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PERFORMANCE SIMULATION MODEL FOR SOLAR THERMAL SYSTEMS IN RURAL APPLICATIONS

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ABSTRACT

The paper presents the use of a method called Equivalent Thermal Network used to formulate mathematical model suitable for SDHW system analyses. Composed algorithms make it possible to perform computer simulations either of weather conditions or system parameters and to determine their influence on the system thermal performance and thus can be used by solar system designers. Steady state analysis confirms that the model is correct and the transient analysis adds new aspects to the thermal performance of such systems. Comparisons with measurements taken on a real object prove the usefulness of the method particularly for local conditions.

Key words: clean energy, SDHW system for food production processes, equivalent thermal network

INTRODUCTION

The most effective use of solar energy is a vital problem not only from the point of view of energy saving aspects but also because of the environment protection, especially in areas that have to be kept clean. Healthy food production in rural areas is in the focus of interest of research carried out at many centres. This paper is going to contribute to the solution to this problem in the field of solar thermal applications [1].

It is comparatively easy to predict the hot water demand for a medium size food production plant. If you consider the use of SDHW system you must also predict the energy gain from it. The paper presents the results

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of a very useful method for evaluation of the whole SDHW system combining solar collectors, pipelines, heat exchangers, accumulation containers and the water outlet points with 10% accuracy of temperature prediction for central-east European climatic conditions.

The schematic layout of the considered SDHW system is presented in fig. 1 and the description is relevant to fig. 2. Fig. 3 shows an example of how the Equivalent Thermal Network can be extended when the system configuration is different from the one presented.

