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Latent heat and cold storage in a solar-driven steam jet ejector chiller plant

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Abstract

This paper presents a plant concept of a solar-driven steam jet ejector chiller with latent heat and cold storage. The concept will be realized in a first demonstration plant. The solar cooling plant will consist of a solar collector field based on evacuated tube collectors with a thermal output of 200 kW, a double stage steam jet ejector chiller with a cooling capacity of 80 kW and two thermal energy storage units, meaning a heat storage unit using polyethylene as latent heat storage medium and a cold storage unit using a paraffin/water dispersion as latent cold storage fluid. While designing the solar cooling plant some preliminary research works have been accomplished with special regard to the development and integration of the heat and cold storage units. The results of this research as well as the overall design of the system will be presented in this paper.

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Keywords: solar cooling; steam jet ejector chiller; latent heat and cold storage; phase change material and slurry

1. Introduction

A lot of solar cooling plants have been realized worldwide so far. Most of them use a sorptive cooling process to generate cold. The sorptive cooling process is thermally driven, permitting the utilization of solar thermal collectors to realize solar cooling. Besides a sorptive cooling process a steam jet ejector chiller (SJEC) can be used to realize solar cooling, too. The SJEC is a thermo-mechanical chiller for chilled water generation. In 1966 Kakabaev and Davletov described in [1] a first solar-driven ejector

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cooling system with a cooling capacity of 1 kW to cool a room with a volume of 37 m³. The motive heat is provided by a parabolic mirror sized 12 m². Freon is used as working fluid and refrigerant. The total efficiency of the system ranges from 0.11 to 0.22. In [2] Huang, Petrenko, Chang and Zhuk describe a solar ejector cooling system combined with flat plate collectors and R-141b as refrigerant. The temperature of the motive heat is 95 °C. The total efficiency of the system is 0.22 at a solar irradiation of 700 W/m². In [3] Hofer presents a small test rig for food storing. The system uses water as working fluid and as refrigerant and a dish reflector to provide solar heat to the SJEC. In [4] Wolpert and Riffat present a 7 kW test plant for air-conditioning of a hospital in Mexico. Water is used as working fluid and refrigerant, as well as for the prototype system described in [5] by Nguyen, Riffat and Doherty. The prototype system has also a cooling capacity of 7 kW and was installed in an existing office in Loughborough, United Kingdom. In [6], a small test rig is described and its operational behaviour investigated. The SJEC has a cooling capacity of 1 kW. It is solar thermally driven by a parabolic trough collector with an aperture area of 10.5 m². The investigation shows that the cooling water temperature as well as the chilled water temperature have a strong influence on the coefficient of performance of a SJEC. Based on these results, a first completely automated prototype with a cooling capacity of 5 kW was developed and is presented in [7]. A more detailed review of solar-driven ejector refrigeration technologies is given in [8].

An important issue for solar cooling is the utilization of thermal energy storages. Even if solar insolation and peak demand for building cooling nearly occur at the same time, heat storage units are necessary to balance out solar intermittency and cooling demand fluctuations. Typically, thermal energy storage units in solar cooling plants are water buffer tanks storing the energy by using a temperature glide. The heat capacity of these storage units is limited to the heat capacity of water and the temperature change, which is technically possible. Applying latent heat storage units as cold and heat storage can increase the storage capacity of the system. This paper describes the intended realization of a solar SJEC using a latent heat and a latent cold storage unit. Furthermore, it gives first results of preliminary investigations gained during the design phase of the solar cooling plant.

Nomenclature

ΔHf	Heat of fusion
COP	Coefficient of performance
DSC	Differential scanning calorimetry
PCM	Phase change material
PCS	Phase Change Slurry
SJEC	Steam jet ejector chiller

2. Demonstration plant

2.1. Description of the demonstration plant

The demonstration plant will consist of a double stage SJEC to produce chilled water for building cooling. The cooling capacity of the SJEC will be 80 kW at a chilled water temperature of 6 °C. Evacuated tube collectors will be used to generate steam. The gross area of the collector field is 400 m² and the thermal output of the solar collector field is 200 kW. A latent heat storage unit based on polyethylene is used to ensure a constant heat supply to the SJEC, even on cloudy days when the solar insolation is unstable. Furthermore, the demonstration plant will be equipped with a latent cold storage unit containing a paraffin/water dispersion, using paraffin as latent heat storage material and water as continuous phase.

