Mobile HIL Test Bench for Low Cost Radiative Heating and Cooling Collectors

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Abstract

This paper presents a mobile hardware-in-the-loop (HIL) test bench that has been developed to simulate a solar assisted cooling and heating system for residential buildings in hot climates. The main component of the system is a low cost uncovered solar collector that is used for the production of night radiative cooling or daytime heating energy (hardware component). The collector was designed for low cost housing projects in Egypt, whose cooling and heating demand was modeled using the program TRNSYS (software component). The design and construction of a mobile HIL test bench is presented together with some performance results from the HIL-tests in cooling mode.

Keywords: HIL test bench, space heating and cooling, solar absorber, radiative cooling

1. Introduction

Low cost renewable heating and cooling systems are of prime importance for developing nations with high population densities and limited financial resources. As an example, Egypt is one of the fastest growing countries worldwide, the population increased from 21 million in 1950 to 98 million in 2017 and is currently ranked on place 14 by total population size worldwide. For the year 2050 a total population for Egypt of 153 million it is expected (UN, 2017). Due to this fast population increase, the state of Egypt is facing many social and economic problems. Providing decent and affordable housing for the lower and middle class and the adaptation of the energy system will be two of these challenges for the future.

During the past few years, Egypt has been suffering from recurrent electricity cut-offs, mainly in summer because of the large cooling demand (Elharidy et al., 2013). The national demand has been exceeding the available produced power from generation plants since 2011.

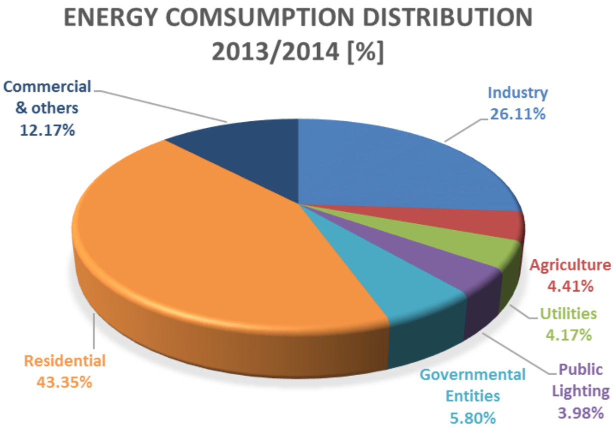

Fig. 1: Electricity-shares sold in Egypt (on all voltage levels) according to the purpose of usage 2013/2014 (Egyptian Electricity Holding, 2014)

Fig. 1 shows the electrical energy consumption distribution among the different sectors in Egypt. The greatest share of the total nationally generated electricity is consumed in residential buildings (43.4%). When considering only the medium and low voltage levels, the residential consumption reaches 51.3% of the total energy sold from the national electricity distribution companies (Egyptian Electricity Holding, 2014).

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doi:10.18086/swc.2017.12.02 Available at http://proceedings.ises.org

Urbanized dense cities lead to higher local ambient temperatures. As a result of this, the use of air-conditioning (AC) units for cooling has immensely increased in Egypt. Conventional AC units represent the major energy consumption of the residential energy demand (Xing Lu et al., 2016, Attia et al., 2012). On the other hand, in winter electric water heating accounts for large shares of electricity demand, even in warm-climate countries. Nowadays, cooling in residential buildings in Egypt is provided by not very efficient split units, which number grows very rapidly (Attia et al. 2012). This leads to frequent electricity cut-offs in summer (Elharidy et al., 2013). Integration of renewable energies to the space cooling and heating in residential buildings could be an environment-friendly and sustainable solution.

Within the research project NightCool, funded by the German Federal Ministry of Education and Research (BMBF), a concept for a low-cost system for heating and cooling applications was developed and simulated in detail.

The developed system consists of uncovered solar collectors for the energy production and an activated ceiling for the energy distribution. Fig. 2 shows the principles of the energy supply system for direct cooling (left) and direct heating (right). The space cooling is achieved at night by circulating the heat transfer fluid in the collectors (radiative cooling) while the space heating is provided during the day by converting the solar energy into useful heat. Since these collectors are not expensive, such a heating and cooling system results to be low-cost. The advantages of such a simple system lie in simple installation and low energy costs (Eicker and Dalibard, 2011), which is very important for solar thermal systems in order to achieve a higher market penetration (IEA SHC Task 54).