Figure 1. SDHW system layout

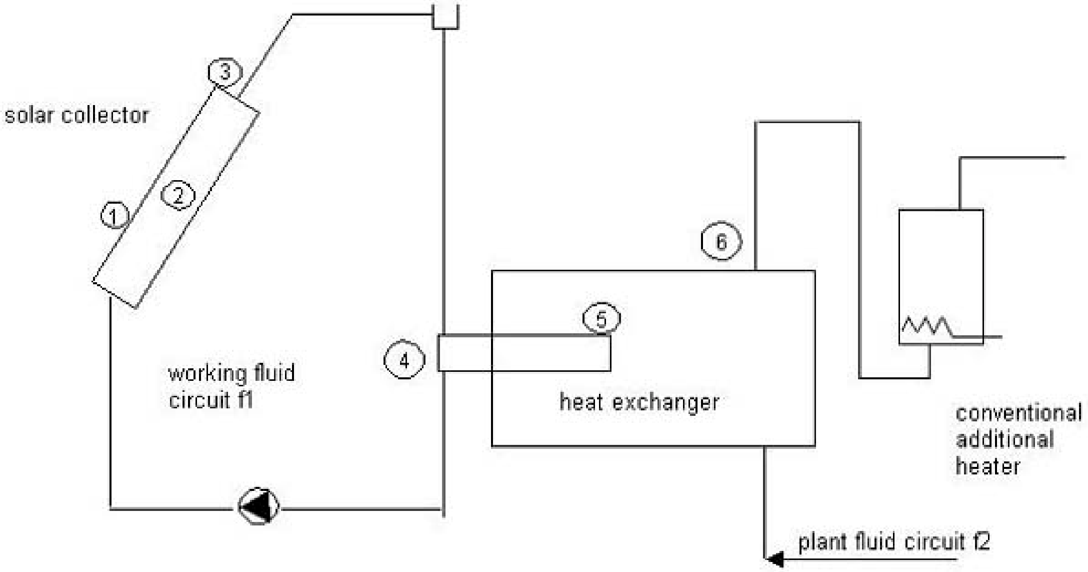

Figure 2. Steady state model for the system shown in fig. 1

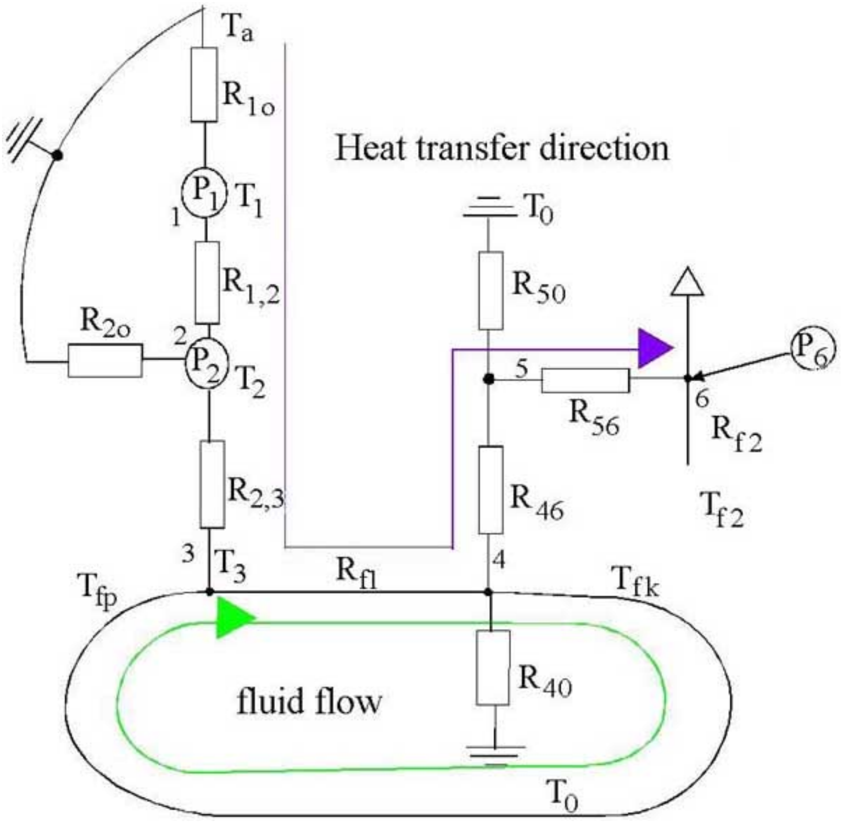

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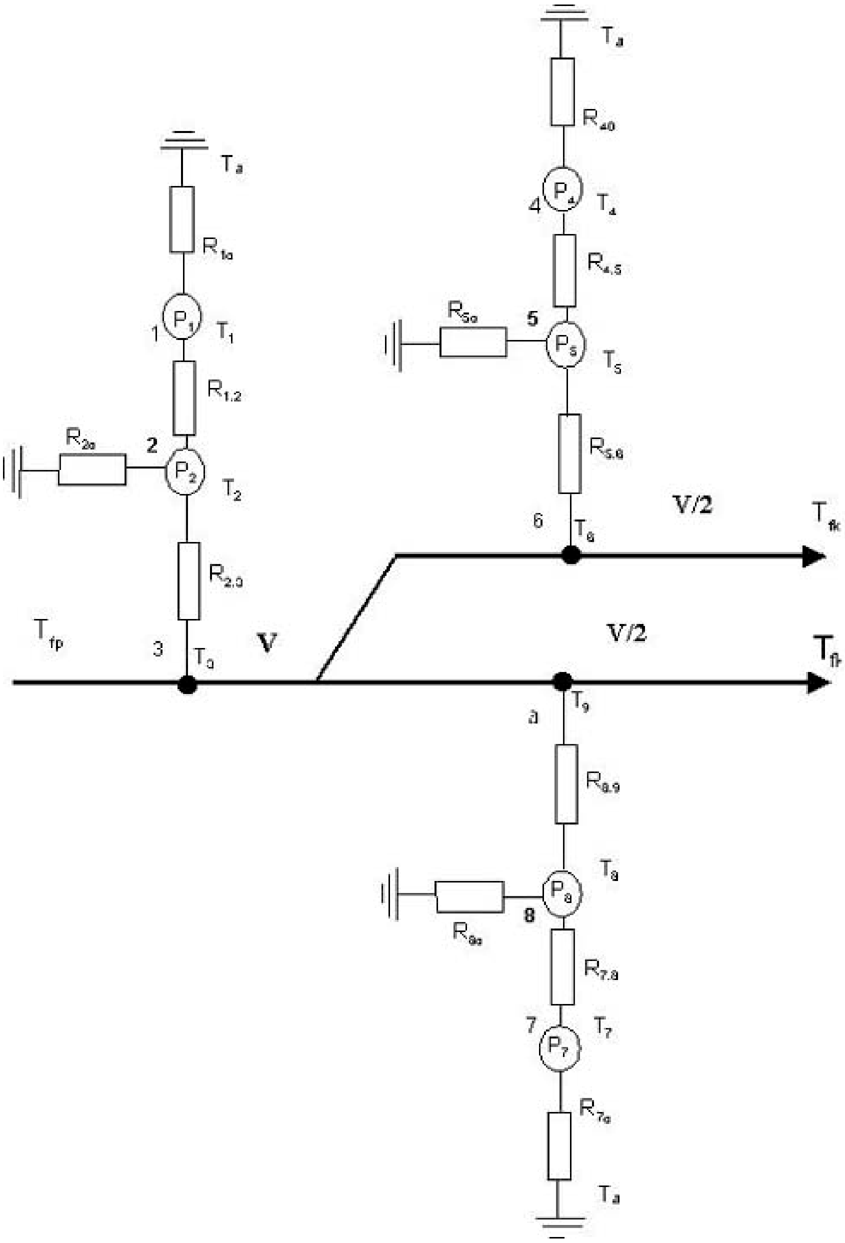
Figure 3. Series – parallel array of 3 collectors



The most interesting point is behind node 6 (from the food production point of view), which is a tap water intake and though the presented model enables simulation along the whole flow of fluids, this paper describes node 6 simulations.

EQUIVALENT THERMAL NETWORK

The method, on which the simulation algorithms are based, is called the Equivalent Thermal Network and takes advantage of the theory of analogy between the current flow in electric RC circuits and the heat transfer in a pipeline SDHW system [2]. The mathematical model is based on a numerical method called Elementary Balance Method, in which every element is represented by a node and relevant balance equations are formulated for it. That is why thermal resistance expresses the total thermal resistance of the whole node and is expressed in K/W. Thermal resistances are distributed in such systems in the way presented in fig. 1. This is the system of nodes and branches marked as the following:

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node 1 – represents the collector glass cover of the mean temperature T_1,
node 2 – is the absorber of the mean temperature T_2, the energy of power P_2 is generated on its surface as the result of the irradiance passed through the cover,
