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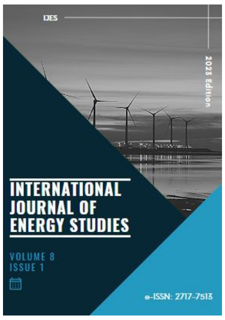

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Model of the combi boiler appliance in TRNSYS for domestic hot water circuit: Experimental and numerical validations of economic mode simulations

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Highlights

- DHW heating circuit is modelled in TRNSYS with experimental validation for eco mode simulations.
- TRNSYS modelling results are presented in comparison with the outcomes of 1D modelling approach.
- TRNSYS model decreases the MAE calculated for the overall temperature profile covering the transient region.

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ABSTRACT

Combi boiler type heating appliances are used nearly in every residential building for both space and domestic hot water (DHW) heating functions. There are challenging targets regarding both of these functions. Since there is a huge laboratory testing procedure behind each appliance design and the structural or operational changes on the regular designs, simulation models could be established for the initial evaluations of the appliance testing. Therefore, due to the estimations from the preliminary results of the simulations, the number of the laboratory tests could be decreased with cost, time, and energy savings. In this study, the main objective is modelling DHW heating circuit of a combi boiler appliance with the help of Transient System Simulation Tool (TRNSYS 18) to calculate DHW outlet temperature under various operating conditions. The TRNSYS model is validated experimentally and compared with the previous works of the authors. A good agreement is achieved in both transient and steady-state regions and the TRNSYS model is found superior when compared to the previously established one-dimensional model of the authors. DHW circuit model is validated only for economic (eco) working mode simulations in this study. Mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) values are compared for the outcomes of the previously constructed one-dimensional model and currently established TRNSYS model with reference to the experimental data. TRNSYS model decreases all of these errors calculated according to the overall temperature profiles including the transient region for the central heating water at the heat cell inlet, central heating water at the heat cell outlet, and the inlet and outlet temperature difference of DHW at the experimentally investigated DHW flow rates of 5 l/min, 7 l/min, and 8.7 l/min.

Keywords: Combi boilers, domestic hot water (DHW) circuit, TRNSYS model, one-dimensional (1D) modelling

1. INTRODUCTION

Combi boiler type heating appliances are advantageous since they are used for both space and domestic hot water (DHW) heating functions which are crucial to the human needs. As shown in the schematic display given in Figure 1, there are four basic components in a typical combi boiler appliance as follows; (i) a primary heat exchanger (HE), (ii) a secondary HE, (iii) a pump, and (iv) a diverter valve. The actual main components of the combi boiler modelled in this study are the heat cell (HC) which has the combustion of the natural gas inside and the plate heat exchanger (PHE) responsible for heating the water demanded by the users as given adjacent to the schematic displays of the primary and secondary heat exchangers, respectively, in Figure 1. Hot combustion products in the HC heats the central heating (CH) water and CH water is sent through the radiators to warm up the indoor air. When there is a user demand, the diverter valve changes the direction of the CH flow, and hot CH water is pumped into the PHE in order to heat the domestic cold water (DCW) requested by the users.

This paper focuses only DHW heating circuit with respect to the modelling tools. There are two basic working modes in combi boilers as economic (eco) and comfort modes details of which are clarified in the next section. The main objective of this paper is to present a practical model of DHW heating circuit of the combi boiler to calculate quick results making use of Transient System Simulation Tool (TRNSYS 18). The authors of this paper previously established one-dimensional (1D) model of the DHW circuit and verified the results experimentally with a good agreement in the steady-state region [1]. Moreover, they also constructed a practical DHW circuit model using a commercial software, Flowmaster® [2].

In this paper, the simulation results of DHW circuit model are compared with the experimental data and the numerical results calculated from the 1D model. The agreement between the TRNSYS model and the experimental and numerical data is tested for only eco mode simulations. The validations of the comfort mode operations are left for future study since the TRNSYS model requires further specifications such as late ignition time and heat retention of the heat cell block.

Although it seems that efficiency is of a primary concern for a combi boiler type heating appliance, comfort level as well is a critical issue. There are six comfort tests as waiting time, temperature variation according to water rate, temperature fluctuation at constant water rate, temperature stabilization time on variation of the water rate, minimum nominal water rate, and temperature fluctuation between successive deliveries according to which comfort level of the appliance is declared with respect to BS EN 13203-1:2006 [3]. This paper focuses only the construction of DHW circuit model in TRNSYS and validation of this model via previous experimental and numerical data only for eco mode. However, the overall target of this ongoing research is adapting the TRNSYS model in question for comfort mode simulations and proposing a laboratory simulation tool for comfort mode trials.

There are various studies in the literature focusing on the comfort and efficiency assessment of DHW production, combi boilers and TRNSYS models of water heaters. A brief summary of the literature is given to highlight the novel sides of this paper and ongoing research. Atmaca et al. (2015) [1] modelled DHW circuit of combi boiler type heating appliances to compare two different type of combi boiler heater concepts. Time dependent 1D modelling equations were established for the flue gas, heat cell wall, CH water in the heat cell, CH water in the PHE and DHW in the PHE and all these equations were solved implicitly to demonstrate the transient temperature profile of DHW at various operating conditions. Atmaca et al. (2016) [2] modelled DHW circuit of a combi boiler using Flowmaster® software and compare the results of this modelling approach with the outcomes of 1D modelling.

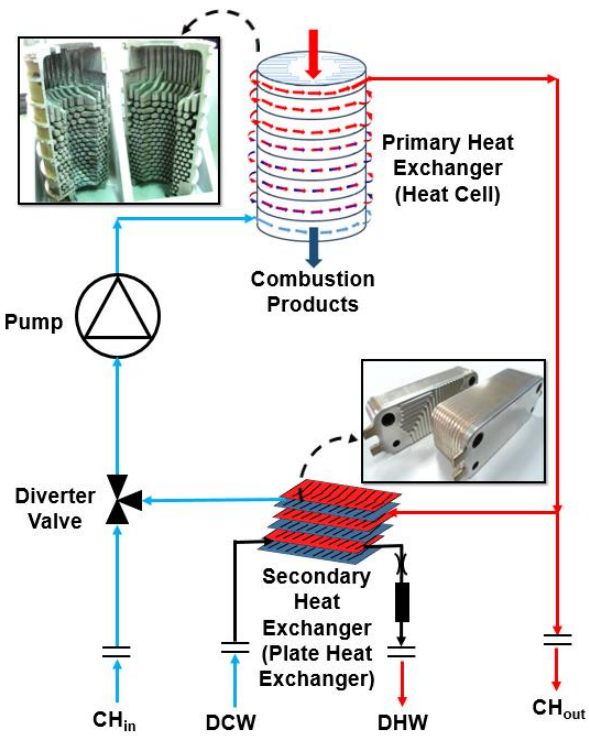

Figure 1. Schematic display of the combi boiler heating appliance with the actual views of the primary and secondary heat exchangers.

