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Numerical Simulation of Thermo-Fluid Properties and Optimisation of Hot Water Storage Tank in Biomass Heating Systems

A 1.5 MW combustion facility burning large bales of soy straw has been built for the purpose of heating 1 ha of vegetable greenhouses located within the complex of Agricultural Plant PKB in Padinska Skela, Serbia. The paper addresses numerical and experimental study of temperature distribution in a cylindrical, 100 m^3 (8 m high, 4 m in diameter) hot water storage tank. The water tank optimization, as well as optimization of the heating facility as a whole, were identified as the main goals of the study performed. Water temperature was measured by a temperature probe inserted in the tank. Measurements were conducted in 256 measurement points, both under steady and unsteady water flow conditions. Water tank optimization analysis was carried out utilizing both steady and unsteady state numerical simulation. The results obtained indicated good agreement between the experimental and computational data acquired.

***Keywords:** heat storage, numerical simulation, measurements, combustion, biomass.*

1. INTRODUCTION

One of the important features of biomass boilers is a need for steady operation. Under steady state conditions, boiler efficiency reaches maximum, its operating life is considerably prolonged and the ratio between heat generation and CO_2 emission is considered to be optimal. On the other hand, a greenhouse heating system is characterized by a very dynamic operation, primarily affected by frequent and rapid changes in environmental conditions, such as the changes in air temperature, intensity of solar irradiation, wind speed, changes caused by diurnal cycle etc. For the said reason, a biomass boiler can only be used in a heating system equipped with a hot water tank. The said hot water tank or heat storage tank enables accumulation of the surplus heat generated during the periods of reduced heat demand, acting as additional heat source in critical periods of low ambient temperatures. In this manner a uniform boiler operation is achieved, enabling reduction of boiler nameplate capacity and reduction of associated investment costs as well. The main reason for the heat storage unit installation is optimisation of the greenhouse heating system. The said primarily refers to proper dimensioning of the heat storage tank, since the costs associated with the installation of the said piece of equipment represent 25 – 30 % of the overall system investments. Due to the said reason, proper dimensioning of the heat storage tank may result in substantial investment as well as operational savings. While uniform water temperature distribution is preferred in some operating regimes, others show better performance with non-uniform temperature distribution. Due to the reasons specified above, it has been concluded that a detail study of the fluid flow and heat transfer properties of the heat storage tank needs to be performed. It has been understood that the study needed to be carried out in various operating regimes i.e. in situations when heat is being transferred to the heat storage tank, as well as situations when heat is being transferred from the tank, or when both processes happen simultaneously. Such study required thermodynamic analysis and analysis of the hot water flow in the heat storage tank to be performed (see [1-4]).

In Padinska Skela, a settlement located near Belgrade, Agricultural Corporation PKB has built greenhouses intended to be used for vegetable production. The specified greenhouses cover an area of 1 ha in total. Greenhouse heating was provided via a newly built 1.5 MW heating facility comprising a biomass boiler burning soy straw. In this manner, heavy fuel oil, previously used for greenhouse heating, was substituted by biomass, in this particular case a by-product of soy production at the PKB. In addition, PKB has also decided to build additional greenhouses, occupying an area of about 5 ha, which would also require a heating system to be installed. Existing heating system comprises a 100 m^3 non-optimised heat storage tank. Taking into account the fact that proper use of biomass as a primary fuel in the system considered can not be achieved without properly optimised heat storage unit, it is clear that optimization of the existing heat storage tank is necessary. The said is also important for the future work of new, substantially larger heating system which shall comprise one or several heat storage tanks.

The main goal of the analysis performed was to determine operating parameters and heat capacity of the

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existing heat storage tank, as well as to develop adequate methods for proper dimensioning and construction of heat storage unit which shall be integrated into new, larger heating system planed to be built. The analysis was carried out by the means of mathematical modelling and numerical simulation of thermal properties of the water stored in the storage tank. Besides the mathematical modelling, measurements of water temperature and flow rate in the heat storage tank were also deemed necessary to be conducted, both under steady and unsteady operating conditions. The main goal of the measurements conducted was to: 1) determine characteristics such as the inlet temperature and inlet flow rate of the water entering the storage tank; 2) assemble a database of water temperature profiles in the storage tank, to be used for validation of the results obtained through numerical simulation. The measurement results could also be used for later correction of mathematical model in the case when discrepancy between measurement and numerical simulation occur.

2. THERMO-FLUID MEASUREMENTS

Measurements presented in the paper represent an integral part of much more extensive measurement campaign carried out in the entire greenhouse heating system. Thermal output of the system considered was determined based on the measurements of water temperature, water flow rate, flue gas composition and soy straw distribution rate.

