Development of Solar Assisted Sorption Unit for Extraction of Water from Ambient Air in the Desert Climate

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Abstract

Climate conditions of desert at Arabian Peninsula exhibit high ambient temperatures and very low humidity ratio values during the year. Development of sorption technology for water extraction from ambient air with use of solar energy only is presented.

Keywords: sorption wheel, PV system, PVT collector

1. Introduction

Lack of potable water resources in the desert regions has led to searching the technologies capable to harvest the water from the ambient air. Number of different technologies has been already developed, tested and applied. However, extreme climate conditions of the desert at Arabian Peninsula restrict the use of the most of them. Autonomous water harvesting unit fully powered only from solar energy resources is an ambitious challenge and subject of development at Czech Technical University in Prague.

2. Climate conditions

Characteristic climate conditions of the selected desert locations at Arabian Peninsula are presented in Tab. 1. Table shows severity of the climate in the aspect of air humidity ratio x_e and temperature t_e and also available solar irradiation H on horizontal plane. Fig. 1 shows also cumulative frequency histograms for humidity ratio and ambient temperature. City of Rijad (Saudi Arabia) exhibits the most extreme conditions (temperature, humidity ratio) compared to other environments (Al Dhaid, Al Faqa, Al-Ain or Burajmi) in United Arab Emirates and therefore its climate data have been selected for the design and evaluation of solar water extraction unit with minimum average daily production 100 litres of water. Climate of coastal city Dubai has been added for comparison.

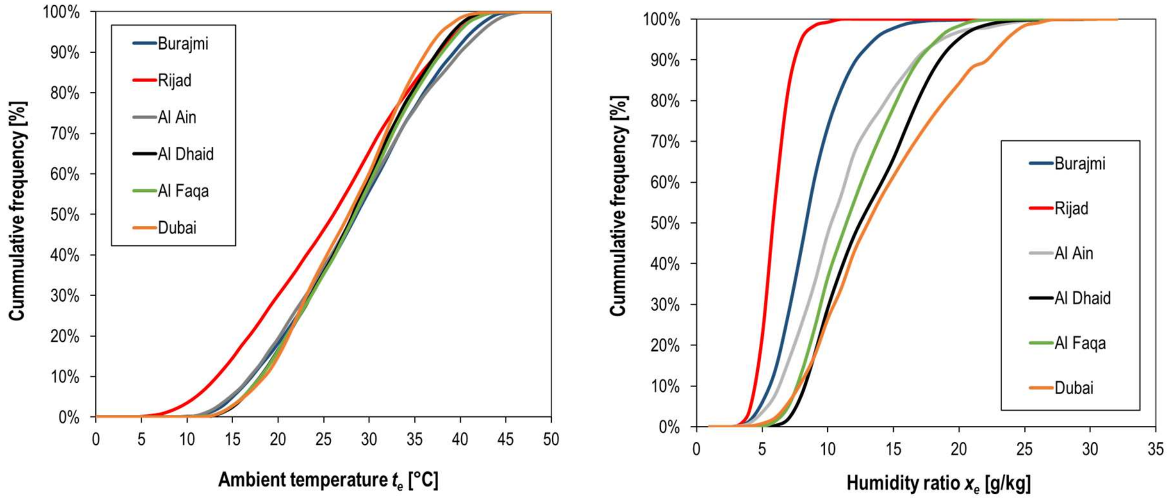

Fig. 1: Ambient temperature and humidity ratio in selected climates at Arabic Peninsula

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Tab. 1: Characteristic parameters for selected climates at Arabic Peninsula

Location	$t_{e,av}$ [°C]	$x_{e,av}$ [g/kg]	$x_{e,min}$ [g/kg]	$x_{e,max}$ [g/kg]	H [kWh/m^2.a]
Rijad (SA)	25.6	5.9	3.0	11.0	2217
Burajmi (UAE)	28.4	8.7	2.7	21.7	1977
Al Ain (UAE)	28.7	11.0	2.2	28.2	2274
Al Faqa (UAE)	28.2	11.9	4.7	24.4	1997
Al Dhaid (UAE)	27.9	13.1	5.3	30.4	1977
Dubai (UAE)	27.8	14.0	2.5	28.3	2128

Tab. 1 shows that different desert locations have very similar temperatures during the year, but differ significantly in humidity ratio. While location of Rijad represents extremely dry climate conditions, desert locations in UAE seem to be more humid thanks to position between two sea coasts (see Fig. 1, right).