Flowmaster® is a popularly used 1D thermal-fluid system simulation tool to provide with the practical results for the early design processes or system analyses. The model established with Flowmaster® [2] was used to calculate DHW outlet temperature at various operating conditions, i.e. DHW flow rates of 5 l/min, 7 l/min, and 8.7 l/min including variable burner power and constant burner power. Transient heat transfer rates for all these DHW flow rates showed a good agreement between the numerical approaches and the experimental data. Although the transient profiles of the heat transfer rates were consistent with the results of the 1D modelling approach and the experimental data, the transient CH inlet and outlet temperature profiles from the HC yielded higher errors. Since temperature difference between the HC inlet and outlet temperature was nearly the same as the experimental data and 1D modelling approach, nearly 10 K difference between the experimental data and numerical results for the CH inlet and outlet temperatures in the steady-state region didn't yield a poor agreement in terms of the heat transfer rate. The main reason for this outcome was the type of the heat exchanger component selected in Flowmaster®. Lastly, DHW temperature difference profile between the inlet and outlet of the PHE as well was calculated in Flowmaster® yielding a satisfactory consistency with the 1D modelling approach and the experimental data.

The advantages and disadvantages of both modelling approaches were discussed in detail in the paper [2]. Actually, Flowmaster® model results are not used for validation in this proposal since Flowmaster® model resulted in relatively high errors for the intermediate temperatures such as CH water temperatures from the HC inlet and outlet. This proposal only uses the numerical results calculated from the 1D modelling equations and the experimental data for only eco mode. The reason for the comprehensive discussion between the previous modelling approaches is to express better the gaps in the modelling approaches with respect to component selection in the softwares. In other words, their limitations are completely bounded up with the component selection and the parameter definition.

Boait et al. (2012) [4] analysed five different domestic hot water heater concepts and concluded that gas-fueled instantaneous hot water systems have higher efficiency than the appliances including storage tanks. Pärisch et al. (2019) [5] proposed a new test procedure for comfort evaluations with future work discussion. Pomianowski et al. (2020) [6] emphasized the attitude of the researches of the recent years focusing on the DHW production although their review paper is directly related to DHW energy efficiency. Haissig and Woessner (2000) [7] gave the details of an adaptive fuzzy control (AFC) algorithm to decrease DHW temperature deviations and set point reaching time with respect to demand changes without using a DCW sensor and fuel type indicator.

So far literature studies focusing on the DHW production in terms of both comfort and efficiency highlights the importance of the developments on the DHW function of the combi boilers. Hence, the need for the laboratory testing and system simulations are essential for the research and development activities. In addition to the previously summarized combi boiler studies [1, 2], there are recent researches one of which was based on the detecting improvement potentials of combi boiler heaters conducted by Ucar and Arslan (2021) [8]. According to the advanced exergy analysis for the space heating function of 24 kW commercial condensed combi boiler, the combustion unit including the main heat exchanger had the highest contribution to the total exergy destruction. Fridlyand et al. (2021) [9] tried to estimate the energy use of the tankless combi boilers focusing on the performance data utilization and thermodynamic models with the modelling tools such as EnergyPlus. Quintã et al. (2019) [10] used a lumped space approach to establish the mathematical model of the tankless gas water heaters. Conservation of energy and mass equations were applied to each component considered as a control volume and these component models were transferred to MATLAB/Simulink to test various appliance concepts and control algorithms.

The last part of the literature study consists of TRNSYS models of the heaters and more specifically water heaters. TRNSYS software is used for the dynamic simulations concerned with the DHW performance with respect to the potential evaluation of various energy sources or heat recovery alternatives. Jordan and Vajen (2001) [11] declared the necessity of more realistic DHW profiles on energy savings for a solar system including a storage tank with a thermosyphon heat exchanger making use of TRNSYS simulations. Andrés and López (2002) [12] created a new physical model using TRNSYS for a solar domestic water heater with a horizontal storage and mantle heat exchanger. Nordlander and Persson (2003) [13] presented the first simulation study of the pellet stoves to be used in house heating and made assessments on the stove efficiency, the distribution of the delivered energy, and the emissions based on the mathematical model constructed with the help of TRNSYS. Persson et al. (2009) [14] created a TRNSYS model of small pellet boilers and stoves for house heating in order to calculate the average efficiency and emissions of the overall system. Bourke and Bansal (2012) [15] developed a new test method to define the annual energy consumption of a domestic solar water heater boosted with a gas instantaneous water heater making use of TRNSYS models. Persson et al. (2019) [16] combined two of the existing models in TRNSYS to create the models of the pellet burner part (Type 210) and the flue gas heat exchanger and boiler water volume (Type 341).

TRNSYS is a widely used simulation tool and there are many other models including space and DHW heating for other applications and comprehensive system analyses [17, 18]. To sum up, there are challenging targets concerned with the combi boiler appliance concepts since they are widely used. Moreover, DHW efficiency and comfort is of critical importance to the users. Lastly, TRNSYS is a popularly preferred modelling tool and it could easily be implemented to the DHW mode simulations of a tankless water heaters (combi boilers) in both eco and comfort working schemes. In this study, eco working mode is simulated and the mean absolute error (MAE) decreasing approximately from 2 °C – 2.5 °C range of 1D model to 0.5 °C – 1 °C interval of current TRNSYS model for the inlet and outlet temperature difference of DHW shows that TRNSYS model is superior to the previously established 1D model of the authors. Hence, the TRNSYS model of the combi boiler would be beneficial for both the literature and the laboratory engineers from this sector to comprehend the initial results of the proposed designs or changes.

2. OPERATION MODES OF THE DHW HEATING FUNCTION

There are two basic operation modes for the DHW heating function, namely economic (eco) and comfort modes. In eco mode, when there is a user demand of hot water, the appliance starts ignition and CH water and DCW is heated. However, in comfort mode, the CH water is heated regularly in the HC according to the control algorithm of the appliance as shown in Figure 2 to provide the users directly with the hot water.

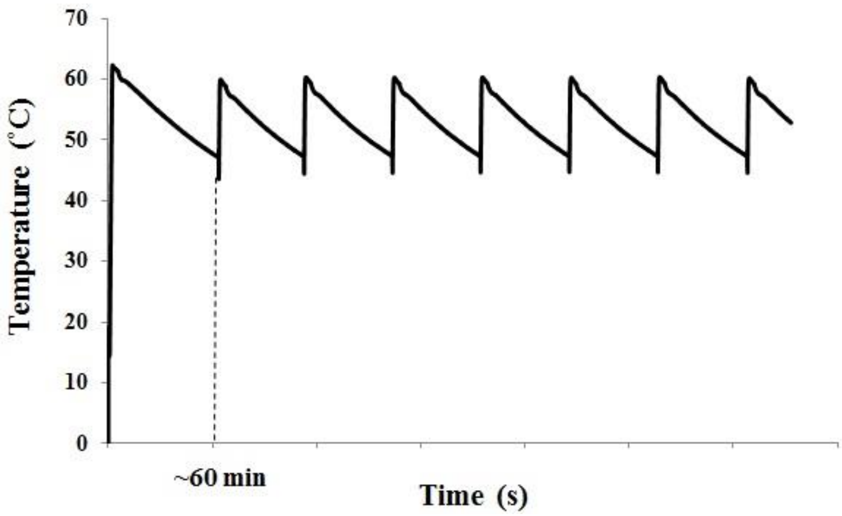

Figure 2. Preheat cycles of the CH water in the HC in the comfort mode [1].

