SZENT ISTVÁN UNIVERSITY

Solar energy utilization in air-conditioning systems

Thesis of PhD work

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Affirmation of supervisors	Affirmation of head of school

CONTENTS

NOTATIONS

A	function factor	[W/m^6 s^2]
A_p	surface of evaporation	[m^2]
C	function factor	[s/m^3]
I	solar radiation intensity	[W/m^2]
L_p	specific heat of evaporation	[J/kg]
m	mass	[kg]
P_h	cooling power	[W]
Q	flowrate	[m^3/s]
t	time	[s]
T	temperature	[°C]
v	velocity	[m/s]

1. INTRODUCTION, OBJECTIVES

The utilization of renewable energies, and among them the solar energy get significance nowadays, in view of the continuous rising of the energy prices and the revalued environmental protection and its official tendencies (for example the EU directives). By the way the solar energy utilization gets significant role in some regions of the world (Germany, USA, China), in spite of the technology's disadvantages such as the production and the consumption generally alters in time that means we have to store the produced energy. Although for this storing there are some good methods with high efficiency, for example the solar cooling is good example as in this case we can utilize the solar energy without storing. By this application the biggest energy demands start up when the solar radiation is the biggest (that's means the cooling demand).

The importance of my research topic is indicated by the fact, that the maximum energy electric consumption in summer in the civilized world's countries match to the winter maximum energy consumption values, mainly as because of the air conditional systems. So, the solar cooling by air-conditioning system take out significant performance to the traditional energy sources by energy production.

The climate change modifies our life largely, our connection with nature. In the last years we could meet some heat waves, droughts, and fry. Over 35 ^{o}C – measured in shadow – temperature fags out the human body. During some days the high air temperature 's negative effects is tried to tide over by us. For this purpose we ease the outside heat effect with standing in a good insulated building and with a good cooling system. Our cooling system can be passive (without energy, with nature or artificial shadows) or active (by machine) cooling. Our heat feeling depends on the air temperature and humidity, so to control these values we use air-conditioning systems.

Air-conditioning systems for domestic utilization generally work with electrical energy, which during some summer days can overload the national electrical grid and power plants. This can have some negative effects for example overloading blackouts or extra emission of the fossil power plants. Depend on a country's power plants' combination it can enlarge the greenhouse gases' emissions in this period.

In Hungary the fossil power plants emit significant amount of carbon dioxide during the electric energy production, that enlarges the global warming effect. The consumption of energy sources significantly from external sources means an energy supply security problem, which makes the country dependent from the energy supply source.

In summer the air-conditioning system operated by solar energy is favorable, because it is direct energy consuming (no store), independently from the electric grid, cost reductive and environment friendly. The usage of cooling systems operated by solar collectors can come into the limelight in our life.

My research aim is to determine how the solar energy can be used for cooling systems, and for low-performance (several kW power) domestic air-conditioning systems. During my research work two main fields were covered: examination of the solar energy utilization's possibilities and choosing the proper cooling technology.

Research aims for the solar energy utilization:

- Determination of the utilizable energy by solar collector according to measuring and numerical model (for a given type of solar collector at a given location).
- Determination of the insurable energy by solar collector for operation of the cooling machine.
- Examination of utilizable cooling effect of solar radiation's generated air moving.

Research aims by cooling technology and air-conditioning:

- Examination of absorption cooling technology operated by solar collectors and solar cells with several working fluid.
- Examination of evaporation cooling technology for air-conditioning systems with porous materials.

2. MATERIALS AND METHODS

In this chapter the used modelling and experimental methods, which were used to reach the research aims are presented.

