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Section: Energy for Buildings

Thermodynamic simulation of solar thermal system

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Abstract

An article presents the thermodynamic simulation study of operating solar thermal collector system. The target of this study is to examine improvement possibilities of actual system by identifying avoidable exergy destruction. The simulation model was created in TRNSYS environment and is based on the real operating solar thermal collector system, installed in Building Energy and Microclimate Systems (BEMS) laboratory. Advanced thermodynamic analysis methods were used for the assessment of the system performance. Presented simulation based method helps to identify the avoidable and unavoidable exergy destruction parts of the component, operated on transient boundary conditions, in the system. The findings of this study reveal that the additional improvements of the system may create more irreversibility than the actual system in the analyzed case. Considering the non-linear behavior of the system, the complex assessment must be used to identify the rational parameters system components, in order to reach the lowest entropy production rate.

Keywords: Solar thermal; thermohidronic loops; exergy analysis; TRNSYS.

Nomenclature

$\dot{E}x$	Amount of exergy in flow (kJ/h)
$\dot{M}$	Mass flow rate (kg/h)
k	specific co-enthalpy (kJ/kg)
P	pressure (Pa)
T	absolute temperature (K)
$\dot{G}$	Global solar radiation flux (kJ/m^2)
A	Solar collector absorber area (m^2)
T_{sol}	Solar temperature (K)
Greek symbols	
τ	time step number
Subscripts	
a	*ambient (dead state) conditions*
x	*calculation point or state*
n	*heat storage layer node*
gen	*generated amount*
sol	*solar*
in	incoming flow
out	outgoing flow
dest	destroyed or lost
ch	charging state
dist	discharging state
st	storage state

1. Introduction

According to the regulations of European Union, all new building built after 2020 must satisfy zero energy building definition [1]. Zero final or primary energy balance must be met by combining passive energy savings and active renewable

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energy transformation systems. While the reduction of passive energy use through the decrease of heat loss in the building envelope is limited due to economic reasons. Solutions for primary energy demand reduction on heating and cooling energy production systems by integrating renewable energy is the next action for seeking this target. There are various methods to design and evaluate the efficient renewable energy systems. However, most of them are based on combination of thermodynamics, fluid dynamics and heat transfer methods and require knowledge on this branch of applied physics. Thermodynamic analysis approach is used to increase performance by selecting rational parameters for main subsystem components.

1.1. Benefits of thermodynamic analysis

The growing interest among scientists and increasing number of scientific publications explicitly indicate that thermodynamic (exergy) analysis is a useful tool for the evaluation of the sustainability of the buildings and their service systems. The use of this analysis could allow to evaluate buildings that strive to be more sustainable through using renewable energy sources, such as solar energy, i.e. not using non-renewable produced energy–exergy [2]. Exergy analysis might be used for various thermodynamic system evaluation and performance assessment. Where fluid flows and heat transfer processes appear, outcomes from exergy analysis supplies information about:

- Quality of heat transfer process instead of quantity in terms of thermal energy transfer. It provides equal terms for different processes like internal energy and fluid kinetic energy change [3].
- Indication about entropy generation sources in system defines the relation to separate causes of irreversibility. Could be used for maximization power or capacity output, maximization of an ecological benefit [4].
- Identifies magnitude of entropy production and highlights the areas of improvement of a system [5].

This approach can also be successfully applied for the evaluation of various energy transformation processes or for the analysis of interconnections of separate energy system. This could provide the ideas on how to adjust the parameters of the products/services and designs [6]. Outcomes of this analysis may help to improve the system by highlighting priorities for component upgrade.

1.2. Thermodynamic analysis of solar energy systems

While a wide literature exists on exergy analysis of power plants the application of the exergy approach to the built environment may be considered at an earlier stage. Nevertheless, most of the energy consumption in the building stock is related to near-environmental temperature thermal uses, namely space heating and cooling and hot water production. [7].

Xiao and Ben evaluated the performance of domestic size solar water heater based on the exergy analysis. From the study, it was found that the proper insulation of collector and storage tank is very important because exergy losses due to imperfect thermal insulation in collector and storage tank is significant and cannot be ignored [8].

Park, Pandey, and others have reviewed energy and exergy analysis of typical renewable energy systems. From the reviews, they argue that exergetic efficiency for solar water heaters were found to be very low in the range of 3–5% as investigated by different authors [9].