Schematics of the heating facility and position of the measuring probes is shown in Figure 1. A probe measuring the hot water temperature (T9) has been positioned in the boiler outlet and the heat storage tank inlet line. Another temperature probe (T10) has been placed in the heat storage tank outlet and the boiler inlet line. Readings of the above two specified temperature probes are deemed to be of special importance due to the fact that the ones define the boundary conditions to be integrated in the heat storage tank mathematical model. Temperature measurements recorded by the specified probes are shown in Figure 2.

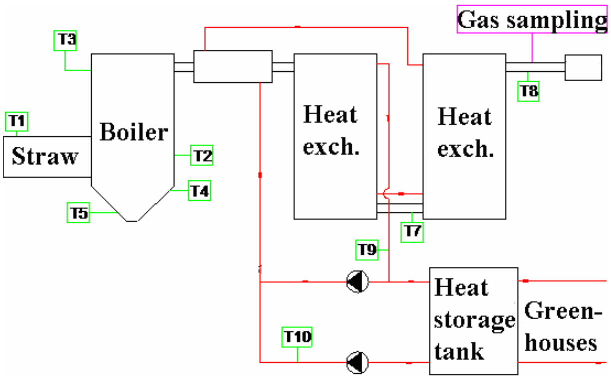

Figure 1. Schematics of the biomass burning heating system

Analysis if the flue gas composition was based on the measurements of O_2, CO_2, CO, NO and SO_2 concentrations in the flue gas. Measured concentrations of O_2 and CO_2, considered to be the most important in the above specified group of flue gas constituents, are shown in Figure 3.

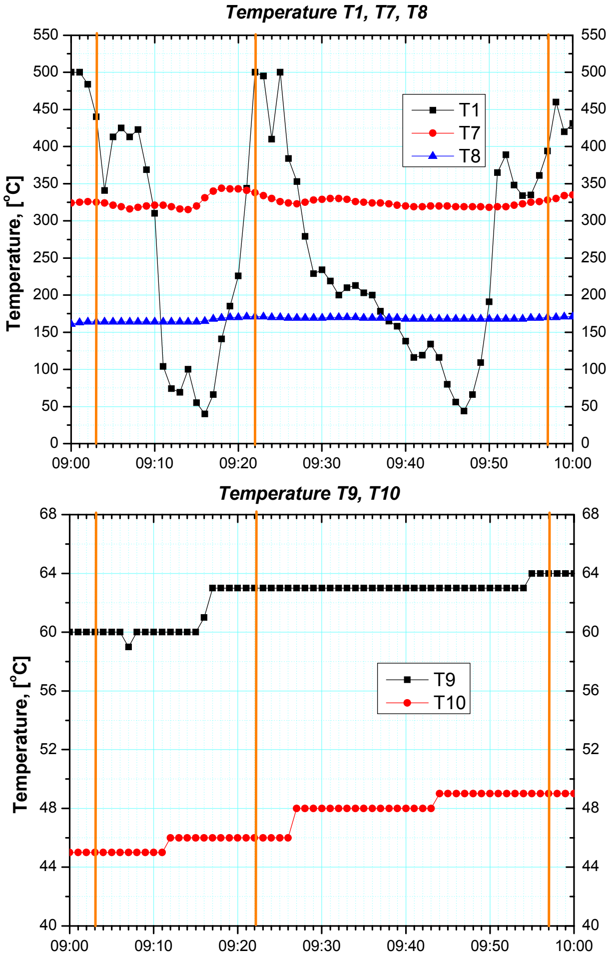

Figure 2. Temperatures measured at the inlet and the outlet of the heat storage tank, respectively

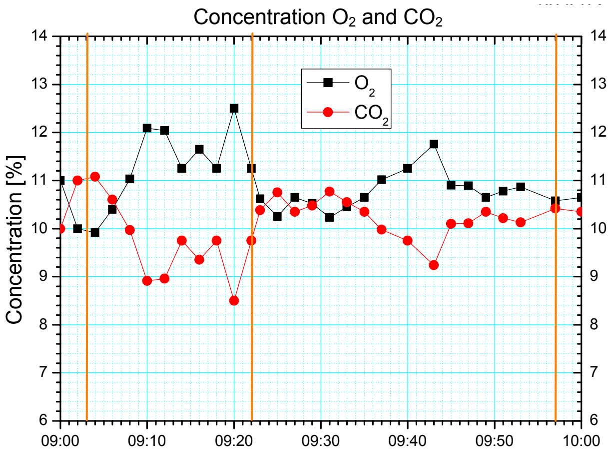

Figure 3. O_2 and CO_2 concentration in flue gas

Prior to describing the measurements conducted with respect to the heat storage tank addressed herein, it is necessary to briefly describe the main tank characteristics. The heat storage tank represents a 8 m high and 4 m diameter cylindrical vessel. The tank is provided with four openings, enabling water inflow/outflow from/to the boiler and water inflow/outflow from/to the greenhouses. In this manner, greenhouses and the boiler are connected indirectly, via the heat storage tank.

