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Modeling a solar desalination

D. Buschert **B. Bitzer**
South Westphalia University of Applied Sciences, Campus Soest,
Lübecker Ring 2, 59494 Soest, Germany
Buschert.Daniel@googlemail.com Bitzer@fat-soest.de

Abstract – In the last years the demand on fresh water continuously increase worldwide and the future demand is difficult to estimate, but due to the growth of population and the increase of the worldwide demand on consumer goods the water demand will also rise in the close and far future. Furthermore more environmental neutral energy resources are needed to fulfill the needed energy requirements in the future. One option is to use solar thermal energy to produce (process) heat. This paper is about the modeling of a demonstration plant in the Egyptian Sunwater project. The energy from renewable energy source is used to operate a water desalination unit and to produce freshwater environmental friendly. The main heat generator for the water desalination unit are solar thermal panels. The produced freshwater is free of ingredients and it can be used, with the accumulation of trace elements, as normal drinking water. The water desalination module works with evaporation and the whole construction will be installed close to a hotel complex in Egypt as a demonstration plant. It is funded by the EU and the Ministry of Higher Education and Scientific Research in Egypt (RDI). This project is a feasibility study to show the possibility to combine solar thermal energy and a water desalination module working with evaporation. It could be an impulse for future research projects and for a freshwater supply not only in dry and hot countries like in Africa. For the installation of the components at the demonstration plant a system model and a simulation was done to combine the right components at the building site to a sustainable system.

Keywords – solar thermal, heat pump, water desalination, modeling

1. Water shortage in the world

In the last years the worldwide amount of fresh water becomes smaller and smaller and this causes shortages or political discussions as now in Palestine. One reason is the global warming, the growth of the population in the world and the continuing and the wasteful use of freshwater. In some areas in the world, like in Kenya, there was not enough rain in the last three years. A lot of animals die on water deficiency, because a lot of water holes dry up and so the animals and of course the people cannot get enough water for their daily use. One reason is the still increasing water sampling and the demand on freshwater. Furthermore the rivers dry up, because of the high withdrawal of water close to the springs. Without fluvial water the water supply of whole regions, for example in Africa, are in danger. A lot of towns all over the world are dependent on the river water for the daily round and for the economy. One good example for a reservoir of water is the Kilimanjaro in Africa. In the last decades the snow on the Kilimanjaro disappears, because of global warming and sublimation of snow and ice. It is well-known that water and other materials change their phase from solid into gas without passing the liquid phase (Fig. 1). This can be shown in the phase diagram of water. This is one reason why the snow cover of the

Kilimanjaro decreases in the last decades. The actual forecasts indicate that in a few decades the whole snow cover will disappear. This could have the effect that the water supply in a few parts in Africa are in danger. Furthermore the city Mombasa in Kenya depends on the freshwater supply because a long pipeline from the mountain to the city was build and the inhabitants need this water for their daily round. Other freshwater resources are not enough available. In a few years they need environmental friendly water desalination units to satisfy their demands on freshwater with saltwater. The most water desalination units work with fossil fuels and this will be very expensive in the next years, because of increasing commodity prices and so the freshwater price will also jump up. With use of fossil fuels more carbon dioxide will be produced and this is another problem, because this is responsible for global warming. The use of fossil fuels is a mixed blessing. The demand of freshwater will rise, but the generation of freshwater will produce again more and more carbon dioxide and this is responsible for higher temperatures and so more freshwater is needed. The Sunwater project tries to find a solution to produce freshwater without producing a huge amount of carbon dioxide.

