Simulation and Analysis of Small-Scale Solar Adsorption Cooling System for Cold Climate

Karolis Januševičius, Giedrė Streckienė, and Violeta Misevičiūtė

Abstract—**In the current study, research on the performance characteristics of an adsorption cooling system supplied by solar energy is presented. The main task for the analyzed system was to ensure cooling load for the non-residential building in cold climate country. A 8.0 kW adsorption thermal cooling system was studied. The system got heat produced by evacuated tube solar collectors. The parametric simulation study was carried using a TRNSYS (Transient Systems Simulation) program to determine the influence of various parameters on the system performance. The dependencies of collector slope and the total absorber area on solar fraction, discarded energy, coefficient of performance, seasonal performance factor were studied. The highest solar fraction, coefficient of performance and seasonal performance factor values were obtained if the collector slope was approximately 30 degrees and the absorber area was 16 m^2 for the analyzed cases. The total primary energy consumption of the system was examined for various cases of primary energy factor for auxiliary heat and consumed electricity. On the basis of the results, it was proposed the expression of total primary energy consumption. The obtained results could be used for the recommendation preparations for decision makers to select a small scale solar cooling adsorption system.**

Index Terms—**Adsorption chiller, coefficient of performance, solar cooling, TRNSYS.**

I. Introduction

Summer cooling is a growing market in buildings services. Increased living standards, occupants' comfort demands and building architectural trends (popular glass buildings) are the main reasons for the increasing energy demand for summer air cooling [1]. Cooling needs are higher in southern European countries. However, there is an increasing need for cooling in other countries too including northern Europe, particularly in office and commercial buildings. Solar energy can significantly contribute to prevent a drastic increase in conventional energy consumption for cooling and to reduce harmful emissions to the environment [2], [3].

The dominating technology in the European market of solar cooling installations is still absorption chillers. Although the coefficient of cooling efficiency of absorption cooler may have a higher value, especially with temperatures above 80 ℃, a possibility of supplying the heating medium with a temperature lower than 70 ℃ causes that among all of the available cooling systems supplied by solar energy, the adsorption refrigerating systems have been recognized as the most advantageous for cooling [3]-[5]. Adsorption chiller using silica gel-water adsorption pair, which could be powered by 60–85 ℃ hot water, the cooling coefficient of performance (COP) is around 0.3–0.5, the cooling capacity is usually 5–10 kW [6]-[9].

Significant development efforts are directed recently to solar cooling technologies based on adsorption systems driven by heat from solar thermal collectors. Hartmann *et al.* [10] made a comparison of solar thermal and solar electric cooling for a typical small office building exposed to two cities (Freiburg and Madrid). They found that main factors affecting the competitiveness of solar thermal cooling systems are the capacity utilization of the collector field, the occupancy scheme of the building (cooling demand), and the COP of the sorption machine. Li and Wu [11] made a theoretical research of an adsorption chiller in a micro combined cooling, heating and power system. They determined that the cooling capacity and the COP of the chiller are influenced significantly by the average value and variation rate of electrical load, as well as the average value of cooling load. It was showed that the water tank also had a great effect on the chiller performance [11].

Beccali *et al.* [12] carried out a detailed assessment of monitoring results of a solar desiccant evaporative cooling system in Italy. Monitoring results showed that the contribution of evaporative desiccant cooling effect achieved 53% of the total energy delivered by the air handling unit and the electric COP during summer operation was 2.4. Another study showed that adsorption cooling system can reduce the electricity consumption by 47% compared to a compression cooling system in an office building [13].

Solar thermal cooling systems are still in their infancy regarding practical applications, although the technology is sufficiently developed for a number of years [2]. Made studies show that the adsorption cooling systems still require significant research, development activities and practicability of these technologies [4]-[11], [14], [15]. It is a quite new topic if it comes to practical applications. Practical measurements show that low driving temperatures, the intermittent operation and less sunnier days have negative effects on the adsorption cooling system operation [15]. The performance of such kind of systems is strongly influenced by both cycle time and the allocation of the duration of the adsorption and desorption steps [16]. The mass recovery process has significant influence both on cooling capacity and COP [17]. Constructional and control oriented adaptations should be done in order to improve the existing systems' performance [18].