There is a special control algorithm such as fuzzy logic algorithm to check the CH water temperature to start the preheat cycles or to start the ignition with respect to the heat retention effects of the HC when hot water is requested. Therefore, the hot CH water directly transfers its energy to the DCW and the transient heating region of economic mode is eliminated in comfort mode. Figure 3 shows the difference between the DHW outlet temperature profiles measured both in eco and comfort working modes.

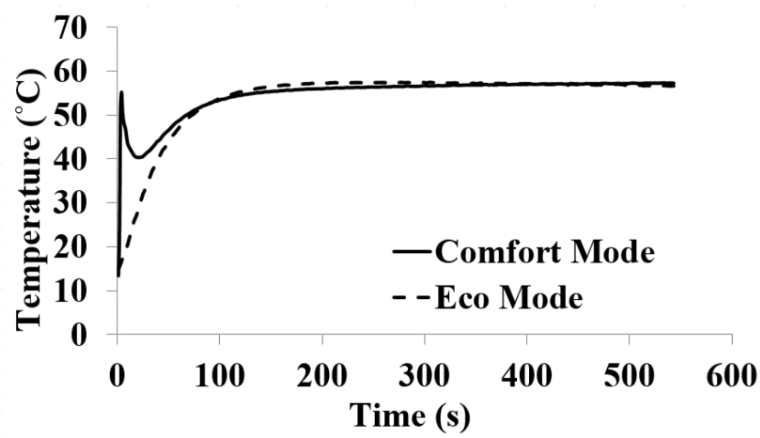

Figure 3. DHW outlet temperature comparison between the eco and comfort modes [1].

3. MODELLING DHW CIRCUIT OF THE COMBI BOILER

TRNSYS model of the DHW circuit is the main objective this proposal. However, 1D model established previously by the authors of this paper [1] is introduced since the outcomes of 1D model is used to show the superiority of the TRNSYS model. Firstly, 1D modelling equations, boundary conditions, and initial conditions are given with respect to Atmaca et al. (2015) [1]. All details from the modelling equations to the solution algorithm were given in the previous investigation [1]. However, modelling equations are described briefly in the following section to clarify the distinctions between the modelling approaches.

3.1. Revision of the One-Dimensional (1D) Model

Combi boiler 1D model is described by the following five equations which are solved implicitly. The control volumes and the water flow directions of the HC and the PHE are given in Figure 4 (a) and (b), respectively to explain the derivations of the equations.

The following equations are for the cooling of the flue gas, the heating of the CH water in the HC, the heating of the HC wall, the cooling of the CH water in the PHE, and the heating of the DHW in the PHE. Overall heat transfer coefficients of the HC are calculated based on the total thermal resistances of the flue gas, HC wall, and the CH water in the HC. However, the overall heat transfer coefficient of the PHE is determined experimentally.

$$\rho_g A_{c,g} c_{p,g} \frac{\partial T_g}{\partial t} = -\dot{m}_g c_{p,g} \frac{\partial T_g}{\partial y_1} - \frac{A_{s,g} U_g}{s} (T_g - T_w) \tag{1}$$

$$\rho_{wt} A_{c,wt(1)} c_{p,wt} \frac{\partial T_{wt(1)}}{\partial t} = -\dot{m}_{wt(1)} c_{p,wt} \frac{\partial T_{wt(1)}}{\partial y_2} + \frac{U_{wt(1)} A_{s,wt(1)}}{z} \left(T_w - T_{wt(1)}\right) - h_\infty \frac{A_o}{z} (T_{wt(1)} - T_\infty) \tag{2}$$

$$\rho_w A_{c,w} c_w \frac{\partial T_w}{\partial t} = k_w \frac{\partial^2 T_w}{\partial y_2^2} A_{c,w} + \frac{U_g A_{s,g}}{s} (T_g - T_w) - \frac{U_{wt(1)} A_{s,wt(1)}}{s} (T_w - T_{wt(1)}) \tag{3}$$

$$\rho_{wt} \frac{V_{chwc}}{l_{PHE}} c_{p,wt} \frac{\partial T_{wt(2)}}{\partial t} = -\dot{m}_{wt(2)} c_{p,wt} \frac{\partial T_{wt(2)}}{\partial x_1} - 2 \frac{U_{PHE} A_{PHE}}{l_{PHE}} (T_{wt(2)} - T_{wt(3)}) \tag{4}$$

$$\rho_{wt} \frac{V_{dhwc}}{l_{PHE}} c_{p,wt} \frac{\partial T_{wt(3)}}{\partial t} = -\dot{m}_{wt(3)} c_{p,wt} \frac{\partial T_{wt(3)}}{\partial x_2} + 2 \frac{U_{PHE} A_{PHE}}{l_{PHE}} (T_{wt(2)} - T_{wt(3)}) \tag{5}$$

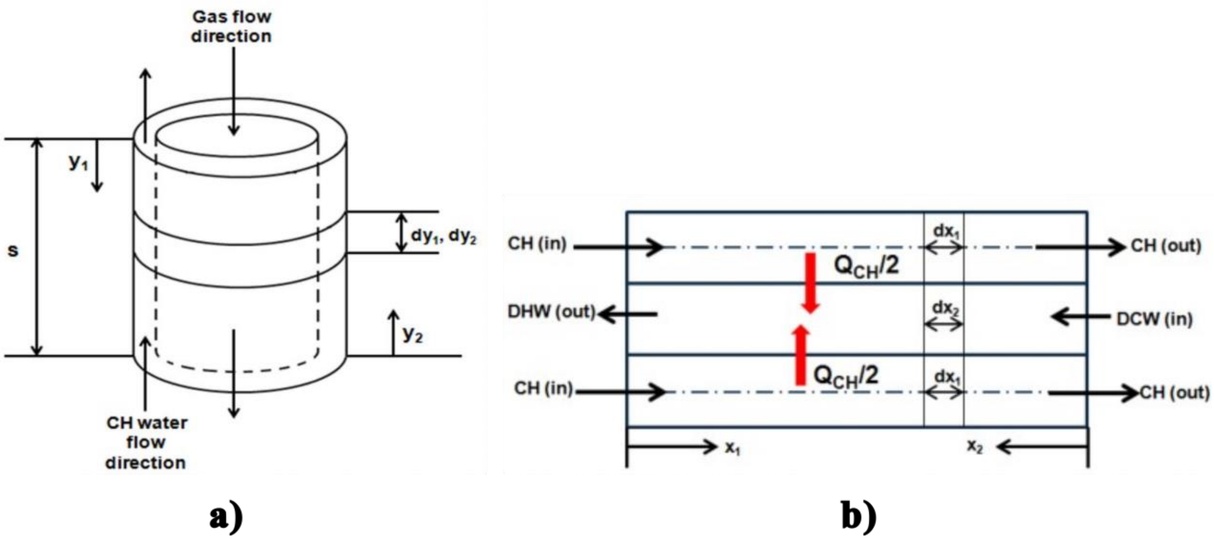

Figure 4. Display of the control volumes and water flow directions for (a) the HC and (b) the PHE [1].