Article authors previously had performed seasonal simulation study of small solar thermal system with different types of collectors preparing domestic hot water in Lithuanian climate conditions. Dynamic exergy analysis showed that average annual exergetic efficiency may reach 3.3% for typical system with flat plate collectors and 2.6% for vacuum tube collectors [10]. In previous work these authors, was clearly identified that system may have better thermodynamic performance with lower efficiency solar collectors. This finding influences need of other improvement search methods based on component interaction

Dynamic exergy analysis are not widely spread ant there are lack of examples of this kind of method for solar thermal systems, despite the fact that dynamic exergy analyses turns out to be recommended whenever systems operate very near-environmental temperature [7]. Typical averaged methods are not accurate and unsuitable when the target of study is to explore improvement potential of system. Main reason of unsuitability is parameter variation in solar thermal systems hydraulic network and demand influenced change of stored energy in accumulation tanks.

2. Solar thermal system

Examined solar thermal system is installed in laboratory of Building Energy and Microclimate Systems of VGTU. It is part of renewable energy system which supplies energy for space heating, cooling and electricity needs of laboratory space. At typical summer conditions this system supplies heat for adsorption cooling machine which supplies chilled water for laboratory space air conditioning needs or solar produced heat could be directly for supply air heating at winter season.

In this laboratory total field of 19 m^2 flat plate collectors, with inclination angle of 29°, directly facing south. Used solar collectors have optical efficiency of 0.805 and following first and second order efficiencies 3.235 $W/(m^2 \cdot K)$ and 0.00117 $W/(m^2 \cdot K^2)$. Collector field is shown in Figure 1.

Fig. 1. The Flat plate solar collectors system of PEMS laboratory

Collector field contains 9 flat plate collectors connected in a row. Propylene glycol is used as antifreeze agent and has influence for specific heat and density of heat caring fluid. Collected heat is stored in 500 liter storage tank. Heat storage is discharged by hydronic network which are connected with other accumulation tanks.

Adsorption cooling process needs stable heat supply of 55–95 degrees temperatures. Due to cooling machine efficiency dependence on supply temperature it is appropriate to supply higher temperatures to maximize cooling output. Study presented in this article focuses on this task.

2.1. Boundary conditions

As mentioned before – system absorbs solar radiation energy and transfers it to demand side, in this case adsorption cooling machine. Discrepancy between supply and demand is balanced by thermal storage. System performance is highly dependent on solar radiation flux and heat demand capacity. For simulation case two summer days was chosen – clear sky sunny day following with cloudy day with periodic sunny hours.

For this study actual measured weather data was used. While only direct solar radiation was measured, splitting to beam and diffused solar radiation was performed in TRNSYS [11] environment by Type 16.

Starting temperatures of fluid in pipes and accumulation tank was set to actual measured ones at same date. Adsorption cooling machine is considered to be outside of examined system boundaries. Behavior of cooling machine was not taken in to account at simulation model, but performance was reflected by including measured heat demand variation during operating hours.

2.2. Simulation model in TRNSYS environment

System connecting solar thermal collectors and adsorption cooling machine was split in to separate parts by different components according to the flow rates, functions and surrounding conditions. Thermal simulation was performed with TRNSYS software.

Calculation scheme of system with state points are shown in Figure 2.