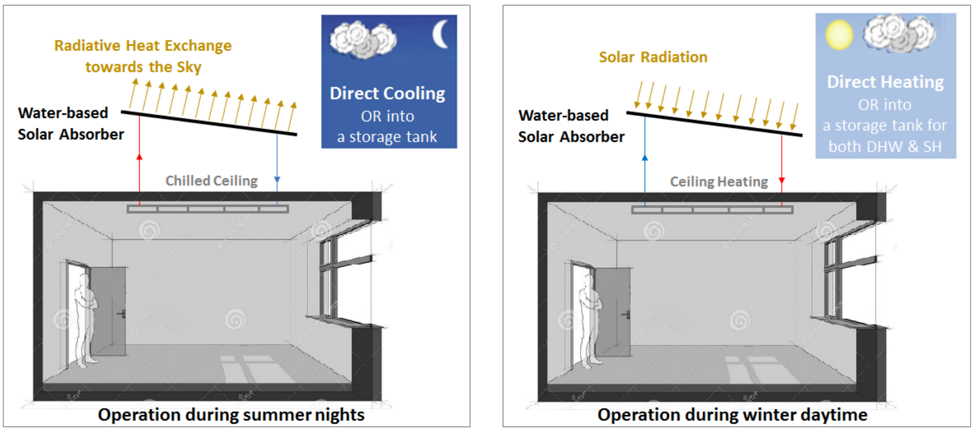

Fig. 2: Energy supply system that provides space cooling in summer (left) and space heating in winter (right)

In order to investigate the potential and limits of such a system, a mobile HIL test bench has been designed and constructed. The present paper aims to show the advantages of using such a HIL environment show its limitations and give some insights for further improvements.

2. Motivation to build a mobile HIL test bench

2.1. Motivation to build a mobile HIL test bench

As before mentioned, the project NightCool aimed to develop a low-cost system for heating and cooling applications for Egyptian climate conditions. The estimation of the achievable return temperatures as well as the cooling power by using solar collectors for radiative cooling applications needs adequate physical collector models.

ISO 9806:2017 specifies test methods for the thermal performance characterization of fluid heating collectors for steady-state and quasi-dynamic conditions (ISO 9806, 2017). Based on this test method parameters for the parameterization of collector models within the simulation environment TRNSYS such as Type 203 (PVT collectors) (Bertram et al., 2011) or Type 1289 (flat plat collectors) can be determined. The deviation between measured collector power output on a test stand and simulated power can vary between night and daytime (Cremers et al., 2015). Especially for night time radiative cooling, the collector parameters determined according to ISO 9806:2017 are not sufficient enough to develop control strategies only by using a simulation model.

The motivation to build the HIL test bench in the NightCool project can be summarized as follows:

- The thermal performance of solar collector at night cannot be modelled accurately with existing available models so that their performance needs to be measured and not simulated.
- Test new market available solar thermal collectors (which thermal performance is not specified by the producer)
- Test the integration of such collector into different systems and for different buildings construction (light or heavy) and achieve a realistic estimation of the dynamics of the system, scalable and adaptable to different kind of loads etc.
- Dimension the system components and optimize the control before it can be installed on a bigger scale

Following table summarizes the main functionalities of the mobile HIL test bench and the benefit by setting up a small scale test environment.

Tab. 1: Main functionalities of the mobile HIL test bench and the need and benefit

Functionality	Need and benefit
Conduct collector performance tests under real conditions and conduct tests of solar collectors at night time	Various solar collectors of different constructions from different producers (basically swimming pool absorbers are recommended) can be tested and a collector with a highest thermal potential and best integration suitability (easily connected hydraulic connections, appropriate mechanical properties, etc.) can be defined For the cooling application, it is essential to know also the cooling potential of different solar collectors. This information is missing in technical data sheets, it can be obtained experimentally.
Analysis of the dynamic behaviour of system components	It is important to understand the behaviour of the solar collector and the building to define optimal control algorithms.
Development and test of control algorithms for heating and cooling systems depending on the defined system	The control algorithm of a system can be easily implemented in a simulation environment such as TRNSYS either for cooling or heating application. An optimal set of parameters such as the set point temperatures to turn on or of the system.
Optimize building construction elements so that they are appropriate for the suggested cooling/heating system	By changing building parameters in the building model on the simulation environment an optimal distribution system can be defined (activated heating and cooling ceiling, floor heating or others)
Estimation of achievable thermal comfort e.g. temperature and relative humidity and analysis of the activation capability of building mass to act as energy storage through different distribution systems e.g. activated ceilings	Direct feedback from the simulation model helps analyse comfort parameters and gives insight into the architectural concept of active and passive measures (active and passive building design).