Boundary and initial conditions are required to calculate the temperature profiles. Two boundary conditions are given to solve the HC wall equation since it is second order partial differential equation. For the others, one boundary condition is enough. The boundary condition of the first CH water equation (CH water in the HC) comes from the outlet temperature of the CH water of the PHE. Similarly, the boundary condition of the second CH water equation (CH water flowing through the PHE) is from the CH water outlet temperature of the HC as follows;

$$T_{wt(1)}(0,t) = T_{wt(2)}((l_{PHE}/dx_1),t) \tag{6}$$

$$T_{wt(2)}(0,t) = T_{wt(1)}((z/dy_2),t) \tag{7}$$

The boundary condition of the flue gas is the adiabatic flame temperature as

$$T_g(0,t) = T_{adia} \tag{8}$$

The boundary condition of the DHW in the PHE comes from the test conditions and it is given as

$$T_{wt(3)}(0,t) = 10\ °C \tag{9}$$

Finally, the boundary conditions of the HC wall heating equation are the convection surface condition [19] and expressed by

$$\left(-k_w \frac{\partial T_w}{\partial y_2}\right)_{y_2=0} = h_\infty\big(T_\infty - T_w(0,t)\big) \tag{10}$$

$$\left(-k_w \frac{\partial T_w}{\partial y_2}\right)_{y_2=s/dy_1} = h_\infty(T_\infty - T_w((s/\,dy_1),t)) \tag{11}$$

Initial conditions are described with reference to the test conditions as

$$T_{g,wt(1),w}(y_{1,2},0) = 10\ °C \tag{12}$$

$$T_{wt(2),wt(3)}\left(x_{1,2},0\right) = 10°C \tag{13}$$

3.2. TRNSYS Model

TRNSYS software used for simulations of various electrical and thermal systems such as heating/cooling, HVAC, and alternative energy sources etc., consists of two parts, namely the kernel and the user interface. Kernel section reading and processing the inputs defined by the user or the model, solves the system/model equations iteratively, determines the convergence, and creates the system variables. In the user interface section, there are models of the system components called "Type" in the existing libraries of TRNSYS. Simulation components can be selected from the types in the library or the components can be created by the user with various programming languages such as Fortran, MATLAB or Python.

In order to simulate the DHW heating circuit of the combi boiler displayed schematically in Figure 1, TRNSYS types are selected from the library in accordance with the characteristics of each component. The combi boiler simulation model created using standard library types in TRNSYS user interface is shown in Figure 5 and all component specifications are given in Table 1 with all details. The colour of the lines in Figure 1 represents the high and low temperature profile of the CH water and DHW as red lines and blue lines are used for hot and relatively cold water, respectively; whereas colour lines in Figure 5 displaying the current DHW circuit model declares the three main sub-sections of TRNSYS model.

TRNSYS model is categorized into three main sub-sections as follows; (i) CH flow circulation, (ii) DHW circuit, and (iii) flow diagrams of the component adjustment and the controlling tools. The first sub-section is the red circuit, in which the CH water flows through a closed loop and the heat input represents the combustion of the natural gas.

Selected components from the TRNSYS library given in the red circuit are Type 114-single speed pump model providing fluid drive, Type 31-pipe model representing the pipeline in the system, Type 5b-counterflow heat exchanger in which the heat is transferred to domestic water (representing the plate heat exchanger), Type 155-MATLAB model for the heat cell component where heat input is defined to replace simply the natural gas combustion, and Type 682 used to include the heat retention of the heat cell as the load module.

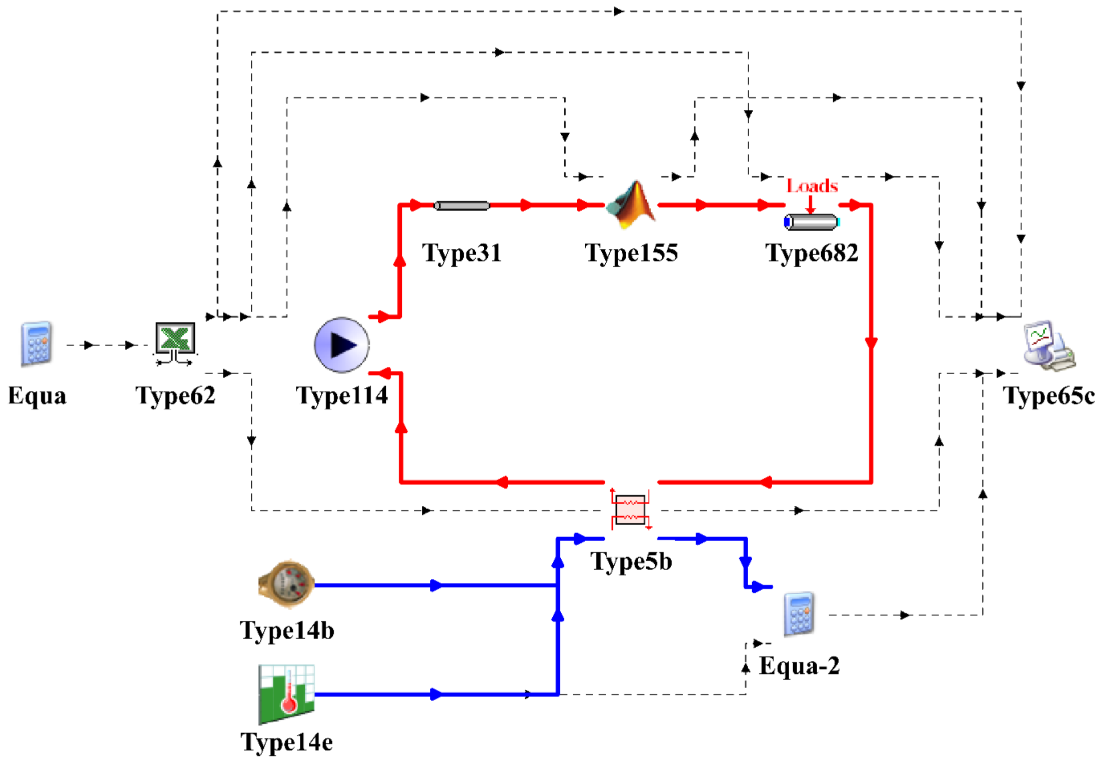

Figure 5. DHW heating circuit model of the combi boiler created in TRNSYS user interface.

Table 1. Modules of the system elements used for the DHW circuit model of the combi boiler in TRNSYS software.

Type Numbers	Library - Type Names
Equa	Equation Model
Type 62	Calling External Programs – MS Excel
Type 14b	Forcing Functions – Water Draw Model
Type 14e	Forcing Functions – Temperature Profile Model
Type 114	Hydronics – Single Speed Pump Model
Type 31	Hydronics – Pipe model
Type 155	Calling External Programs - MATLAB
Type 5b	Hydronics – Counter Flow Heat Exchanger Model
Loads Type 682	Load and Structures – Flow Stream Loads Model
Type 65c	Output – Online Plotter with File

The second main sub-section obtaining the DHW by heating the DCW according to the user demand is shown in the blue circuit. Type 14b of mass flow rate specification and Type 14e for temperature declaration components in the blue circuit represent user request and provide time-dependent demand data. In addition, Type 5b is used as the plate heat exchanger, which is one of the combi boiler components and the blue circuit passes on the load side of Type 5b-counterflow heat exchanger model. Lastly, the temperature difference between DHW and DCW is calculated using Equa-2.

