly during the night and during overcast day in the period from autumn to spring.

G – a generation of electricity through the device of ORC directly powered by thermal energy drawn from the solar collector. If living space does not require heating, the condensation of heat from ORC is removed to the environment. This occurs mainly during the day from spring to autumn.

H – a generation of electricity using devices of ORC powered by thermal energy accumulated in the accumulation deposit. The temperature level device driver for ORC depends on the temperature of the deposit. If living space does not require heating the condensation of heat from ORC device is removed to the environment. This occurs mainly during the night and during overcast day in the period from spring to autumn.

2.3. Simulations of work

Until now numerical simulations which took into account the conditions of heat exchange on the various elements of the thermal system have been carried out. Especially those conditions that would make the thermal system work efficiently in the climatic conditions of Wroclaw. In the case of deposits its size, density and specific heat of granite, its relative filling volume of the deposit, the conditions of heat transfer from the air, the thickness and thermal conductivity of thermal insulation were included. To protect the deposit and insulation against damages a maximum level of the deposit temperature (400° C) was established. In the case of the collector the geometry of its free movement was included as well as the size of the mirror, its degree of concentration and reflection coefficient. The process of absorption of solar radiation took into account the factor of the glass gallery transmittance, glass covers the absorber vacuum and the emissivity of the outer surface of the ribs and the degree and rate of penetration of heat into the air inside the pipe. The heat exchange between the deposit and the living space resulted from the previously described isolation of deposits, similarly the heat loss from the deposit to the ground under the building was taken into consideration. The heat load of the heating system resulting from the loss of heat insulation of building partitions and ventilation of living conditions are described as linear terms of the instantaneous temperature difference. Only the nominal heating capacity for outside temperature of 0 ° C was defined, while for other values of ambient heating capacity was calculated as proportional to the temperature difference.

Simulation results for operating deposits on an annual basis and for various values of heat loads are shown on Figure 4. The obtained results demonstrate the merits of conducting further research on an innovative system that will completely cover the energy needs of residents.

The size of the elements of the system such as the deposit and a solar collector depends on the assumed intensity of the building and the same parameters of their work. While considering such low-energy house, depending on the degree of concentration of the collector optical system, we can calculate the length of the side of deposits and the mirror size (Tab. 1).

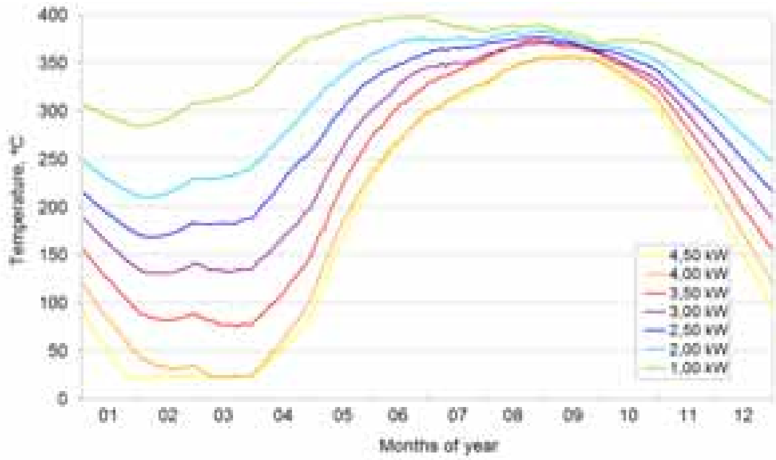

Fig. 4: The graph with the course of temperature changes in accumulation deposit, depending on the heat load

Detailed assumptions used to simulate are as follows: a nominal capacity of about 2.5 kW at an ambient temperature 0° C (that is about 80 kWh/m^2year), an usable building ok.180m^2, 1m insulation of deposits, a concentrating linearly collector with a mirror inclined 60 ° from level with a single axis of rotation.

Tab. 1: The size of the system components depending on the degree of concentration

The degree of concentration of the collector mirror	The side of deposits	The size of the mirror
	m	m^2
40	3.2	12
60	2.7	8
80	2.2	4

The graph below (Fig.4) shows the temperature distribution in the deposit throughout the year, taking into account the information contained in Table 1. The higher degree of mirror concentration, the longer is the term of the maximum temperature presence in the accumulation deposit.