2. Solar thermal

Due to the global warming renewable energy sources are needed which produce no or less carbon dioxide [1]. So alternative power or heat generators are one aspect to save the environment. Our sun spends a lot of energy every day which can be used. The advantage is that the sun do not send a bill and the sun is present every day. The measurements for a long time show that the mean extraterrestrial solar irradiance is 1367 W/m² on the averaged distance of the sun and the earth during the whole year. The real solar constant (SC) varies through the year, because of the elliptical orbit of the earth around the sun. This can be described with following formula [4]:

$$\mathrm{SC}=1356+48.5\cos\big(0.017(d-15)\big)\left[\frac{W}{\mathrm{m}^2}\right] \quad (1)$$

Where d is the number of the day in the year. This amount is without any atmospheric disturbance and under perpendicular solarization. On the earth's surface the measured solar irradiance can be up to 1000 W/m². It depends on the angle of incidents, the location at the earth and so the resultant air mass AM which is defined as the relative optical path length y through the atmosphere relating to the minimal optical path length x (Fig. 2):

$$\mathrm{AM}=\frac{y}{x} \quad (2)$$

It is also possible to use a trigonometric equation for the zenith angle θ, if the angle is relative small:

$$\mathrm{AM}=\frac{1}{\cos(\theta)} \quad (3)$$

The above equation is just very simple which do not include the curvature of the

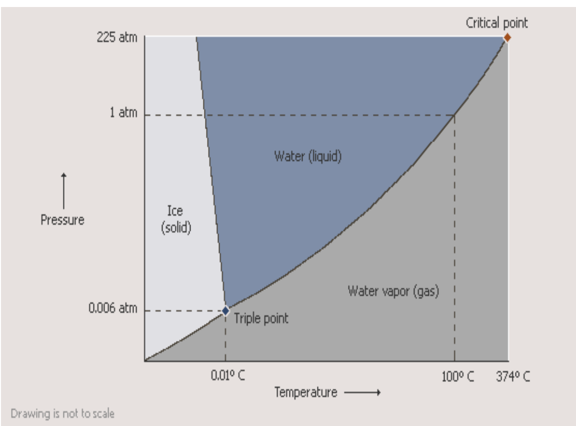

Fig. 1: Phase diagram of water

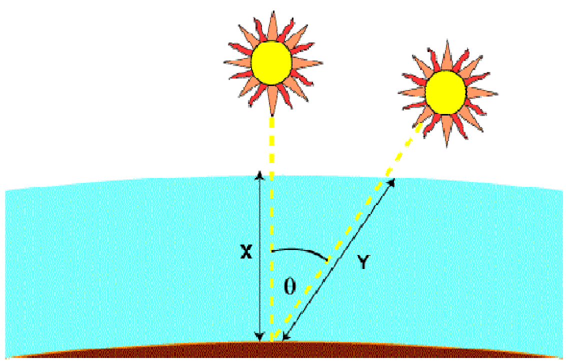

Fig. 2: Air mass [6]

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atmosphere. If the curvature is considered one possibility to describe the air mass is the following equation [6]:

$$\mathrm{AM} = \frac{1}{\cos(\theta) + 0.506(96.080 - \theta)^{-1.364}} \quad (4)$$

The Fig. 2 shows the different paths through the air in the dependency of the zenith angle θ. The zenith angle is the angle of one point under the zenith. The zenith is on the other hand the perpendicular point over the horizontal plane. Without the atmosphere the AM is defined as zero and the air mass for perpendicular incidence is 1. A longer way through the atmosphere means that more emitted solar radiation is scattered, absorbed and reflected as infrared radiation. (1) and (4) are just two easy equations which were included into the simulation for the daily solar irradiance.

In Fig. 3 the estimation of the Egyptian solar irradiance on 5 different days in one year are shown. Furthermore the sunrise and sunset can be read off on the diagram. This is the intersection with the abscissa. The summertime was not considered during this calculation. As can be seen in this figure the global solar irradiance during the year is between 850 W/m² and 1000 W/m² and the value is relative constant during the whole year. This information is very important to plan the complete demonstration plant and to do an adequate simulation [2]. So the sun can be used for a cost effective energy production during the whole year in Egypt.

At the moment there exist two different technologies which convert sun energy into useable energy. The first one is the photovoltaic which directly generates electrical power and the other technique is solar thermal which is used to generate (process) heat. The most panels are calibrated with an air mass off 1.5, this means a maximum solar irradiance on the earth surface of 1000 W/m². In the Sunwater project, which will be explained later, there will be used solar thermal panels to generate process heat. In the solar thermal panels, water with a few ingredients will be heated by the sun to generate process heat. The ingredients protect the solar thermal panels and avoid corrosion inside the collectors. The collectors are specially coated and geometrical designed to reach the maximum performance. The best collectors have a conversion factor up to 80 % of the solar radiation. So a lot of needed energy can be produced by solar thermal.

