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A CONCEPT FOR A SOLAR ADSORPTION COOLING SYSTEM

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Abstract
In the current paper a possible usage of sorption cooling systems, seen as important factor for utilization of low parameters thermal energy (60÷90°C), has been investigated. A list of equations for designing of installations using solar radiation energy for supplying an adsorption ice water generator AIWG has been presented. A concept for an adsorption cooling system consisting of four following modules: generating, accumulating, transmitting and using the solar radiation energy has also been presented. Such parameters as: pressure, temperature, cooling power, thermal power demand and a coefficient of cooling efficiency COP, needed for operation of the adsorption adsorption ice water generator with a cooling power of 0.5 kW, have also been shown. Additionally, an impact of atmospheric conditions variation on operation of the cooling systems and keeping a state of a thermal comfort in a room has also been investigated.

Streszczenie
W artykule rozważono zastosowanie sorpcyjnych układów chłodniczych jako istotnego czynnika wykorzystującego energię termiczną o niskich parametrach 60-90°C. Przedstawiono zestaw równań dla zaprojektowania instalacji wykorzystującej energię promieniowania słonecznego do napędu adsorpcyjnej wytwornicy wody lodowej. Zaprezentowano koncepcję adsorpcyjnego systemu chłodzenia składającego się z czterech modułów: wytwarzania, akumulacji, przesyłu i wykorzystania energii promieniowania słonecznego. Przedstawiono również parametry pracy adsorpcyjnej wytwornicy wody lodowej o mocy chłodniczej 0.5 kW, tj. ciśnienia, temperatury, moc chłodniczą, zapotrzebowanie na moc cieplną i współczynnik wydajności chłodniczej COP. Dodatkowo rozważony został wpływ zmienności warunków atmosferycznych na pracę systemu chłodzenia oraz na zachowanie komfortu cieplnego w pomieszczeniu.

Keywords: **Solar cooling; Adsorption chiller; Adsorption ice water generator; Thermal comfort.**

DESIGNATION

A – surface area, m2
C – specific heat (capacity), kJ/(kg K)
ΔT – difference of temperatures, K
ΔT_{skH_2O} – difference of condensation temperatures and of water receiving the heat at an inlet of an exchanger, K
N – absorptivity per 100g of deposit (bed), g H_2O/100g
η – efficiency,
Q_{1kgH_2O} – unitary stream of heat from evaporation process, W/kg H_2O
Q – thermal power, W
q – unitary heat, kJ/kg

q_{r1kgH_2O}	–	amount of heat needed for regeneration process, kJ/kg H_2O
τ	–	time, min
U	–	coefficient of heat penetration, W/(m^2 K)
V	–	volume, m^3
$\dot{V}$	–	stream of volume, m^3/h
$\dot{W}$	–	thermal conductivity, W/K
W_s	–	amount of adsorbent, kg

Lower index

15	–	time of 15 minutes
60	–	time of 60 minutes
a	–	heat and coolness accumulation system
ad	–	adsorption
ads	–	adsorber
A_{ads}	–	exchanger of adsorber
A_{par}	–	exchanger of evaporator
A_{skr}	–	exchanger of condenser
c	–	heat
ca	–	total
ch	–	coldness / coolness
de	–	desorption
g	–	heating water circulation
H_2O	–	water
L	–	ice water circulation
p	–	heat and coolness transmission system
pa	–	evaporation
par	–	evaporator
s	–	sorbent
sk	–	condensation
skr	–	condenser
w	–	heat and coolness generation system
wyk	–	coolness regulation and utilization system
z	–	cold water circulation
+	–	excess

1. INTRODUCTION

According to the development directions for provision systems of heat, coldness and electricity in buildings, presented for example in theses [1, 2, 3], alternative solutions such as decentralized systems of energy supplying or central heating and cooling systems supplied largely by renewable energy, would have to be taken into consideration during all new buildings construction. And this is why the currently presented issues are strictly connected with one of the key elements of reducing demand for primary energy in building and installation systems.

In order to reduce the demand for energy used for heating-and-ventilation purposes some new innovative and low-energy technologies (eg. passive buildings) are being introduced, and thermo-modernization processes in existing buildings are carried out in a dynamic way in the whole building sector. One of the result of those undertakings is an increase of leakproofness in buildings [4, 5]. In summer time this leads to a lack of possibility for carrying away internal gains of heat, and consequently it results in an increase of demand for coldness. Because of that low power refrigerating systems (from a few to a more than dozen kW) play a more and more important role in the whole building sector.