Water temperature in the heat storage tank has been performed by means of specially fabricated “L” shaped probe. Four thermocouples had been installed in the horizontal section of the “L” shaped probe. The probe was inserted through the top of the tank. Upon being inserted, the position of the probe within the tank was fixed, in a manner providing the vertical section of the probe to be aligned with vertical axis of the tank. In such position, probe could have been freely rotated and moved along the axis, enabling temperature measurement to be performed in any region inside the tank. Temperature measurements have been performed in seven horizontal cross-sections. In each of the seven horizontal cross-sections temperature was measured in 32 measurement points, performed by successive 45° angle probe rotation. Measurement points have been vertically distributed at 1 m distances, with the first measurement point located 0.5 m from the top of the tank. Due to the hot water inflow/outflow pipes positioned at the bottom of the tank, the lowest horizontal cross-section enabling water temperature measurement was located 2 m above the bottom of the tank. Results of the averaged temperature measurements, carried out in each of the cross sections mentioned previously and obtained in the above described manner are shown in Figure 4. T1 denotes the thermocouple located closest to the tank wall while T4 represents the thermocouple placed closest to the central axis of the tank.

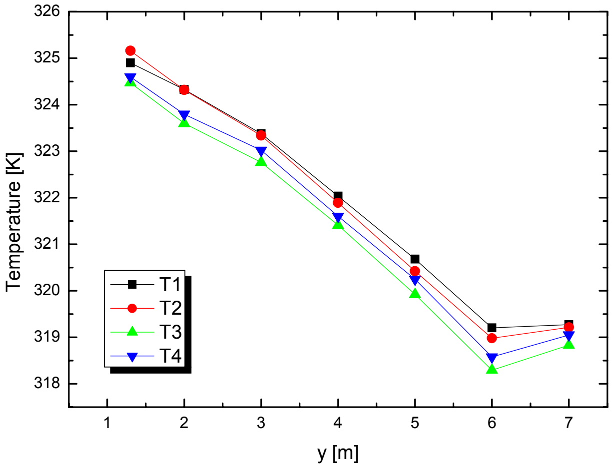

Figure 4. Steady state temperature measurements

As seen in the Figure 4, a uniform temperature distribution across the horizontal cross-sections has been recorded, while certain temperature gradient has been determined to occur in the vertical direction.

In order to estimate a period during which the greenhouses can be heated by thermal energy recuperated in the heat storage tank, with the boiler out of operation, temperature measurements during unsteady operating conditions have been carried out. For this purpose the boiler was turned off and the water temperature measured during 90 minutes. Results obtained in the case specified are shown in Figure 5.

3. NUMERICAL SIMULATION OF THERMO-FLUID PROCESSES IN HEAT STORAGE TANK

Laboratory for Thermal Engineering and Energy, housed within the Institute of Nuclear Sciences “Vinča”, has developed the in-house computational fluid dynamics codes, capable of simulating all relevant thermo-fluid processes occurring under unsteady operating conditions in the thermal storage tank. However, a certain problem has been encountered with respect to mesh generation. Without the use of appropriate mesh generation software, mesh generation is extremely time consuming and drastically slows down the optimisation process which is associated with frequent changes in geometry. A solution for the problem specified was found in the use of commercial codes, where special care is taken to provide good integration of pre-processing (mesh generation), processing and post processing phases of modelling process. Up-to-date commercial codes have various built-in tools enabling simple and fast generation of unstructured meshes to be applied to complex geometries. Due to their ability to support complex mathematical models, the specified commercial codes may be used as a viable research tool.