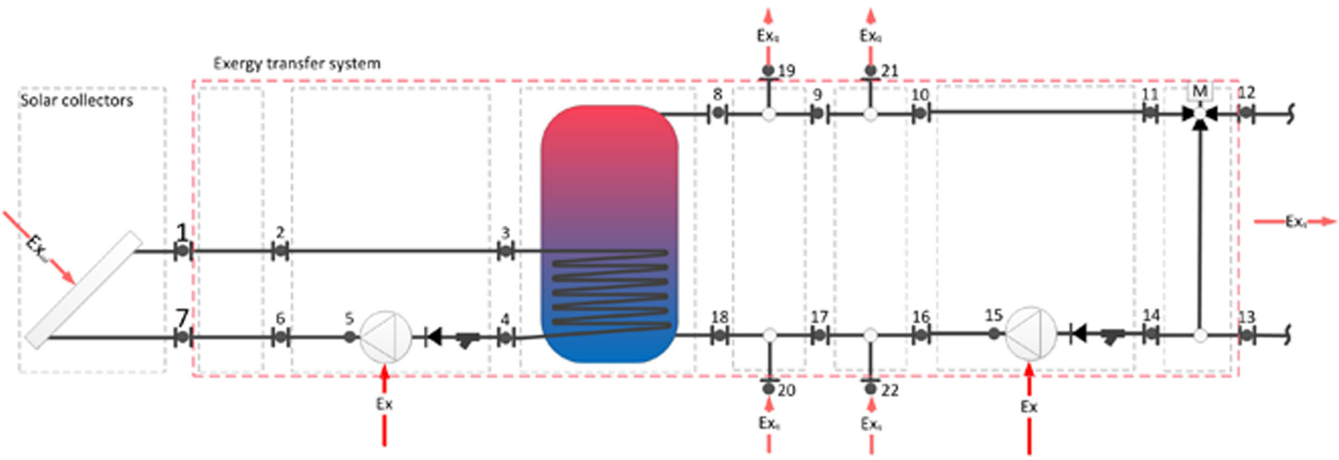

Fig. 2. Solar thermal system scheme divided in to subsystems by dashed lines

Following TRNSYS models or Types were used for model creation in this environment:

- Type 1289 – Flat plate solar collector with IAM correction factors.
- Type 534 – accumulation tank with coiled heat exchanger.
- Type 31 and Type 586 – For pipes with heat loss and pressure drop.
- Type 741 – variable flow pump with power draw is calculated from pressure rise, overall pump efficiency, motor.

Pressure changes due to fluid property variation were calculated with TRNSYS Type 586 and hydronic network resistance changes flow resistance effect expressed by K_{vs} coefficients suitable for real system component behavior. Pressure change in hydraulic loop was used to calculate power needed to overcome pressure drop and ensure flow rate. Amount of needed power was treated as sum of exergy used in pumps for sustaining fluid flow and efficiency dependent losses.

Simulation model was based on actual system performance and calibrated to match behavior of actual equipment. Parameter tuning target was to reduce cumulative error between simulated and measured temperatures in critical points of system. Wider explanation of system splitting to subsystems is given in 3.4 section. For simplification reasons other two accumulation tanks was treated as branch connections to examined solar energy transfer chain. Actual measured values of outgoing/incoming flow were feed for calculations. An additional auxiliary heat source was switched off, for period when calibration data was collected.

3. Thermodynamic analysis

The exergy of a system in a given environment is considered as an maximum theoretical work that might be extracted from it. For describing processes in thermodynamic analysis terms exergy balance (Eqn 1) are used:

$$\sum \frac{d\dot{E}x}{d\tau} + \sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{dest} \tag{1}$$

This formulation summarizes sum of stored, incoming and outgoing exergy flows equal to destroyed exergy.
Expanded version of exergy balance (Eqn 2) shows

$$\frac{d\dot{E}x}{d\tau} + \sum\left(1 - \frac{T_a}{T_{sun}}\right)\cdot Q_s + \dot{E}x + \sum\left(\dot{M}_{in}\cdot k_{in}\right) - \sum\left(\dot{M}_{out}\cdot k_{out}\right) = \sum T_a S_{gen} \tag{2}$$

For open systems where capacity effects could be neglected, firs balance member describing stored exergy are equal to zero. Second member expresses added or subtracted exergy in form of heat. Following member describes added exergy in forms of mechanical work or solar radiation (for solar collector component) Exergy carried by fluid flow are presented in formula which (Eqn 3) combines expression of enthalpy and entropy multiplied by absolute dead state temperature. Usage of this formula for each time step (τ_k) enables to include it simulation programs as it was previously done [12] for incoming and outgoing exergy flow.

$$\left(\dot{M}_x \cdot k_x\right) = \dot{M}_{x(\tau)} \cdot Cp(T) \cdot \left(\left(T_{x(\tau)} - T_{a(\tau)}\right) - \cdot T_{a(\tau)} \cdot \ln\left(\frac{T_{x(\tau)}}{T_{a(\tau)}}\right)\right) \tag{3}$$

For specific cases as solar collectors, heat storage and demand side, individual adaptations of this formula, were used. Efficiency of process of i-th subsystem could be expressed by exergetic efficiency (Eqn 4). This efficiency is used to identify weakest components in energy supply chain and measure the magnitude of exergy destruction

$$\varepsilon_i = 1 - \frac{\dot{E}x_{dest}}{\dot{E}x_{in}} = \frac{\dot{E}x_{out}}{\dot{E}x_{in}} \tag{4}$$

This efficiency evaluation number is used for components like solar thermal collectors and others, where capacitance effects could be neglected due to small influence. While overall system efficiency is highly dependent on capacitance effects on heat storage – system performance formulation takes in to account capacitance. Formulation of system efficiency is given in 3.3 section.