3. Mobile HiL test bench

3.1. Working principle and construction

The mobile HIL test bench has been designed and constructed within a research project aiming to develop a low-cost space heating and cooling system for Egyptian climate conditions. The working principle of the HIL test bench (Figure 3) is based on hardware-in-the-loop (HIL) simulation, a technique that is used in the development and test of real-time embedded systems. The mobile HIL-Box consists of an uncovered solar collector (hardware component) and a building simulation model (software component). It enables to conduct real-time measurements and simulations to calculate at each time step the dynamic change of the system parameters such as room temperature and ceiling temperature, as well as the cooling or heating power. The solar collector is replaceable, so that different solar collectors can be tested. The building and the distribution system are defined in the simulation environment TRNSYS (www.trnsys.com). Thus, an optimal solar system combination, solar collector (collector-type, -size, etc.) and building properties (construction, size, materials, etc.) can be chosen. In other words, the HIL test bench enables to optimize the building and the system at the early planning stage.

The main weather data (ambient temperature T_a, relative humidity RH, horizontal global irradiance G_{hor}, net long-wave radiation G_L and wind velocity w) and system parameters (inlet and outlet temperature T_{in} and T_{out}, flow rate $\dot{m}$) are measured and acquired by several ethernet input modules connected with the software LabVIEW. The measured data are given as inputs to the TRNSYS building model which calculates the building behavior and the system response, such as room temperature T_{room} and the outlet temperature of the cooling ceiling T_{cc}. In the hydraulic system the simulated T_{cc} is the same as the inlet collector temperature T_{in}. It is read in LabVIEW and transmitted as set-point temperature via an analog output module to the temperature control unit (TCU). The TCU regulates then the fluid inlet temperature of the solar collector, i.e it sets the inlet temperature equal to the T_{cc} Based on the temperature difference ($T_{in} – T_{out}$) and the fluid flow rate the cooling or heating power of the solar collector can be calculated.

$$Q = \dot{m} c_p (T_{out} - T_{in}) \qquad \text{(eq. 1)}$$

where c_p is the fluid heat capacity.

In the next step, the collector response and the weather data are measured and the procedure is repeated (see Figure 3).

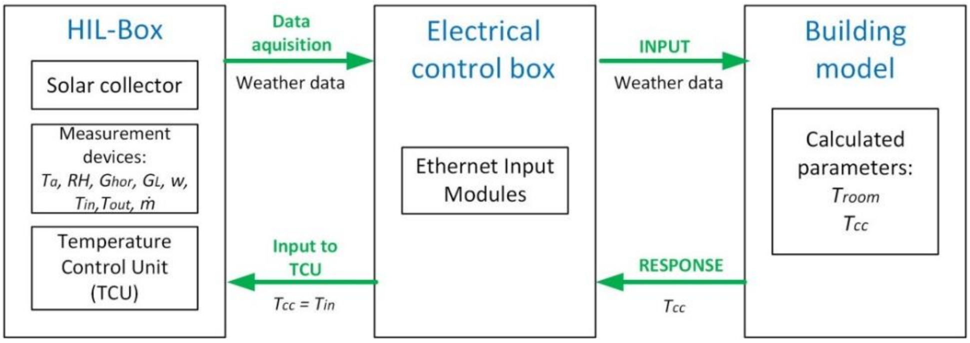

Fig. 3: Working principle of the HIL test bench

The measuring box is shown in Figure 4 and its main components are listed in Table 2.

