Analysis of the influence of variable insulating power of a storing tank on energy effects in the conversion system of solar radiation

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Summary. The work presents the results of energy analysis for a system consisting of solar collectors, a heat pump, and a storing tank. Based on the formulated accounting equations, changes in the amount of the collected heat and water temperature in an accumulation tank in particular months and in a daily cycle were estimated. The amount of water in an accumulation tank and insulation power of its walls was accepted as decisive variables. Periods, when application of the system elements accepted for the analysis is rational, were determined along with dependence allowing (based on parameters of the surrounding climate and insulation power of tank walls) determination of the recommended temperature of water stored in a tank. The influence of insulation of storing tank walls on final energy effects was analysed as well.

Key words: storing tank, insulation power, solar collectors

INTRODUCTION

The system of using heat as a result of solar radiation conversion, except for solar collectors and elements, is composed of an accumulation tank as well. In this tank, effective energy, which was formed as a result of conversion, is collected and stored enabling its most effective use by an installation user. A composition of elements, which make the system efficient both currently (during radiation) and in the periods when there is no radiation is an essential issue. Collectors and a storing tank are elements which directly decide on efficiency and exploitation characteristics of an installation. Many scientific works have been published within these issues and construction and exploitation directives, put in practice, have become a standard equipment of solar installations. However, existing technical solutions do not shut the way against new concepts, concepts analysed by many researchers from different scientific centres. Thus, Kumar and Rosen [2011] examined the collector - tank system in which a storing tank divided into two independents of variable volume, parts was applied: one of them subjected to direct radiation, collected a heated factor and was used to satisfy current energy demands, whereas the other (thermally insulated) served for long-term heat storing. The discussed issues were determined by accounting equations and optimal participation of these volumes was determined as well. The influence of the setting angle of a collector on efficiency of storing heat was calculated. Kalogirou [1997] analysed the system consisting in a cylindrical collector and a storing tank. The considered elements of the system were described by variables used in the analysis of heat issues, a numeric programme was worked out, work efficiency was determined and economic analysis of the suggested solution was carried out. In the conclusion, it was stated that this system, compared to standard solutions (with flat collectors) brings positive energy effects whereas a period of return of the incurred financial outlays is accepted in practice. Smyth et al. [2001] presented mathematical dependencies, which are used to describe energy effects and efficiency (energetic and optical) for the system composed of a modified, as far as structure is considered, collector (of two different lengths) which has been integrated with a tank storing a heated factor. In a tank, from its top part, liquid was used to satisfy current demands, the remaining amount was stored. The authors also determined differences in efficiency in different time of diverse climatic conditions (temperature, sun exposure). In another work, the authors [Smyth et al.] carried out energy estimation, calculating the amount of heat, which was formed out of radiation conversion, received by the analysed components of the installation and the final energy efficiency. Hazami et al. [2005] analysed energy efficiency at using a modified structure of a solar collector cooperating with a standard accumulation tank. The modification of a collector consisted in using capillary pipes covered with a high solar radiation absorbent material integrated in one structure. Heated water was directed for heating a greenhouse. Comakli et al. [2012] worked out a mathematical model (solved with the use of MATLAB application) for optimisation of collectors' sizes and for accumulation of tank volume. For variable climatic conditions, radiation conversion effectiveness was estimated and optimal tank volume was determined. Alkilani et al. [2011] carried out an overview of research works, covering analysis of materials which are subjected to a phase change (Phase Change Material) used in heat storing systems including also solar energy installations. In the discussed systems, it was commented that a proper selection of a storing medium, a degree of filling, the size of a material (a proper surface and the value of phase change heat decide on storing efficiency. They also reported necessity to carry out simulation research of operation of such installation. Szargut and Stanek [2007] worked out a two-criteria optimising model for analysis of ecology and energy issues in a flat liquid collector. Geometric parameters of a collector (a gauge and a diameter of pipes where a circulation factor flows) and a collector surface in an annual heat demand aspect constituted accepted decisive variables. Hinti et al. [2010] analysed energy effects at using a PCM body (paraffin) as a storing material. Material was placed on two layers inside a storing tank. As a result of the research they determined thermal effects of a storing factor and daily changes of its temperature in the ratio to a tank filled with water. Haillot et al. [2012] presented a mathematical model (solved mathematically) for the system consisting of a solar collector cooperating with a sequential model of an accumulation tank filled with PCM material. Each section was described with a separate equation whereas connection between particular sections occurred through connection between streams of liquid flowing in and flowing out to particular bed segments. A formulated model was subjected to a verification procedure, whereas working out the effects of storing ability for the discussed system was a final effect. Hossain et al. [2011] in his review work presented structures and mathematical dependencies for estimating energy effects of solar energy installations. Moreover, results of analysis of influence of collectors' types, structure of storing tanks (except for accumulators filled with a PCM body) on efficiency of solar radiation conversion were presented. Palacios et al. [2012] presented results for a tank inside of which thermal stratification of water collected was applied. At the first stage, laboratory research were carried out (at a forced spraying of liquid into a tank by the use of nozzles), whereas at the second stage, a worked out methodology was repeated in real conditions of solar installation. As a result of the research, thermal effects of a storing factor in an accumulation tank were determined. Lima et al. [2006] presented optimisation results (with the use of the TRNSYS application) of a thermo-siphon solar installation, where they determined an optimal slope angle of a collector for diverse climatic conditions. They also determined energy outlays and incurred investment costs for functioning of a system including flat solar collectors. Kurpaska et al. [2004] analysed efficiency of energy conversion in flat solar collectors cooperating with accumulation tanks. Based on the analysis, which was carried out, efficiency of radiation conversion and efficiency of storing liquid in a tank were determined. Whereas, in the work [Kurpaska et al. 2012] results of energy efficiency analysis of flat and vacuum solar collectors operation were presented for the system, in which heated water was stored in an accumulation tank of a variable volume.