The solar-driven SJEC will be erected at the University of Applied Sciences in Karlsruhe, Germany. The solar collector field will be installed on the sawtooth roof of the workshop building LB and the SJEC in a 40 ft container, as depicted in Fig. 1, which will be placed on the eastern side of the building LB. An open cooling tower will be installed on the top of the container for the heat rejection system.

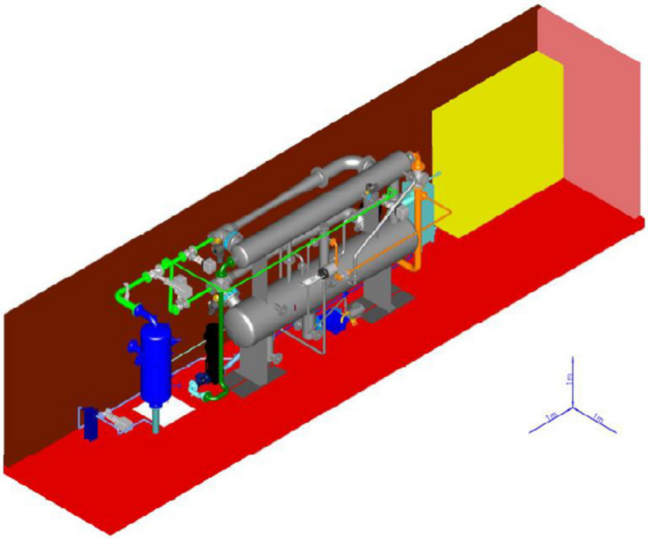

Fig. 1. Image representation of the double stage SJEC in a 40 ft container without heat storage unit

Besides the SJEC the container will also house the heat storage unit. The cold storage unit will be installed in the basement of building LB. Due to the fact that one supply network of the building is used for cooling in summer time and for heating in winter time, the network cannot directly be supplied with PCS and a hydraulic separation of the cold storage unit and the supply network by a heat exchanger is necessary.

2.2. Steam jet ejector chiller

The SJEC is a thermo-mechanical chiller for cold generation. An exemplary process scheme of a single stage SJEC is given in

Fig. 2. The SJEC uses water for the motive steam generation, and as refrigerant. Water boils at a low pressure level in the evaporator. The necessary heat of evaporation is the cold provided by the process in form of chilled water. The water vapour is compressed by a steam jet ejector, which serves as compressor in the refrigeration cycle, to a higher pressure level and fed into a condenser. The driving energy of the ejector is supplied by motive steam, which can be generated by solar energy. The motive steam and the water vapour of the evaporator are mixed in the ejector and are both liquefied in the condenser. The condensation takes place at a temperature higher than the ambient temperature, so that the heat from the

condensation process can be rejected to the atmosphere. The condensate of the condenser is fed back to the evaporator and to the motive steam generator respectively. A SJEC can be realised as open process without hydraulic separation between the solar collector and the SJEC or the chilled water network and the SJEC. The evaporator can be designed as a flash evaporator and the condenser as a direct contact condenser in such a way that both devices are basically vessels. The steam jet ejector consists of a motive steam nozzle, a mixing chamber and a diffuser. Thus the whole solar cooling system is simple in design and a high reliability of operation can be expected.

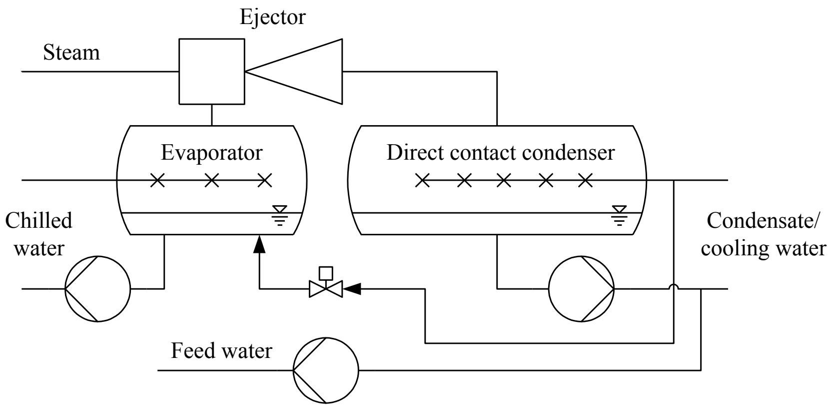

Fig. 2. Exemplary process scheme of a SJEC (single stage)

A steam jet ejector chiller has a special operational behaviour. The steam consumption of the SJEC is strongly related to the cooling water temperature. This relation is depicted in Fig. 3 with data taken from [9] adapted to the designed parameter of the plant. At the nominal design point of the system the steam consumption of the SJEC is 221 kg/h.