2.1. Development of experimental devices

For the study of the solar cooling I have developed the following experimental devices. For examination of heat utilization by solar collector I have set up an experimental fluid circuit with measuring points (Fig. 1). I have built an experimental system for absorption cooler and solar collector with application of an insulated box. (Fig. 2). I have analyzed the absorption cooler with solar cells, too. As other possibility solution for cooling I have analyzed porous pots filled with water (Fig. 3). I have studied an alternative cooling technology based on solar energy generated air moving (Fig. 4). I have evaluated the experimental measurements at the laboratories of the Department of Physics and Process Control, Szent István University.

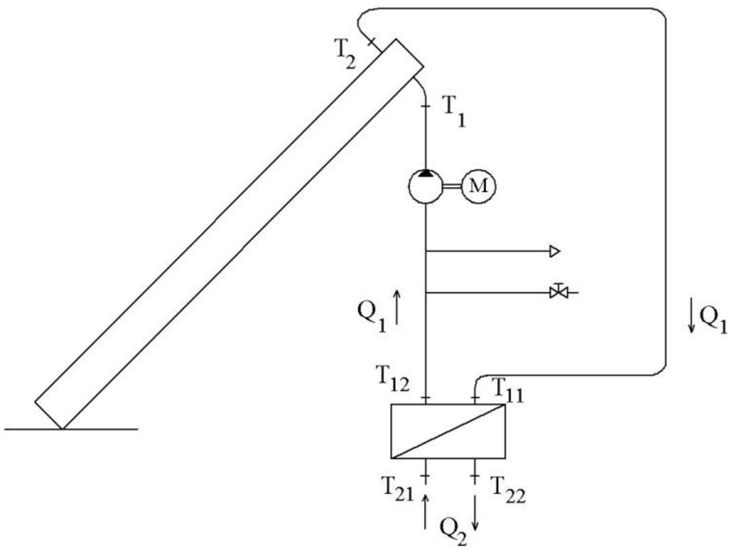

Fig. 1. Solar collector with measuring points

The energy was collected by a vacuum tube (heat pipe) solar collector (useful area of 1.485 m^2, 15 vacuum tubes, with the diameter of 5.8 cm and length of 180 cm). The utilized energy were used through a laminar heat exchanger.

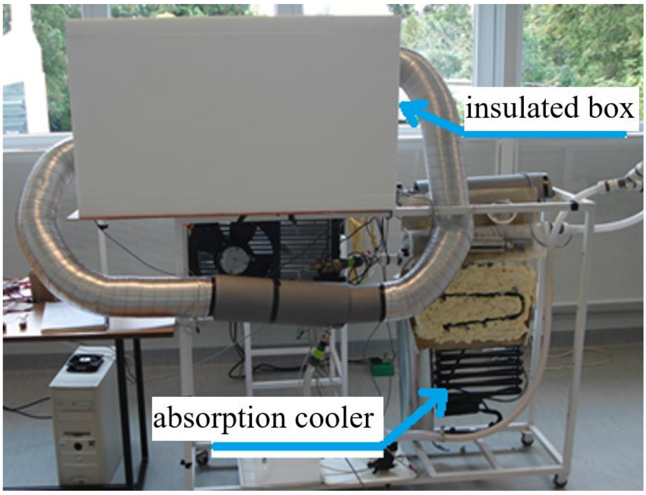

Fig. 2. Experimental cooling system

I have used a refigerator's cooling aggregate for the experiments. The used absorption cooling aggregate is filled with ammonia and water. In the returning pipe an ultrasonic heat meter and a pump were installed.

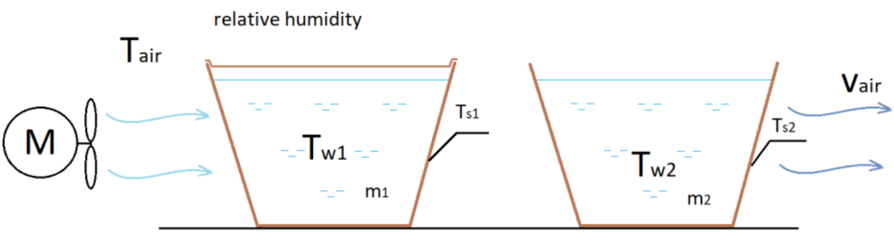

Fig. 3. Experimental evaporation cooling with the measured parameters (closed and open pots filled with water)

During the examination of porous pots, I have determined the heat loss values during evaporation of water. These pots are unpolished and have not glaze. I have measured evaporation mass flow and decrease of the temperature of these pots filled with water.