3.1. Solar radiation exergy on solar collector

In evaluating the performance of solar energy systems using exergy analysis method, calculation of the exergy of radiation is very crucial. However, its calculation is a problem of unquestionable interest, since exergy represents the maximum quantity of work that can be produced in some given environment. According to Petela [13] maximum exergy carried by solar radiation may be found by formula (Eqn 5):

$$\dot{E}x_{sol} = A \cdot \dot{G} \cdot \left(1 + \frac{1}{3}\left(\frac{T_a}{T_{sol}} \right)^4 - \frac{4}{3}\left(\frac{T_a}{T_{sol}} \right) \right) \tag{5}$$

It should be mentioned that presented calculation of overall system efficiency are most sensitive for this quantity, because it supplies highest exergy flow which are transformed to small amount of usable heat in solar collectors. There are different approaches to treat solar radiation exergy (like suggested by Pons [14]) but this approach was used due to comparability reasons, by concern that it is mostly used formula for transformation from solar radiation energy to exergy.

3.2. Interpretation of heat storage process

The main purpose of an accumulation tank is to achieve a time delay between the energy supply and energy demand. Stored exergy in accumulation tank is the most important variable for the definition of the storage system. The exergy associated to the storage process in heat balance must be added to the exergy consumption. Exergy balance for accumulation tank [12] could be expressed as equal sums of charging – discharging flows and stored with destroyed quantities of exergy:

$$\dot{E}x_{in} + \dot{E}x_{out} = \dot{E}x_{st} + \dot{E}x_{dest} \tag{6}$$

Charge, storage and discharge cycle efficiencies could be calculated when the storage are fulfilled and discharged totally [15]. This approach is suitable for accumulation tank performance assessment on rating test conditions and for design performance assessment. For dynamic operating conditions when accumulation tank are not fully charged or discharged, performance criteria must be based on time dependent exergy balance. This interpretation lets to calculate storage efficiency at given time step and lets to take in to account effect of system component interaction. Performance of storage was calculated with respect to actual state of charging, storing, discharging and combined charge and discharge conditions. Stored exergy content change (Eqn 7) is used for determining exergy destruction rates on system scale independently for system state:

$$\Delta\dot{E}x_{st} = \sum \dot{M}_n(\tau) \cdot Cp(T) \cdot \left(\left(T_n(\tau) - T_n(\tau-1)\right) - \cdot T_a(\tau) \cdot \ln\left(\frac{T_{n(\tau)}}{T_{n(\tau-1)}} \right) \right) \tag{7}$$

Content of stored exergy could be expressed by formula (Eqn 8)

$$\dot{E}x_{st} = \sum \dot{M}_{n(\tau)} \cdot Cp(T_{(\tau)}) \cdot \left(\left(T_{n(\tau)} - T_{a(\tau)}\right) - \cdot T_{a(\tau)} \cdot \ln\left(\frac{T_{n(\tau)}}{T_{a(\tau)}} \right) \right) \tag{8}$$

Overall storage efficiency could be expressed as a product of exergetic efficiency and duration divided by whole period length. This may lead to average value thru examined period. For this case storage exergetic performance is evaluated in each time step.

3.3. Interpretation of overall system efficiencies

Many authors have analyzed heat storage process in different detail levels and various boundary conditions. In the system which harmonizes exergy transfer between extraction and demand sides, exergy storage process is main influencing factor of system performance. Due to that system efficiency coefficients are expressed in same way as they are used for storage process assessment.