Non-domestic buildings such as institutional buildings

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contain different types of functional spaces which require different types of heating, ventilating and air conditioning (HVAC) systems. In addition, such buildings should maintain optimal comfort conditions with minimal energy consumption and minimal negative environment impact [19]. One of the main reasons to use thermal cooling system for non-domestic buildings is the cooling demand during the summer seasons for such buildings coincides with the solar energy gain [13].

Construction and use of adsorption refrigerating systems of low power, supplied by solar energy, is usually made for southern countries [2], [10], [15], [19], [20]. However, such applications still require deeper investigations in cold climate countries. In this study, a solar adsorption cooling system in a non-domestic building in cold climate is analyzed using TRNSYS 17 simulation software. A deeper analysis of the use of low power adsorption machine to obtain thermal comfort in rooms of the institutional building, relevant to external atmospheric conditions, has been executed. Therefore, the aim of this study is to investigate a solar-assisted adsorption cooling facility performance based on the cooling demand and the local meteorological data. A 8.0 kW adsorption thermal cooling system is analyzed for the institutional building.

II. Solar Assisted Cooling System

Research object is solar assisted cooling system. This system layout is based on laboratory of Building Energy and Microclimate Systems (BEMS). The analyzed system is a part of renewable energy system which supplies energy for space heating, cooling and electricity needs of laboratory space. The heat from solar collectors is supplied for adsorption chiller at typical summer conditions. Adsorption chiller supplies chilled water for laboratory space air conditioning needs. Solar produced heat could be directly used for supply air heating during cold period of the year.

The evacuated tube solar collectors of laboratory systems are analyzed. The total effective area of solar collectors is 9.8 m^2. Collectors are shown in Fig. 1. There are ten evacuated tube solar collectors connected in a row. Water-propylene glycol mixture (33%) is used as antifreeze and has influence on specific heat and density of heat transfer medium. Collected heat is stored in 500 liters storage tank. Storage tank is discharged by hydronic loop. The solar assisted cooling system with adsorption chiller is presented in Fig. 2.

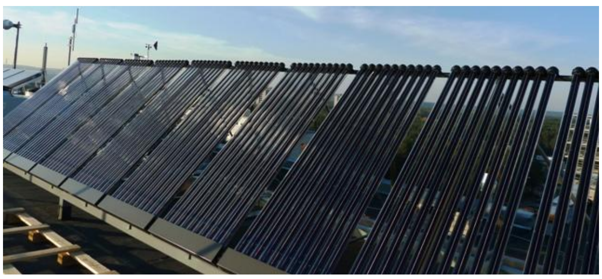

Fig. 1. The evacuated tube solar collectors of BEMS laboratory.

Adsorption cooling process needs stable heat supply of 55–95 C temperatures. Due to cooling machine efficiency dependence on supply temperature, it is appropriate to supply higher temperatures to maximize cooling output. The cooling system of BEMS laboratory is presented in Fig. 2. The analyzed system consists of evacuated tube solar collectors (9.8 m^2), heat storage tank (500 l), auxiliary heater (15 kW), adsorption chiller (8 kW), cooling tower and cold storage tank (300 l).

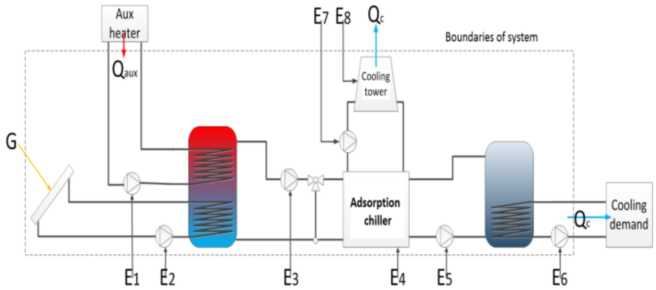

Fig. 2. Solar assisted cooling system with adsorption chiller.

The adsorption chiller and cold storage tank are presented in Fig. 3.

Fig. 3. Adsorption chiller and cold storage tank in laboratory technical room.