3. Extraction of water from ambient air

There are many commercially available units for harvesting the water from air (El-Ghonemy, 2012), which operate on the principle of direct condensation of water vapour from the air on the cooler, more or less effectively performing. Such units can be used in regions with year-round or seasonally high humidity ratio. However, condensation units cannot harvest significant amount of water in case of extremely dry deserts, as analysed further. Therefore, the water harvesting unit under development is based on the sorption system.

3.1. Condensation unit

To show the functionality of simple condensation unit with low temperature of cooler surface about 5 °C (see Fig. 2) the simulations have been performed with use of hourly climate data for Rijad (inland) and Dubai (sea coast). The unit works with total flowrate of ambient air 3500 m^3/h. Annual daily average water production of condensation unit in Rijad is about 30 litres per day. If the condensation unit would be operated in Dubai, the average daily water production will reach 200 litres per day thanks to significantly more humid climate (see Tab. 2).

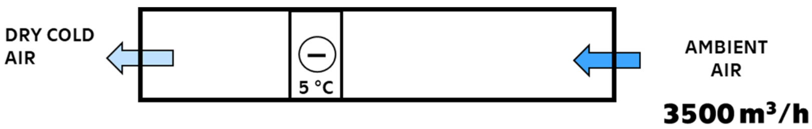

Fig. 2: Condensation unit for extraction of water from air

3.2. Adsorption unit

Proposed unit works with adsorption of water molecules on the surface of solid desiccant in the rotary enthalpy heat exchanger (see Fig. 3). Desiccant material (silicagel) adsorbs the water molecules from flowing ambient air to its surface and dehumidified air slightly heated flows back to ambient environment. Ambient air with significantly low flowrate (one third) is used for regeneration of desiccant. Before entering rotary heat exchanger, the air flow is heated to high temperature up to 80 °C. Water molecules are released from the surface into regeneration air flow. Thus regeneration air is humidified to higher humidity ratio and cooled down (evaporation). Humid air than enter the cooler with low surface temperature (5 °C) and water vapour easily condenses as liquid water. To compare the performance of water production with simple condensation, the unit with identical total flowrate of ambient air 3500 m^3/h has been modelled (2700 / 800 m^3/h). Annual daily average water production of adsorption unit in Rijad is about 170 litres per day. If the adsorption unit would be operated in Dubai, the average daily water production will reach 400 litres per day (see Tab. 2). The model of adsorption unit is based on psychrometric calculations.

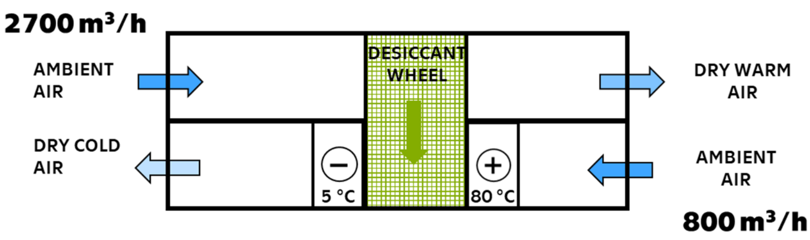

Fig. 3: Adsorption unit for extraction of water from air

The results shown in Tab. 2 has been evaluated for same total flowrates and maximum cooling power of the units for given climates. The advantage of adsorption principle is evident from the figures of water production and energy performance. In case of Rijad climate, the adsorption unit has almost 20 times lower energy demand for litre of produced water. In case of Dubai climate, the differences in results between principles are lower. Fig. 4 shows the water production balance during the year for Rijad climate for both technologies.