System operating at storing or stand-by state (Eqn 9), when no circulation pumps are operating or otherwise all fluid flows in hydraulic loops are equal to zero

$$\varepsilon_{st} = \frac{\left(\sum \dot{E}x_{st(\tau-1)} - \sum \dot{E}x_{st(\tau)}\right)}{\sum \dot{E}x_{st(\tau-1)}} \tag{9}$$

When system is operating in charging state efficiency could be expressed as (Eqn 10):

$$\varepsilon_{ch} = \frac{(\sum \dot{E}x_{st(\tau-1)} - \sum \dot{E}x_{st(\tau)})}{\sum \dot{E}x_{in}} \tag{10}$$

Discharging of the system without charging (Eqn 11):

$$\varepsilon_{dist} = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in} + (\sum \dot{E}x_{st(\tau-1)} - \sum \dot{E}x_{st(\tau)})} \tag{11}$$

For typical cases of systems with storage effects these three coefficients are used to express system performance. When short time step is used, additional formulation is needed when simultaneous charge and discharge of heat storage were performed. Combined mode (Eqn 12) when system internal energy in parallel is increased by solar collector flow and decreased by demand supply should be expressed:

$$\varepsilon_{ch+dist} = \frac{\sum \dot{E}x_{out} - \left(\sum \dot{E}x_{st(\tau-1)} - \sum \dot{E}x_{st(\tau)}\right)}{\sum \dot{E}x_{in}} \tag{12}$$

Overall storage efficiency at various states could be obtained by multiplying each exergetic efficiency by duration of time and dividing from overall period length; or as average value of transient exergetic performance, which are calculated considering current state of system.

3.4. Avoidable and unavoidable exergy destruction.

Identification of avoidable exergy destruction was formalized by Tsatsaronis [16] and others. This term expresses difference between actual and minimum (unavoidable) exergy destruction in system component. For seeking the target of solar thermal system exergy output maximization avoidable exergy destruction identification are important to eliminate ineffective solutions of possible improvements.

This method is appropriate when system component interacts with each other and efficiencies are dependent on surrounding components. For components surrounded with others, influence is made from both sides – mainly by temperature levels. Typical layout of exergy supply system as transfer chain is shown in Figure 3.

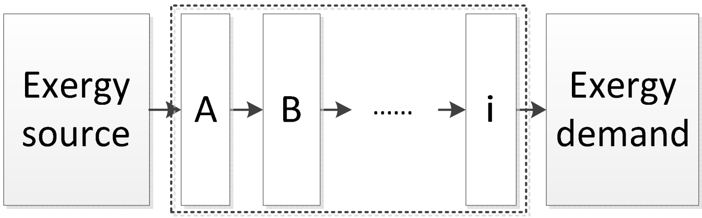

Fig. 3. System treatment as exergy transfer chain

System components might be analyzed as a individuals, but treating them as exergy transferring subsystems creates possibility to use on transfer efficiency for similar components like supply and return pipes, couples of branch connection and three way mixing valve component. This helps to reduce complexity of calculation process and creates simple to interpret calculation model layout.

Due to transient boundary conditions same component creates variable amount of exergy destruction in different time periods. While comparing renewable energy system thermodynamic analysis with relatively stable power plant and manufacturing processes where regular and advanced exergy analysis are used, this difference creates main difficulties and creates need for transient thermodynamic simulation. While component has interaction with each other and efficiency relations, effects of performance improvement could be explored more accurately with calibrated simulation model. Performance parameters used in calculation are presented in Table 1.

Table 1. Performance parameters for regular and avoidable exergy destruction calculations

Performance parameter	Actual parameter	Possible improved parameter
Solar collector efficiency (a1)	0.805 (3.24)	0.850 (2.95)
Heat exchange coefficient for piping	1.15 W/m^{2}K	0.75 W/m^{2}K
Total efficiency of pump	0.35	0.50
Heat exchange coefficient of accumulation tank	0.75 W/m^{2}K	0.45 W/m^{2}K
Internal mixing in thermal storage	+20 kg/h	0 kg/h
Pressure drop of hydraulic loops	18.0 + 6.5 kPa	16.0 + 5.3 kPa

By replacing actual parameter values with possible improved ones, change of overall system efficiency in given conditions and exergy destruction and entropy production rates was monitored. According to advanced exergy analysis methods [5, 17] system simulation was performed with all possible improved and unimproved performance parameter combination in order to find highest performing one. By subtracting entropy production number calculated as unavoidable case from actual systems entropy production, avoidable exergy production was identified. Unavoidable exergy destruction is identified as a minimum value in