The third main sub-section contains the adjustment and control tools and is indicated by the dashed black line. When the third main sub-section components are considered in hierarchical order from left to right in this circuit schematic view of Figure 5, the first input component is used to define the current time in seconds and the nominal power of the combi boiler for the investigated operating condition through the calculation module named "Equa". Then, the power modulation, heat retention effects of the heat cell in the CH circuit, and the multiplication of the overall heat transfer coefficient and the heat transfer area (symbolized with the UA designation of the counterflow plate heat exchanger) provided by the experimental data are included in the simulation by using Type 62-Excel module as the time-dependent input style. Experimental measurements required to define the time-dependent power modulation, UA coefficient and the load profile are expressed in detail in the next section. Finally, all outputs from the simulations such as the temperature difference between DCW and DHW, the CH water temperature at the HC inlet and outlet are printed using Type 65c-online plotter.

A comprehensive model is created by using the time-dependent experimental data included in the simulation as the inputs for the control and adjustments of Type 155-MATLAB Module (heat cell with combustion energy input), Type 682-the flow stream loads model, and Type 5b-counter flow plate heat exchanger components. The energy input as a result of the combustion, the heat retention effects in the CH circuit, and the UA coefficient of the counter-flow plate heat exchanger are defined in the Type 62-Excel module, as shown in Figure 5, and all these inputs are transmitted to Type 155-Matlab Module (heat cell), Type 682-the flow stream loads model, and Type 5b-counter flow plate heat exchanger, respectively.

Three main inputs of the DHW circuit model in TRNSYS are the burner power modulation, UA profile during heating of the DHW, and the HC load profile. The power modulations provided as the inputs to the simulations are given in the plots of the result section for all of the investigated operating conditions. Percentages of the burner power higher than 100% is because of the difference between the maximum power values of the space and DHW heating functions. The time-dependent variations of the UA coefficient used in the plate heat exchanger component are presented in Figure 6. In addition, time dependent data of the heat retention effects in the CH circuit are included in the simulation since it affects the variation of the outlet temperature of the CH water from the HC and hence the transient heat transfer to the DHW. The main reason for this situation is that the components in TRNSYS software include no mass content to store heat for the simulations. Therefore, elaborate data collection and calculations of some of the inputs from these data are required to evaluate the transient heat transfer in a more realistic way.

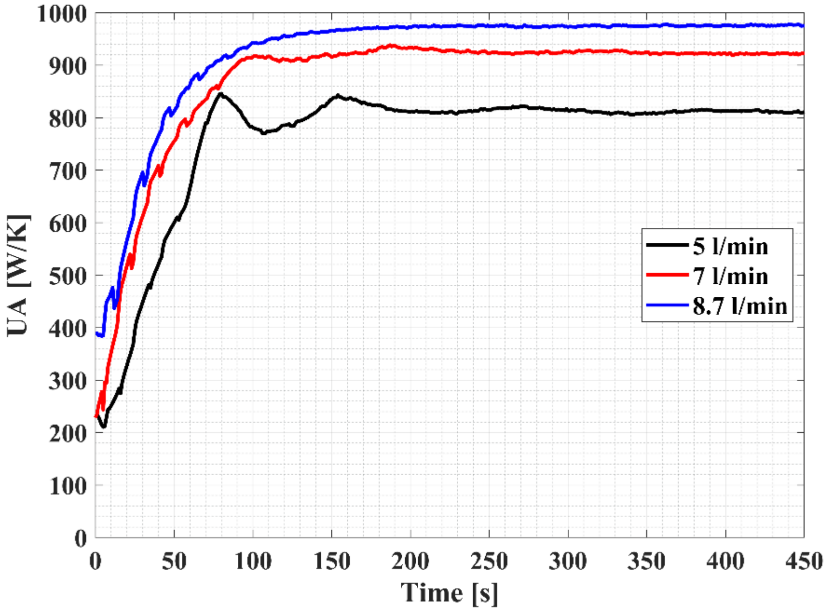

Figure 6. Variation of the UA coefficient for the Type 5b-counterflow plate heat exchanger.

4. EXPERIMENTAL TEST RIG

The details of the experimental test rig were explained comprehensively by Atmaca et al. (2015) [1]. The test rig is a commercial setup which is widely used for the comfort and efficiency evaluations of the combi boilers. CH inlet and CH outlet temperatures of the HC and DHW inlet and outlet temperatures of the PHE are measured with this test rig shown in Figure 7. The main measurement equipments are data logger, T-type thermocouples, and the flow meters. The data logger has an accuracy of ±0.04%, while the thermocouples have an error range of ±1.0 °C. Lastly, the flow meters of the test rig has measurement accuracy of ±1% of the read flow rate. Experimental "UA" values are obtained from these measurements.

In the TRNSYS model of this proposal, some of the model parameters are to be defined experimentally to estimate the transient DHW temperature profile better. The power profile of the appliance is measured directly. Temperatures of the CH water from the inlet and outlet of the HC and DHW inlet and outlet temperatures from the PHE are recorded as well in order to determine both the variation of the UA coefficient based on the operating conditions as shown in Figure 6 and load profile of the HC representing the stored energy by the HC mass block.

The amount of energy transferred to the DHW could easily be determined. By using this energy and the logarithmic mean temperature difference of the PHE, variation of the UA coefficient is obtained. Moreover, the difference between the measured power and the energy transfer rate to the DHW is used as the HC load profile. These aspects are of vital importance in order to determine the transient behaviour of the appliance.

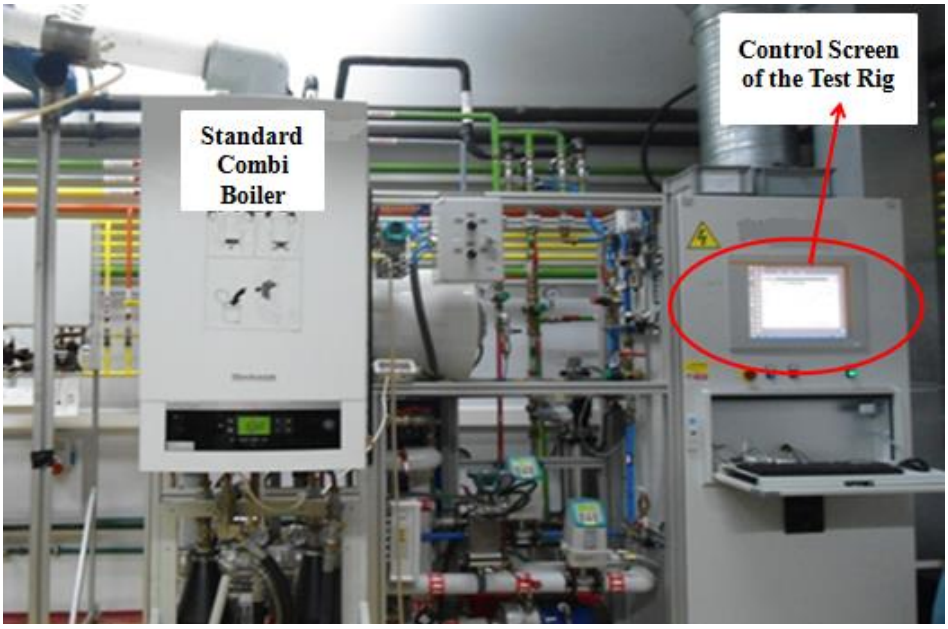

Figure 7. Combi boiler test rig [1].