Tab. 2: Characteristic parameters for selected climates at Arabic Peninsula

Parameter	Condensation unit		Adsorption unit	
	Rijad	Dubai	Rijad	Dubai
Max. cooling power [kW]	21	29	21	29
Electricity demand [MWh/a]	30	70	12	13
Water production [m^3/a]	14	143	96	175
Average water production [l/day]	37	391	262	480
Performance factor [kWh/l]	2.2	0.49	0.12	0.07

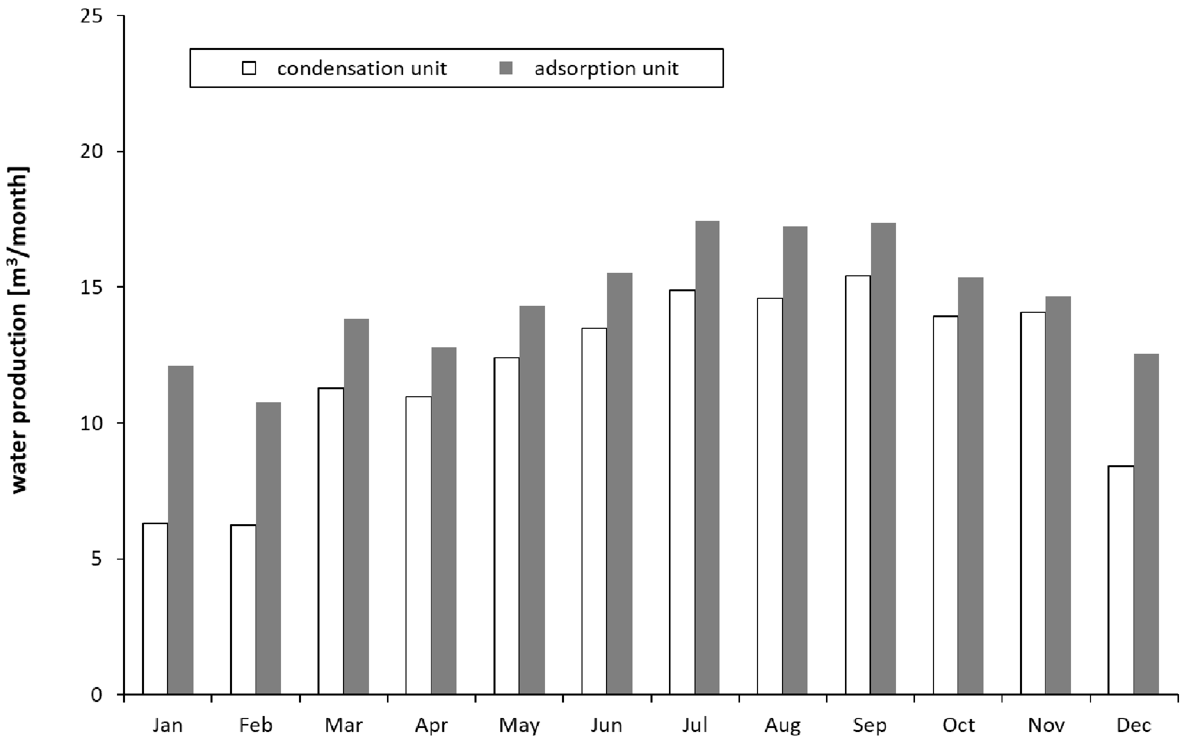

Fig. 4: Comparison of technologies for Rijad climate

4. Prototype of adsorption unit and testing

Air handling unit equipped with a rotary desiccant wheel, integrated refrigerant cycle and additional liquid cooler and heater has been designed and built for testing purposes and further development of theoretical model. The design range of air flowrates is up to 4000 /1500 m^3/h (process air / regeneration air). Internal cooling cycle is based on the refrigerant R134a in order to achieve high temperatures up to 80 °C for regeneration at condenser. The heat from cooling at evaporator is recovered for preheating of the regeneration air on condenser side. Second serial condenser is placed to output of process air channel to transfer the residual heat power from cooling to outflowing process air. Variable speed compressor allows a control of the unit at variable conditions and to reduce power input of the unit when possible. If needed, heating exchanger is used to increase the temperature of regeneration air leaving the condenser by additional heat source, e.g. solar thermal collectors. Heat exchanger placed prior to the evaporator allows to precool the regeneration air leaving the sorption wheel and thus reduces the required cooling power and electric power input of refrigerant loop. The cross section of the unit is presented in Fig. 4 together with photo of the prototype installed in test chamber.