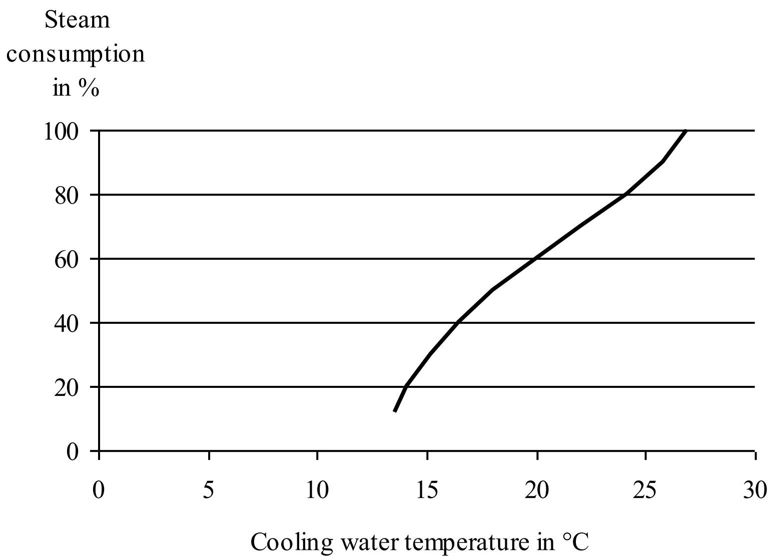

Fig. 3. Expected steam consumption of SJEC related to the cooling water temperature, characteristic taken from [9]

The steam consumption of the SJEC decreases significantly, when the cooling water temperature decreases while the cooling capacity remains almost constant. This means that at lower ambient air temperatures when the heat rejection system provides cooling water on a lower temperature level the coefficient of performance (COP) of the SJEC rises. In view of a typical cold load curve for a comfort cooling system, which is characterised by long operation periods at ambient air temperatures below the nominal design point, a higher mean COP value than the nominal COP value of the SJEC can be expected. When the cooling water temperature decreases under the temperature level of the chilled water the operating mode 'free cooling' can be easily realised by switching off the ejector. In this operating mode the cooling capacity is provided by the heat rejection system.

2.3. Heat storage of the plant

The function of the heat storage unit in the system is to ensure the constant supply of motive steam to the SJEC. Furthermore, the space for the erection of the heat storage unit is limited due to the intended installation into the container, so that the volume of the heat storage unit should be as small as possible. This leads to the use of a phase change material (PCM) to realize a latent heat storage unit. The PCM is used as storage material which stores heat energy in form of latent heat of fusion during a phase transition over a temperature shift. The latent heat of fusion of a material is higher than the sensible heat capacity of the material so that the use of a PCM allows increasing the heat density of a storage unit and therefore to reduce its volume.

In a first approach the operating temperature of the heat storage unit was assigned to be in the range from 120 °C to 150 °C. In view of this temperature range the listed storage materials in Table 1 were considered for the heat storage unit.

Table 1. List of considered storage materials for the heat storage unit

Storage material	Temperature in °C	Specific heat of fusion in kJ/kg
Water (mentioned as reference)	120-150	*128.5* (sensible heat!)
Polyethylene PE-HD [GHR 8110]	122-133	150-200
Polyethylene PE-UHM [GUR4120]	124-134	150-200
Polyethylene Licocene PE 4201	125-130	246
Polypropylene Licocene PP 6102	142-148	70
Polypropylene Licocene PP 7502	155-165	106
KNO_3-$NaNO_2$-$NaNO_3$ (53-40-7)	142	80
Mannitol	164-167	294-325
Palatinitol (Isomalt)	145	170

In some preliminary tests the heat of fusion and the thermal stability of the material were investigated. The preliminary tests were conducted in an oven and include heating-up and afterwards cooling down the material. This procedure was conducted 30 times, with constant measuring of the temperatures of the oven and the material. The maximum temperature was 180 °C. Especially polyethylene shows a high specific heat of fusion in combination with a good thermal stability and market availability so that polyethylene was chosen as PCM for the heat storage unit. The temperature curves and additional differential scanning calorimetry (DSC) measurements before and after the tests indicate no change of the temperature range and the specific heat of fusion. But as depicted in Fig. 4 a visual change of the material can be observed so that it was decided to limit the maximum temperature of the heat storage unit of the SJEC plant to 145 °C.