At the moment there are two different solar thermal systems interesting for the Sunwater project, the vacuum tube solar collector and the flat plat solar collector. The tube collectors normally have a higher efficiency but they are more expensive. The efficiency of the flat plate solar collectors is lower, but they are much cheaper. Due to the financial reason the decision is to use flat plate collectors for this project. In the Sunwater project solar thermal collectors from the company Solar Egypt are used. The idea is at the moment to install more

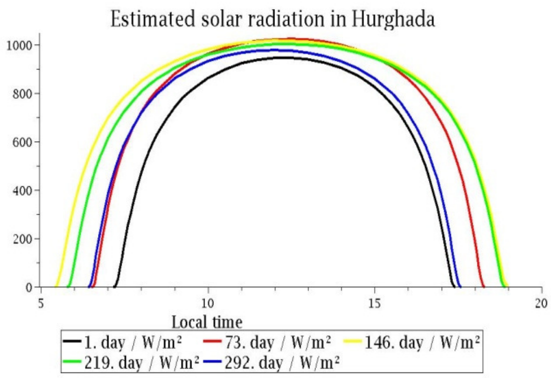

Fig. 3: Estimated solar radiation in Egypt on 5 different days in the year [3]

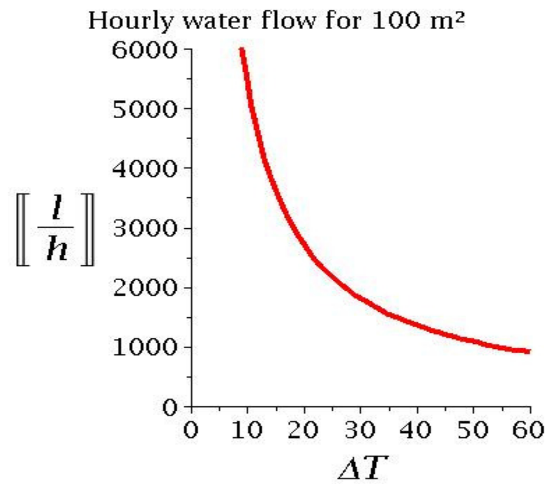

Fig. 4: Hourly water flow for 100 m² solar thermal area

than 240 m² solar thermal area at the building site in Egypt. One solar collector will have the size of round about 2 m². Due to the budget and the high solar irradiation in Hurghada just advantageous components are used for the solar thermal panels. The aluminum pipes and stripes in the panels are painted in black. This is much cheaper than to use coated copper pipes. The conversion factor for this solar thermal panels is round about 50 %. For the high solar irradiation in Egypt such a low conversions factor is high enough to operate the demonstration plant. A balance between the costs and the energy efficiency had to be found.

For 100 m² the calculated estimation of the maximal amount of heated water is displayed in Fig. 4. The calculation includes among others the heat capacity of water

$$c = 4185 \frac{\mathrm{J}}{\mathrm{kg\,K}} \tag{5}$$

and the maximal daily solar radiation which is up to 1000 W/m². On the abscissa there is plotted the temperature difference between the desired temperature of 90 °C and the incoming water temperature. On the ordinate the amount of the water is plotted which should flow through the solar thermal panels to gain the favored water temperature. If the temperature difference between the incoming and outgoing water is just 10 °C the amount of water is up to 5500 l/h. If the difference of the water temperature is much higher, for example 60 °C, the flow of water is just round about 900 l/h. The water difference may not be higher than 70 °C, because of the climate situation in Hurghada. Ambient temperatures are seldom under 20 °C. The amount of water inside the collectors is roughly 200 l.

The produced heat will be stored and buffered in a heat storage tank, as can be seen in Fig. 5 and the dimension of the heat storage tank is 5 m². The collectors and the heat storage tank are included into one water circuit, so the water can be directly taken out of the heat storage tank without any heat exchangers. The cold water is taken out at the bottom of the tank and the heated water is inserted at the top into the tank. The solar thermal controller controls the flow of the water by measuring different temperatures and controlling the pump. The pump adjust the speed of the water flow inside the collectors so that the water which comes out of the solar thermal panels have a temperature of 90 °C or higher. This high temperature is needed to operate the water desalination unit to convert the saltwater into freshwater.