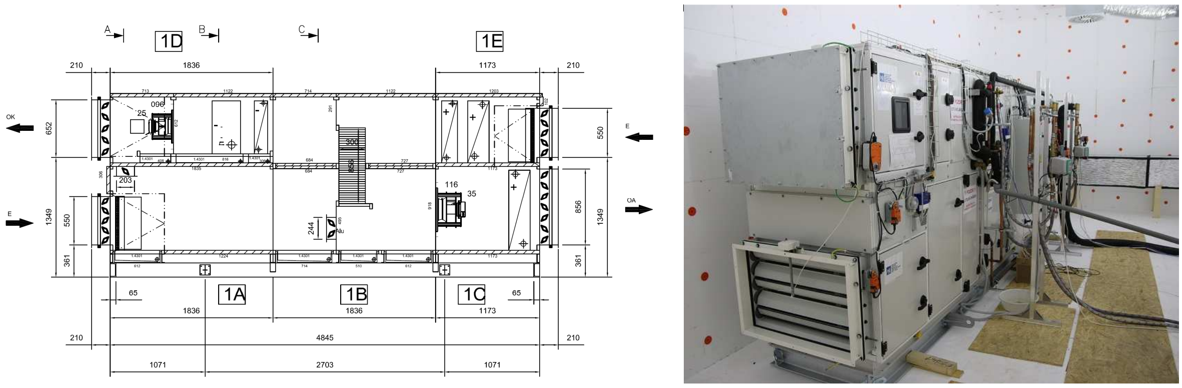

Fig. 4: Prototype of the adsorption unit (cross section, installed in testing chamber)

Tab. 3: Testing conditions in the test chamber

State of air	t_e [°C]	x_e [g/kg]
1	20	6.0
2	20	10.0
3	30	2.5
4	30	5.0
5	30	7.5
6	30	13.0
7	40	10.0
8	40	16.0
9	40	20.0
10	35	24.0

The unit has been tested to further develop the theoretical model of sorption wheel, water production and to investigate its energy performance. External air loop of the test chamber provides the range of climate conditions from cold dry air to humid hot air. Testing conditions (states of air) are summarized in Tab. 3. The model of sorption wheel had to be corrected based on the results from measurements. The air flow rates during the experiment were 2100 / 700 m^3/h. Principle correction was non-adiabatic release of water vapour from the desiccant surface of the sorption wheel, which finally results in lower cooling power required at the evaporator of the cooling cycle (less energy needs). Comparison of developed model with measurement is shown in Fig. 5.