Tab. 2: List of the main components of the HIL test bench

Number	Component	Manufacturer
1	Solar collector, length 1,8 m	AQSOL
2	Temperature control unit Variocool VC 2000	Lauda
3	Pyrgeometer LP PIRG 01	Delta Ohm
4	Pyranometer LP PYRA 02	Delta Ohm
5	Anemometer “Windgeber – compact” 4.3519.00.161	Thies Clima
6	Temperature and relative humidity sensor HD9008TRR	Delta Ohm
7	Air vent valve	Solar
8	Temperature sensor	Omega
9	Ball valve	-
10	Valve Motor	Oventrop
11	3-way diverter valve Tri-M TR	Oventrop
12	Magnetic inductive flow sensor induQ	SIKA
13	Flexible pipes	-
14	Copper tubes	-
15	Roller Shutter	Turtle24
16	Electric control box	Consists of many components

Fig. 4: HIL test bench: a) general view closed, b) general view open, c) and d) weather station, e) hydraulic system, f) electric control box

The simplified hydraulic scheme of the HIL test bench is shown in Figure 5. The solar absorber is connected to the temperature control unit Lauda and the thermal fluid, forced by the pump, circulates through the absorber. The flow rate is regulated by a valve with motor. The valve can be partly closed to reduce the flow rate. When the valve is closed completely, there is no flow through the absorber.

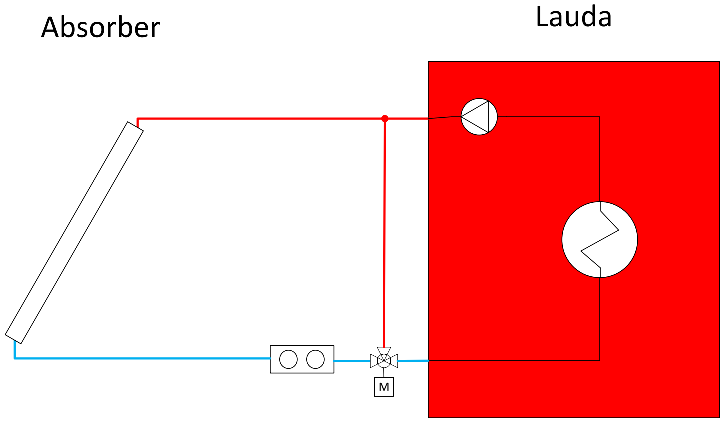

Fig. 5: Simplified hydraulic scheme of the HIL test bench (Lauda is the temperature control unit)

3.2. Data communication

The coupling between LabVIEW and TRNSYS requires a data communication between two softwares, which is achieved by the means of ASCII files (text files read and written by both programmes). The different steps of this communication has been programmed in LabVIEW and are shown in Figure 6.

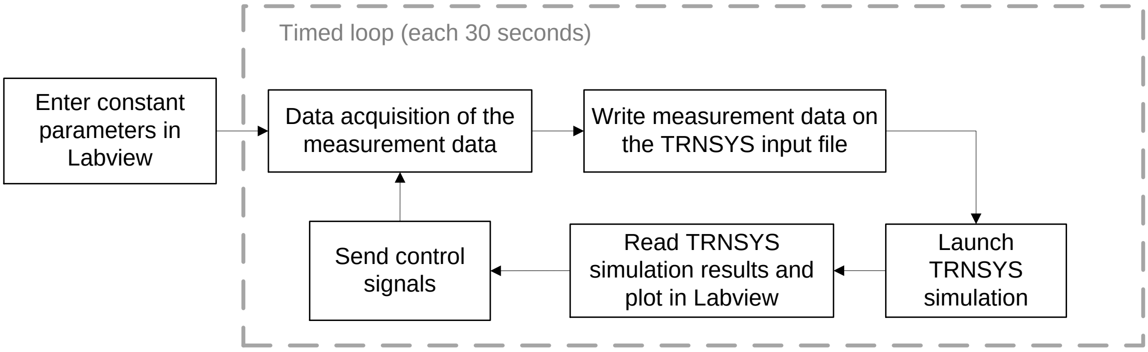

Fig. 6: Data communication steps between Labview and TRNSYS for the HiL configuration

In the first step, the parameters which remain constant during the whole HIL test have to be entered by the user in the LabVIEW graphical interface in order to define the system size as well as the main control parameters. In addition the path locations of the necessary different files have to be defined.

In the second step, the measurement data are acquired in LabVIEW via the I/O modules and written in a ASCII file to be read in TRNSYS. The data required by TRNSYS are listed in Table 3.