It results explicitly from a review of the research works that the issue of functioning of the solar installations energy elements is a current research problem. Therefore, the main purpose of this study is to carry out analysis of the influence of insulation changes of the heated water accumulation tank walls on energy effects of the solar radiation conversion system in a solar installation.

MATERIAL AND METHODS

A system consisting of solar collectors and an accumulation tank is the object of the research. This system can be found in facilities of the Department of Production and Power Energy of the University of Agriculture in Kraków. Heat reception from a tank is carried out through a membrane exchanger, which is connected to a compressor heat pump. Warm water heated in result of solar radiation conversion constitutes a lower source of a heat pump at the same time. Heat is supplied to the laboratory plastic tunnel from a buffer tank of a heat pump through a heating system (a standard system and exchangers of a liquid-air type). Fig. 1 presents a scheme of a research stand.

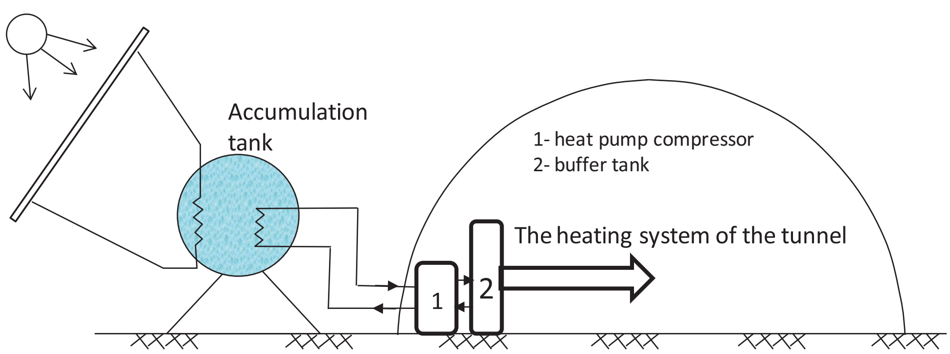

Fig. 1. A schematic representation of a laboratory stand for analysis of solar radiation conversion in the hybrid system

An issue on cooperation of the said system with an accumulation tank of variable insulation power constitutes a discussed problem. Fig. 2 presents a scheme of the said system along with accepted symbols. Analysis was carried out based on Pluta's methodology [2000].