3. Water desalination unit

At present time there exist a lot of different possibilities to convert saltwater into freshwater. A few possibilities are reverse osmosis desalination, multi stage flash evaporation or electrodialysis. For the Sunwater project a water desalination unit is used which needs process heat to convert

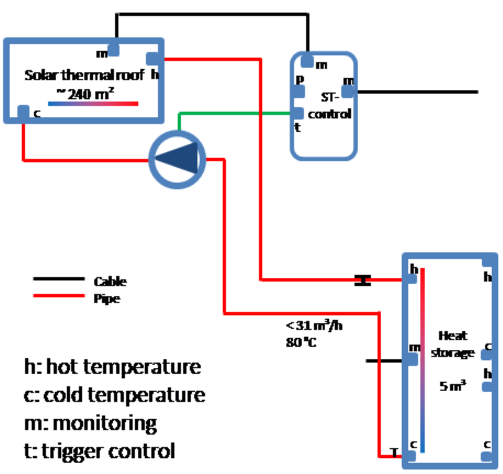

Fig. 5: System model of the solar thermal panel and the heat storage tank

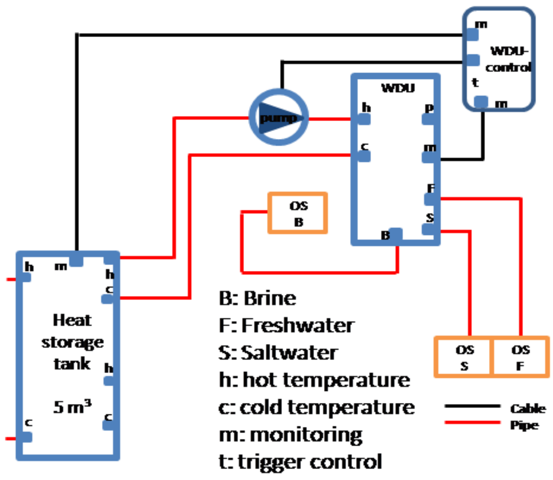

Fig. 6: System model of the heat storage tank and the water desalination unit

saltwater or brackish water into freshwater. With the use of process heat, which is generated with solar thermal panels, the usage of the water desalination unit is relative environmental neutral. This water desalination unit works with evaporation. Evaporation is a phase change from liquid into gas without boiling (Fig. 1). An approximately formula which describes the evaporation is the equation of Penman which was invented in the year 1948 [2]:

$$E = \frac{\Delta(R_n - G) + \rho_L c_p C_{at} \delta_e}{\lambda_W(\Delta + \gamma)} \quad (5)$$

where:

E = Rate of evaporation (kg m^{-2} s^{-1})
Δ = Slope of the saturation vapour pressure curve (Pa K^{-1})
R_n = Net irradiance (W m^{-2})
G = Soil heat flux (W m^{-2})
ρ_L = Density of air (kg m^{-3})
c_p = Heat capacity of air (1004 J kg^{-1}K^{-1})
C_{at} = Atmosspheric conductance (m s^{-1})
δ_e = Vapour pressure deficit (Pa)
γ = Psychometric constant (ca. 0.6 hPa K^{-1})
λ_W = Latent heat of vaporization (2.5 MJ kg^{-1})