Tab. 3: Data transferred from LabVIEW to TRNSYS

Variable	**Name**	**Unit**
Ambient air temperature	Tamb	°C
Ambient air relative humidity	RH	%
Horizontal solar irradiance	Gh	W/m²
Effective sky temperature	Tsky	°C
Collector outlet fluid temperature	TcolOut	°C
Collector mass flow rate	mdotCol	kg/h
Collector aperture area	Acol	m²
Specific heat of the collector fluid	cp	kJ/kgK
Density of the collector fluid	rho	kg/m³
Pipe diameter	dpipe	m
Pipe length	Lpipe	m
Building orientation	TURN	°

Then the TRNSYS program is run and the LabVIEW program stops until the simulation is finished. At the end of the simulation, the main results are written by TRNSYS in a text file, read by LabVIEW and shown for visualization (see Figure 7).

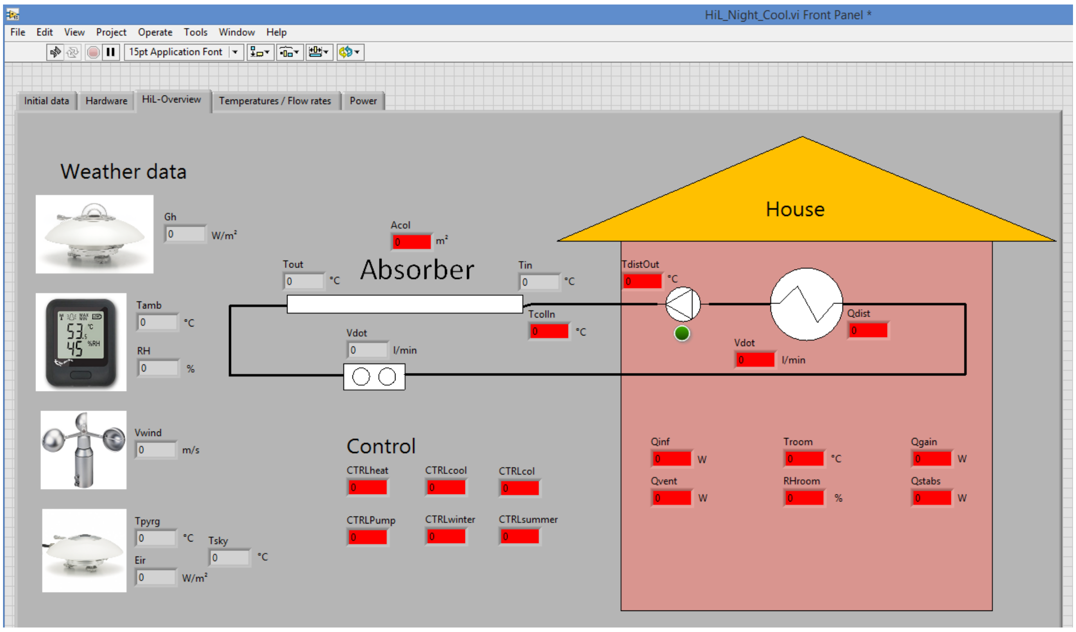

Fig. 7: Screenshot of the HiL visualization in Labview (grey: measurement data, red: simulated data)

The data that are passed from TRNSYS to LabVIEW are listed in Table 4.

Tab. 4: Data communicated from TRNSYS to LabVIEW

Variable	**Name**	**Unit**
Outlet fluid temperature of the building heating/cooling distribution system	TdistOut	°C
Collector inlet temperature (after pipe)	TcolIn	°C
Building room temperature	Troom	°C
Control signal of the pump	CTRLpump	[0/1]
Heating/cooling power transferred to the building (+/-)	Qdist	W
Relative humidity of room air	RHroom	%
Infiltration gains	Qinf	W
Ventilation gains	Qvent	W
Radiative internal gains	QgainRad	W
Convective internal gains	QgainConv	W
Total solar radiation absorbed at all inside surfaces of zone	Qtsabs	W
Control signal heating	CTRLheat	[0/1]
Control signal cooling	CTRLcool	[0/1]
Control signal collector	CTRLcol	[0/1]
Control signal season	CTRLseason	[0/1]
Control signal winter	CTRLwinter	[0/1]
Control signal summer	CTRLsummer	[0/1]

Depending on the simulation results, the appropriate control signals of the inlet temperature to the solar collector and the flow rates are sent via the I/O modules.

4. Example of measurement results

In this section, some results obtained in cooling mode with the developed HIL test bench are shown exemplarily. The test bench has been operated for commissioning tests during one week between the 12th and the 19th of June 2017 for a typical Egyptian building and under the climate conditions of Stuttgart.