4. Results

The results of performed simulation study are presented as exergetic efficiency number for simulated performance and transient variation of this thermodynamic quantity. Component parameter influence to overall system performance are expressed as exergy destruction and entropy production rates

4.1. Transient efficiency of actual case

At typical summer conditions, solar collector system performance parameters changes due to ambient conditions and demand side parameter variation. Amount of exergy transferred through the system is highly dependent on variation of ambient temperature. For reducing this aspect and comparability purposes system behavior on dynamic condition are expressed as thermodynamic efficiency variation in Figure 4.

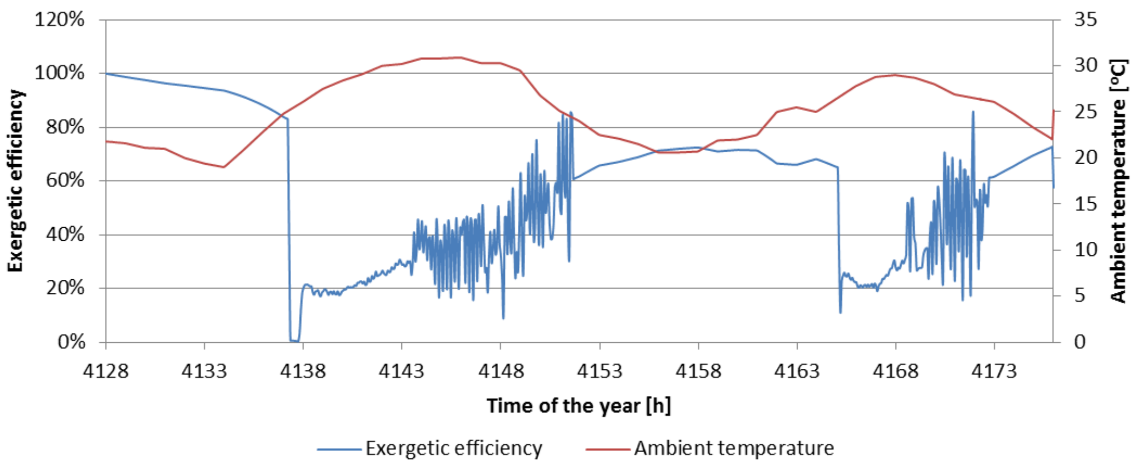

Fig. 4. Solar thermal system exergetic efficiency variation with respect to ambient temperature

Due to small simulation step (1 minute) and cooling machine behavior high fluctuations of exergetic efficiency could be seen. Effects of thermal lag plays the role on exergetic efficiency for short periods when the pump in solar collector loop starts to operate, but temperature wave do not have reached virtual calculation point yet While temperature is lower than outgoing from heat storage, no transformed exergy is accounted and efficiency drops close or below zero. Due to exergy quantity dependence on ambient temperature level overall system efficiency may increase when actual stored energy rate are decreasing. Due to that in relatively small time steps could create appearance of exergetic efficiency values higher than 1. To eliminate this phenomenon, amount of generated entropy is presented instead of destructed exergy quantity.

4.2. Typical system improvement solutions

In this case it is reasonable to perform this type of analysis because simple replacement of better performing component may lead to overall system performance decrease from **57.3%** on actual conditions to 55.9%. Reducing entropy production in components where this quantity reaches highest magnitudes: solar collectors are responsible for 81% of exergy destruction in system. This is typical solution suggested by many authors [4–6, 17, 18], is to focus on reduction of exergy destruction on components where it reaches highest magnitudes. This strategy works if relation between component efficiencies relatively independent. At this case single component improvement, in terms of exergy efficiency leads to opposite results at system level. Overall solar thermal system performance change, when component parameters are exchanged, are shown in Table 2

Table 2. Influence of parameter improvement on system level

Performance parameter	exergy destruction in system level	efficiency change after component improvement	entropy production change after component improvement
Solar collector efficiency	81%	–0.4%	+1.9%
Accumulation tank heat exchange coefficient	10%	–0.6%	+0.4%

Explanation of these effects could be connected with temperature influenced amounts of exergy. Due to increased temperatures on more efficient solar collectors energy loses increases and due to higher quality non-transferred heat exergy destruction increases in all system components. Same effects are created with single improvement of accumulation tank insulation level (decreases heat exchange coefficient) – increased temperatures create higher exergy destruction rates in solar collector loop due to increased average operational temperatures. This finding leads to conclusion that in some cases focus on subsystems with highest exergy destruction rates are not effective. It shows that at this case subsystem interference must be taken in to account, when seeking to improve overall system performance.