Fig. 4. Left: sample of polyethylene before tests; right: polyethylene sample after tests

Based on the results of the preliminary tests the heat storage unit is currently being designed according to Fig. 5. The heat storage unit consists of a vessel and five heat storage modules. The vessel contains a defined water level and is connected to the solar collector field and the SJEC. Steam from the solar collector field flows into the vessel and is liquefied in the water while it heats up the water. To remove the steam again, the vessel pressure is reduced by tapping steam from the top of the vessel. The water boils and the temperature of the water decreases. The polyethylene is housed in the storage modules. To charge the modules hot water from the vessel is pumped through the storage modules. During the discharging process the water boils in the storage modules and the steam flows into the vessel. The pump is bypassed so that the liquid level in the modules remains constant related to the liquid level in the vessel. In case of the storage being completely loaded or if there is not enough steam from the solar collector field to charge the heat storage unit and drive the SJEC at the same time, the heat storage unit can be bypassed so that the steam from the solar collector field can be directly used to operate the chiller.

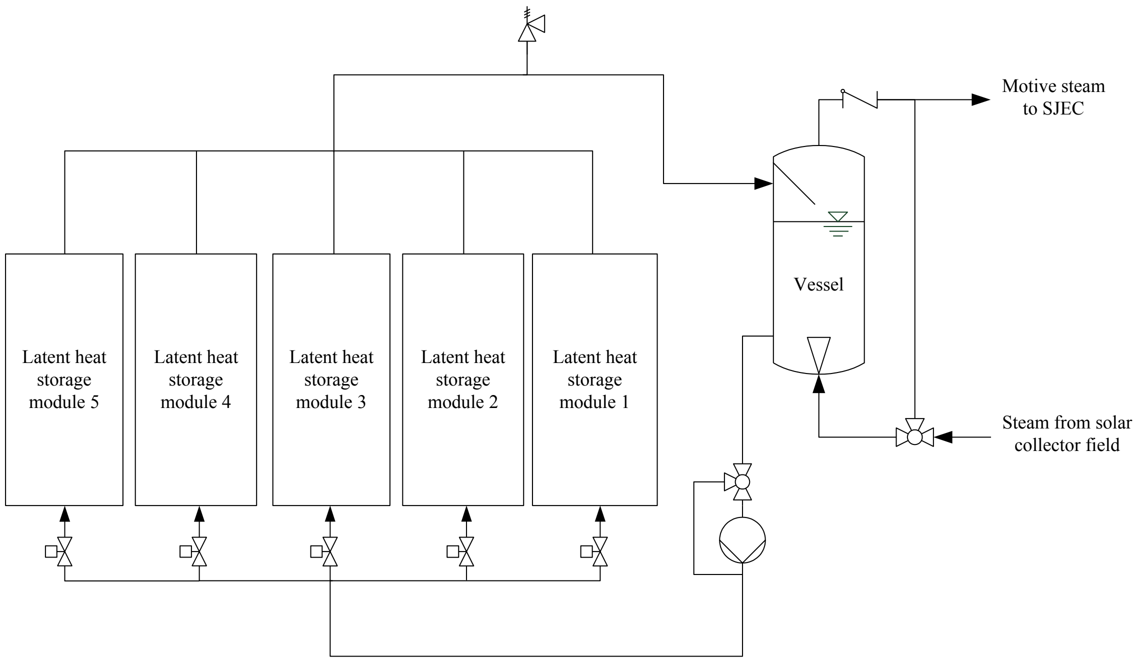

Fig. 5. Process scheme of the heat storage unit

The storage modules will contain 800 kg polyethylene. The latent heat capacity of the storage will be 120 MJ and the sensible heat capacity will be 30 MJ within the temperature range of 120-140 °C. This is enough to produce 62.5 kg steam or to operate the SJEC for more than 15 min at full load under nominal operating conditions.