4.1. Constant parameters

The main constant parameters assumed for the test of the measurement box are summarized in Table 5.

Tab. 5: Main constant parameters

Parameters	Value	Unit
Collector area	70	m²
Fluid density	1043	kg/m³
Fluid specific heat	3.675	kJ/kgK
Cooling set point	22	°C
Activated ceiling area	114	m²
Initial building temperature	23.5	°C

4.2. Weather data

Figure 8 shows the main measured weather data during the considered period: the ambient temperature T_{amb}, the sky temperature T_{sky} which is calculated with the help of the downward longwave radiation measured with the pyrgeometer and the global irradiance on the horizontal plane G_h.

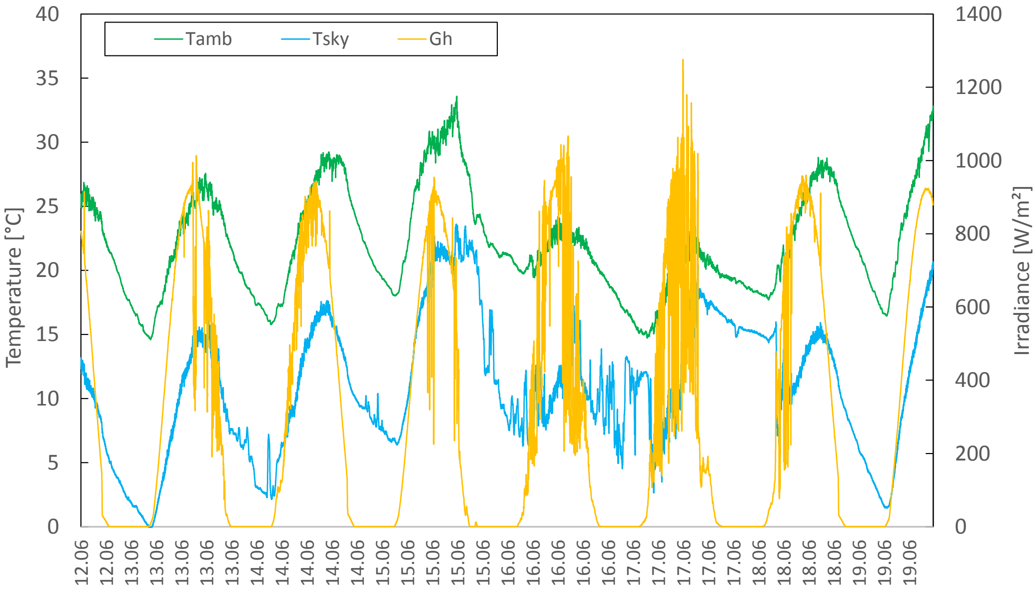

Fig. 8: Main weather data during the measurement period

4.3. Collector operation

Figure 9 shows, in addition to the ambient and sky temperatures, the main collector measured values: the inlet and outlet temperatures T_{in} and T_{out} as well as the volumetric flow rate V_{dot}. The collector is operated in cooling mode, i.e. at night according to a defined control strategy.