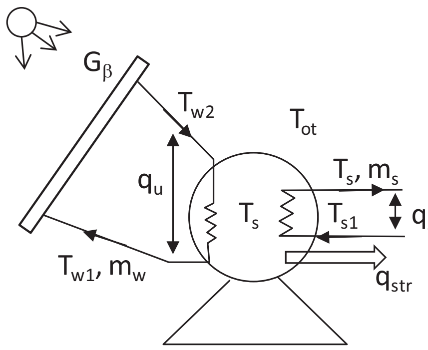

Fig. 2. Components of tank balance

The following constitute elements of thermal balance of an accumulation tank:
- energy stream (of useful heat) q_u supplied to a tank from a solar collector,
- energy stream received from a tank by a user (tank load) q_s,
- heat losses from a tank to environment- q_{str}.

Full tank mixing of average water temperature T_s was assumed in the analysis (water storing occurs without thermal stratification). According to the accepted symbols, equation, which influences change of water temperature, takes the following form:

$$V_s \rho_w c_w \frac{dT_s}{d\tau} = q_u - q_s - q_{str} \tag{1}$$

Heat losses bound from the heat of water pipes, which transport water from a tank to a system user, were omitted in the analysis.

Particular components of heat balance were calculated out of the following dependencies:

$$q_u = A_k F_R \left[G_\beta (\tau\alpha) - U_k \left(T_S - T_{ot} \right) \right] \tag{2a}$$

$$q_s = m_s c_w \left(T_s - T_{s1} \right) \tag{2b}$$

$$q_{str} = U_s A_s \left(T_s - T_{ot} \right) \tag{2c}$$

As a result, upon including equations (2a, 2b and 2c) a standard line differential equation in relation to a temporary water temperature change in a tank (T_s) is obtained in the following form:

$$V_s \rho_w c_w \frac{dT_s}{d\tau} = A_k F_R \left[G_\beta (\tau\alpha) - U_k \left(T_S - T_{ot} \right) \right] - \\ - m_s c_w \left(T_s - T_{s1} \right) - U_s A_s \left(T_s - T_{ot} \right) \tag{3}$$

This equation was solved with finite differences method with a constant time step$\Delta\tau$. Considering a weak variability during functions which appear in this equation and high thermal volume of water in a tank, application of the explicit differential schemes ensures a stable solution even for one-hour time steps [Pluta, 2000]. Therefore, in a differential notation (3) this equation is reformulated as follows:

$$T_s^{\tau+\Delta\tau} = T_s^\tau + \frac{\Delta\tau}{V_s \rho_w c_w} \left\{ A_k F_R \left[G_\beta (\tau\alpha) - U_k \left(T_S - T_{ot} \right) \right] - \\ - m_s c_w \left(T_s - T_{s1} \right) - U_s A_s \left(T_s - T_{ot} \right) \right\} \tag{4}$$

Particular symbols stand for: V_s- water volume in an accumulation tank, m^3; ρ_w- water density, kg·m^{-3}; c_w- water specific heat; kJ·kg^{-1}·K^{-1}; A_k- collectors surface area, m^2; F_R- coefficient of heat removal from collectors, [-]; G_β- energy of total radiation which gets to a collector, kJ·m^{-2}·hour^{-1}; τα- transmission and absorbency coefficient for radiation which gets to a collector, [-]; U_k- substitution coefficient of heat losses from the surface of a collector, W·m^{-2}·K^{-1}; T_{ot}- environmental temperature, °C; m_s- water stream collected by a user, kg·hour^{1}; T_s, T_{s1}- temperature of supply and return of water, which supplies a heat receiver, °C; U_s- coefficient of heat transfer through the surface of an accumulation tank, W·m^{-2}·K^{-1}; A_s- heat exchange surface of an accumulation tank, m^2.