5. RESULTS AND DISCUSSION

There are three validation cases comprised of 5 l/min, 7 l/min, and 8.7 l/min DHW flow rates. For each flow rate, CH inlet and outlet temperatures of the HC and the temperature difference of the DHW between the inlet and outlet of the PHE are presented with the concerning power profile. Furthermore, each plot displays the temperature profile obtained from the 1D model of Atmaca et al. (2015) [1], the TRNSYS model, and the experimental data. All conclusions are supported by the mean absolute error (MAE), mean square error (MSE), and root mean square error (RMSE) calculations tabulated in Table 2 and Table 3 for the temperature profile of the steady-state region and the overall temperature distribution including the transient region as well, respectively.

MAE and MSE are important regression metrics. MAE is defined as the average of the absolute errors between the calculated and measured values and formulated as

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|y_{exp,i} - y_{theo,i}\right| \tag{14}$$

The MSE is the average of the square of the error and given as

$$MSE = \frac{1}{n}\sum_{i=1}^{n}\left(y_{exp,i} - y_{theo,i}\right)^2 \tag{15}$$

The RMSE is the square root of the MSE and shows the degree of the agreement between the calculated and measured values as expressed below

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(y_{exp,i} - y_{theo,i}\right)^2} \tag{16}$$

Figure 8 (a), (b), and (c) show the CH inlet temperature, CH outlet temperature, and DHW inlet and outlet temperature difference, respectively for 5 l/min DHW user demand. It is obvious that the steady-state temperature estimation is satisfactory for both the 1D model and the TRNSYS model. However, in the transient region at which power modulation is observed, the TRNSYS model yields closer temperature variations to the actual temperature profile.

Figure 9 compares the CH inlet temperature, the CH outlet temperature, and the DHW inlet and outlet temperature difference for 7 l/min DHW user request. Like previous comparison displayed for 5 l/min DHW flow rate, TRNSYS model results in less error in the transient region. The TRNSYS model has dependence on the experimental data. Hence, the TRNSYS model is superior to 1D model especially for the transient temperature profile. Lastly, Figure 10 is the comparison for the third validation case of 8.7 l/min DHW flow rate.

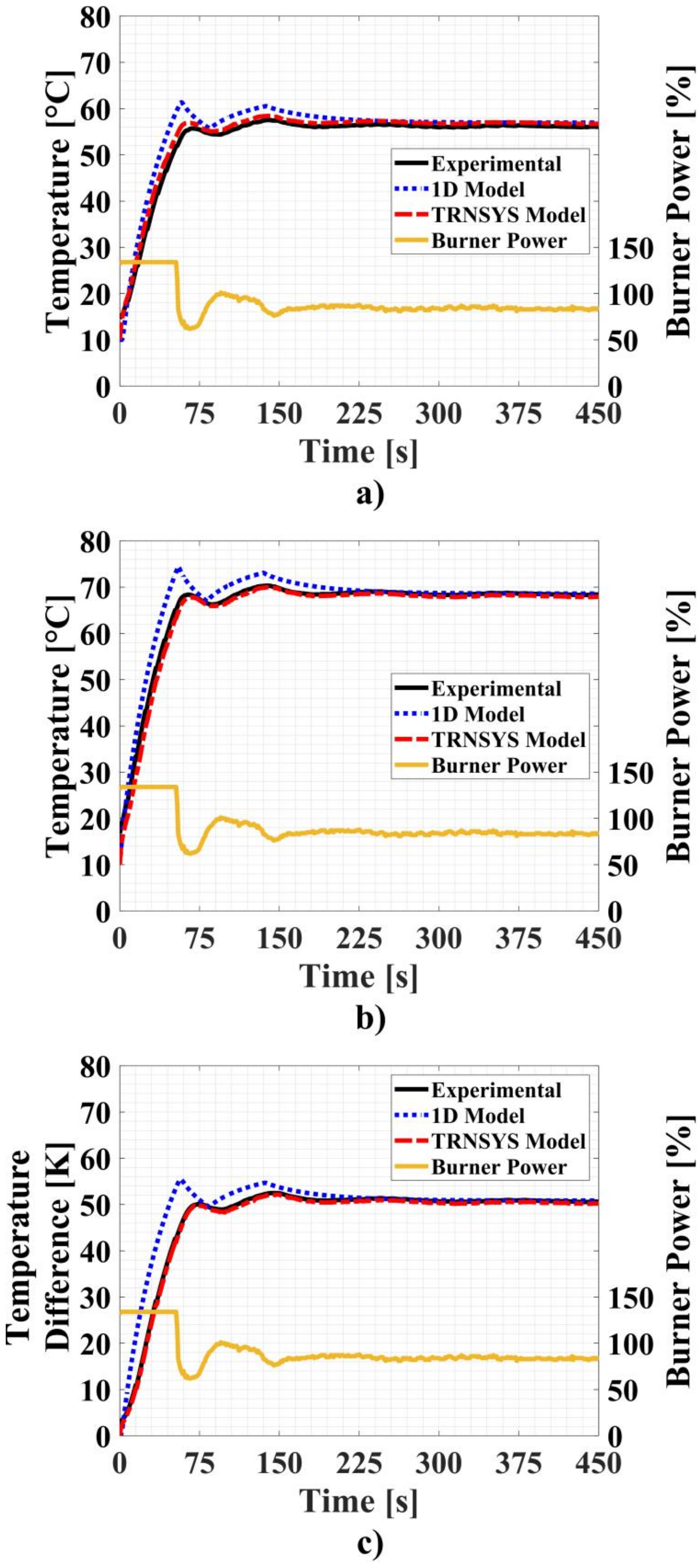

Figure 8. Comparison of (a) the CH inlet temperature, (b) the CH outlet temperature, and (c) the DHW inlet and outlet temperature difference among the 1D model, TRNSYS model, and the experimental data for 5 l/min DHW flow rate.