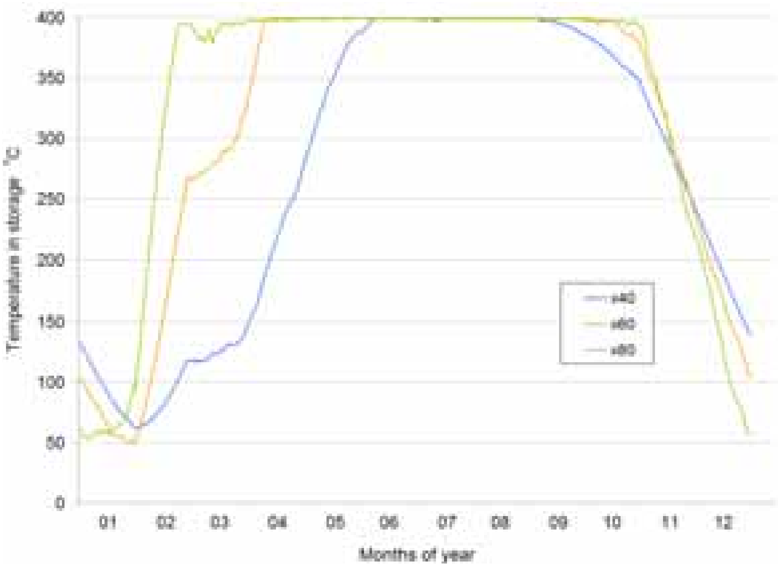

Fig. 5: Changes in the deposit temperature for the annual cycle of solar collectors with varying degrees of concentration

2.4. Characteristics of a deposit

The most important value which characterizes the size of the heat accumulator in the form of granite deposit is its thermal set of characteristic features. A Sample isobaric cooling process of the deposit is shown schematically on Figure 2.

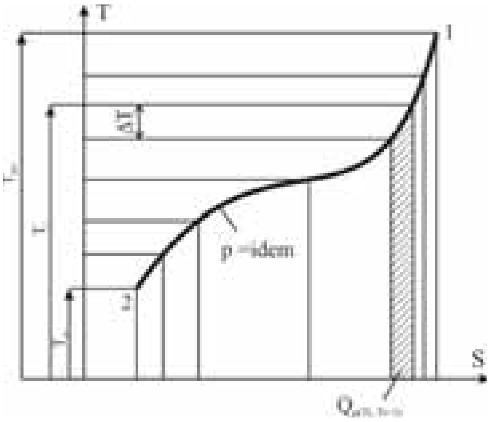

Fig. 5: Isobaric cooling process of the deposit (Kolasiński, 2010)

Cooling curve can have different forms and is conditioned by the heat exchange, the intensity of cooling, external conditions as well as a load.

By analysing the curve and dividing the temperature axis into sections of equal ΔT it is possible to build thermal characteristics of heat sources in the form of a histogram. The histogram for the process of Figure 5 is shown in Figure 3.

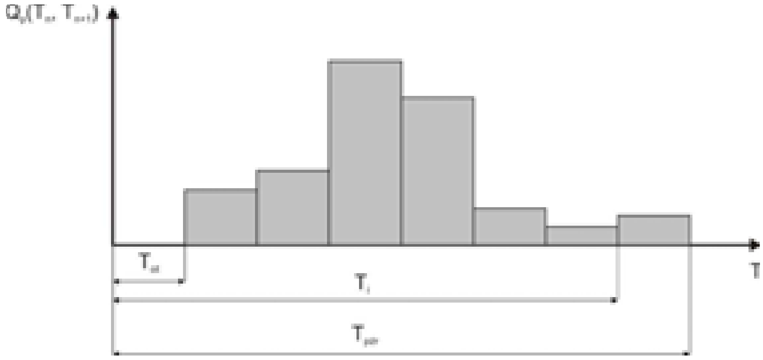

Fig. 6: Histogram of the cooling deposit (Kolasiński, 2010)

The histogram provides an analysis of the possible amount of heat which can be obtained from the deposit by cooling it by a given temperature difference ΔT. This value can be determined by the equation (Kolasiński, 2010):

$$Q_{p(T,T_o)} = I(T) - I(T_o) = m\left[i(T) - i(T_o)\right] \qquad \text{(eq. 1)}$$

The deposit thermal capacity is very helpful in determining the size of it. For solids, the influence on their heat capacity have: a field of temperature, overall dimensions of a body, density and specific heat capacity defined as c_p. The heat capacity dependence for a case of isobaric cooling of a solid at temperatures T_n and T_{n+1} can be determined as:

$$dC(n, n+1) = dm \cdot c_p(T)\Big|_{T_n}^{T_{n+1}} \qquad \text{(eq. 2)}$$

The amount of heat recovered can be determined from the relation:

$$Q = \int_{T_o}^{T} C \cdot dT \qquad \text{(eq. 3)}$$

According to the authors this seems the best way of possible use of heat accumulated in the deposit to cover all energy needs of potential customers. In order to carry out such energy conversion processes, it is necessary to propose a dedicated hybrid energy conversion system. It combines in its design: heat exchangers, an air-conditioning system and a generator system. This system will be discussed in greater details later.