From the presented form of this equation, it results that, in the first stage, water temperature in a tank should be accepted, and then new temperature in time should be calculated τ+Δτ, which is a temperature in the next time step.

Therefore, while having a value of solar radiation intensity in the next hours of solar operation, value G_β should be added. Thus, the following methodology was applied: firstly, solar declination was calculated from Cooper's formula, then hour angle of solar radiation and equivalent radiation angles on the sloping surface (surface of collectors) and the horizontal surface were determined. Correction factors of direct, diffusion and reflection radiation were calculated in the next stage. The given procedure was applied for particular hours of solar operation in the months accepted for analysis.

A compressor heat pump of an average coefficient of energy efficiency COP=1.8 was assumed as a heat receiver. For this case, at an accepted temperature difference (T_s-T_{s1}) water mass stream received by a receiver was calculated.

RESULTS AND A DISCUSSION

Analysis was carried out for the following data: water volume in an accumulation tank V_s= 2 and 6m^3; initial water temperature in a tank $T_{s\tau=0}$=10°C; surface of heat exchange of an accumulation tank A_s=22m^2; coefficient of heat penetration through a tank cover, U_s= 2.5; 2; 1.5; 1; 0.5 and 0.3 W·m^{-2}·K^{-1}; collectors surface A_k=12,1m^2; coefficient of heat losses from collectors U_k=6 W·m^{-2}·K^{-1}; coefficient F_R=0.7975; stream of water collected by a receiver, m_s= 310 kg·hour^{1}; temperature difference

T_s-T_{sl}=5K. Angle of inclination of collectors (constant for the discussed period) equal to 43° was assumed in the analysis and a constant value albedo on the level of 0.2 was accepted. Calculations were carried out for a town located at the latitude 52°N (Warsaw) for which radiation data (diffusive and direct) and temperature values of air were available.

Fig. 3 and 4 presents change of water temperature in a tank as a function of variable heat losses coefficient in a tank for two exemplary months (January, June).

When analysing the course of these dependencies, it may be determined that the change of insulation of a tank casing (resulting in changed amounts of heat transferred from a tank to the surrounding air) results in a varied final water temperature in a tank. At the initial water temperature in a tank (10°C) which was assumed for calculations, increase of walls insulation results in decreasing heat losses (for a period when the temperature of environment is lower than the water temperature in a tank), in case of a reverse relation, a reverse tendency occurs. Simultaneously, it may be noticed that the increased water amount collected in a tank results in less differences in the course of the collected water temperature changes.

Fig. 5 and 6 presents daily courses of heat balance changes (as a difference between heat obtained from collectors and heat losses to environment and heat used for operation of a heat pump) for the months above listed.

As it may be noticed, cooperation of a heat pump is impossible in January as is would require that heat necessary for heat pump operation be delivered to a tank. Whereas, in June this cooperation is possible, since heat from solar radiation conversion fully covers heat demands for pump operation and additionally there is a possibility to use it for other purposes (e.g. to water plants). One may notice that the change of tank insulation causes diversity in the final heat balance. Moreover, variable tank volume influences an hour course of heat balance value.

It results explicitly from the presented values that in summer, storing heat in a tank of higher insulation power is more rational due to the assumed real parameters of the operation system elements. For example, in May, depending on tank insulation power, there is