On the other hand it is crucial to remember about ensuring comfortable conditions of an internal microclimate for human beings as they stay indoors for a large part of a day (24-hour period). It is then necessary to deliver a minimum required amount of fresh air and at the same time lower the air temperature to the level corresponding to the range of the thermal comfort during the summer time. Additionally one must remember about heat excesses coming from electrical and electronic devices (which are higher from year to year, and are especially significant in the passive or zero-plus-energy technologies) [6].

The mentioned above contradiction causes that the following phenomenon is observed in buildings of extreme low energy-consumption level (15 kWh/(m^2 per year): there is lower demand for energy for heating purposes in winter time, and there is higher demand for cooling energy in summer time.

2. A CONCEPT FOR THE ADSORPTION COOLING SYSTEM

2.1. A referential room

The proposed concept of the adsorption cooling system supplied by solar radiation energy has been worked out for a referential room with a cubic capacity of 30 m^3. A maximum cooling power of AIWG has been referred to average hourly levels of the solar radiation intensity for a referential day in summer time. The day chosen was the one with the highest intensity of solar radiation, in accordance with data included in the paper [7]. As a result of the conducted balance of excesses and losses of heat the maximum level of the cooling power of AIWG was 500 W. A summary of data regarding the demand for coldness in the referential room, depending on the intensity of the solar radiation, has been presented in Figure 1. On the basis of the calculations made it has been concluded that the maximum demand for the cooling power was registered after 12:00 hrs. In the considered case (i.e. during the day of the maximum level of the heat profits) it was necessary to cool the room during the whole 24-hour period, also at night. Between 20:00÷4:00 hrs the demand for the cooling power was within the range between 50÷200 W. And this is why (i.e. in order to ensure a required level of heat for the drive of the refrigerating machine during the whole day-and-night period), it was also necessary to plan accumulators of heat and coldness for the cooling system. They allowed to store an excess of the thermal power which was used at night time as a drive of AIWG. In an analogical way the stored excess of the coldness was used when the intensity of the solar radiation was at an insufficient level.

2.2. The system characteristics

The adsorption refrigerating system, supplied by solar radiation energy comprised of four basic mod-

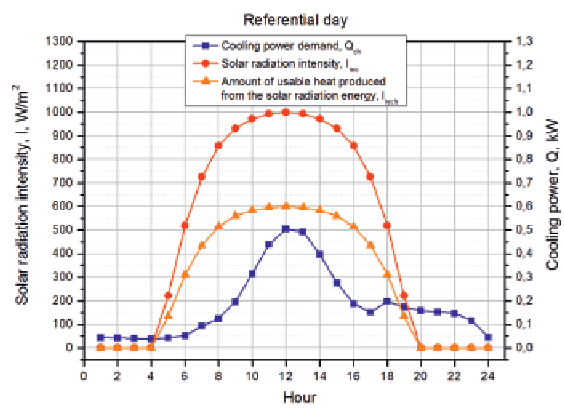

Figure 1.
Hourly demand for the cooling power for the referential room and for the referential day