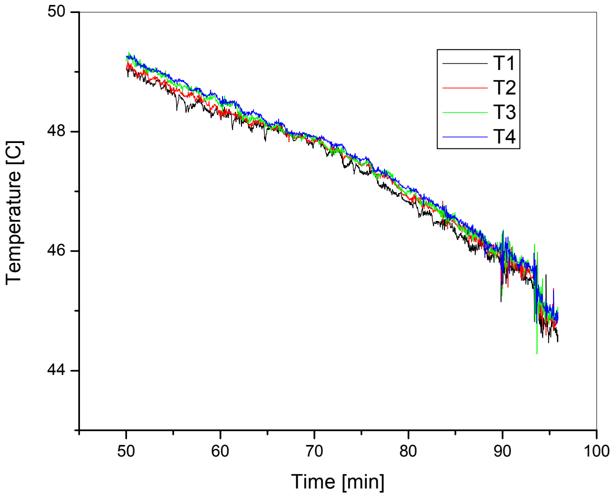

Figure 5. Unsteady state temperature measurements

A theoretical background of the processes occurring in the heat storage tank is provided hereafter, as well as details of the numerical setup and related flow modelling procedure.

3.1 Governing equations

The system of partial differential equations describing mass, momentum and energy conservation is used to model the water flow considered. The equations are Reynolds-averaged in order to produce the following system:

The continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho U_j\right)=0 . \tag{1}$$

Momentum equation:

$$\frac{\partial}{\partial t}\left(\rho U_i\right)+\frac{\partial}{\partial x_j}\left(\rho U_i U_j\right)=$$

$$=-\frac{\partial P}{\partial x_i}+\frac{\partial}{\partial x_j}\left(\mu_{\mathrm{eff}}\left(\frac{\partial U_i}{\partial x_j}+\frac{\partial U_j}{\partial x_i}\right)\right). \tag{2}$$

Energy equation:

$$\frac{\partial(\rho h_{\text{tot}})}{\partial t} - \frac{\partial p}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j h_{\text{tot}}\right) =$$

$$\frac{\partial}{\partial x_j}\left(\lambda \frac{\partial T}{\partial x_j} + \frac{\mu_{\text{t}}}{\text{Pr}_{\text{t}}}\frac{\partial h}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(U_j \cdot \tau\right) + S_E . \quad (3)$$

The well known closure problem associated with the Reynolds-averaged equations is solved using the eddy viscosity hypothesis. Effective viscosity is expressed as a sum of molecular and eddy viscosity:

$$\mu_{\text{eff}} = \mu + \mu_{\text{t}} . \quad (4)$$

The standard two-equation $k - \varepsilon$ turbulence model is employed to compute turbulent velocity and length scale needed to model the turbulent viscosity. The turbulent viscosity is expressed as:

$$\mu_{\text{t}} = \text{C}_{\mu} \rho \frac{k^2}{\varepsilon} \quad (5)$$

and the transport equations are shown below.

For the turbulence kinetic energy:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j k\right) =$$

$$= \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_{\text{t}}}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right) + P_k - \rho\varepsilon . \quad (6)$$

For the turbulence kinetic energy dissipation rate:

$$\frac{\partial(\rho \varepsilon)}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho U_j \varepsilon\right) =$$

$$= \frac{\partial}{\partial x_j}\left(\left(\mu + \frac{\mu_{\text{t}}}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right) + \frac{\varepsilon}{k}\left(\text{C}_{\varepsilon 1} P_k - \text{C}_{\varepsilon 2}\rho\varepsilon\right) . \quad (7)$$

Model constants are shown in the Table 1 below.

Table 1. Constants of $k - \varepsilon$ turbulence model

σ_k	σ_ε	$\text{C}_{\varepsilon 1}$	$\text{C}_{\varepsilon 2}$	C_μ
1.0	1.3	1.44	1.92	0.09

P_k is the turbulence production due to viscous and buoyancy forces and is modelled in accordance with the following equation:

$$P_k = \mu_{\text{t}} \frac{\partial U_k}{\partial x_i}\left(\frac{\partial U_k}{\partial x_i} + \frac{\partial U_i}{\partial x_k}\right) -$$

$$- \frac{2}{3}\frac{\partial U_i}{\partial x_i}\left(3\mu_{\text{t}} \frac{\partial U_k}{\partial x_k} + \rho k\right) + P_{kb} . \quad (8)$$

Since the Boussinesq buoyancy model is used, the buoyancy production term P_{kb} is modelled in accordance with the following expression:

$$P_{kb} = \frac{\mu_{\text{t}}}{\rho \sigma_\rho} \rho \beta g_i \cdot \frac{\partial T}{\partial x_i} \quad (9)$$

The buoyancy production term is included in both k and ε equations.

3.2 Numerical setup and boundary conditions

In the first phase of flow modelling, numerical mesh was generated and preliminary calculations were conducted using the commercial CFD codes Fluent 6.3 and CFX 11.0. Comparison of the commercial codes mentioned was carried out with respect to their suitability for solving the problem considered, accuracy of calculation and post processing options. Although both codes have showed excellent characteristics with respect to all of the criteria mentioned, CFX has been adopted as a preferred tool for the heat storage tank modelling.