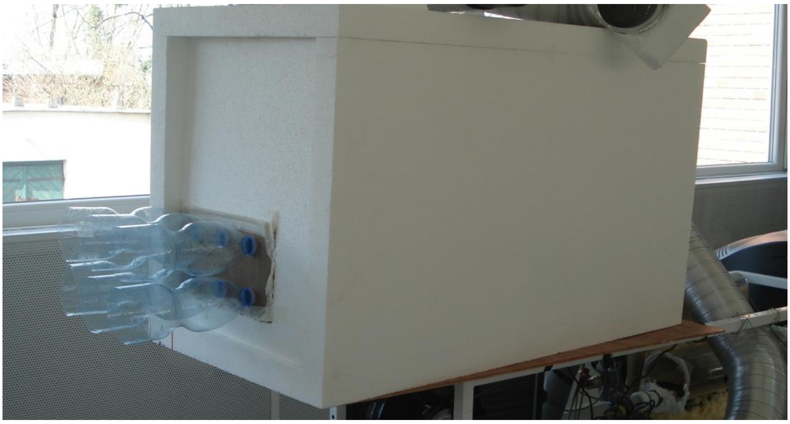

Fig. 4. Experimental alternative cooler with bottles

I have determined the real working principle of the EcoCooler with own experimental device, where I used several size of pet bottles. I have installed the bottles on a wood plate according to the Fig. 4.

2.2. Introduction of measuring methods

For solar collector system the working fluid was distilled water. Temperature measurement has been done at four points with PT1000 sensors (Fig. 1.). The working fluid's flow rate was measured by an ultrasonic flow meter. The actual direct and indirect solar radiation was measured by a Kipp & Zonen CM-11 pyranometer (on horizontal level and collector level).

I have measured the cooling power of absorption cooling circle. The examined cooling aggregate can be operated by electrical energy or by heat. The maximum power of cooler was 170 W. The cooler's power was utilized by a heat exchanger, and the secondary low circuit's working fluid was water, ethylene and propylene glycol.

During the examination of the porous materials I have determined the cooling power and from that the required evaporation surface for a given cooling power. The measurement devices were PT1000 temperature sensors, NEC H2640 infrared camera, Peakmeter MS6252A airflow-meter and a digital scale. The measured data were analyzed by Report Generation Lite and Excel programs.

During the examination of the bottle cooling I have examined several flow cross-sections by PET bottles. These were 4 - 35 mm diameter holes on bottle caps. I have measured the temperature values by PT1000 sensors.

2.3. Modification of experimental devices

For the modification of the experimental cooler I have installed an individual heat exchanger (Fig. 5).

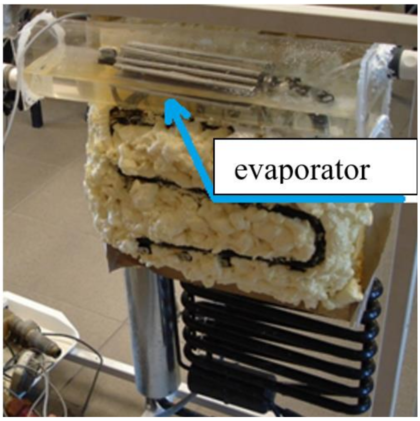

Fig. 5. Absorption cooler with individual built heat exchanger

The absorption cooling system was operated by solar cells (PV) and solar collectors. The produced electrical energy from PV was converted by an 24V/12V DC/DC converter to cooler's aggregat. In this time the voltage and amperage values were recorded. The heat energy from vacuum tube collector was utilized by an individual heat exchanger, which was installed into the cooler's boiler (Fig. 6).