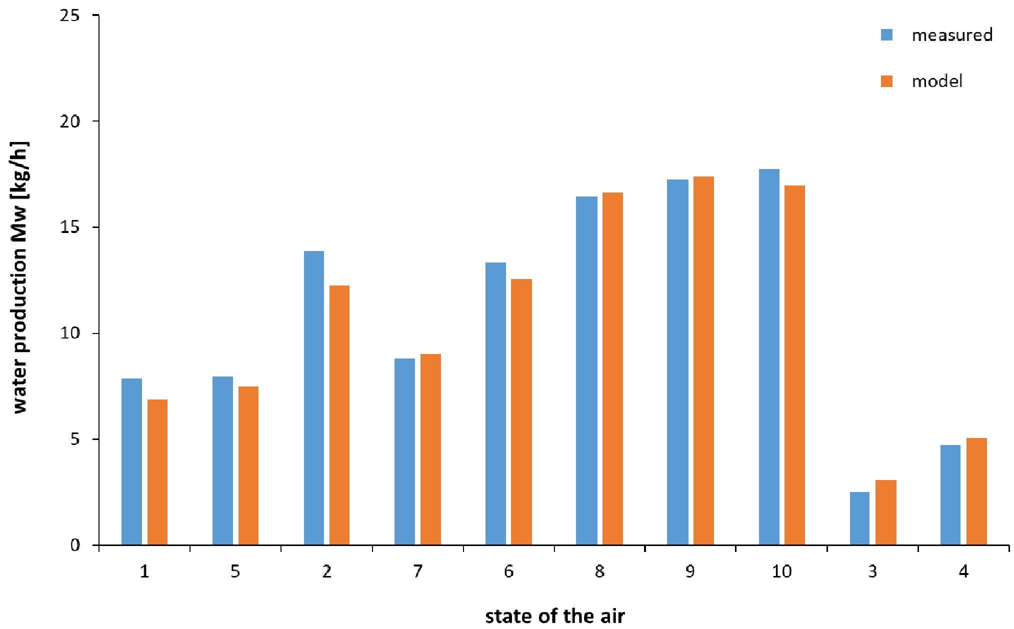

Fig. 5: Comparison of corrected model and measurements

5. System layout and modelling

Core of the system for harvesting the water from desert air is the adsorption unit. To operate the unit autonomously in the desert environment, only renewable energy sources available in the desert could be used. Cooling cycle based on speed controlled compressor will be driven by electricity from the photovoltaic modules coupled with battery storage. Heating of process air in case of insufficient temperature of regeneration air at output of condenser will be provided by solar thermal collectors (alternatively with glazed PVT collectors) coupled with thermal water storage tank. Heat removal from precooling heat exchanger will be realized by night radiant cooling (to clear sky, low ambient temperatures) by unglazed PVT collectors in combination of the storage of night cold. The scheme of the system is outlined in Fig. 6.

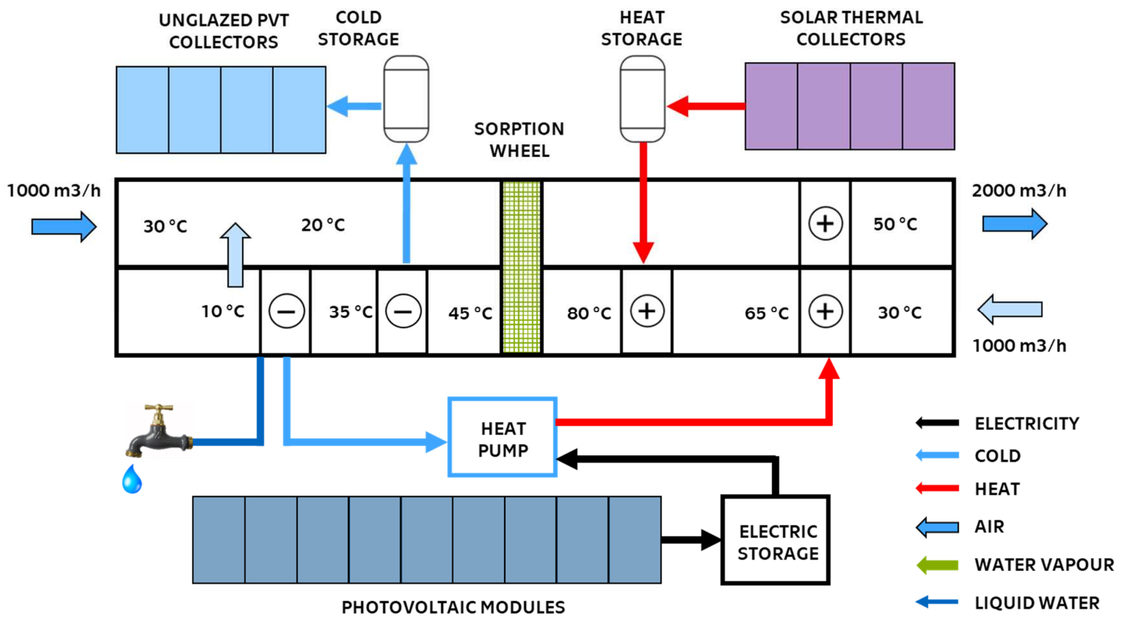

Fig. 6: Principle scheme of solar assisted adsorption system for extraction of water from ambient air in the desert climate