3.3 Modelling procedure

Commercial CFD code ANSYS CFX 11 [5] was used to model the water flow and heat transfer in the investigation conducted. Transient simulations were used to model thermal conditions in the hot water tank. The conservation equations were solved using the Finite Volume method and collocated variable arrangement with Rhie-Chow interpolation to prevent pressure-velocity decoupling. The software employs a coupled, fully implicit solver using a transient evolution of the flow starting from the initial conditions. The said reduces the number of iterations required for the convergence to the steady state or calculation carried out for each time-step within a time dependent analysis. Physical time-steps used in the transient evolution provide a means of controlling the problem solving procedure. CFX uses a multi-element type mesh comprising hexahedra, tetrahedra, wedges and pyramids. Flow variables (velocity, pressure, enthalpy, etc.) were defined in the corners of each element, located in the centre of each control volume used for solving the conservation equations. Linear equations were solved using an Algebraic Multigrid method.

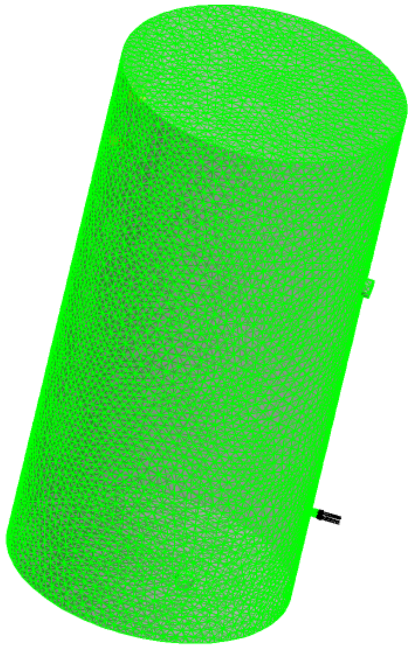

Figure 6. Unstructured numerical mesh used in simulations

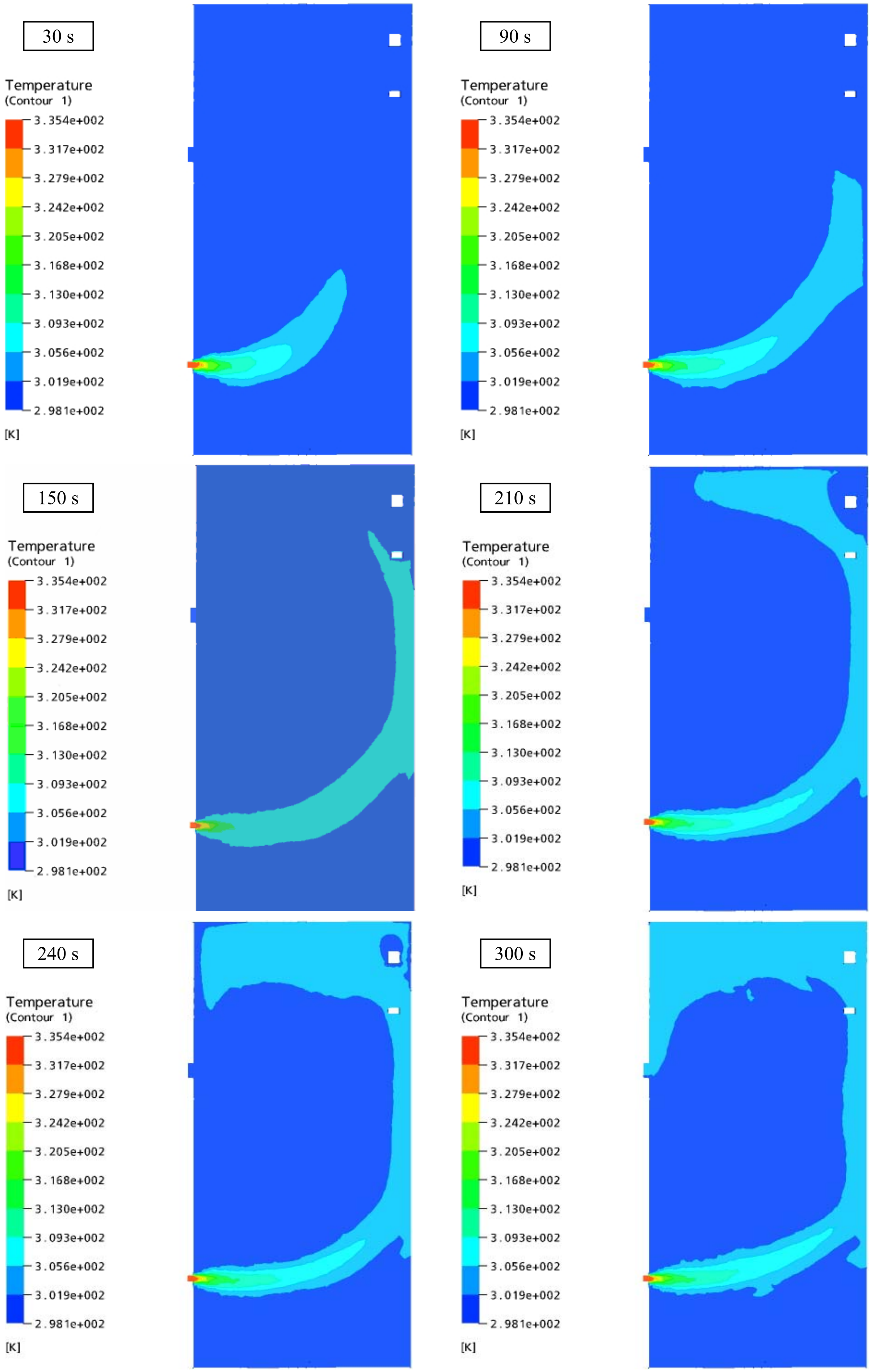

Figure 7. Temperature profiles at the vertical cross section that passes through the inlet, for the first five minutes of heating

Since measurements were performed under steady and unsteady operating conditions of the heating system considered, computer simulations were run for both operating regimes accordingly. The same unstructured numerical mesh was used in both cases. The domain was subdivided into 500000 control volumes (Fig. 6). Large number of computational cells was necessary to enable accurate calculation