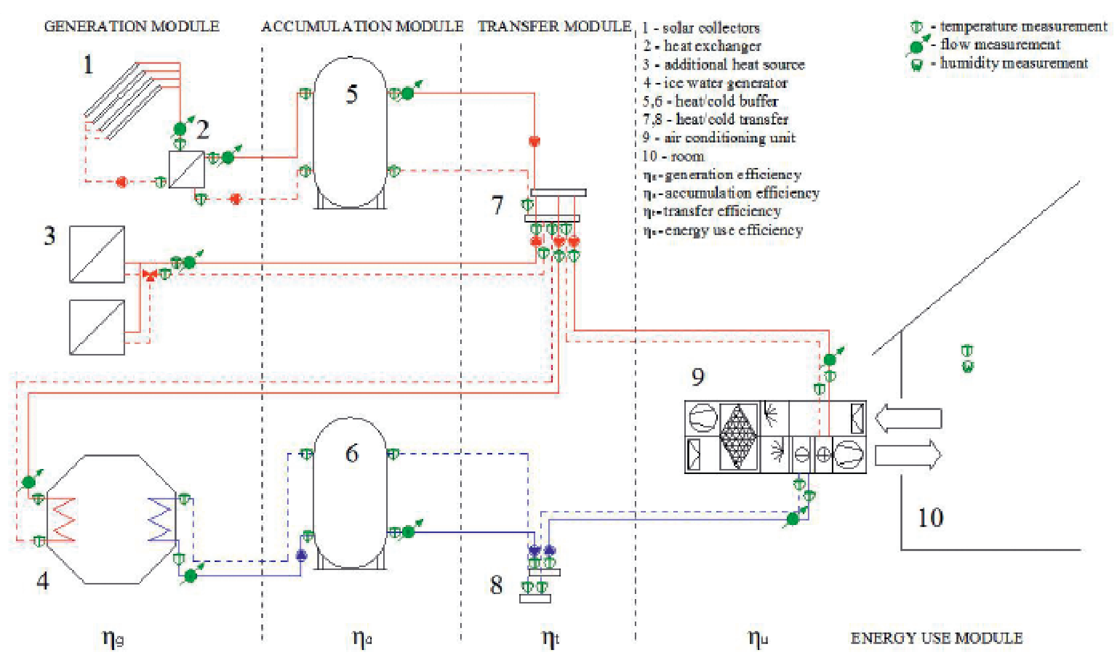

Figure 2.
Diagram of the adsorption cooling system, supplied by solar radiation energy [8]

ules: a generation one, an accumulation one, a transmission one and an utilization one. The generation module was responsible for creating heat and coldness. It included a set of solar collectors, an additional source of heat and AIWG. The accumulation module included accumulators of heat and coldness. They allowed to define and configure levels of possible to be achieved levels of cooling power in the created conditions. The next set of modules was used for transmission and utilization. It consisted of transmission-and-measurement fixtures and elements necessary for division and distribution of coolness in the referential room. Crucial and characteristic feature for the module was an efficiency of heat and coldness transmission. A diagram of the adsorption cooling system, supplied by solar radiation energy has been presented in Figure 2.

3. ADSORPTION GENERATOR OF ICE WATER

For construction purposes of an adsorption generator of ice water prototype one has worked out several equations which made possible to calculate basic parameters of its operation.

3.1. Basic parameters of the adsorption generator of ice water

An operation of AIWG was assumed in conditions of under-pressure created by a vacuum pump. The working medium was water. The initial conditions of refrigeration process, resulting from a specifity of the working medium were determined in a following way: the water vaporization pressure, which is to be achieved in order to start the cooling process, according to [9], is 2451.7 Pa, with the temperature of 20.8°C. During the continuous operation of the machine one envisaged lowering the temperature of the working medium. On that basis there were several following values of the initial temperatures of the working medium determined: 20°C, 16°C and 12°C. The whole duration of the cooling process was divided into two separate phases: the adsorption (cooling effect) and the regeneration. On the basis of data available in relevant literature [10] the time needed for the adsorption and desorption was estimated at the same level, with no relation to a real duration of the process itself.

3.2. Determination of amount of the working medium – adsorbate

The specified duration of the adsorption (cooling) process was at the level of τ_{ad}=15 min; heat produced during the water vaporization q_{paH2O}=2460.2 kJ/kg was read when the values of pressure and temperature were $p_{par,ad}$=1961.3 Pa and $t_{par,ad}$=17.2°C, respectively. In order to calculate a unitary stream of heat received from the vaporization process one proposed the following equation:

$$\dot{Q}_{1kgH_2O} = \frac{q_{par,ad}}{\tau_{ad}}, \qquad \frac{W}{kgH_2O} \tag{1}$$

For calculating the cooling power of AIWG Q_{ch}=500 W the amount of the working medium was determined as follows:

$$V_{H_2O} = \frac{\dot{Q}_{ch}}{\dot{Q}_{1kgH_2O}}, \qquad m^3 \tag{2}$$

The estimated minimum amount of the working agent taking part in the vaporization process to obtain 500 W of the heat stream was $1.83 \cdot 10^{-4}$ m^3 of water.

3.3. Choosing an appropriate kind and amount of the adsorbent

As an adsorbent in the conceptual AIWG one used a broad-porous silica gel (type SG). According to data presented in [11] an absorptivity of the adsorbent is N_{s60}=28 $g_{H2O}/100g_{\text{of adsorbent}}$ when we assume that the duration of the adsorption is equal to 1 hour, the height of the bed is 1 m, and the velocity of the flow of humid air is below $v_{pow} \leq 0.25$ m/s. The value of the absorptivity was determined for a minimum relative humidity at a level of 50%. In relation to the above the equation for calculating the absorptivity of the sorbent in a function of the duration of the process and the height of the bed was formulated as follows:

$$N_{s15} = \frac{0.8 \cdot N_{s60} \cdot \tau_{ad}}{\tau_{60}}, \qquad \frac{gH_2O}{100g\ of\ adsorbent} \tag{3}$$

For construction reasons of the adsorber's accumulator presented in Figure 3 as well as features of the adsorbent itself there were two adsorption columns used, both of the height of 0.8 m and diameters of 0.192 m. Such solution allowed to use maximum of 30 kg of adsorbent, with a volume of 0.0462 m^3. For the investigation purposes the determined amount of sorbent was at a level of W_s=4.1 kg.