3. An ORC generator for a solar house

There are different ways of producing electrical energy from the sun (Trieb et al., 1997; Mills, 2004) which include, among others photovoltaic and solar thermal systems with a Stirling engine, with Peltier modules, or with Rankine cycles. For the proposed system, the best seems to be a generator of ORC by virtue of temperatures possible to obtain within one year during the discharge of the deposit. The literature on the subject mentions such heat sources that supply the ORC system as biomass (Obernberger et al., 2002), waste heat (Hung et al., 1997), geothermal water (Saleh et al., 2007), various systems associated e.g. with biodiesel (Kane et al., 2003) as well as flat (Wang et al., 2010; Wang et al., 2010) and focused (Jing et al., 2010) solar collectors. Plans for adding the electricity generators to existing solar systems occur during the analysis of larger objects such as hospitals (Bizzarri and Morini, 2006), dairies (Schnitzer et al., 2007) or greenhouses (Sonneveld et al., 2010).

Depending on the heat source and the specificity of a given system a detailed analysis is carried out and only relevant factors are taken into account (Desai and Bandyopadhyay, 2009), other factors, for example, for the solar desalination of water (Delgado-Torres and García-Rodríguez, 2010; Kosmadakis et al., 2009) and for the geothermal system (Saleh et al., 2007).

3.1. Factor selection

One of the most important issues related to the design of ORC systems is the selection of the working medium. A wide range of modern low-boiling factors can be found currently on the market, which the shortened list is shown in Table 2.

Tab. 2: Some potential factors of operating ORC systems

No.	Chemical name	Chemical formula	Trade name	Molar mass	Boiling temperature at atmospheric pressure	Heat of evaporation
	-	-	-	g/mol	K	kJ/kg
1	n-Butane	C_4H_{10}	R600	58.1	272.6	383.8
2	Isobutane	C_4H_{10}	R600a	58.1	261.3	328.4
3	1,1,1,3,3-Pentafluorbuthane	$CF_3CH_2CF_2CH_3$	R365mfc	148.1	314.5	200.8
4	1,1,1,2-Tetrafluorpenthane	$CH_2F\text{-}CF_3$	R134a	102.0	248.0	215.5
5	1,1,1,3,3-Pentafluorpropane	$CHF_2CH_2CF_3$	R245fa	134.1	288.4	208.5
6	1,1,2,2,3- Pentafluorpropane	$CHF_2CF_2CH_2F$	R245ca	134.1	298.2	217.8
7	Dichlorotrifluorethane	$CHCl_2CF_3$	R123	152.9	301.0	171.5
8	2-Chloro-1,2,2,2-Tetrafluorethane	CF_3CHClF	R124	136.5	261.2	146.5
9	1,2-Dichlorotetrafluorethane	$C_2Cl_2F_4$	R114	170.9	276.7	136.2
10	1,1,2-Trichloro-1,2,2-Trifluorethane	CCl_2FCClF_2	R113	187.0	320.4	143.9
11	-	$CF_3CH_2CF_2CH_3$	SES 36	184.5	308.8	129.3

The most important issues related to the choice of the working medium are:

• the character, type and the temperature of the upper heat source,

• thermodynamics parameters,

• chemical stability,

• impact on the structural elements,

• toxicity,

• ozone depletion potential ODP,

• warming potential GWP,

• ability to penetrate the vapour refrigerant through the cracks.

The nature of the work has an impact on the most important parameters of the system, including its efficiency.
The method of selection of the working medium to the heat and energy conversion system, and its related issues are presented in detail in (Kolasiński P., 2010) and (Gnutek Z. et al., 2009).

For the proposed further in the article the ORC system cooperating with granite deposit a potential working medium can be: SES36, R123, R113 and R245fa. The most appropriate of these seems to be R245fa. This choice is dictated by both the thermodynamic parameters of this factor as well as the safety of residents. This factor indeed has a relatively low pressure in the temperature range that interested the authors, because it has a low penetration ability, and does not form explosive mixtures with air (BOC GASES, 2011).