in regions where high fluid temperature and velocity gradient occur, such as the inlet and the outlet of the vessel where turbulent mixing was expected to be encountered. In order to accurately simulate the specified domains, it was therefore necessary to incorporate turbulent flow regimes into the mathematical model used. An average time needed for the system to reach the steady state was three hours. Consequently, the specified three-hour period was taken into account in unsteady-state calculations performed.

4. RESULTS

Numerical simulation of unsteady operating conditions was performed for the first three hours of heating. Initial temperature in the tank was uniform, equalling 300 K, while the temperature of the hot water entering the tank equalled 336 K. Temperature variations in the tank occurring during the first five minutes of heating, are presented in Figure 7. The figure presents several consecutive time frames of temperature distribution in a vertical plane passing along the central axis and through the hot water inlet tank opening.

The effects of natural convection can be clearly observed, causing the upward flow of hot water to the upper sections of the tank. The said trend of hot water upward flow remained present during the entire heating process. The said trend resulted in a cold water zone to be formed in the tank region below the hot water inlet opening. The situation encountered can be clearly seen in Figures 8 and 9, showing temperature distribution in the same vertical cross sectional direction established after two and three hours of heating, respectively. In addition, formation of cold water zone in the storage tank is additionally contributed by the position of cold water inlet opening which provide an inflow of cold water from the greenhouses and into the tank.