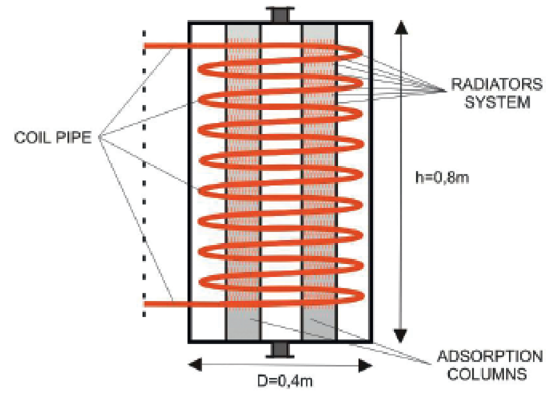

Figure 3.
Diagram of the adsorber of AIWG

3.4. Establishing the temperature of the heating agent and the demand for thermal power needed for the sorbent regeneration

A key criterion for choosing suitable parameters for AIWG was a range of temperatures of the heating agent for the regeneration process. The basic assumption was the operation of the machine while the temperature of the heating medium is below 95°C. Higher temperatures are not possible to be achieved in Polish climate conditions while using commonly available solar collectors. On the basis of available data for relevant devices [12, 13] the lowest level of the temperature of the heating agent was defined as 60°C. Below this temperature of the heating agent there is no need for cooling and that results from an insignificant intensity of the solar radiation. Such range of temperatures allows taking advantage of flat-plate liquid solar collectors. For determination of the heat stream for the regeneration process of the sorbent's bed the following equation was used:

$$\dot{Q}_{crs} = \frac{q_{r1kgH_2O} \cdot V_{H_2O}}{\tau_{de}}, \qquad W \tag{4}$$

It was assumed that the desorption time is equal to the adsorption time $\tau_{de}=\tau_{ad}$=15 min. Amount of the heat needed for that type of sorbent's regeneration, on the basis of materials presented in paper [35] is $q_{r1kgH2O}$=5861.5 kJ/kg H_2O, when we base the calculation on a kilo of the adsorbed water.

3.5. Calculating the volume of the heat and coldness calculators

On the basis of the so-far assumed parameters of AIWG operation volumes of the heat and coldness stores were determined. The heat store was defined in such a way that it could ensure the adsorbent's regeneration even in the case of a temporary lack or insufficient intensity of the solar radiation. In an analogical way the coldness store was prepared in such a way that it could deliver ice water for the cooling system also during the process of regeneration. Despite the fact that there were highest profits of the solar radiation at the same time as there was the maximum demand for coldness, it is necessary to use the heat and coldness accumulators because of a significant inertia of the system and enclosure of the room. That means that conditions inside the room are changing slowlier than parameters of the external air. And therefore if there is a sudden drop of the solar radiation intensity in the room, then inside the room the demand for coldness will still exist. The accumulators were foreseen in order to guarantee appropriate cooling power during a whole 24-hour period. The carried out balance of the excesses and losses of the heat assumes a continuity of ice water delivery, and this is why there were two devices of that type used, working alternately. When there was the adsorption process taking place in one of the devices, there was regeneration going on in the other one. The thermal balance presented in Figure 4 refers to the referential day with a maximum value of the solar radiation intensity.