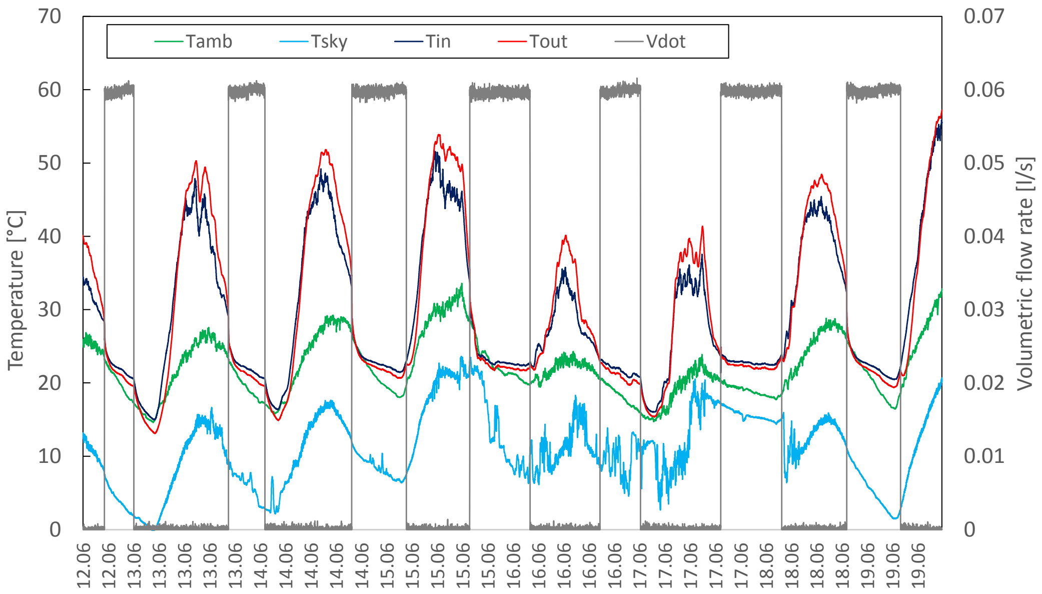

Fig. 9: Collector operation during the measurement period

4.4. Building behavior

Figure 10 shows the simulated building temperature T_{room}, the collector specific power $Q_{dotColSp}$ transferred to the building, as well as the total building specific gains $Q_{dotGains}$. The collector specific power is based on the collector area (70 m²) whereas the building specific gains are based on the apartment floor area (115 m²). $Q_{dotColSp}$ is defined positive when cooling is provided to the building. $Q_{dotGains}$ includes the internal gains, the solar gains, as well as the ventilation and infiltration gains.

It can be seen that the building temperature T_{room} increases suddenly when the collector pump is switched ON at the beginning of the night. This is due to the still hot fluid which is in the pipes and the collector and is pumped to the building causing a temperature increase in the room. This can be easily solved by appropriate changes on the control parameters.

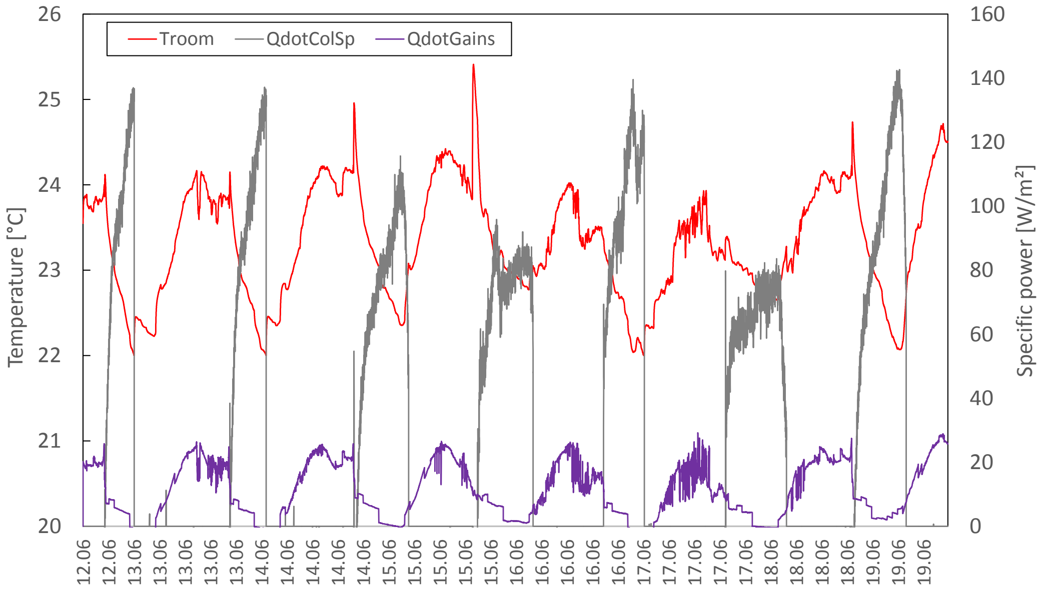

Fig. 10: Main building results during the measurement period

In order to see the influence of the investigated system on the building temperature, a reference system (i.e. without collectors) has been simulated. Figure 11 shows the room temperatures of the reference system and the night cooling system for the three first nights of the considered measurement period. Due to the control problem mentioned earlier, the room temperature of the radiative cooling system is higher at the beginning of the night (i.e. the building is actually heated up) than the reference system. When the cooling power of the collector is positive (i.e. the building is cooled down), the room temperature is lower than the reference system. The pump is stopped when this temperature reaches 22°C.