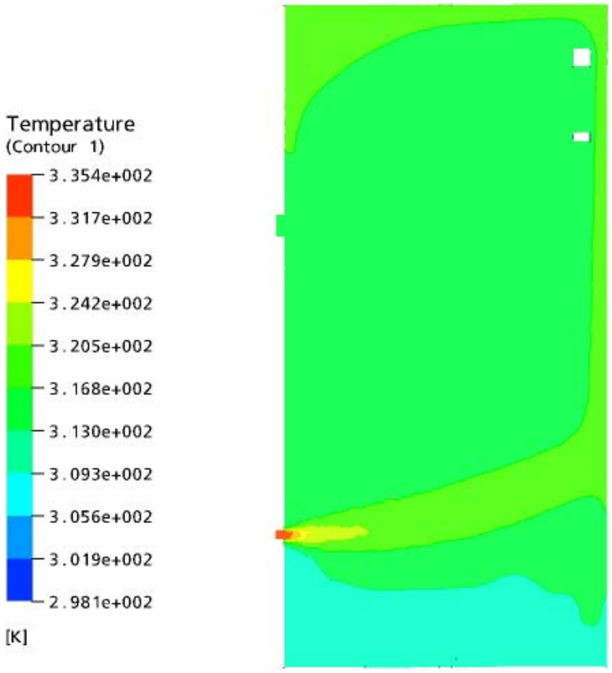

Figure 8. Temperature distribution after two hours of heating

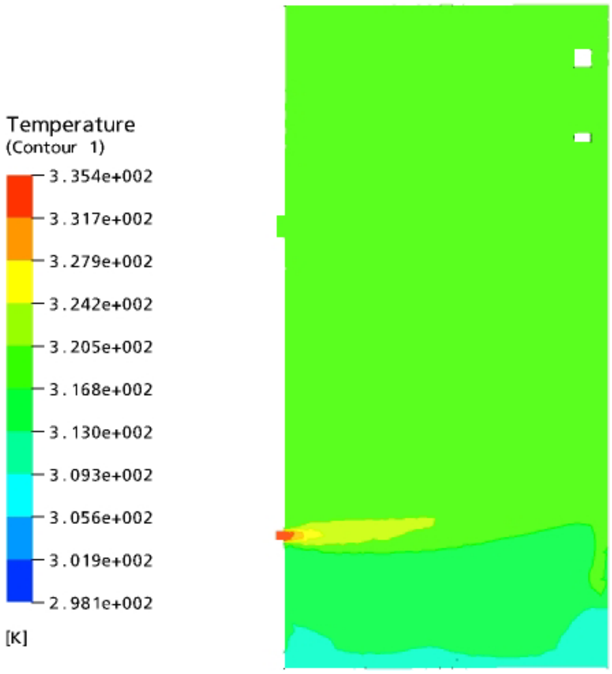

Figure 9. Temperature distribution after three hours of heating

Figure 10 shows temperature variation along the central axis, occurring during the first hour of heating. The *y* coordinate value denotes the height of the water tank. The peak observed in the graph corresponds to the position of the hot water inlet opening. In other tank regions relatively uniform temperature distribution is observed.

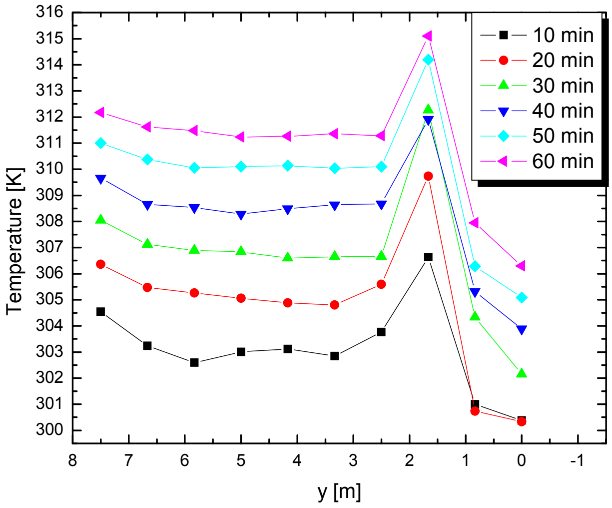

Figure 10. Temperature profile along the central axis

Temperature distribution in the vertical plane passing along the central axis and through the hot water inlet opening (the *xy* plane from the Figure 7), calculated for a time frame corresponding to the moment three hours after the heating commencement, are shown in Figure 11. Temperatures indicated in the legend and numbered from *xy*1 to *xy*8, relates to the vertical temperature profiles calculated at different distances from the hot water inlet opening, the most distant being the location denoted as *xy*1, while *xy*8 is the location closest to hot water inlet opening. As seen in the figure, relatively uniform temperature distribution is observed, both along the height direction, as well as across the cross section, with deviation noted only in sections near the bottom of the tank.

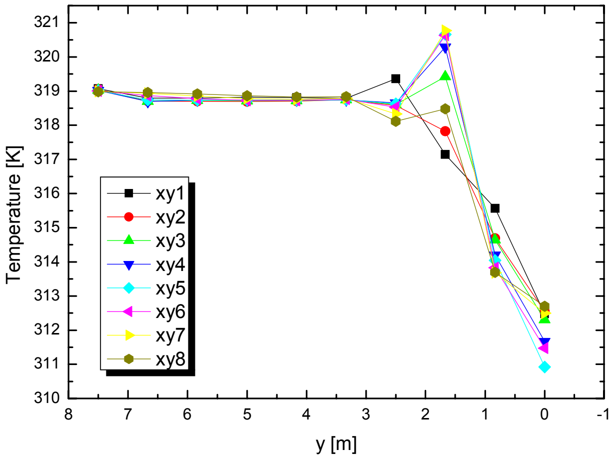

Figure 11. Vertical temperature profiles, as calculated

Comparison of the results obtained by numerical simulation with the results of steady state experimental investigation is shown in Figure 12. A very good agreement between the two data sets is observed in the upper tank region, with discrepancies between the numerical and measured data being around 0.5 K. However, in the lower tank region a more pronounced discrepancies between the numerical results and the values obtained through measurement is observed, with noted discrepancies of up to 5 K. The calculated temperature profile is more uniform than the profile determined through measurements. In general, although the calculated temperature profile shows good agreement with the profile determined through measurements, some corrections in the model are still necessary in order to account for the discrepancies observed in the lower tank region.

