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Parametric Investigation of a Standard Combi Boiler for Domestic Hot Water (DHW) Heating Function

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Abstract **–** Combi boilers heating space and domestic hot water (DHW) demanded by the users are so popular today as natural gas is widely available. In this study natural gas consuming combi boilers are investigated for DHW heating function via a theoretical model. For space heating function, very efficient appliances have been manufactured with the implementation of the condensing technology. However, there is still a huge gap to increase DHW efficiency and comfort level which differs from market to market. However, as the common point, all the users want to have hot water in a very short time without fluctuations when they create demand. Therefore, there is a real challenge between the brands in terms of research and development activities in this area. As a part of these kinds of researches, in this study, DHW heating function has been modelled as 1D transient energy equations of the heat exchangers in a standard combi boiler, and the theoretical model has been validated with the experiments. However, the main objective is carrying out a parametric investigation on the main heat exchanger of the combi boiler with the established mathematical model.

Keywords**:** Combi boilers, Domestic hot water (DHW), Heat cell (HC), Plate Heat Exchanger (PHE), Mathematical modelling, Parametric investigation.

Nomenclature:

ρ_g density of flue gas, kg/m3
ρ_{wt} density of water, kg/m^3
ρ_w density of HC wall, kg/m^3
c_{pg} specific heat of flue gas, J/kg-K
c_{pw} specific heat of HC wall, J/kg-K
c_{pwt} specific heat of water, J/kg-K
T_g temperature of combustion gases, ˚C
$T_{wt(1)}$ temperature of CH water in HC, ˚C
$T_{wt(2)}$ temperature of CH water in PHE, ˚C
$T_{wt(3)}$ temperature of DHW in PHE, ˚C
T_{adia} adiabatic flame temperature, ˚C
T_∞ surrounding air temperature, ˚C
T_w HC wall temperature, ˚C
$\dot{m}_{su(1)}$ mass flow rate of CH water in HC, kg/s
$\dot{m}_{su(2)}$ mass flow rate of CH water in PHE (per channel), kg/s
$\dot{m}_{su(3)}$ mass flow rate of DHW in PHE (per channel), kg/s
$\dot{m}_g$ mass flow rate of flue gas, kg/s
$A_{sa,g}$ HC inner heat transfer area (from gas domain), m^2
$A_{cs,g}$ cross-sectional area through which flue gas flows, m^2
$A_{sa,wt(1)}$ HC outer heat transfer area (to CH water), m^2
$A_{cs,wt(1)}$ cross-sectional area through which CH water around HC flows, m^2
A_o outermost area of HC (contact area with the surrounding air), m^2
$A_{cs,w}$ HC wall cross-sectional area along y_2 direction, m^2
A_{PHE} heat transfer area of one plate, m^2
h_g convective heat transfer coefficient of flue gas in the HC, W/m^2-K
$h_{wt(1)}$ convective heat transfer coefficient of CH water in the HC, W/m^2-K
$h_{wt(2)}$ convective heat transfer coefficient of CH water in PHE, W/m^2-K
$h_{wt(3)}$ convective heat transfer coefficient of DHW water in PHE, W/m^2-K
h_∞ natural convection coefficient of surrounding air, W/m^2-K
$U_{wt(1)}$ overall heat transfer coefficient between CH water and HC wall, W/m^2-K
U_{PHE} overall heat transfer coefficient between CH water and DHW in PHE, W/m^2-K
U_g overall heat transfer coefficient between flue gas and HC wall, W/m^2-K

l_{PHE} length of PHE, m
s HC length, m
z CH water flow length around the HC, m
k_w thermal conductivity of the HC wall, W/m-K
η_{fin} fin efficiency
$R_{t,g\text{-}w}$ total thermal resistance between flue gas and HC wall, K/W
$R_{t,wt(1)\text{-}w}$ total thermal resistance between CH water and HC wall, K/W
$R_{t,PHE}$ total thermal resistance between CH water and DHW in PHE, K/W
R_0 inner radius of HC wall, m
R_1 average of outer and inner radius of HC wall, m
R_2 outer radius of HC wall, m
R_3 outermost radius of HC
V_{CHWC} volume of CH water per channel of PHE, m^3
V_{DHWC} volume of DHW per channel of PHE, m^3
Q_{CH} energy transferred from CH water to DHW in PHE, J

Abbreviations:

CH *central heating*
DHW *domestic hot water*
DCW *domestic cold water*
PHE *plate heat exchanger*
HC *heat cell*
HE *heat exchanger*
CV control volume
CHWC *central heating water channel*
DHWC *domestic hot water channel*
BC *boundary condition*
IC *initial condition*

1. Introduction

Integrated space/water heating appliances commonly called combi boilers as shown in Fig. 1 generally have two heat exchangers.

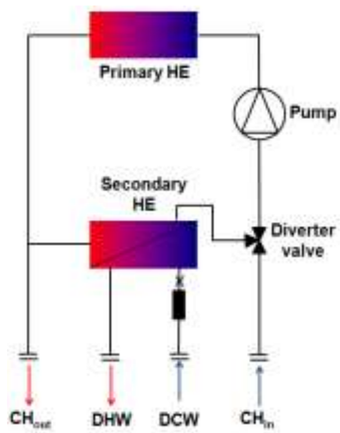

Fig. 1. Schematic view of a standard combi boiler.

The primary heat exchanger is responsible for heating the system water that is sent to the radiators for space heating. In times of DHW demand, the space heating function is interrupted and the system water heated in the primary heat exchanger is sent through the secondary heat exchangers to heat up the tapped water (DCW) demanded by the users.