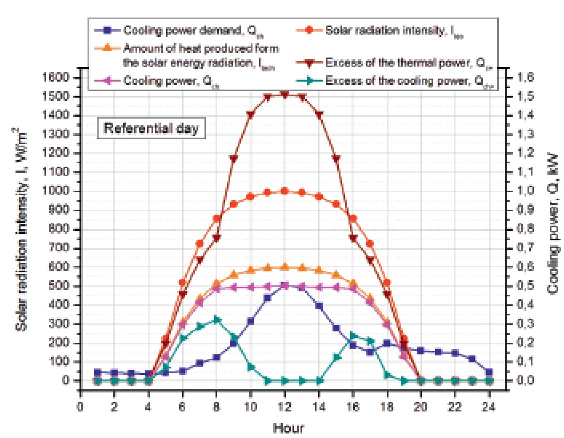

Figure 4.
Balance of the heat and coldness demand of AIWG for the referential day

The volume of the heat accumulator V_c and the coldness accumulator V_{ch} was calculated from the following equation:

$$V_c = 3600 \cdot \frac{\dot{Q}_{c+}}{C_{H_2O} \cdot \Delta T_{ads}}, \qquad m^3 \tag{5}$$

$$V_{ch} = 3600 \cdot \frac{\dot{Q}_{ch+}}{C_{H_2O} \cdot \Delta T_{par}}, \qquad m^3 \tag{6}$$

3.6. Calculating the areas of the heat exchangers

The surface areas of the heat exchangers were calculated on the basis of data included in arguments prepared by Zalewski [14]. There were panel heat exchangers installed in the evaporator and condenser. The surface area of the exchanger in the evaporator A_{par} was calculated as follows:

$$A_{par} = -\frac{\ln\left(1 - \frac{\dot{Q}_{par}}{\dot{W} \cdot \Delta T_{sk-H_2O}}\right) \cdot \dot{W}}{U_{A_{par}}}, \qquad m^2 \tag{7}$$

The surface area of the exchanger in the condenser A_{skr} was determined in the following way:

$$A_{skr} = -\frac{\ln\left(1 - \frac{\dot{Q}_{skr}}{\dot{W} \cdot \Delta T_{sk-H_2O}}\right) \cdot \dot{W}}{U_{A_{skr}}}, \qquad m^2 \tag{8}$$

In the adsorber one used a coil pipe equipped with radiators with the surface of the heat exchange calculated from the following equation:

$$A_{ads} = -\frac{\ln\left(1 - \frac{\dot{Q}_{ads}}{\dot{W} \cdot \Delta T_{sk-H_2O}}\right) \cdot \dot{W}}{U_{A_{ads}}}, \qquad m^2 \tag{9}$$

3.7. Calculations for streams of heating, cooling and ice waters

The stream of ice water $\dot{V}_{H_2OL}$ was defined with the estimation that the cooling effect will allow to lower the temperature of the ice water by ΔT_L=5°C, and from the given below equation:

$$\dot{V}_{H_2OL} = 3.6 \cdot \frac{\dot{Q}_{ch}}{C_{H_2O} \cdot \Delta T_L}, \qquad \frac{m^3}{h} \tag{10}$$

The stream of the heating water $\dot{V}_{H_2Og}$ was calculated from the equation:

$$\dot{V}_{H_2Og} = 3.6 \cdot \frac{\dot{Q}_{crs}}{C_{H_2O} \cdot \Delta T_g}, \qquad \frac{m^3}{h} \tag{11}$$

The stream of the cold water $\dot{V}_{H_2Oz}$ was determined by using the equation:

$$\dot{V}_{H_2Oz} = 3.6 \cdot \frac{\dot{Q}_{sk}}{C_{H_2O} \cdot \Delta T_z}, \qquad \frac{m^3}{h} \tag{12}$$

3.8. Specific cooling power of AWWL

The specific cooling power of AIWG (Specific Cooling Power – SCP) was defined according to the equation 1.13:

$$SCP = \frac{\dot{Q}_{ch}}{W_s}, \qquad \frac{W}{kg\ of\ sorbent} \tag{13}$$

3.9. Coefficient of the cooling efficiency of AIWG

The coefficient of the cooling efficiency of AIWG was determined in accordance with the following equation:

$$COP = \frac{\dot{Q}_{ch}}{\dot{Q}_{crs}}, \qquad - \tag{14}$$

3.10. System efficiency

The total efficiency η_{ca} of the cooling system was achieved through determination of partial efficiencies [15], namely the efficiency of heat and coldness generation η_w, the efficiency of heat and coldness accumulation η_a, the efficiency of heat and coldness transmission η_p as well as the efficiency of coldness regulation and utilization η_{wyk} according to the following dependence:

$$\eta_{ca} = \eta_w \cdot \eta_a \cdot \eta_p \cdot \eta_{wyk}, \qquad - \tag{15}$$

4. CONCLUSIONS

On the basis of the conducted balance of excesses and losses of heat for the referential room as well as dependences that determine basic parameters of AIWG the following operation conditions for the cooling systems have been received:

1. AIWG with a power of $\dot{Q}_{ch}$=500 W is to cover demand for the cooling power within a period of 24 hours, for the referential room with a cubic capacity of 30 m^3.
2. The power feed for AIWG is to come from five flat-plate solar collectors (Aparel KSC A2

VCr1), each one with an active flank (surface) of 2.10 m^2.