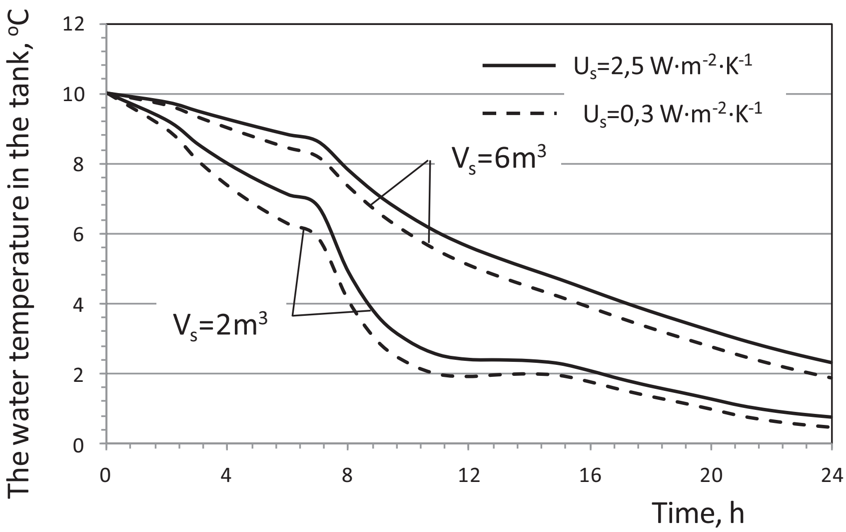

Fig. 3. Daily change of water temperature in a tank for January

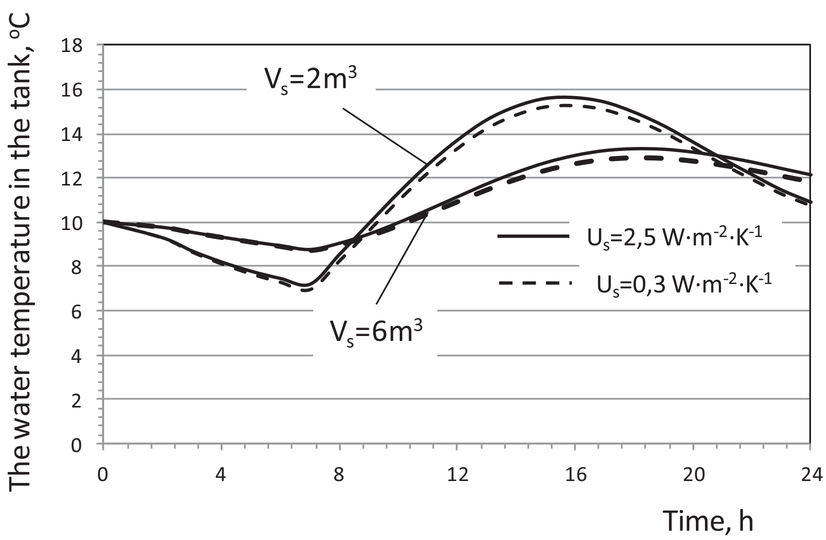

Fig. 4. Daily change of water temperature in a tank for June

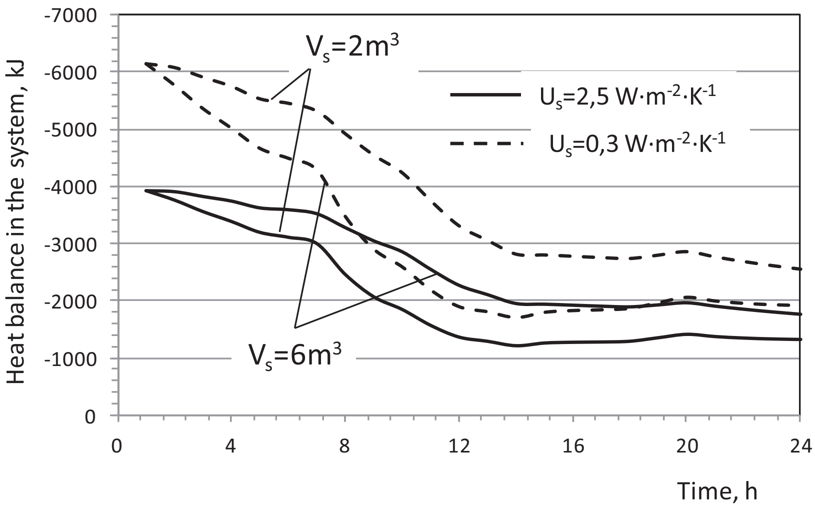

Fig. 5. Daily change of heat balance elements in January

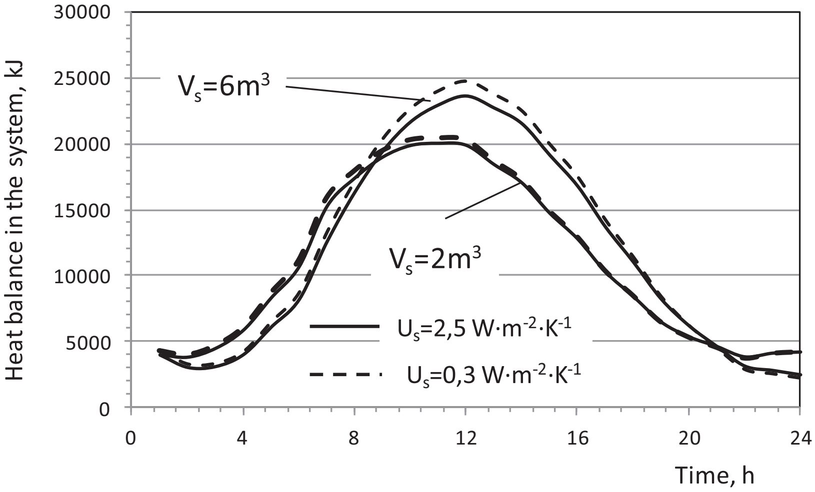

Fig. 6. Daily change of heat balance elements for June

Table 1. presents results of calculations of heat balance for the discussed cases.

Table 1. A monthly course of heat balance changes (MJ) for diversified insulation and water volume in an accumulation tank

specification		months											
V_s, m^3	U_s, W·m^{-2}·K^{-1}	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
2	2,5	-71	-62	-20	72	183	265	306	283	167	69	-18	-40
	2,0	-66	-58	-18	73	182	263	305	281	166	68	-17	-37
	1,5	-61	-54	-16	73	181	262	303	279	165	68	-15	-34
	1,0	-56	-49	-14	73	180	260	301	277	164	68	-13	-31
	0,5	-51	-45	-11	73	179	259	299	275	163	68	-12	-28
	0,3	-48	-43	-11	73	179	258	298	275	163	69	-11	-27
6	2,5	-94	-82	-45	68	199	288	333	308	179	61	-41	-54
	2,0	-87	-76	-41	68	197	286	330	305	177	61	-38	-50
	1,5	-80	-70	-38	69	196	283	327	302	176	61	-35	-46
	1,0	-73	-64	-34	70	194	280	324	299	174	61	-32	-43
	0,5	-66	-58	-31	70	192	278	321	296	173	62	-29	-39
	0,3	-63	-55	-29	70	192	277	320	295	172	62	-27	-37

a surplus in the final heat balance daily from 179 MJ (for U_s= 0.3 W·m^{-2}·K^{-1}, a tank of V_s=2m^3) to 192 MJ (for U_s= 0.3 W·m^{-2}·K^{-1}, a tank of V_s=6m^3). It may be also noticed that for the discussed system, using a hybrid system only from April to October is justified. In other months, exploitation is not energy justified. For the whole year an energy surplus is in the range from 1018 (U_s= 0.3 W·m^{-2}·K^{-1}, tank of V_s=2m^3) to 1041 MJ (U_s= 0.3 W·m^{-2}·K^{-1}, for V_s=6m^3). Obviously, this result would be different in case of assuming different water temperature in an accumulation tank.

Having formulated dependencies, calculations for the months when the system was used (from April to October) were carried out for determination of forecast water temperature in a tank (for V_s=6m^3) in relation to changing conditions of the surrounding climate and insulation of tank walls. Temperature forecast should be understood as such its value for which there is no difference between temperatures at the beginning and at the end of the analysed 24-hour storing cycle.