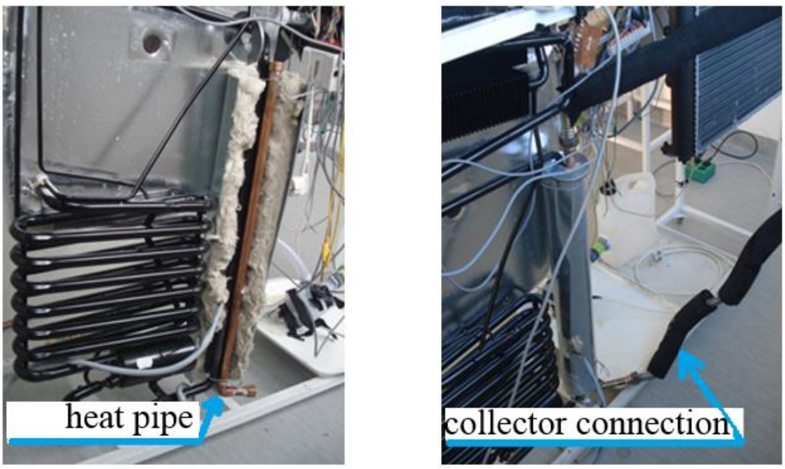

Fig. 6. Absorption cooler connected with solar collector

3. RESULTS

In this chapter the new scientific results of the research work are presented, which give support of the solar cooling systems' application.

3.1. Maximum heat power of solar collector

I have set up an elementary model for the heating power of a solar collector. The result data and the measuring experiences according to the model show that the volumetric flow rate ($Q = \dot{V}$) has significant effect on the produced heat power of the collector through a heat exchanger. The relationship was determined as some usual distribution functions, namely the power is increasing if the flow rate increases but after a given value it decreases. During the modelling the following form $f(x) = A \cdot x^n \cdot e^{-cx}$ was used. From the measured data, the following function could be evaluated:

$$P(\dot{V}) = 60 \cdot \dot{V}^2 \cdot e^{-9 \cdot \dot{V}}. \quad (1)$$

This function has a correlation coefficient of R=0.7 (Fig. 7).

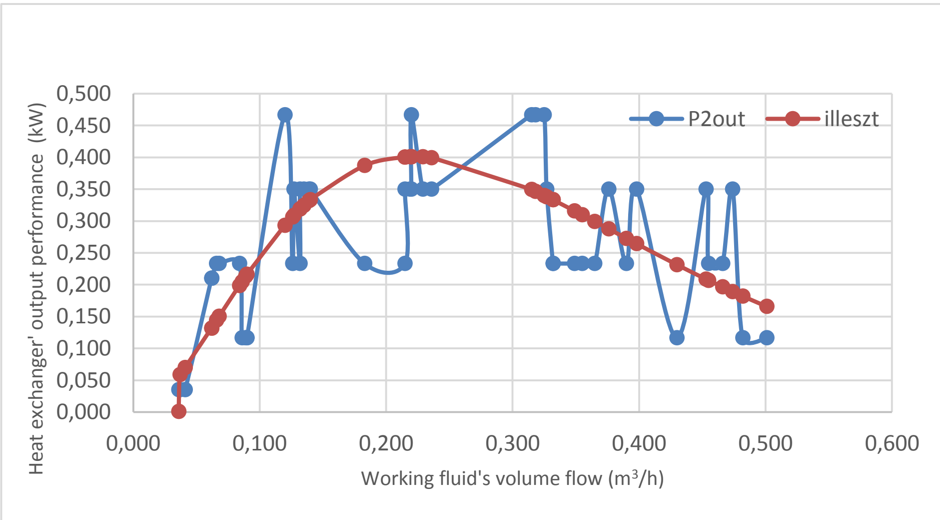

Fig. 7. Heat exchanger's output power data with trend line

During the examination the introduced vacuum tube collector was connected to the absorption cooler through an individual heat exchanger. For cooler's working the solar collector has to supply the working (cooling) fluid's evaporation temperature. Otherwise the evaporation process does not start in the cooling circle.