The hydraulic schema of BEMS laboratory systems (Fig. 2) is used for creating model of the thermal cooling system in TRNSYS.

III. Performance Evaluation

The system performance was analyzed by estimating simulation results. The simulation was carried out from March 25th to November 9th. The simulation time step was chosen 5 min.

In order to evaluate system performance, the following performance criteria were involved in this study:

1) Solar fraction in the overall chilled water production f_{sol}.
2) Unutilized heat of solar collectors (the rate of energy discarded) $Q_{surplus}$.
3) Coefficient of performance of adsorption chiller COP_{ch}.
4) Seasonal performance factor of overall system SPF_{sys}.
5) Primary energy consumption E_{PE}.

The percentage ratio of the thermal energy produced by solar collectors (Q_{sol}) to the total needed cooling system energy ($Q_{ch.h}$) is known as the solar fraction which can be expressed as (1)

$$f_{sol} = \frac{Q_{sol}}{Q_{ch.h}}. \tag{1}$$

The total needed cooling system energy consists of thermal energy generated from the solar collectors and the auxiliary heater. In this case, losses from heat storage and needed energy to cover them from auxiliary heater were not included into calculations. This ratio could be used to assess suitability of selected solar collectors parameters and their area.

Properly designed solar energy hot water system should fit the highest possible production rate with amount of needed heat to meet the demand. During the evaluation of collectors' area on the system performance, the appearance of high temperatures indicates the higher risk of the system stagnation. An additional calculation of an unutilized heat of solar collectors was performed. The rate of energy which is discarded to keep the fluid at the boiling point is shown in (2)

$$Q_{surplus} = \dot{m} c_p (t_{in} - t_{boil}) . \quad (2)$$

where, $\dot{m}$ represents flow rate, c_p is the fluid specific heat, t_{in} is the inlet temperature ant t_{boil} is the boiling point of fluid. TRNSYS Type13 was used for this evaluation.

The efficiency of a cooling system can be evaluated based on its COP. COP is the ratio between the cooling capacity required to supply air conditioning (Q_c), and supply heat input needed for the adsorption chiller ($Q_{ch.h}$). This parameter shows performance of the cooling chiller at simulated conditions and is defined as (3)

$$COP_{ch} = \frac{Q_c}{Q_{ch.h}} . \quad (3)$$

Seasonal performance factor (SPF) expresses the overall system efficiency by taking all consumed electricity (E) and produced cold energy (Q_c) during the analyzed time period. Additionally, heat supplied by the auxiliary heater was included into calculations. SPF_{sys} can be expressed as (4)

$$SPF_{sys} = \frac{Q_c}{\sum E + Q_{ch.h} \cdot (1 - f_{sol})} . \quad (4)$$

A primary energy consumption criterion is selected to evaluate system's operational sustainability. Final energy consumed in the system was converted to the primary energy by using (5)

$$E_{PE} = \sum (E_x \cdot f_{PE.El}) + \sum (Q \cdot f_{PE.H}) . \quad (5)$$

where, E_x represents electricity consumed in the system elements, Q is auxiliary heat supplied for the thermal cooling system.

Primary energy factor for electricity ($f_{PE.El}$) conversion was used. The minimum value of this factor could be low as 0.7, when electricity from the renewable energy sources is used. The maximum value is 2.6 which specifies typical European electricity network. Due to high possible variation of primary energy factor for heat ($f_{PE.H}$) supplied from auxiliary heater (from 0.1 for biomass to 2.6 for direct electricity) these factors are considered as variables for parametric analysis.

IV. TRNSYS Model

TRNSYS is a transient system simulation program with a modular structure that was designed to solve complex energy systems problems by breaking the problem down into a series of smaller components known as Types [21].

A. Description of System Model

System consists of four main hydronic loops with circulation pumps (Fig. 4). Energy is transferred through loops by inducing mass flow rates according to control signals:

1) From solar collectors to hot storage tank;
2) From hot storage tank to adsorption chiller;
3) From adsorption chiller to cold storage tank;
4) From cold storage tank to demand side.