node 3 – represents the working fluid in the collector of the mean temperature T_{f1},
node 4 – represents the working fluid in pipelines and in the heat exchanger,
node 5 – is the heat exchange of the mean temperature T_5 of the coil pipe,
node 6 – represents the plant fluid of the mean temperature T_{f2}, in which the heat power P_6 that comes from a conventional electric heater, can be focused.

Resistance symbols are the following:

R_{1a} – thermal resistance between the collector glass cover and the ambience of the air temperature T_a,
R_{12} – thermal resistance between the collector glass cover and the absorber,
R_{2a} – thermal resistance between the absorber and the ambience towards the collector housing,
R_{23} – thermal resistance between the absorber and the working fluid,
R_{f1} – thermal resistance of the heat transfer to the fluid (not indicated in the figure but, of course, included in the system of equations describing the model),
R_{4o} – thermal resistance between the ambience and the piping system towards the ambience, which, in this case, is the interior of a building/boiler room of temperature T_o,
R_{45} – thermal resistance between the working fluid and the heat exchanger coil pipe of the mean temperature T_5,
R_{5o} – thermal resistance between the ambience in the building and the heat exchanger coil pipe towards the heat exchanger shell,
R_{56} – thermal resistance between the heat exchanger coil pipe and the plant fluid,
R_{f2} – thermal resistance of the heat transfer to the plant fluid.