3. Water with a heat of vaporization equal to q_{paH2O}=2460.2 kJ/kg, with the pressure of $p_{par,ad}$=1961.3 Pa and the temperature of $t_{par,ad}$=17.2°C, is to be a working medium.
4. Initial conditions of the cooling process, resulting from the specifity of the working medium are the following: the pressure of the water vaporization which is to be obtained in order to start the cooling process has to be equal to 2451.7 Pa, with the temperature equal to 20.8°C.
5. The whole cooling process consists of two phases: adsorption and regeneration. The time needed for adsorption and desorption is $\tau_{ad}= \tau_{de}$ =15 min.
6. An appointed minimum amount of the working medium taking part in the vaporization process in order to receive 500 W of the heat stream is $1.83 \cdot 10^{-4}$ m^3 of water.
7. Broad-porous silica gel (type SG with absorptivity of N_{s60}=28 g_{H2O}/100 g_{bed}) has been proposed as the adsorbent with the following assumptions: the time needed for the adsorption is 1 hour, the height of the bed is 1 m, and the velocity of the flow of damp air is kept at the level below $v_{pow} \leq 0.25$ m/s. For the investigation purposes the amount of the adsorbent used is W_s=4.1 kg, whereas the required amount of the heat needed for regeneration is $q_{r1kgH2O}$=5861.5 kJ/kg H_2O, with scaling for one kilogram of the adsorped water. The heat stream needed for the regeneration of the sorbent bed is $\dot{Q}_{crs}$=1192 W.
8. Calculated volumes of heat and coldness accumulators are V_c=0.169 m^3 and V_{ch}=0.112 m^3, respectively.
9. In the evaporator and the condenser one has used panel heat exchangers, with surfaces equal to A_{par}=0.85 m^2 and A_{skr}=1.26 m^2, respectively. In the adsorber a tubular (coil pipe) heat exchanger, equipped with radiators of the heat exchange surface equal to A_{ads}=2.01 m^2 has been proposed.
10. Streams of the ice, heat and cold water are $\dot{V}_{H_2OL}$=0.043 m^3/h, $\dot{V}_{H_2Og}$=0.017 m^3/h and $\dot{V}_{H_2Oz}$=0.042 m^3/h, respectively.
11. Specific cooling power of AIWG is SCP=122 W/kg of the sorbent.
12. A theoretical coefficient of the cooling efficiency AIWG is equal to COP=0.42.
13. An adsorption refrigerating system, supplied by solar radiation energy is to consist of four basic modules: a generation one, an accumulation one, a transmission one and an utilization one. A calculated total efficiency of the system is η_{ca}=0.3.

On the basis of the above assumption a conceptual project of the adsorption ice water generator has been worked out. The diagram of AIWG has been shown in Figure 5.

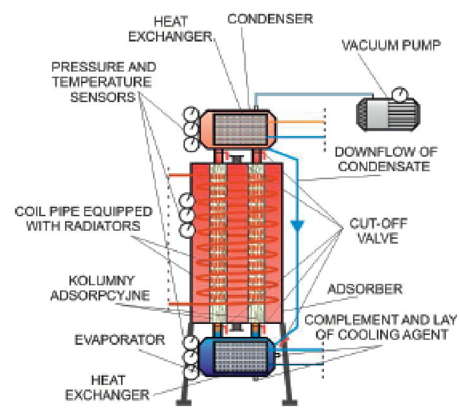

Figure 5.
Adsorption generator of ice water supplied by solar radiation energy

Adsorption ice water generators supplied by solar radiation energy might be used in public utility buildings, detached houses, sports centers, and in different energy-saving buildings. The basis for a selection of particular solar installation is a demand for heat needed for AIWG regeneration. If the system is designed and used in a way appropriate for particular demand and climate conditions, envisaged energy and economic effects should be achieved. In Poland there are relatively good conditions for taking advantage of solar energy by adjusting types of systems and characteristics of devices using that sort of energy to a specific character, structure and distribution of the solar radiation in time. In connection to the intensity variation of solar radiation energy in a 24-hour period it is necessary to accumulate produced coldness in buffer tanks.

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