Due to the chosen distribution system (thermally activated ceiling), both temperatures merge together as soon as the collectors are not operated. Indeed, the activated ceiling of the TRNSYS building model assumes a unique thermal coupling to the building air node. Therefore, the cooling provided by the collectors cannot be transferred to the building thermal mass, causing a quick drop in the room temperature which has no effect on the room temperature during day time. A better option would be in this case to connect the collector loop to an activated concrete core so that the building thermal mass can be cooled down during the night and therefore providing additional thermal comfort during the day.

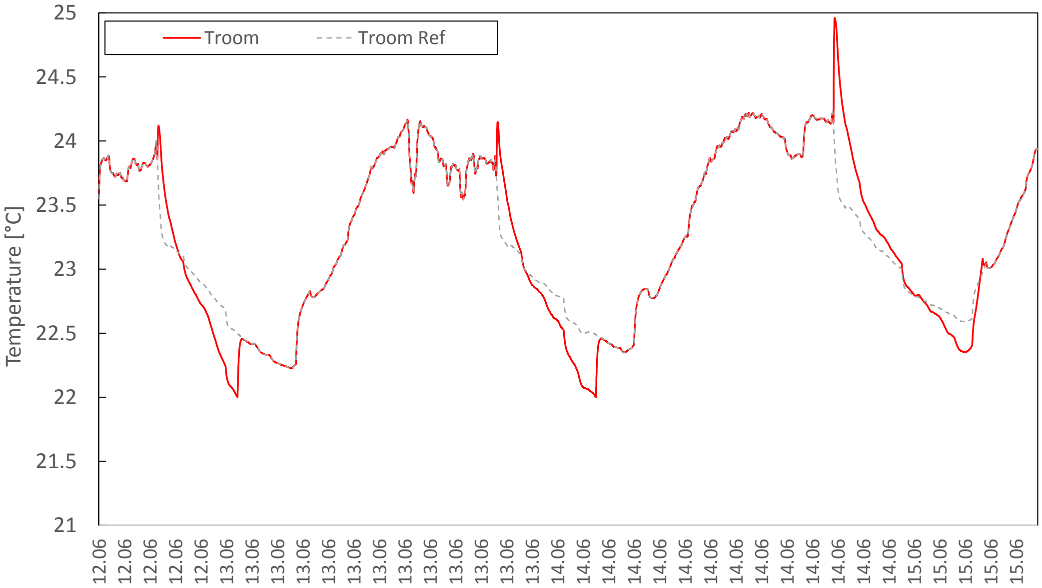

Fig. 11: Comparison of the room temperatures with the night cooling system (red line) and without (grey dashed-line)

4.5. Summarized results

Table 6 shows the main summarized measurement results over the considered measurement period. These values have been averaged or integrated only during the collector operation, i.e. when the collector pump was running (see Figure 9).

Table 6: Summarized main measurement results over the considered period

Parameter	**Value**	**Unit**
Collector mean specific cooling power	75.9	W/m²
Mean sky temperature	9.3	°C
Mean ambient temperature	20.3	°C
Mean wind velocity	0.3	m/s
Mean downward longwave radiation	363.2	W/m²
Total cooling energy (one collector)	8,9	kWh

5. Conclusions and outlook

The present paper presents a mobile Hardware in the Loop test bench that allows to test solar assisted heating and cooling systems based on low cost uncovered solar collector for the Egyptian climate. This test bench can be used for collector testing and for system testing in a hardware in the loop configuration. The measurement results show that a 70 m² collector could provide an average of 76 W cooling power per square meter and would be suitable for the cooling of a 120 m² apartment. With the developed test bench, many kind of collector integrations can be tested for different building constructions and system definitions. Also the control algorithm of the system can be tested and optimized before the implementation in real systems.

The developed test bench will be transported to Egypt and further used for both collector and system testing at the German University of Cairo (GUC). In particular the following improvements will be done by modifying the systems in the TRNSYS model:

- Activate the building thermal mass (Type 56) by changing from chilled ceiling to activated ceiling
- Integrate a water store in the system for domestic hot water preparation
- Add a water storage to store the cold at night and use it during the day
- Modify the control so that the collector energy yield is increased

6. Acknowledgements

The project NightCool was supported by the German Federal Ministry of Education and Research (BMBF). Support code: 01DH14021.

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