3.2. Evaporation cooling with porous materials

Ceramic pots made from clay can leak the fluid through its wall, which became gas after evaporation. During this process the fluid is cooled down.

During evaporation cooling the temperature drop of the cooling liquid was determined as (Fig. 8):

$$T(t) = 0{,}000003\ t^2 + 0{,}0163\ t + 36{,}791. \qquad (2)$$

This form is valid in the 1062-1234 g/h evaporation mass flow range.

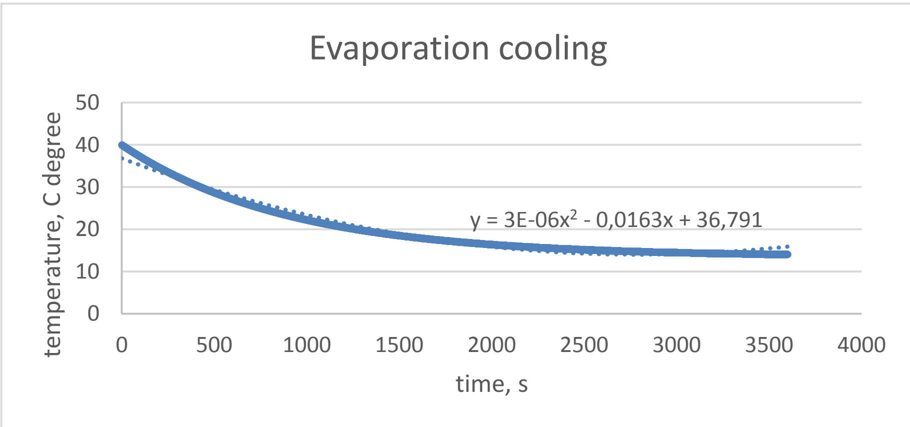

Fig. 8. Cooling temperature by evaporation

According to calculation the ceramic surface need for 1000 W cooling performance is 1,29 m^2. The calculated value valid in case of evaporated water by 1234 g/m^2 h mass flow rate. We can determine a porous materials' evaporation mass flow with measurement and based on these values we can calculate the necessary surface. This value can be calculated by following form according to the cooling power:

$$A_p = \frac{L_p \cdot \dot{m}}{P_h}. \qquad (3)$$

The cooling power has been determined by the evaporation mass flow (Fig. 9). According to the measured data, the reached temperature values can be ideal for air-conditioning systems, because bigger temperature differences can be harmful for the human body.