STEADY STATE ANALYSIS

Fig. 2 presents the model for the steady state analysis [3] which is based on a state matrix equation

$$\overline{T} = \Lambda^{-1} \cdot \overline{P} \tag{1}$$

where particular single column matrices are:

temperature matrix: $\overline{T} = \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix}$, input matrix: $\overline{P} = \begin{bmatrix} P_1 + \dfrac{T_a}{R_{1a}} \\ P_2 + \dfrac{T_a}{R_{2a}} \\ \dfrac{T_o}{R_{4o}} \\ \dfrac{T_o}{R_{4o}} \\ \dfrac{T_o}{R_{5o}} \\ P_6 + \dfrac{T_{f2p}}{R_{f2}} \end{bmatrix}$, and the state matrix Λ is:

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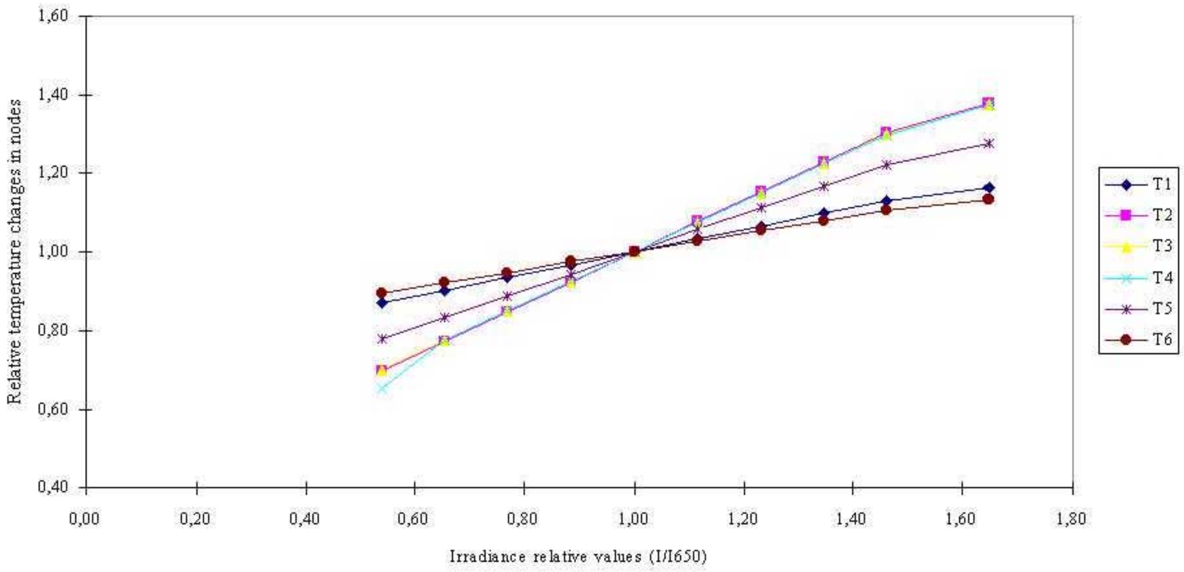
$$\Lambda := \begin{bmatrix} \frac{1}{R1a}+\frac{1}{R12} & -\frac{1}{R12} & 0 & 0 & 0 & 0 \\ -\frac{1}{R12} & \frac{1}{R12}+\frac{1}{R2a}+\frac{1}{R23} & -\frac{1}{R23} & 0 & 0 & 0 \\ 0 & -\frac{1}{R23} & \frac{1}{R23}+\frac{1}{Rf1} & \frac{1}{R45}-\frac{1}{Rf1}+\frac{1}{R4a} & -\frac{1}{R45} & 0 \\ 0 & \frac{-1}{R23} & \frac{1}{R23}-\frac{1}{Rf1} & \frac{1}{R45}+\frac{1}{Rf1}+\frac{1}{R4a} & -\frac{1}{R45} & 0 \\ 0 & 0 & 0 & -\frac{1}{R45} & \frac{1}{R5a}+\frac{1}{R56}+\frac{1}{R45} & -\frac{1}{R56} \\ 0 & 0 & 0 & 0 & -\frac{1}{R56} & \frac{1}{R56}+\frac{1}{Rf2} \end{bmatrix}$$