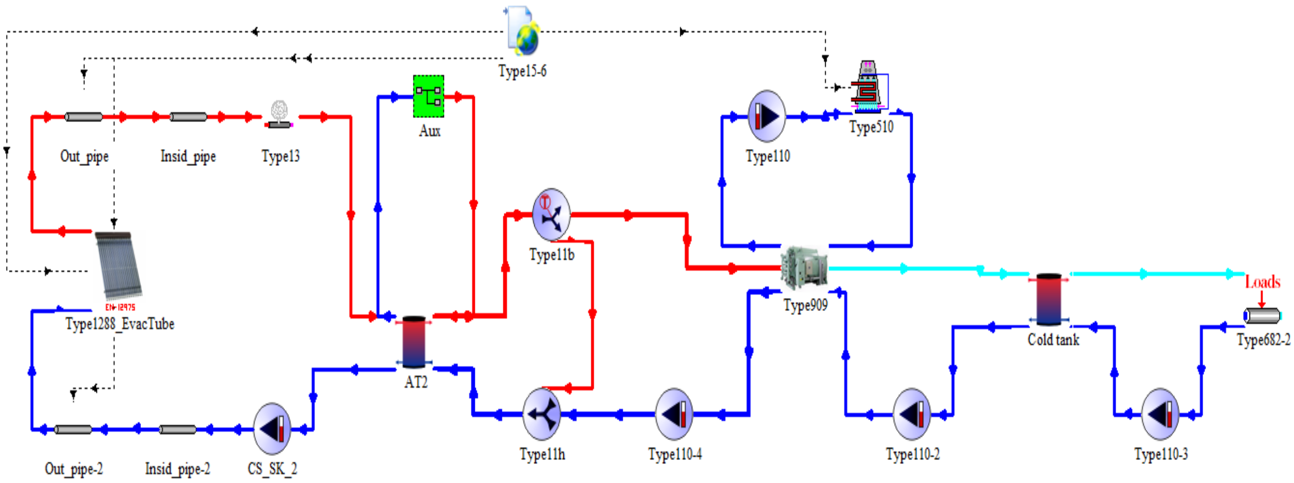

Fig. 4. System model using TRNSYS.

The controller switches the circulation pump on in solar collector loop when temperature difference between solar collector outlet and inlet of solar heat exchanger inside hot storage tank appears more than 3 ℃. Setpoint in cold storage tank is set to 7 C. Controller turns on cooling chiller and cooling tower when temperature rises more than 2 ℃ above setpoint.

Solar energy is harvested from the evacuated tube solar collectors and circulated in the primary water circuit to maintain its hot water temperatures. The harvested energy then transferred to the hot water storage tank through the immersed heat exchanger in hot storage tank. The second loop is used to deliver hot water from hot storage tank to the adsorption chiller, when controller turns on it. The third loop delivers cooled fluid to cold storage tank volume. The fourth loop discharges cold storage tank through immersed heat exchanger and delivers cooled fluid to demand side.

Auxiliary heater is needed to boost the hot water temperature when it falls below the system's driving temperature. The main components of the system are described below.

B. Evacuated Tube Solar Collectors

Evacuated tube solar collectors are modeled with Type 1288 which calculates dynamic efficiency as a function of inlet temperature can be obtained using Hottel Whillier (6)

$$\eta = \eta_0 - a_1 \frac{(T_{in} - T_{amb})}{I_T} - a_2 \frac{(T_{in} - T_{amb})^2}{I_T} \tag{6}$$

where, η_0 is the optical efficiency, a_1 is the first order coefficient and a_2 is the second coefficient. T_{in} is the water inlet temperature to the collector and T_{amb} is the ambient air temperature. I_T is the total incident radiation on the collector per unit area.

In this study, the optical efficiencies of solar collectors for the first and second order coefficients were taken to be 0.85, 1.38 and 0.0013, respectively.

C. Circulation Pumps

There are modeled six circulation pumps (Type 110). Their powers and flow rates are respectively:

1) Solar collector loop: 83 W, 0.22 kg/s;
2) Heat storage tank discharge loop: 83 W, 0.28 kg/s;
3) Cold storage tank charge loop: 118 W, 0.28 kg/s;
4) Cooling tower loop: 173 W, 0.42 kg/s;
5) Auxiliary heater loop: 83 W, 0.28 kg/s;
6) Demand supply loop: 83 W, 0.33 kg/s.