Inside of the water desalination units there are a few bypasses which enhance the efficiency of the desalination unit. Due to this special and patented technology this water desalination unit has a very high efficiency. The GOR (gain output ratio) factor is higher than 4. This is a measure of evaporator performance that represents the ratio of mass flow of distillate to steam input. The working temperatures is up to 95 °C. Additional no chemicals or membranes are used to clean the salt- or brackish water. In a few cases toxic ingredients can also be filtered out and the produced freshwater can be used for a lot of different applications, like for drinking or irrigating the fields or gardens. Another aspect to choose this water desalination unit was that the numbers of supported units can be varied. If a huge amount of waste or process heat is available the numbers of units can be fitted to this energy amount and all units can be used to desalinate the seawater. For this project two standard water desalination modules will be manufactured and they will be installed into a fright container. In the container there are also other needed equipments installed which are important for the desalination, like pumps, raw water and freshwater storages tanks. Furthermore a switch cabinet and a remote system will also be included. With this technology the water desalination unit can be controlled and monitored from all over the world. The water desalination module will be built in Germany and sent to the demonstration plant in Hurghada in Egypt. In Fig. 6 is the system model of the water desalination module and the heat storage tank shown. The needed heat for the water desalination is taken out at the top of the heat storage tank and it is transported into the water desalination unit. After the heat exchange with the seawater the water is transported back to the bottom of the heat storage tank. This is also a closed circuit and so no other safety measures, like heat exchangers, have to be included into the storage tank. With this heat the water is desalinated and converted into freshwater. The remaining seawater (brine) and the freshwater will be transported back into the existing water system for later use. The shown heat storage tank in Fig. 6 is the same than in Fig. 5.

4. Modeling

In the project a model for a solar thermal water desalination unit is invented. The first idea was to include a solar thermal field, a water desalination unit, one heat pump and two heat storage tanks. Furthermore a controller for monitoring and a weather station should be included. A system model of the demonstration plant can be found in Fig. 7. For the simulation a toolbox for Matlab was used. After a few preliminary tests with this toolbox and small modifications a possibility was found to simulate the demonstration plant like in the system model. This model can be found in Fig. 9. This includes the mentioned components, but also different temperature sensors or logical operators which control the different pumps. For example the pump in the solar

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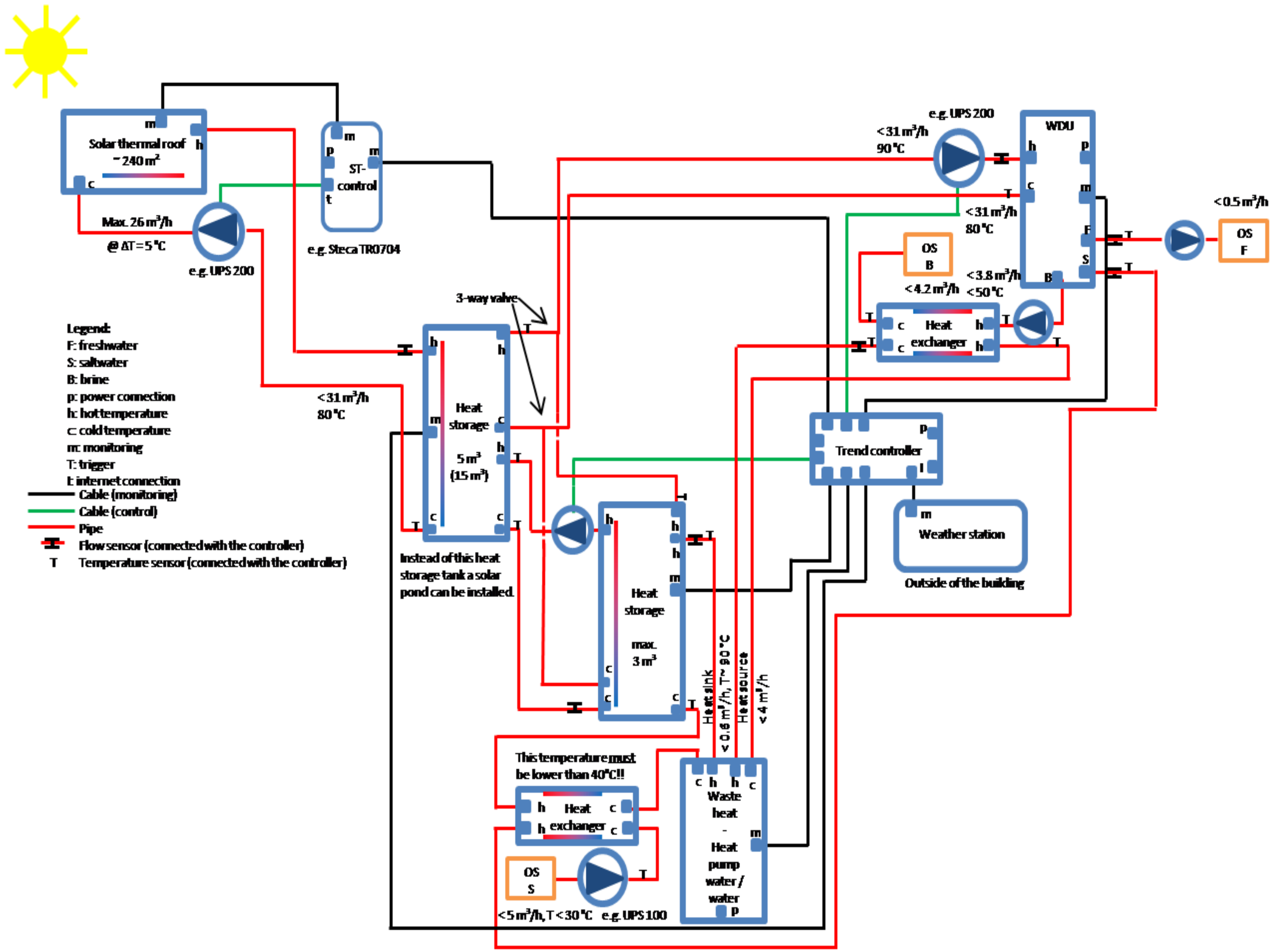