Particular thermal resistances R are computed in strict accordance to heat transfer through radiation, convection and conductance [1, 2], taking into account heat transfer conditions to the ambient suitable for local climate. Inputs P represent the supply of energy that comes from solar radiation understood as the product of irradiance, i.e. the energy gain from collectors W/m^2 and collector surface. The example of steady state simulation results in all nodes is presented in fig. 4, which shows the simulation of their dependence on irradiance and gives the image of how temperatures in nodes change at different solar energy availability. The graph is plotted in relative values, i.e. related to the values reached at the irradiance of 650 W/m^2.

Figure 4. The dependence of temperatures in nodes 1-6 on irradiance at established ambient temperature 283K in relative values related to the temperature change reached at 650 W/m^2



TRANSIENT ANALYSIS

However, the real dynamic of the system can only be presented through the steady state analysis. The inputs are always transient and because of thermal capacity assigned to all nodes, the operation of the whole SDHW system is always transient. The basic equation describing the transient state is eq. 2.

$$\frac{d\overline{T}(t)}{dt} = -(\mathbf{c}^{-1}\Lambda)\ \overline{T}(t) + \mathbf{c}^{-1}\,\overline{P}(t) \qquad (2)$$

where **c** is the thermal capacity matrix of all nodes.

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The solution to this differential equation has been reached by standard MathCad 7.0 software. This solution is an exponential function of temperatures in all nodes:

$$T_j\left(t\right)=T_{pi}(0)+\sum_{i=1}^{6}\Theta_{j,i}(1-e^{-\frac{t}{\tau_i}}) \qquad (3)$$

where:

Θ – temperature increase
τ – time constant

Time constants are the point of interest in this paper. They decide when the process of real heating begins after the sunrise and when the heat accumulated in the volume of the heat exchanger can be effectively used.

Aware of these, we can allow the collectors work for some time without introducing the working fluid to the whole SDHW system. Then we know when is the time when the water in the tank is the hottest. In the climatic conditions of central east European countries this may decide if the system can operate without a conventional heating, which is preferred, or how much of the additional power must be added to the system, and when. The table below presents exemplary determined time constants, response time and steady temperatures for particular nodes at established ambient conditions: irradiance I = 600 W/m^2 and ambient temperature T_a = 283K.

Table 1. Exemplary determined time constants τ, response time t_u and steady temperatures T for particular nodes

Node no.	Node description	Time constant τ (s)	Steady temperatures T(K)	Response time t_u(s)
1	collector cover	351	288.9	1053 (17.5 min)
2	absorber	5	325.6	15
3	working fluid node 3	674	325.1	2022 (33.7 min)
4	working fluid node 4	152	320.3	456 (7.6 min)
5	heat exchanger coil pipe	29	311.3	87
6	accumulated plant fluid	6200 (1.7 h)	300.2	18600 (5.2 h)

Fig. 5 and Fig. 6 present only exemplary dynamics of the system. Fig. 5 presents temperature curves for all nodes in a certain period of time relevant to the response time. All curves are plotted for temperature increase in ith node (Θ_i) reached for the ambient temperature 283K and *x* seconds of exposure time. Particular graphs are marked then Θi-1(283,x), which comes automatically from MathCad.