D. Thermal Energy Storage Tanks

A stratified storage tank with 10 nodes is modeled (Type 534). The overall tank loss coefficient is assumed to be 0.75 W/m^{2}K for hot storage tank and 0.5 W/m^{2}K for cold storage tank, respectively. The fluid in the storage tank interacts with the fluid in the heat exchangers (through heat transfer with the immersed heat exchangers), with the environment (through thermal losses from the top, bottom and edges) and with flow stream that passes into and out of the storage tank. The storage tank is divided into isothermal temperature nodes. Each constant-volume node is assumed to be isothermal and interacts thermally with the nodes above and below through several mechanisms: fluid conduction between nodes, and through fluid movement.

E. Auxiliary Heater

Type 6 is auxiliary heater which elevates temperature of flow stream when temperature decreases below setpoint. It operates like an externally controlled ON/OFF heating device. Energy is delivered to the hot storage tank by immersed heat exchanger. The auxiliary heater has a heating capacity of 15 kW and the setpoint temperature is set to be 70 ^{o}C.

F. Adsorption Chiller

Type 909 models an adsorption chiller; relying on performance data files containing normalized capacity and COP ratios as a function of the hot water, cooling water and chilled water inlet temperatures. Rated power of adsorption chiller is 8 kW.

G. Cooling Tower

Type 510 models a closed circuit cooling tower. This device used to cool a liquid stream by evaporating water from the outside of coils containing the working fluid. The working fluid is completely isolated from the air and water in this type of system. Rated power of fan is 450 W.

H. Tempering Valve

Type 11b is used as a temperature controlled flow diverter to model a tempering valve. The setpoint temperature is selected to be 85 C.

I. Pressure Relief Valve

Thermal systems which employ a liquid (e.g. water) as a heat transfer medium typically include a pressure relief valve to discard the vapor (e.g. steam) if the liquid begins to boil. This component can be used to describe a pipe relief valve or a tank relief valve. Type 13 is used for this purpose.

Type 13 monitors inlet temperature, flow rate, and a comparison temperature. Energy is discarded whenever the comparison temperature is greater than the specified boiling temperature of the fluid. Loss of mass when the relief valve is open is assumed negligible. The outlet flow is always equal to the inlet flow rate. This amount of energy is presented as the analyzed parameter.

J. Meteorological Data and Cooling Load

The simulation is carried out using the Typical Meteorological Year (TMY) data bank from Meteonorm for Vilnius city. Type 15-6 was used in the model.

Building cooling load depends on many parameters like building orientation, building size, gain, ventilation, infiltration and climatic conditions [22].

Cooling load used in simulation was generated by Type 686 as synthetic demand based on defined peak load and modifying sine-wave functions used to account for seasonal variations, time-of-day variations and weekday/weekend differences. This model represents a quick method of providing realistic loads without the time-intensive modeling required for a real building.

Using synthetic loads, various cooling profiles could be determined. This helps to imitate different building behaviors. Short cooling season with high peak loads could represent energy efficient building with passive cooling demand reduction solutions, whereas long cooling season with high peak load imitates highly glazed facades.

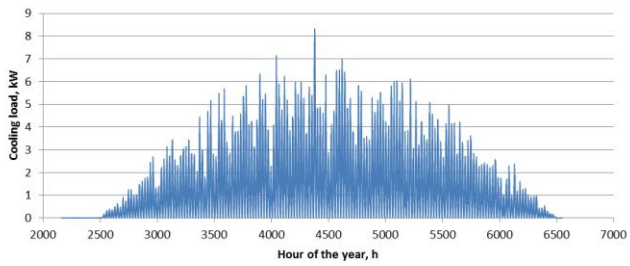

Fig. 5. Cooling load profile.

The cooling load profile generated by Type 686 is presented in Fig. 5.

The design peak cooling capacity of 8 kW was estimated and used for cooling load characterization. This parameter was used to analyze following operational parameters of the system.

The total annual cooling demand was 3375 kWh during 4000 hours cooling season. It reached its peak in the month of July.