Fig. 7: Complete system model of the Sunwater project in Egypt

thermal circuit must be switched off when the output temperature of the solar collectors is lower than the temperature inside the heat storage tank, because it makes no sense to pump hot water through the solar thermal collectors, if the temperature output is lower than the temperature input, this happens for example, when the solar irradiance drops or in the night. This would have the effect that the temperature will be reduced in the heat storage tanks and so needed energy is wasted to the environment. The pump which delivers the water to the water desalination unit must be switched on and controlled, when the operation temperature reaches the needed temperature of 90 °C. Another problem is that there is no model block for the water desalination unit, so a solution must be found to simulate this part of the system. Furthermore the existing model for the heat pump could not be used, because the simulation results seems to be useless in this simulation. For the simulation with the Matlab toolbox different input data were used. For the weather data a combination of measured data from Egypt and simulated data were consulted. The simulated data was the daily solar irradiance which was mentioned in the first section. Furthermore technical data were used, like the size of the flat plate collectors or the optical effectiveness of the collectors. For the water desalination a needed temperature of 90 °C and a volume flow between 8 and 12 m³/h was calculated and this was included into the simulation. With this and

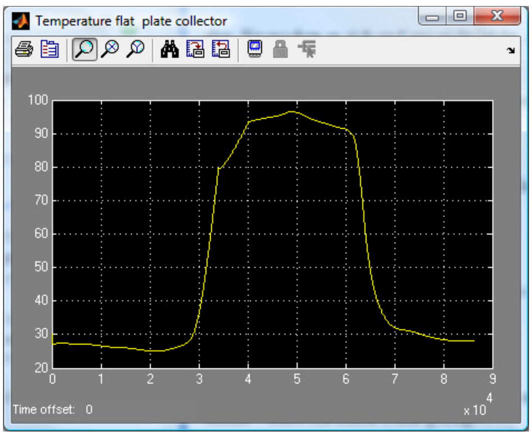

Fig. 8: Temperature output at the solar thermal collectors

a lot of other data the simulation was started and modified. With this results the components were adopted to find a solution for the demonstration plant in Egypt. In Fig. 8 the temperature output at the collectors is shown. During the day a temperature of 90 °C can be reached. If the volume flow in the collectors is modified the needed temperature could be reached earlier in the morning and also later in the evening and so the working time of the water desalination unit can be enhanced. At the moment it is not possible to control the volume flow in the simulation with the pumps. They can just be switched on or switched off with a constant volume flow. In the final installation the volume flow can be varied and so the working time should be enhanced.