The whole system has been modelled with use of hourly simulation model. The detailed optimization analysis has led to several improvements of the initial idea, especially concerning the recirculation flap (see Fig. 6). First design of components for the demonstration system has been done: 70 m^2 of unglazed PVT collectors as a source of cold and electricity, coupled with 30 m^2 of PV modules and 20 m^2 of solar thermal collectors as a source of heat. Results of average daily production of water in Rijad for the case of grid connected system and in the case of autonomous operation with use of local renewables only is shown in Fig. 7. For this purpose, volume of water storage for cooling has been considered 2 m^3, for heating 1 m^3. Battery storage 25 kWh was needed. The results reveal the dependency of the production on available solar radiation. There is underproduction of generated water during the winter and therefore water storage has to be applied as a part of the system. Daily average water production 100 litres calculated from annual figures shows the potential to meet the target, but further optimization (volume of storage tanks, capacity of battery storage) is needed by more detailed parametric simulations, especially with use of advanced control of the system operation (shifting the production to hours with higher humidity, increase of flowrate, balancing the use of electricity and cold). The realistic operation of the energy sources (night cooling, PV system in extreme conditions) will be proved in demonstration installation in the desert located in UAE during 2019.

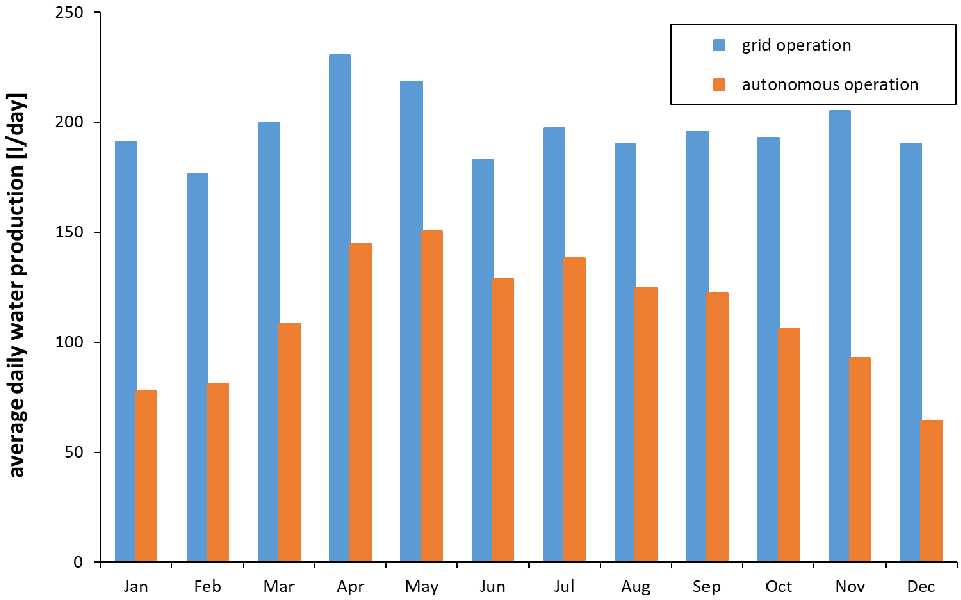

Fig. 7: Water production of the system for Rijad climate

6. Conclusion

The development of the adsorption unit for extraction of water from ambient desert air fully powered from solar energy has been presented. The unit has been built and tested in laboratory and existing theoretical model describing the behaviour has been further developed. The system concept of the autonomous unit has been developed with use of renewable energy sources available in the desert climate. First calculations of potential production of the autonomous solar water from air extraction system based on adsorption unit has been performed. The initial target for production 100 litres of water per day can be achieved even in Rijad climate.

7. References

El-Ghonemy, A.M.K., 2012. Fresh water production from / by atmospheric air for arid regions using solar energy: Review. Renewable and Sustainable Energy Reviews, 16 (2012), pp. 6384–6422, https://doi.org/10.1016/j.rser.2012.06.029

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