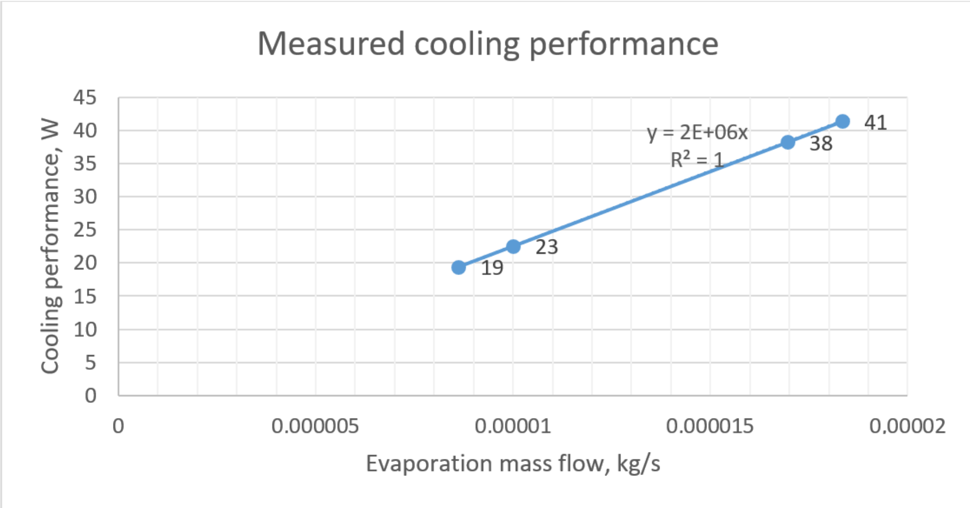

Fig. 9. The cooling power depending on evaporation mass flow

3.3. Air flow for cooling with solar energy

In the hot periods the human body cannot tolerate well the environmental temperature which is higher than the body temperature. For this problem the cooling with bottles can be a solution for a long hot time periods, as the inside air temperature of buildings can be decreased by this technology.

Application of this method the air is moving up along the solar radiated surface, which cause a pressure change, which can be used for taking off the inside hot air. If the outside air temperature reaches 30 °C, the air starts moving according to pressure change (low density air layer). The evolving air flow is intensive above 35 °C outside temperature.

I have heated the one side of experimental devices with a 1000 W power heat radiator, and I have measured the temperatures at the inlet point (T_2 temperature) and inside of insulated box (T_1 temperature). These values can be seen on the Fig. 10. On the t_1 and t_2 timeline it can be visible good the „cooling effect", when the outside air temperature is increasing, the inside air temperature is decreasing. This was caused by air flow, which moved the hot air. The outside air is warming up by the heated surface, so the air is moving up.

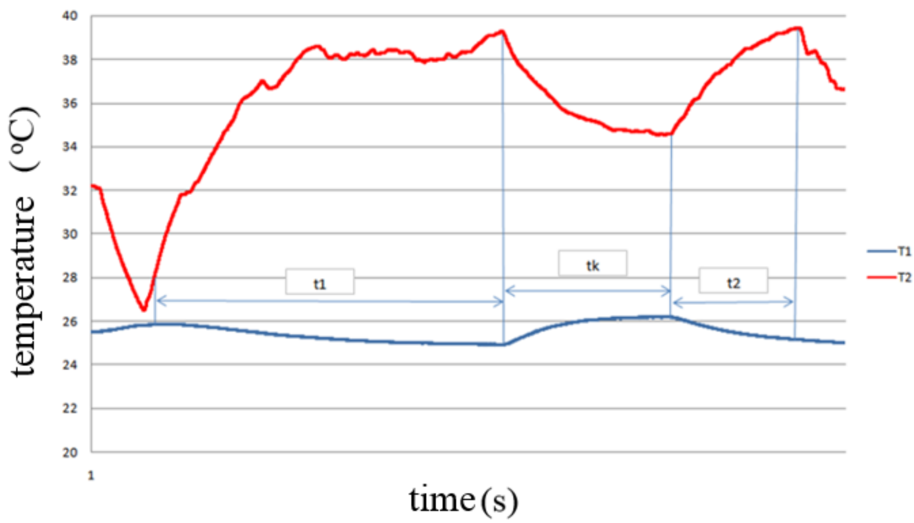

Fig. 10. Changing of temperature

The bottles' form prevents the hot air from getting into the building, so the outside air is coming up next to the bottles. The size of bottle's neck blocks the outside air moving into the building. According to the measurements up to 30 mm diameter hole the hot air cannot move into the building; under 16 mm diameter the incoming air flow is not numerous. So the optimal cross-section is between 16 and 30 mm diameter hole by bottles.

Summarized it can be determined, that by solar radiated surface can cause a cooling effect by generating air flow (Fig. 11).