Figure 5. Temperature increase curves for all nodes in first 7200 s from the starting point of simulation

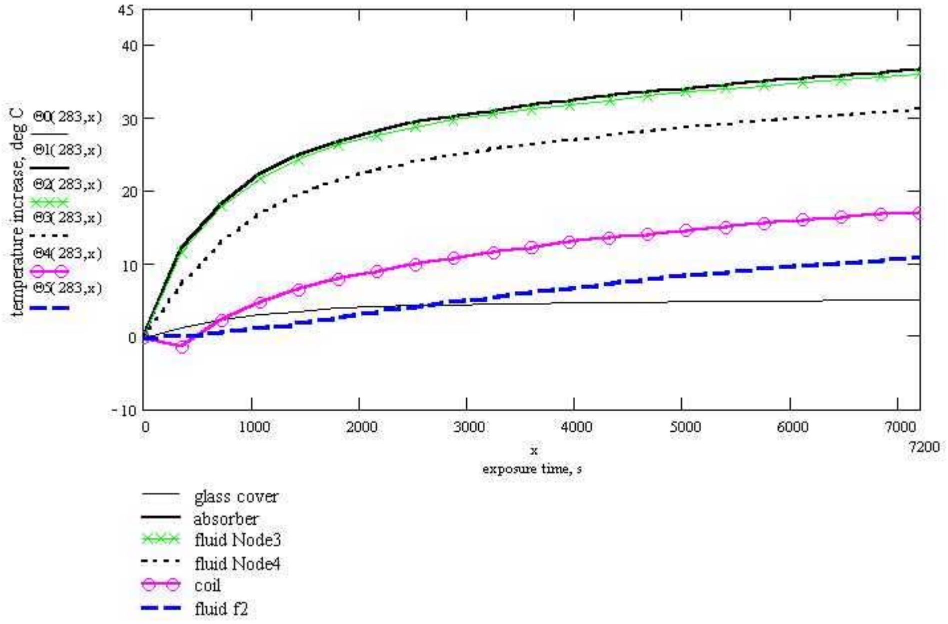

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Figure 6. Transient temperature increase Θ(*t*) for the heat exchanger coil pipe forms the vertical axis, the horizontal axis *z* is time period: 0 to 190 s (in 20 substitutions every10 s) for 11 subsequent substitutions of ambient temperature of T_a: 273 +n·5 K (n = 0, 1...11), on the other horizontal axis *n*;