During the simulation it becomes obvious that it makes no sense to install a small heat pump with a few kW to enhance the working time of the demonstration plant, because the needed energy of the water desalination unit is quite high. The needed power for one module is up to 60 kW at a temperature of 90 °C in one hour. So the money which is saved for the heat pump and other components will be invested into a larger solar thermal area. Furthermore it seems to be difficult to reach the 90 °C with the flat plate collectors. The simulation with the toolbox promises that this temperature can be reached, but other project partners fear that in practice the temperature of 90 °C cannot be reached with the used flat plate collectors. While this paper is written a test will be arranged to clarify if it is possible to get the temperature or not. The results will be presented at the conference in Granada.

In Fig. 10 the working time of the water desalination unit is shown. The yellow bars indicates the working time of the WDU. In the solar morning and in the solar evening the water desalination unit cannot be operated the whole time, because the solar irradiance is too low to get enough power with it. So the WDU must be operated in shorter time intervals or the produced power must be buffered in the heat storage tank. If the heat storage tank is

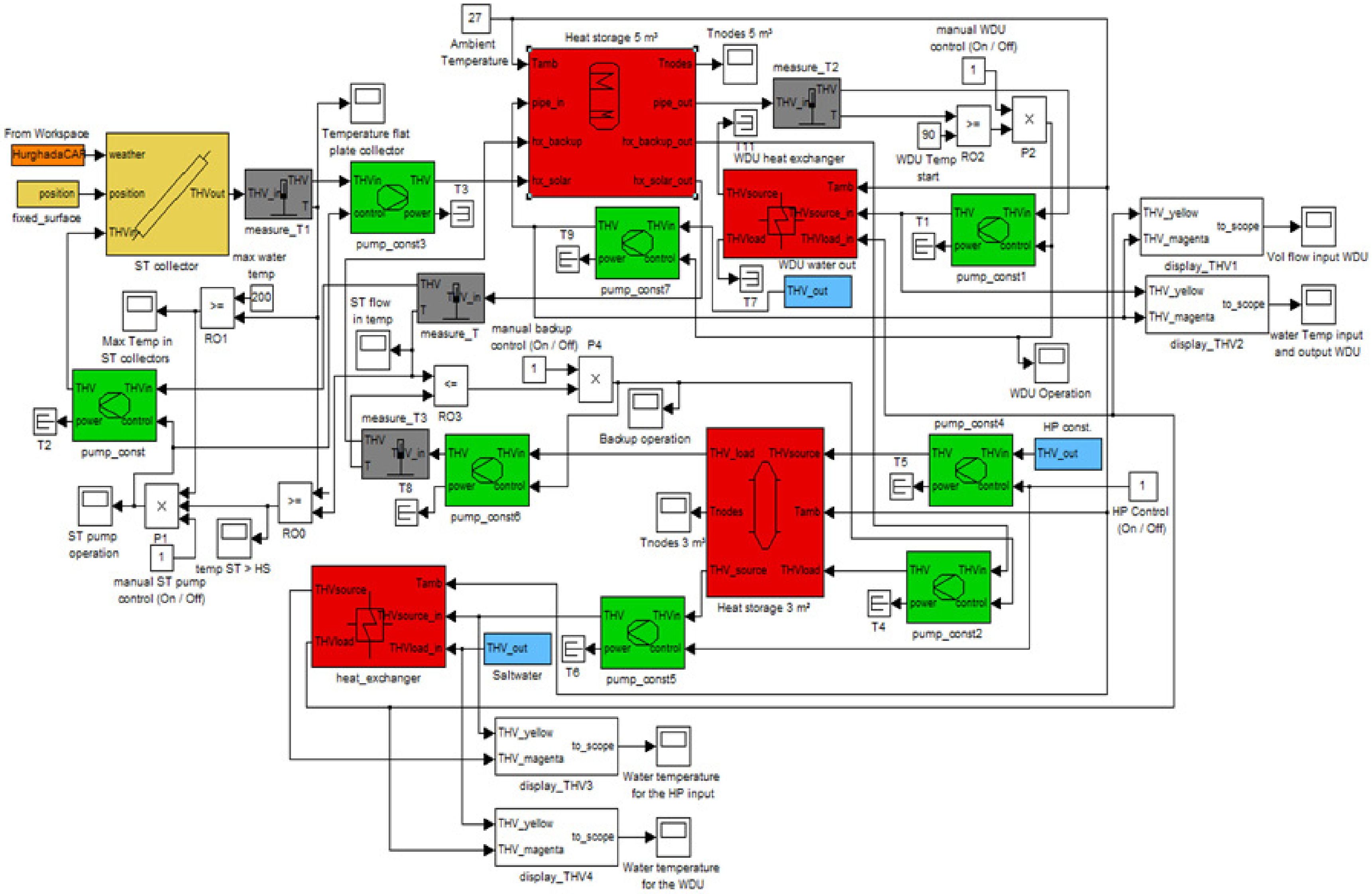

Fig. 9: Model with a Matlab toolbox

loaded the WDU can be switched on. With the installed 240 m² solar collector area the working time of the water desalination unit will be 5 hours every day. With the optimization at the end of the project the working time will hopefully be enhanced to get more freshwater out of the water desalination module. So the cost efficiency can be raised in later realizations. During the project test phase different data will be measured which helps to optimize the demonstration plant. These data will be analyzed and so the simulation of the complete demonstration plant can be enhanced. In the next months, a complete simulation program with all components will be invented to simulate the whole system. The results will hopefully be presented at a later conference in 2011 or 2012.

5. Sunwater Project

In the Sunwater project a demonstration plant will be built in the tourism sector Hurghada in Egypt. It will be implemented into an existing hotel at the Red Sea which satisfies the actual demand on freshwater with a reverse osmosis water desalination system. The actual amount of desalinated water is 400 m³ every day. The needed saltwater for the evaporation system will be taken out of the existing saltwater delivery system and it will be converted with solar thermal energy in the evaporation system into freshwater. The freshwater itself will be returned into the existing water system and the brine which remains during the desalination process will also be returned into the brine