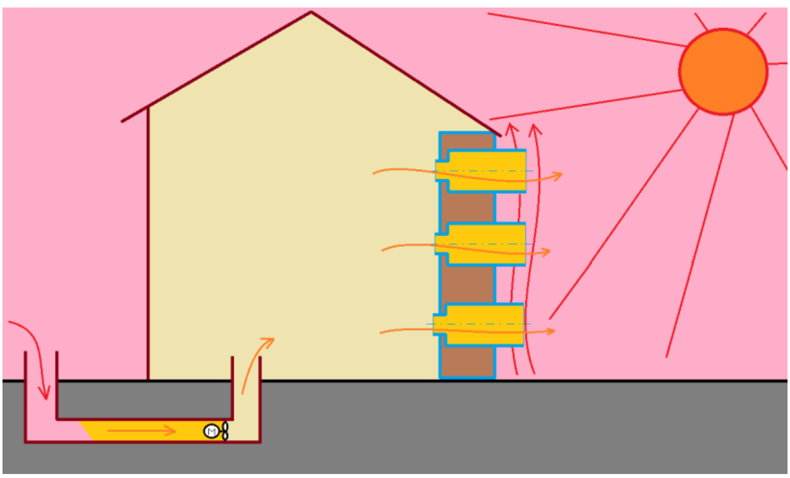

Fig. 11. The EcoCooler's work principle with cooling tube

4. NEW SCIENTIFIC RESULTS

1. Maximum heat power of a vacuum tube collector for cooling

I have created an elementary model for determining the heating power of a solar vacuum tube collector for air-conditioning. I have determined the form of usable heat energy from secondary side of heat exchanger from solar collector, which is the following function $P(\dot{V}) = A \cdot x\dot{V}^n \cdot e^{-c\dot{V}}$. According to this formula the heat power depends on primary side volume flow rate ($\dot{V}$), which I have verified with experimental results. I have identified through measurements the (heat pipe system) vacuum tube solar collector's coefficiencies as (A=60 $Wm^{-6}s^2$, n=2, C=9 sm^{-3}, R=0.7). These results are valid at the 800-1000 W/m^2 solar radiation range.

2. Requirements of solar cooling technology working

According to measuring data I have determined the working point requirements of solar utilization devices and absorption cooler.

I have testified the requirement of working point by solar collector, which is ensuring the minimal temperature of cooling fluid by evaporation temperature. Accordingly if solar collector's working fluid do not reach the cooling fluid's evaporation temperature, the cooler do not start, so it does not cool.

I have verified that the solar cells can supply the minimal temperature for cooler. So the solar cells can ran the cooler stable.

3. Air flow for cooling with solar energy

I have investigated an alternative cooling technology's method, which can be used without electrical grid and I have determined its main parameters. The working method of this method is that by solar radiation the outside air is heated up near a surface, it is moving up and the pressure change of the moving air can be used take out the inside hot air from a building. I have validated the effect's physical explanation by experiments.

According to my measurements I have determined that the cooling effect is depending on the size range of bottles (evaporation and heat losses in building). Bottle's neck has to be between 16 and 30 mm diameter. If the outside air temperature reaches 30 °C, the change of pressure start an air flow.

Above 35 °C the air flow is intensive, during this process the air velocity is increasing, so the evaporation and heat losses of inside surfaces is increasing.

4. Evaporation cooling utilization for air-conditioning

I have examined the heat losses of porous pots filled water as working fluid. Based on examination of little samples I have determined the relationship of heat losses and evaporation mass (volume) flow. I have identified the main parameters and attributes of process. In this case according to measuring I have created a parabolic model depend on temperature, which can use to determinate the minimal temperature with the following evaporation mass flow rate 1062-1234 g/h:

$$T(t) = 0.000003\ t^2 + 0.0163\ t + 36.791.$$

I have established that the evaporation cooling with porous materials is applicable for air-conditioning, because the difference of temperature is between 8-10 ºC, which is optimal for human body.

5. CONCLUSIONS AND SUGGESTIONS

During my PhD work I have got some results by solar cooling, which give support for application of alternative air-conditioning and cooling, which work independently and without fossil fuels.