For the obtained results, equation which was found and which includes the relation between temperature values and independent variables (the form of a power model was selected based on the highest value of determination coefficient; this relation was determined with non-linear estimation with quasi-Newton method at the retained coefficient of convergence of 0.001) takes the following form:

$$T_{pr} = -11467,6 \cdot \sum R_{zew}^{-1,016} + 2,51 \cdot t_{ot}^{0,576} + 0,226 \cdot U_s^{0,45}$$

Within the use: 7775≤R_{zew}≤16363 kJ·m^{-2}; 7.97≤t_{ot}≤ 17.57°C; 0.3≤U_s≤2.5 W·m^{-2}·K^{-1}

Comparison between the forecast temperature from the suggested model and the calculated temperature was presented in fig.7.

One may notice that this comparison is convergent, therefore the dependence, which was found, may be used for determination of the suggested water temperature in an accumulation tank. From the presented dependence, it appears, that the decrease of the heat transfer coefficient of tank walls from 0.5 to 2.5 W·m^{-2}·K^{-1} for the minimum temperature values and the sum of radiation, causes the necessity to rise the recommended temperature of almost 2.5% (calculated as a relative difference in comparison to the temperature at the minimum insulation of a tank. Whereas at the maximum values of parameters of the surrounding climate, the increase of tank insulation results in the necessity to increase water temperature in a tank of 1.7%.

CONCLUSIONS

1. For the assumed elements of the system, it is energetically rational to use the discussed system from April to October.
2. The recommended water temperature in an accumulation tank is described by a relation:

$$T_{pr} = -11467,6 \cdot \sum R_{zew}^{-1,016} + 2,51 \cdot t_{ot}^{0,576} + 0,226 \cdot U_s^{0,45}$$

Within the use: 7775≤R_{zew}≤16363 kJ·m^{-2}; 7.97≤t_{ot}≤ 17.57°C; 0.3≤U_s≤2.5 W·m^{-2}·K^{-1}

3. The increase of insulation of accumulation tank walls causes that the assumed value of water temperature for the heat receiver decreases: within the assumed range of changes of the surrounding climate parameters, the scope of relative temperature changes (for the maximum insulation power) is within the range 1.7 to 2.5%.

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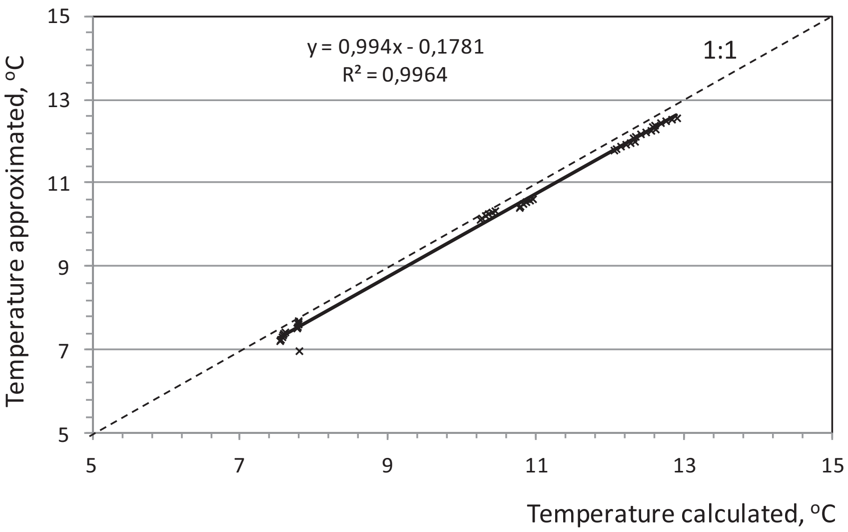

Fig. 7. Comparison between the approximated water temperature in a tank and a calculated temperature

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