V. RESULTS AND DISCUSSION

In this section, the simulation results of the solar assisted cooling system are presented. Analyzed results represent the sum of integrated values for the whole cooling season. Simulation time step is 5 minutes.

The effect of changing collector's area and inclination angle on solar fraction is presented in Fig. 6. The system solar fraction is increasing when the area of absorber increases. The biggest solar fraction value for cooling season is obtained if the collector slope is approximately 30 degrees and the absorber area is 16 m^2 for the analyzed cases.

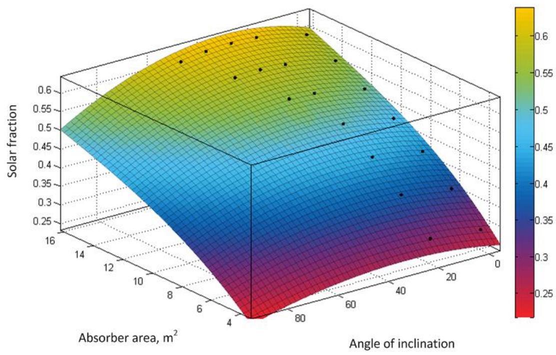

Fig. 6. Effect of changing collector's area and inclination angle on solar fraction.

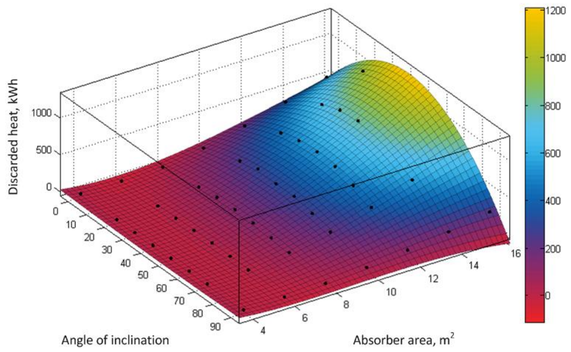

Fig. 7. Effect of changing collector's area and inclination angle on discarded energy.

The effect of changing collector's area and inclination angle on discarded energy is presented in Fig. 7. As can be seen from Fig. 7, discarded heat has the parabolic dependency on absorber area and inclination angle of the collector. For the analyzed case, if the absorber area is in range from 4 m^2 to 8 m^2 it was determined that the discarded energy is almost constant at different inclination angles of solar collector.

The discarded energy rate is directly related to solar fraction and it has exponential dependency. The highest discarded energy rate is obtained when the solar fraction is 0.6.

The thermal efficiency of adsorption chiller can be quantified by using COP. Fig. 8 shows the dependency of the COP on collector area and inclination angle of analyzed system. The results have shown that the dependency of COP has polynomial surface. The COP is changing slightly, approximately only 1 % for analyzed range.

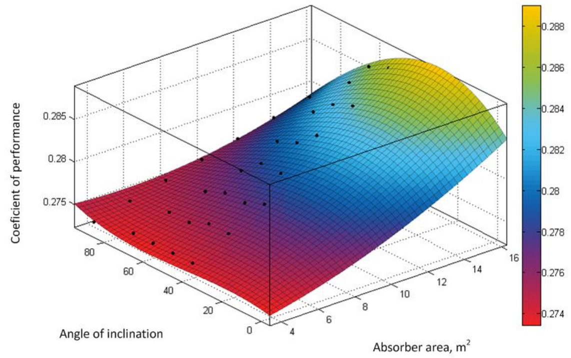

Fig. 8. The dependence of the COP on collector's area and inclination angle.

The effect of changing collector's area and inclination angle on SPF of system is presented in Fig. 9. Calculated SPF value is higher than COP of the adsorption chiller.

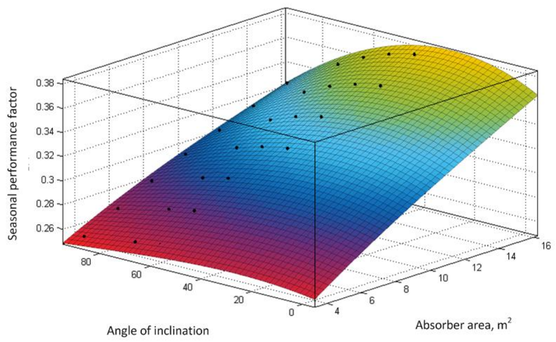

Fig. 9. The dependence of the system SPF on collector's area and inclination angle.