I have created an elementary model for a heating power of solar vacuum tube collector for air-conditioning based on solar radiation data. I have determined the heat power from collector, which depend on volume flow rate. I have identified the vacuum tube solar collector’s coefficiencies in a validity range.

I have set up an experimental system for solar cooling. I have used an absorption cooler in this system. During measuring I have examined the working of cooler with solar cell and solar collector. I have determined the working point requirements of solar utilization devices and absorption cooler. I have examined the cooling system with individual heat exchangers. Requirement of working point with solar collectors the reach of minimal temperature for boiler. By solar cells the minimal current for electric heater can be ensured.

I have examined heat losses of porous pots with homogeneous fluid. I have measured the evaporated water’s cooling effects. I have determined the relationship of heat losses and evaporation mass (volume) flow with little samples. According to measured temperature change I have established that the evaporation cooling with porous materials is applicable for air-conditioning.

I have worked up an alternative cooling technology’s method, which can use without electrical grid and I have determined its main parameters. Application of this method by a surface heated up by solar radiation can heat and move the outside air up and the caused pressure change can be used for take out the inside hot air from a building. I have validated the effect’s physical explanation by experiments.

6. SUMMARY

Nowadays in summer periods the air-conditioning systems' energy consumption is comparable to the energy consumption of the heating systems in winter. This energy demand means that the fossil fuel power plants are producing more power and the electric grid will be more load in Hungary. For the problem there is an alternative solution as the solar cooling, solar energy utilization for air-conditioning systems. The main advantage of the solar cooling is that the energy demand and the energy production are at the same time. So we do not need to store the energy.

In this thesis a vacuum tube collector's energy utilization (operated during summer), and an absorption cooler working with solar energy are presented. By the way an evaporation cooling is measured with ceramics. Alternative solution is measured by solar energy via air moving's utilization at a bottle device.

Based on measuring I have calculated a vacuum tube collector's heat performance on a typical sunny day and an absorption chiller's cooling performance heated by a solar cell according to my measuring data. By both measuring the transfer fluid was water. The heating and the cooling performances are depended on two parameters: the fluid flow rate and the difference of temperatures. The solar cells and collectors are able to ensure the energy needed directly in the necessary time for the absorption cooler, but it needs to ensure the minimal temperature for the boiler.

According to the little samples I analysed the evaporation cooling's possibilities with ceramics. I measured the temperatures' changings with infra camera. Based on water evaporation I showed that we can do a good cooling to solve it. According to measuring data I could show that the cooling with bottles is applicable by air-conditioning systems within a real temperature range.

The showed new scientific solutions could be easy the engineers' work by solar cooling and air-conditioning planning.

7. MOST IMPORTANT PUBLICATIONS RELATED TO THE THESIS

Referred articles in foreign languages

1. **Szilágyi A.**, Seres I.: Solar energy utilization in solar air-conditioning systems, Mechanical Engineering Letters, Szent István University, Gödöllő, 2012., Vol.8., pp. 61-67.
2. **Szilágyi A.**, Farkas I., Seres I.: Development of a solar assisted absorption cooler, Mechanical Engineering Letters, Szent István University, Gödöllő, 2016., Vol. 14., pp. 26-32.
3. **Szilágyi A.**, Farkas I., Seres I.: Evaporation cooling with ceramics in air-conditioning system, Journal of Scientific and Engineering Research, 2018, 5(11), pp. 152-157.

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4. **Szilágyi A.**, Farkas I., Seres I.: Párologtató hűtés kerámiákkal, Energiagazdálkodás, 59. évf., 2018., 3-4. sz., 34-38. o.
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6. **Szilágyi A.**, Farkas I., Seres I.: Szoláris klimatizálás lehetőségei az állattartó telepeken, Mezőgazdasági Technika, 2019., 1. sz., 2-6. o.