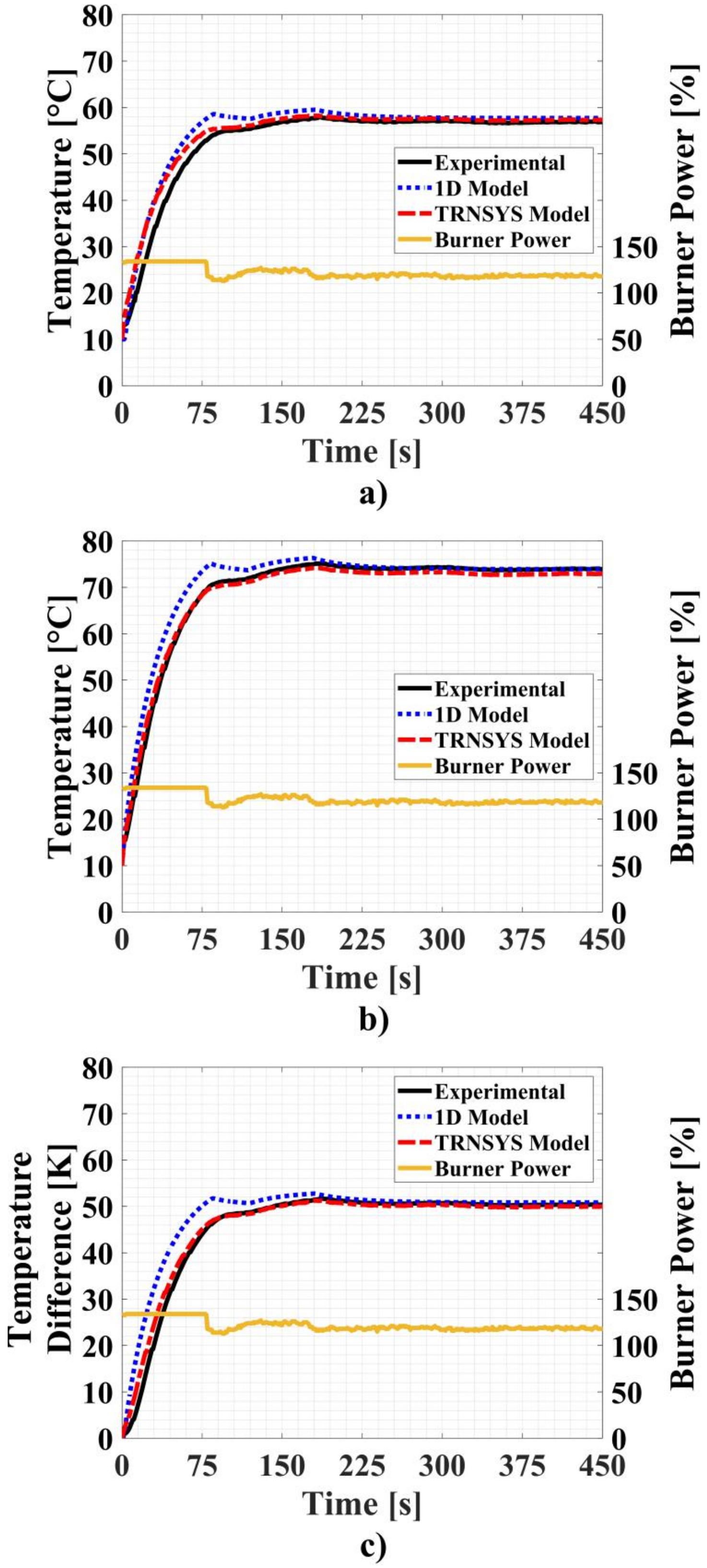

Figure 9. Comparison of (a) the CH inlet temperature, (b) the CH outlet temperature, and (c) the DHW inlet and outlet temperature difference among the 1D model, TRNSYS model, and the experimental data for 7 l/min DHW flow rate.

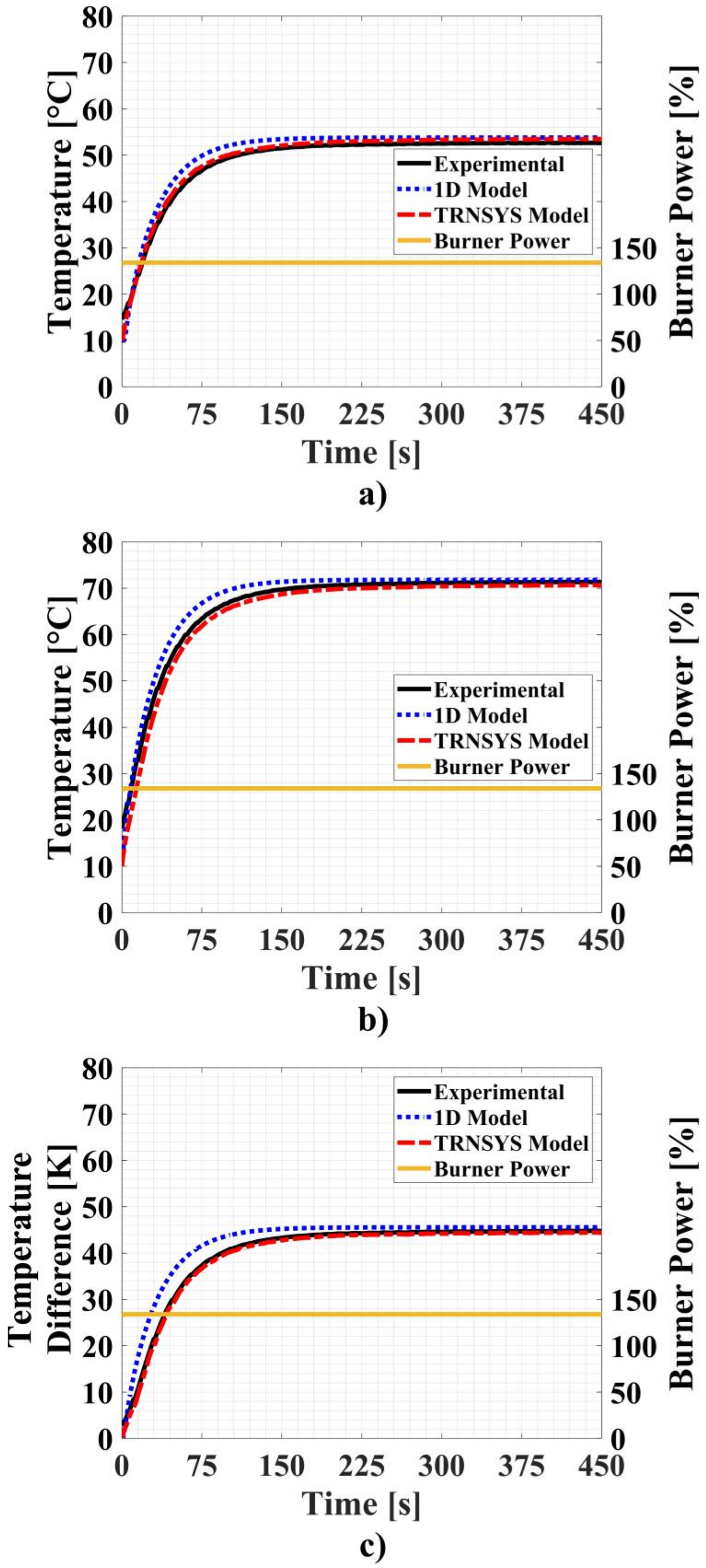

Figure 10. Comparison of (a) the CH inlet temperature, (b) the CH outlet temperature, and (c) the DHW inlet and outlet temperature difference among the 1D model, TRNSYS model, and the experimental data for 8.7 l/min DHW flow rate.

To sum up, for the steady-state temperature estimation, TRNSYS model error is less than the 1D model or they are nearly the same. Moreover, TRNSYS model decreases the error substantially for the overall temperature profile including the transient region. The comparison for DHW temperature difference between the inlet and outlet of the PHE is the most critical since all effort is for providing the users with the requested water with a high comfort level. When considering this DHW temperature difference including both the transient and steady-state region, the MAE decreases from 2.04 °C, 2.39 °C, and 2.12 °C calculated with the 1D modelling approach to 0.46 °C, 0.81 °C, and 0.53 °C of TRNSYS model for 5 l/min, 7 l/min, and 8.7 l/min, respectively.