$z := 0..19 \quad t_z := z \cdot 5$

$M_{j,z} := K4\left(d43_j, t_z\right)$

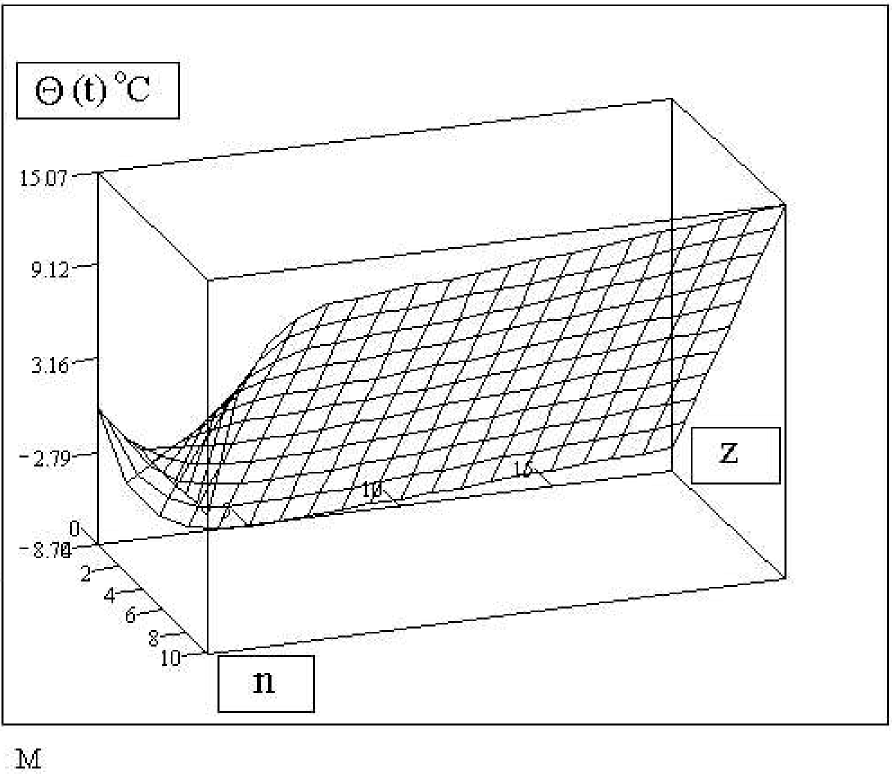

Fig. 6 presents the most interesting dynamics of node 5. This node can either be cooled or heated and this is because its location is inside the building. Its temperature can sometimes be higher than the ambient one especially in the morning and that is why the operator must wait the time indicated by the graph when the temperature increase becomes positive before collector water can be led to the heat exchanger. The advantage of MathCad is that the graph of two changing function variables on horizontal axes can be plotted together as a quasi-spatial graph. However, the programme itself gives no possibility to properly describe each axis in it.

The verification of the model and the method was possible because a real object was constructed and served for the purpose of measurements. However, its configuration differed from the one presented as the reference but it was only a matter of changes in its ETN and then the method to perform simulations was the same.

The figures below (fig. 7 and fig. 8) present the real nodes 1, 2 and 3, i.e. the collectors and the image of the whole measuring system that comes from the data acquisition system which incorporates a DAS card Advantech PCL-818HG and Genie software.

Fig. 8 presents the print screen image of the measuring systems that is why some names in it are Polish as they appear on the screen, but this is an English version software and as such is used in the presentation.

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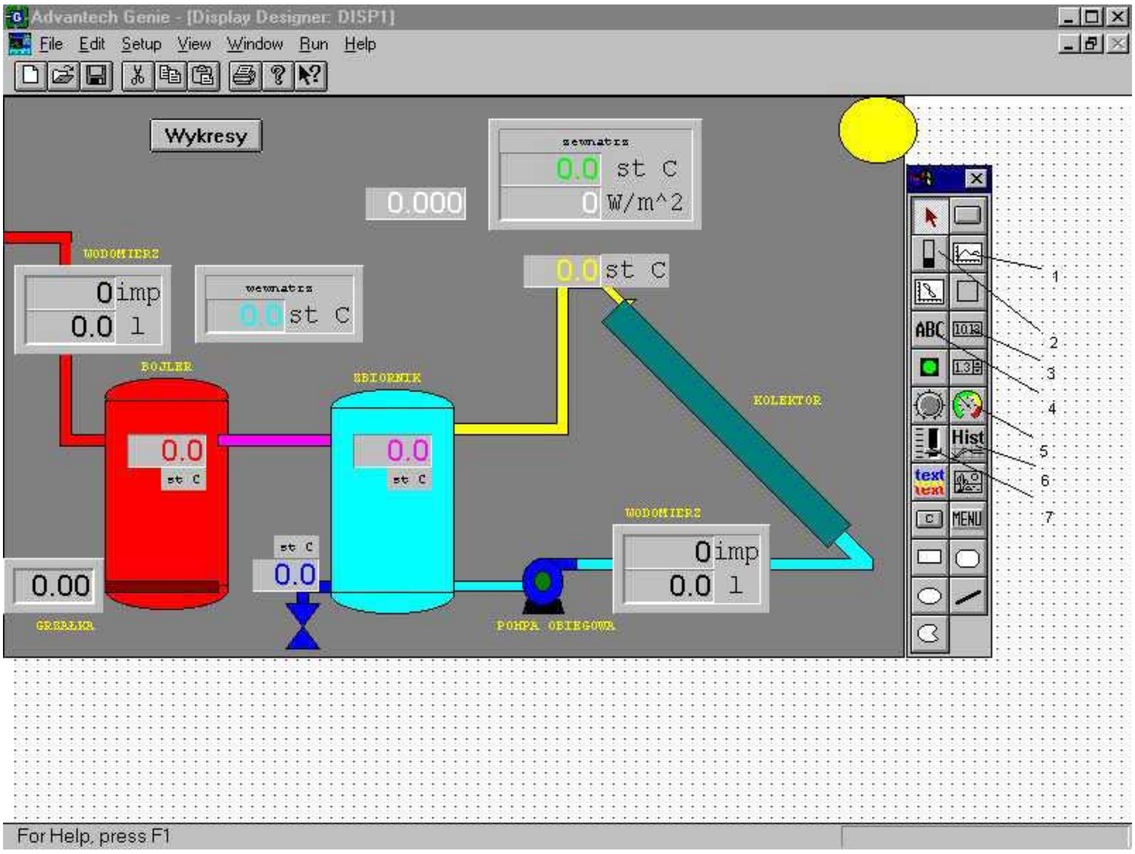
Figure 7. Metalplast Collectors localized in an SDHW system in Legionowo, Poland