2.4. Cold storage of the plant

Besides the heat storage unit the system is also equipped with a cold storage unit. Normally water buffer tanks are used in chilled water networks to realize a cold storage unit. The cold is stored as sensible heat over a temperature shift and the energy density is limited to the technical possible temperature shift and the heat capacity of water. Due to the fact that chilled water networks operate with a narrow temperature spread between supply and return flow the possible temperature shift is not high and the water buffer tanks have to be designed respectively big to realize the necessary cold capacity in the cold supply. Using a PCM as storage material could be also an alternative for the cold storage unit to increase the energy density. Especially paraffin is discussed as PCM for cold storage and cooling applications in the temperature range from 0 to 25 °C. Table 2 lists paraffins with its temperature range of the phase transition and the corresponding heat of fusion.

Table 2. Exemplary list of paraffins as PCM for a cold storage unit

Storage material		Temperature range in °C	Specific heat of fusion in kJ/kg
Water (mentioned as reference)		5-15	*42* (sensible heat!)
RT 10	melting	8.7-11.7	176
(paraffin blend)	freezing	5.9-8.5	178
RT 20	melting	17.2-24.2	142
(paraffin blend)	freezing	17.8-21.9	155
Heptadecane	melting	19.9-22.7	168
(degree of purity 99,9 %)	freezing	17.2-19.9	158
Parafol 14	melting	4-8	220
(tetradecane 97 %)	freezing	-1-1.5	225
Parafol 16	melting	17.4-20.7	249
(hexadecane 97 %)	freezing	13.6-15.9	251
Parafol 14/16 mixture	melting	6-13	170
(13 vol.-% of Parafol 14)	freezing	4-10.5	162
Parafol 16/18 mixture	melting	15-19.5	170
(67 vol.-% of Parafol 16)	freezing	11-17	169

Some approaches use paraffin as bulk in the storage unit in which a heat exchanger is placed to transfer heat into the bulk or from the bulk. Chilled water flows through the heat exchanger and charge or discharge the cold storage unit. A disadvantage of such a storage system is that in the solid state of the paraffin the heat transfer from the chilled water to the paraffin is low. To compensate this effect the area of the heat exchanger must be increased. An alternative to overcome this disadvantage is the use of a paraffin/water dispersion instead of bulk paraffin. The paraffin is dispersed in form of small droplets surrounded by water as continuous phase. When the paraffin freezes the dispersion becomes a suspension, when the paraffin melts the dispersion becomes an emulsion. In both cases the dispersion itself remains liquid and such a fluid is called phase change slurry (PCS). Fig. 6 shows a picture of a paraffin/water dispersion proposed as PCS for cold storage applications.

Fig. 6. Picture of a paraffin/water dispersion

The use of a PCS as storage fluid instead of bulk PCM allows designing the cold storage unit as a simple buffer tank, because the PCS is pumpable. At the same time the PCS has a higher heat capacity than water so that the energy density of a PCS buffer tank is higher than the energy density of a water buffer tank. The diagrams in Fig. 7 display the results of DSC-measurements of two paraffin/water dispersions.

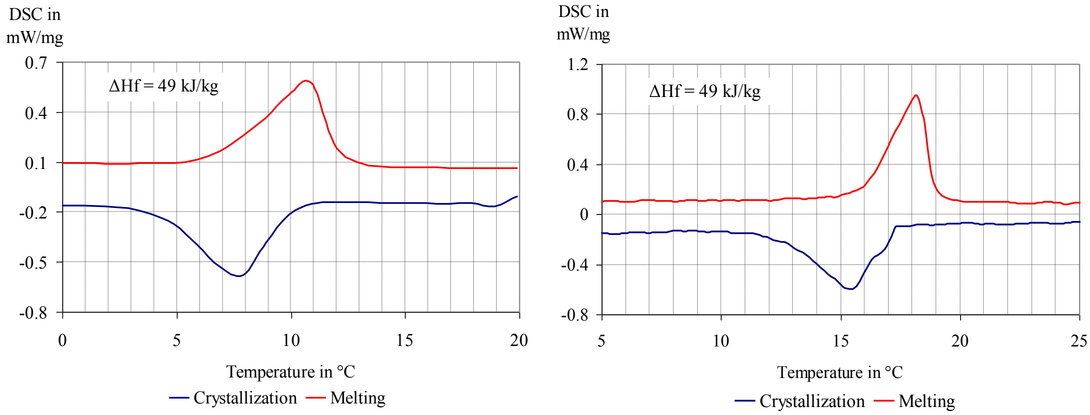

Fig. 7. DSC measurements of two 30 wt.-% dispersions, left: Parafol 14/16 mixture; right: Parafol 16/18 mixture