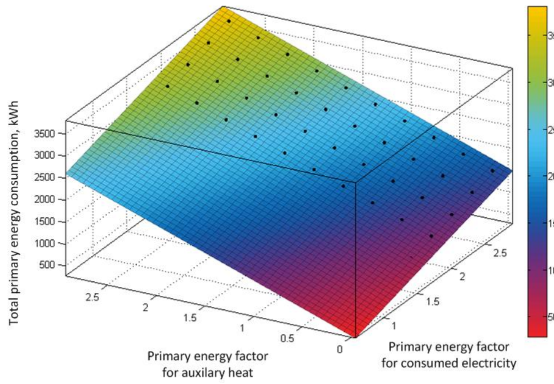

Fig. 10. Variation of total primary energy consumption.

It happens due to calculation method, when denominator is reduced by heat supplied by solar collectors and energy consumed in fans and circulation pumps was added in calculations. The relation of SPF to absorber area is almost linear. The highest values of COP and SPF are reached when the inclination angle of the collector is approximately 30 degrees.

The total primary energy consumption of the system is presented in Fig. 10. This figure shows an influence of primary energy factors on total primary energy consumption.

In many EU countries building energy rating procedure takes primary energy consumption as measure of energy performance and sustainability. When building demands and loads are known, simplified methods could be used for system concept selection and comparison with typical refrigerant cooling systems.

System parameters, characterizing main design assumptions and cooling demand must be known:

1) cooling demand (Q_C) – could be determined according to methods like EN ISO 13790;
2) cooling capacity (P_C) – determined by transient or quasi-steady state methods;
3) duration of cooling season (τ_C) – determined according to EN ISO 13790;
4) adsorption machines efficiency (COP) – at rated condition;
5) inclination angle of solar collectors (φ) – as design assumption;
6) absorber area of evacuated tube solar collectors (A_{SC}) – as design assumption;
7) total rated power of circulation pumps and cooling tower fan (W_{rated}).

Total primary energy consumption could be expressed as (7):

$$E_{PE} = \left(\frac{Q_C}{COP} \cdot \left(1 - f_{sol}\left(A_{SC};\varphi\right)\right)\right) \cdot f_{PE.H} + \\ + \left(\sum W_{rated} \cdot a\left(P_C;\tau_C\right)\right) \cdot f_{PE.El}. \tag{7}$$

Suggested correlation function based on simulation results, when zone cooling capacity and cooling season duration are known, is determined as (8)

$$a = 3956 - 18.67 \cdot P_C - 0.0268 \cdot \tau_C. \tag{8}$$

Suggested expression (9) of solar fraction when inclination angle and absorber area are predicted follows

$$f_{sol} = 0{,}1065 + 0.04832 \cdot A_{SC} + 0.001943 \cdot \varphi - \\ - 0.001074 \cdot A_{SC}{}^2 - 3{,}324 \cdot 10^{-5} \cdot A_{SC} \cdot \varphi - \\ - 2.619 \cdot 10^{-5} \cdot \varphi^2. \tag{9}$$

Usage of these suggested formulas are limited to single cooling unit system with typical evacuated tube collectors in climate similar to Lithuania.

VI. Conclusion

In this study, a solar assisted cooling system in non-residential building was evaluated using TRNSYS 17 simulation software. The study outlined the potential of using a solar assisted cooling system under cold climate. The proposed system consists of an adsorption chiller, evacuated tube solar collectors, heat and cold storage tanks. A TRNSYS model was simulated using a typical meteorological year. The system's technical performance was evaluated. Furthermore, this study investigated the factors that affect the performance of a solar assisted cooling system like different solar collector's areas and inclination angle.

The obtained results could be used for preparation of the recommendations for developers and decision makers to select small scale solar assisted cooling system. Furthermore systems' economical evaluation should be made for more rational system selection.

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