It is obvious so far that the TRNSY model sensitivity is better since it relies upon more experimental data in terms of UA coefficients variations, power modulation, and the load profile of the HC presenting the stored energy in the HC. 1D model as well uses the experimental UA coefficient. However, TRNSY model uses UA coefficient with respect to the transient behaviour of the appliance. Hence instead of a constant value, UA variation profile is inserted into the PHE model. The power modulation is inserted in both of the models. As for the load profile insertion of the TRNSYS model, 1D model solves the HC wall heating equation directly. This aspect increases the dependence of the TRNSYS model on the experimental data but improves the model predictions. Lastly, all MAE, MSE, and RMSE values are presented in Table 2 for the steady-state region comparisons and in Table 3 for the overall temperature profile covering the transient region.

6. CONCLUSION

TRNSYS model is established for the DHW heating function of the combi boiler appliance. DHW circuit is previously modelled by the authors of this paper and validated experimentally. A good agreement was achieved using this 1D model for the steady-state region. However, the previous model still needs improvement when the transient region is considered. The authors also used a commercial software to create the model of the DHW and it has also negative and positive sides when compared to the 1D model. The model with a commercial software is just given as the literature summary of the paper.

In this paper, the main objective is to establish a simple TRNSYS model for the DHW circuit of the combi boiler and to show the functionality of the TRNSYS for this kind of applications. For the steady-state region error, TRNSYS model yields less error or the error level is the same as the 1D model. Moreover, the previously established error range of 1D model in the steady-state region has already found satisfactory. The most important contribution of this TRNSYS model is the decrease in the error for the full temperature profile covering the transient region. However, the TRNSYS model still needs improvement due to the high dependence on the experimental data.

Table 2. MAE, MSE, and RMSE comparisons between the 1D model and the TRNSYS model with reference to steady-state region (between 200-500 seconds).

Error		**5 l/min**		**7 l/min**		**8.7 l/min**	
		1D model	**TRNSYS model**	**1D model**	**TRNSYS model**	**1D model**	**TRNSYS model**
$T_{CH,in}$	**MAE**	0.9110	0.6967	0.9420	0.4655	1.2762	0.7690
	MSE	0.8815	0.4897	0.9170	0.2201	1.6457	0.5935
	RMSE	0.9389	0.6998	0.9576	0.4692	1.2828	0.7704
$T_{CH,out}$	**MAE**	0.2466	0.4255	0.1817	1.0303	0.6850	0.7309
	MSE	0.1138	0.1836	0.0531	1.0642	0.5085	0.5360
	RMSE	0.3374	0.4284	0.2304	1.0316	0.7131	0.7321
ΔT_{DHW}	**MAE**	0.2042	0.4034	0.4627	0.4352	0.9734	0.3719
	MSE	0.0801	0.1640	0.2340	0.1929	0.9759	0.1389
	RMSE	0.2830	0.4050	0.4838	0.4392	0.9879	0.3727

Table 3. MAE, MSE, and RMSE comparisons between the 1D model and the TRNSYS model including the transient and steady-state region (0-500 seconds).

Error		**5 l/min**		**7 l/min**		**8.7 l/min**	
		1D model	**TRNSYS model**	**1D model**	**TRNSYS model**	**1D model**	**TRNSYS model**
$T_{CH,in}$	**MAE**	2.0664	0.9281	2.0829	1.2145	1.8319	0.7740
	MSE	7.5479	1.1563	7.3945	4.0742	4.0661	0.7153
	RMSE	2.7473	1.0753	2.7193	2.0185	2.0165	0.8458
$T_{CH,out}$	**MAE**	1.5852	0.7713	1.7332	1.0187	1.5202	1.2788
	MSE	6.9088	1.5431	8.6573	1.2464	3.7819	2.9822
	RMSE	2.6285	1.2422	2.9423	1.1164	1.9447	1.7269
ΔT_{DHW}	**MAE**	2.0414	0.4636	2.3897	0.8144	2.1203	0.5276
	MSE	16.2029	0.2494	17.0709	1.8399	7.8590	0.3656
	RMSE	4.0253	0.4994	4.1317	1.3564	2.8034	0.6047

7. FUTURE WORK

This paper is a part of a research subject focusing on the DHW circuit modelling of the combi boiler. Previously, a 1D model was established with the mathematical equations and a commercial software as well was used. This proposal simply constructs a TRNSYS model, but two important parameter definitions are made with respect to the experimental data. UA coefficient definition and the heat storage (retention) profile (capacity) are added to the model based on the experimental data.

As of the future study targets, the dependence of the DHW circuit model on the experimental data is decreased. Hence, a journal paper titled as "TRNSYS model of the combi boiler domestic hot water circuit with a focus on the parameter definition of the plate heat exchanger" is planned to investigate the effects of the UA coefficient definition. Moreover, TRNSYS model of the DHW heating function for the comfort mode simulations are planned to be validated.

NOMENCLATURE

ρ	Density, kg/m^3
c_p	Specific heat, J/kg·K
T	Temperature, ˚C
$\dot{m}$	Mass flow rate, kg/s
A_s	Heat transfer surface area, m^2
A_c	Flow cross-sectional area, m^2
A_{PHE}	Heat transfer area of each plate, m^2
h	Convective heat transfer coefficient, $W/m^2 \cdot K$
U	Overall heat transfer coefficient, $W/m^2 \cdot K$
l_{PHE}	Length of the PHE, m
s	HC height, m
t	Time, s
z	CH water flow length around the HC, m
k	Thermal conductivity, W/m·K
V_{chwc}	volume of the CH water at each hot water channel of the PHE, m^3
V_{dhwc}	Volume of the DHW at each cold-water channel of the PHE, m^3
dx_1	Control volume length in x_1 direction, m
dx_2	Control volume length in x_2 direction, m
dy_1	Control volume height in y_1 direction, m
dy_2	Control volume height in y_2 direction, m
Q_{CH}	Amount of heat transferred from CH water to DHW
T_{adia}	Adiabatic flame temperature, ˚C

UA	Multiplication of the overall heat transfer coefficient and the heat transfer area, W/K
n	Total number of the measurements or calculations from a specified point
y	Measured or calculated parameter, i.e. temperature

Subscripts

g	Hot combustion gases
wt (1)	CH water in the HC
wt (2)	CH water in the PHE
wt (3)	DHW in the PHE
w	HC wall
wt	Water
∞	Surrounding air
s	Surface
in	Inlet
out	Outlet
exp	Experimental
theo	Theoretical
i	i^{th} number of the measurement or calculation

Abbreviations

CH	Central heating
DHW	Domestic hot water
DCW	Domestic cold water
PHE	Plate heat exchanger
HC	Heat cell
MAE	Mean absolute error
MSE	Mean square error
RMSE	Root mean square error

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DECLARATION OF ETHICAL STANDARDS

The authors of the paper submitted declare that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Okan Gök: Construction of the TRNSYS model, evaluation and interpretation of the results, preparation of the manuscript, final check of the paper template, and proofreading.

Ayşe Uğurcan Atmaca: Previous experimental analyses, numerical calculations of 1D model, evaluation and interpretation of the results, preparation of the manuscript, final check of the paper template, and proofreading.

Hürrem Murat Altay: Previous numerical calculations of 1D model and evaluation and interpretation of the results.

Aytunç Erek: Evaluation and interpretation of the results, preparation of the manuscript, final check of the paper template, and proofreading.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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