4.3. Avoidable part of exergy destruction and entropy generation

Avoidable exergy destruction shows technical limits which are possible to reach with the best performing component available in market. All possible combinations of component parameter sets were examined and magnitudes of exergy destruction were identified for all cases. Results are presented in Figure 5.

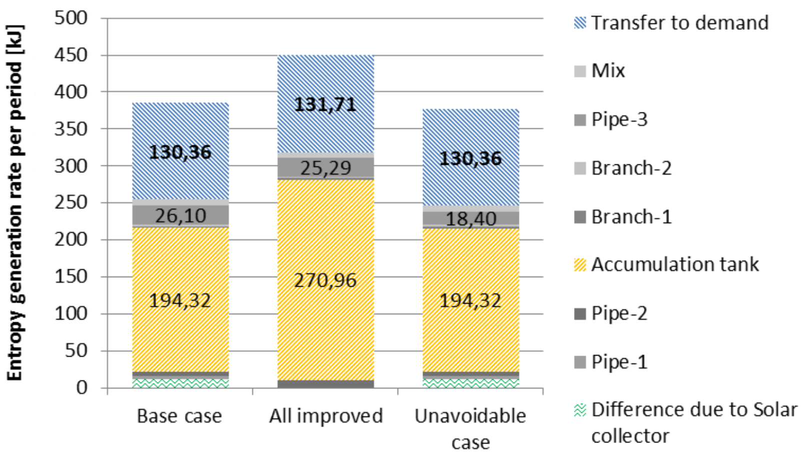

Fig. 5. Entropy generation rate comparison

In this case upgrade reducing accumulation tank heat exchange coefficient with surroundings creates higher exergy destruction rates due to increased temperatures in tank volume. Due to higher temperature levels, smaller decrease creates more entropy production instead of same amount of lost energy in lower temperature level. This finding is correct for system level if no additional auxiliary heat source is connected to heat storage. At this case, lower temperatures induce better performance of accumulation tank. Overall system efficiency increases to due to dominating exergy destruction rate in system level created by heat storage.

There was identified that actual entropy production rate with actual parameters are 1949.1 kJ. This amount could be split in to unavoidable (1940.7 kJ) and avoidable (8.4 kJ). This small amount of avoidable entropy generation shows that system operates close to rational point at selected conditions, in terms of exergetic efficiency.

5. Conclusions

Despite the fact, that possibilities of control strategies was not explored, findings of presented work shows possible ways to maximize exergy output for solar thermal system which feeds cooling machine. Due to temperature dependent coefficient of performance (COP) of adsorption chiller improvements suggested by exergy analysis are important when seeking to minimize electricity use of overall process. Main findings of this study show that:

- Simple replacement of better performing component may lead to overall system performance decrease from **57.3%** on actual conditions to 55.9%. Without taking in to account solar radiation transformation to useful heat, system exergetic performance decrease from 68.7 to 67.9% at the same conditions. This finding shows that it is unreasonable to upgrade all system parameters for seeking better exergetic performance or in other words – higher amount of transferred exergy to demand side.
- Upgrading energy transforming component with highest exergy destruction may reduce entropy generation on actual component, but total system exergy efficiency decreases. Dead state condition independent entropy production increases by 1,9% after solar collector efficiency increase and by 0.4% after accumulation tank heat exchange coefficient decrease.
- Advanced thermodynamic analysis based methods may suggest combination of suitable improvements for system. Chosen method of exergy analysis algorithm allows exploring dynamic subsystem behavior for selected time period in much wider perspectives.
- Used method allows rational parameter selection for minimum entropy production in complex systems with heat storage and exchange devices. In the systems with larger number of heat transfer devices, this type of analysis may reveal

rational parameters and may help to avoid unnecessary investment on higher performance components if solutions with reduced material amounts created better performance on system scale.

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