3.2. The ORC systems cooperating with the house solar energy system

A proposed technical configuration of the ORC system is presented on Figure 7.

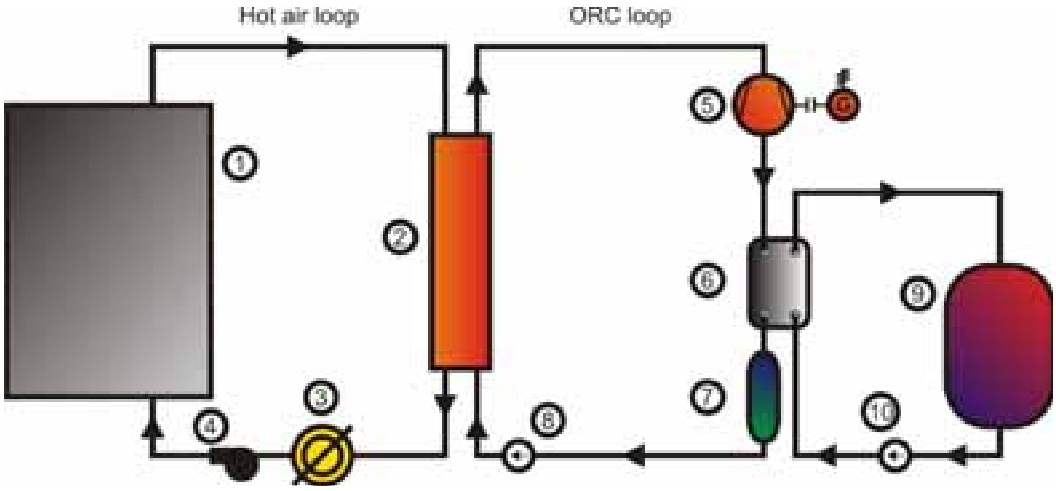

Fig. 7: The ORC system cooperating with the house solar energy system: 1 – thermal storage deposit, 2 – evaporator, 3 – central heating system, 4 – hot air fan, 5 – volumetric vane expander with power generator, 6 – condenser, 7 – liquid working substance reservoir, 8 – vane pump, 9 – hot water storage, 10 – water pump

In this arrangement, cooling of the deposit is forced by the air fan (4). Hot air is directed to the counter-current heat exchanger with filling (2) forming ORC evaporator system, which cools, giving both heat low-boiling working medium. The chilled air is directed to the heating system (3). The liquid working medium ORC system - R245fa is taken from the tank (7) and through the pump blade (8) is pumped into evaporator (2), where the evaporation occurs during isobaric transformations. Then vapour is directed to the expansion machine (5) connected through magnetic coupling with 230V/60Hz power generator that could provide coverage for residents of the demand for electricity during all year. In order to minimize the dimensions of energy, the conversion system seems to be a deliberate application of expansion vane volume machines. They are characterized by small size in relation to the power and low noise emissions. The working medium, after work in expander, is directed to a counter-plate condenser (6) water-cooled with hot water tank (9), where after the condensation it flows into the tank (7).

4. Summary

Buildings' thermal systems powered by solar energy use usually flat solar collectors and thus their working medium reaches a relatively low temperature. Although they are sufficient for heating and preparation of domestic hot water, they are not conducive to long-term accumulation, which would satisfy the needs of thermal comfort also on cloudy days or in the winter.

According to numerical simulations, the authors proposed a system with high-temperature concentrating solar collector and accumulation of heat in the deposit of granite - that would ensure energy self-sufficiency of single-family home residents in Polish climatic conditions. It would allow for the production of electricity, air conditioning in the summer and air heating in the winter.

Both for traditional buildings and energy efficient houses, obtained temperatures change according to a type of a working medium of the concentrating solar collector. It also affects the size of accumulation and therefore the entire architectural structure of the object.

The proposed system of the production of electricity with generator ORC, because of the required parameters, should fully cover the needs of residents of the building and therefore provide them with energy self-sufficiency. This opens up the possibility of using this type of solutions for the construction of buildings in areas without access to the media.

The next step to verify the concept of an autonomous house will be annual experimental studies of the set-up built in scale that will be started on next month. It is also planned to draw up detailed histograms for the full-size object and make the cost benefits be analyzed in depth.

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