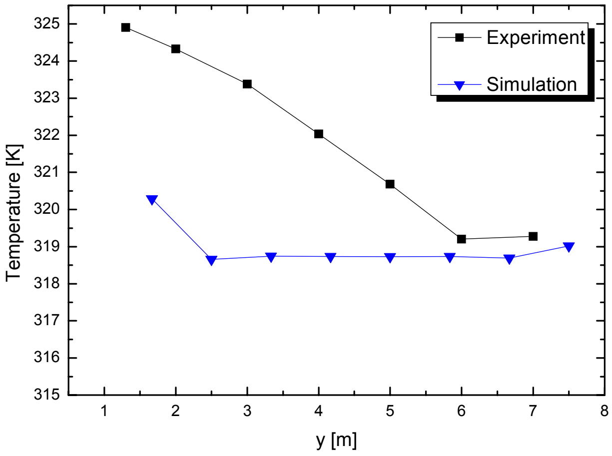

Figure 12. Comparison between results obtained by simulation and measurement

5. CONCLUSION

The paper presents numerical analysis of the processes occurring in the hot water storage tank, aimed at gaining a thorough understanding of the flow characteristics and temperature distribution in the hot water tank. The level of confidence the commercial CFD packages can provide with respect to their use for complex flow simulation, where effects of turbulence and buoyancy have to be taken into account, was also analysed.

Analyses performed indicate that mathematical models employed in the modern commercial CFD packages enable flexible and to a certain point accurate results. However, complexity of the physical processes analysed require a level of precaution to be employed in general use of commercial CFD packages.

Numerical simulation of thermo-fluid properties, carried out both under the steady and unsteady operating conditions of the heating system, have shown a very good agreement with respective measurements carried out in various tank regions. This especially holds for the unsteady operation simulation. However, a certain discrepancy between the results of numerical simulation and measurements obtained was observed in the lower region of the hot water storage tank. Discrepancies between temperature values obtained through numerical simulation and respective measurements in this region of the tank were up to 5 K. The said discrepancies may be attributed to the fact that measurements took about 2 hours to complete. Since the conditions in the water tank during the specified period were evolving, there is a possibility that some measurements have been recorded for unsteady operating conditions. Future research shall focus on the analysis of the most probable source of errors encountered in the calculations performed. Analysis of the flow regimes established during the measurements performed shall be carried out first, followed by appropriate modification of the related mathematical models. The main goal of the activities specified would be the provision of more accurate tool to be used for prediction of thermal stratification in hot water storage tanks.

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NOMENCLATURE

k	turbulence kinetic energy
P_k	production of k
P_{kb}	production of k by buoyancy
h_{tot}	total enthalpy
$C_{\varepsilon 1}$	model constant
$C_{\varepsilon 2}$	model constant
C_{μ}	model constant

Greek symbols

σ_k	model constant
σ_ε	model constant
ε	turbulence kinetic energy dissipation rate
μ_{eff}	effective viscosity
μ	dynamic visosity
μ_{t}	turbulent or eddy viscosity
β	thermal expansion coefficient
λ	thermal conductivity

МОДЕЛИРАЊЕ СТРУЈНО-ТЕРМИЧКИХ ПРОЦЕСА И ОПТИМИЗАЦИЈА РАДА АКУМУЛАТОРА ТОПЛОТЕ У ГРЕЈНИМ СИСТЕМИМА СА ТОПЛОВОДНИМ КОТЛОМ НА БИОМАСУ

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За потребе загревања 1 ha пластеника на пољопривредном добру у Падинској Скели, које се налази у оквиру ПКБ корпорације, изграђен је грејни систем са котлом на биомасу, у коме се топлота добија сагоревањем балиране сојине сламе. Због нестационарних ефеката загревања појавила се потреба за укључивањем акумулатора топлоте у систем грејања. Овај рад има за циљ нумеричку и експерименталну студију извршену са циљем оптимизације акумулатора топлоте у предметном грејном систему, као и оптимизацију целокупног грејног система. У акумулатору топлоте капацитета 100 m^3, у коме се складишти загрејана вода, извршена су мерења у 256 тачака, како у стационарном тако и у нестационарном режиму рада котла. Анализа оптимизације је извршена нумеричком симулацијом која је обухватала и стационарне и нестационарне режиме. Добијени резултати показују добро поклапање резултата добијених експериментом и нумеричком симулацијом.