Figure 8. Graphic presentation of the measuring system appearing on a screen



CONCLUSIONS

Another exemplary graph can serve the purpose of conclusions, i.e. the graph of coincidence between simulated values and measurements (fig. 9). This comparison proves that the simulation model is reliable and can be very useful to design SDHW systems and predict their short and long – term performance. This is especially vital for the construction of a food production process procedure to take advantage of this clean technology. It is important to decide when the hot water produced by the system can be used most effectively either to wash such products as fruit and vegetables, or glass packaging.

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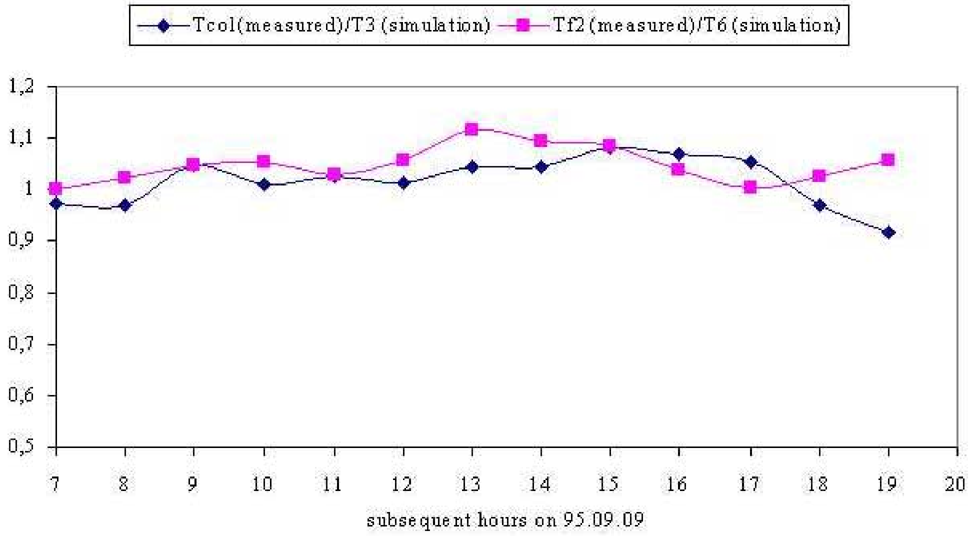
Figure 9. Comparison between measured and simulated values at: node 3 – Tcol (measured)/T3 (simulation), node 6 – Tf2 (measured)/T6 (simulation)



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