The peaks of the crystallization and melting curves indicate the heat of fusion during the phase transition. In both measurements the dispersion has a paraffin concentration of 30 wt.-% while the heat of fusion ΔHf is equal to 49 kJ/kg. The sensible heat of the dispersion is not considered here.

3. Summary

Apart from sorptive processes to realize solar cooling a steam jet ejector chiller in combination with solar thermal collectors can be used, too. Due to its simple design steam jet ejector chiller represent a promising alternative to generate chilled water for comfort cooling with thermal energy. Such a plant will be erected at the University of Applied Sciences in Karlsruhe, Germany. A solar collector field based on evacuated tube collectors with a gross area of 400 m² and a thermal output of 200 kW will be installed on a sawtooth roof of building LB. Evacuated tube collectors are used to produce steam which serves as motive fluid for a steam jet ejector. The ejector is the compressor of the refrigeration cycle producing chilled water. The cooling capacity of the steam jet ejector chiller will be 80 kW at 6 °C chilled water temperature. A latent heat storage unit with polyethylene as phase change material and a latent cold storage unit with a paraffin/water dispersion as phase change slurry store thermal energy in the process. The steam jet ejector chiller and the heat storage unit will be housed in a 40 ft container on the eastern side of the building. The cold storage unit will be erected in the basement of the building LB.

The steam jet ejector chiller has a special operational behaviour. When the cooling water temperature of the heat rejection system decreases due to a low ambient air temperature, the steam consumption of the steam jet ejector chiller also decreases significantly, while the cooling capacity remains almost constant. Assuming that cooling applications often operate at an ambient air temperature lower than the ambient air temperature at the design point of the system, the mean coefficient of performance can be expected to be higher than the nominal coefficient of performance. The latent heat and the latent cold storage units will reduce the required space of the total plant and ensure to balance out solar intermittency and cooling demand fluctuations.

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References

[1] Kakabaev A, Davletov A. A Freon Ejector Solar Cooler. AS Turkmen SSR. *Geliotekhnika* 1966;2(5):42-48.

[2] Huang BJ, Petrenko VA, Chang JM, Zhuk KB. A Solar Ejector Cooling System Using Refrigerant R141b. *Solar Energy* 1998;64:223-226.

[3] Hofer T. *Solare Kälteerzeugung mit Dampfstrahltechnik*. Munich, Germany: Diplomarbeit FH-München; WS 97/98.

[4] Wolpert JL, Riffat SB. *Hybrid Solar/Gas Cooling Ejector Unit for a Hospital in Mexico*. http://www.kenes.com/ises.abstracts/Htm/0171.htm, Great Britain: Institute of Building Technology, School of the Built Environment, University of Nottingham; 1999.

[5] Nguyen VM, Riffat SB, Doherty PS. Development of a solar-powered passive ejector cooling system. *Applied Thermal Engineering* 2001;21:157-168.

[6] Pollerberg C, Ali AHH, Doetsch C. Solar driven steam jet ejector. *Applied Thermal Engineering* 2009; 29:1245–1252.

[7] Pollerberg C, Jaehnig D, Doetsch C. Prototype of a Solar Driven Steam Jet Ejector Chiller. *Proceedings of the 3rd International Conference on Solar Air-Conditioning,* Palermo, Italy; 2009. ISBN 978-3-941758-06-9.

[8] Abdulateef JM, Sopian K, Alghoul MA, Sulaiman MY. Review on solar-driven ejector refrigeration technologies. *Renewable and Sustainable Energy Review* 2009;13:1338-1349.

[9] GEA Wiegand GmbH. *Kühlen unter Vakuum*. GEA Wiegand GmbH, Einsteinstraße 9-15, 76275 Ettlingen, Germany: Product Information Brochure.