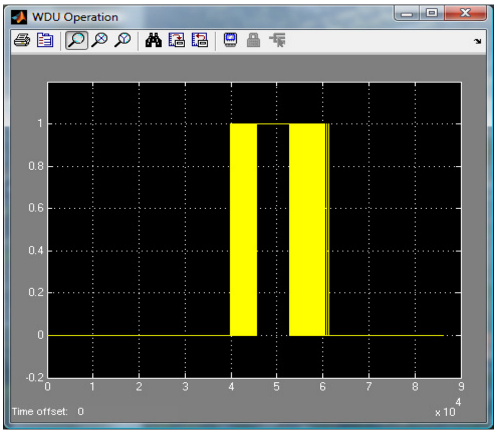

Fig. 10: Operation time of the water desalination unit (Yellow bars show the desalination working time)

from the reverse osmosis system. Furthermore the first idea was to install a heat pump as a backup system for cloudy days and to extend the working time in the morning and in the evening. During the day the heat pump could be used to store heat in a second heat storage tank which can support the solar thermal panels in the evening or in times with less solar irradiation. The idea is to use a heat pump which recovers the heat in the brine to new process heat. With this combination a better and more effective performance is guaranteed. The heat pump has to produce a water temperature in the range up to 90 °C. Normal high temperature heat pumps which works with surrounding air or groundwater have a very bad efficiency in this temperature range and so a waste heat pump is desired for the demonstration plant. With the use of a heat pump the system is relative environmental friendly, because the COP (Coefficient Of Performance) can be 4.5 or higher. It depends on the different temperature levels [4].

The used heat storage tank is used to save heat during the day and has a buffer tank to support the water desalination in hours when the sun irradiation is reduced because of clouds or in the evening when the zenith angle is higher and so less energy is available.

Furthermore a weather station will also be installed which collect different weather information like solar irradiance, wind speed and direction or humidity.

In the whole system (Fig. 7) a monitoring system will be included to measure different data and to analyze the system just in time. With this data a modification and optimization of the construction should be possible after the installation and testing stage in the summer 2010. An adoption to further projects will also be possible. Furthermore the gathered data, like the weather information, the freshwater production or different temperatures in the whole system will be presented online on the project homepage and it will show the effectiveness of the whole construction. This is still in investigation and this will be finished in the next months.

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