The energy is supplied with the natural gas in the primary heat exchanger which is also called the heat cell (HC) as shown in Fig. 2 (a). The cross-flow conical HC has many pin fins inside to increase the heat transfer area between the flue gas and the CH water. The energy of the flue gas (products arisen at the end of combustion) is transferred to the system water (central heating (CH) water) in the HC and the energy of the CH water is transferred to the tapped water (DCW) in the secondary heat exchanger which is plate heat exchanger (PHE) as shown in Fig. 2 (b). The number of the plates is dependent upon the power of the heating appliance and corresponding counter-flow PHE to the heat cell at issue has 24 plates.

Fig. 2. (a) The conical heat cell and (b) plate heat exchangers with different number of plates.

In the literature, there are many academic researches modelling various kinds of heat exchangers under different operating conditions. Bunce et al. (1995) modelled a two-fluid heat exchanger, operating in a steady state working mode with constant inlet and outlet temperatures of the fluid streams. Junxiao et al. (1998) created a lumped parameter model for a two-pass gas-to-gas crossflow heat exchanger to investigate its transient behaviours. Mishra et al. (2006) investigated numerically the transient temperature response of cross-flow heat exchangers and Ünal (1998) modeled triple-concentric tube heat exchangers. Ataer et al. (1995) proposed three different simulation techniques to predict the transient response of cross-flow, finned-type heat exchangers. Gut et al. (2003) developed a mathematical model in algorithmic form in order to simulate temperature profiles in all channels, the thermal effectiveness, the distribution of the overall heat transfer coefficient, and the pressure drop of gasketed plate heat exchangers. As being different from the above-mentioned studies, our model includes simultaneous coupling of two heat exchangers simulating the working of an exact system such as a water heater or a combi boiler concept. In other words, our study creates the missing link between the detailed academic researches and the necessities of the real life problems.

As the methodology of the study, 1D transient energy equations have been solved in Matlab numerically. The numerical results have been compared with the experimental data and the mathematical model has been verified. As the main objective of the study, the validated model has been used to investigate various HC material alternatives and different CH water channel depths around the HC. The effects of the changes on the DHW outlet temperature are graphically displayed and interpreted.

2. Working Modes

The working modes have been summarized basically as eco and comfort mode for DHW heating function. In eco mode if there is hot water demand, the heat exchangers start working, otherwise they don't. However, in comfort mode, the CH water is heated regularly and kept between a critical temperature limit whether there is hot water request or not. Due to the hot CH water kept in the system, DHW set temperature is reached rapidly when compared to eco mode as shown in Fig. 3.

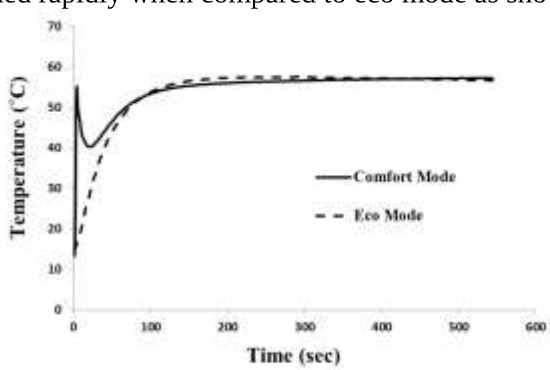

Fig. 3. Comparison of experimental DHW outlet temperature in eco and comfort mode.

3. Numerical Model

The mathematical model has been constructed with the combination of the heat exchangers given in Fig. 2. Transient energy equations are 1D and there are no thermal energy sources within the exchangers. The mass flow rates of both streams do not vary with time. Fluid passages are uniform in cross-sections. The convective heat transfer coefficients on each side are constant. Longitudinal heat conduction within the fluids is neglected. The heat transfer surface area on each fluid side is uniformly distributed in the heat exchangers. In PHE, thermal resistance of the plates considered asnegligible. The fouling resistance in PHE is negligible.

3.1. Mathematical Equations

A cylindrical model has been built up for the conical heat cell as shown in Fig. 4 and PHE model is approximated to two subsequent channels of the cold and hot water as shown in Fig. 5.

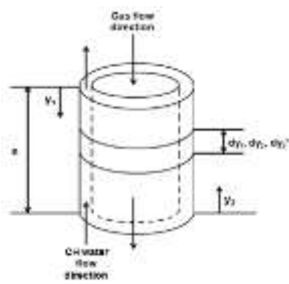

Fig. 4. CVs of the conical HC.

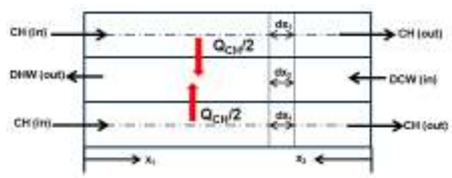

Fig. 5. CVs of the PHE.

For the conical HC, three equations are defined as gas cooling, HC wall heating, and CH water heating and given respectively.

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

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

$$\rho_{wt} A_{cs,wt(1)} c_{pwt} \frac{\partial T_{wt(1)}}{\partial t} = -\dot{m}_{wt(1)} \, c_{pwt} \frac{\partial T_{wt(1)}}{\partial y_2} + \frac{U_{wt(1)} A_{sa,wt(1)}}{z} (T_w - T_{wt(1)}) - h_\infty \frac{A_o}{z} (T_{wt(1)} - T_\infty) \tag{3}$$

Total thermal resistances are also modeled for CH water and gas domain as it is shown in Fig. 6 according to Incropera et al (2006).

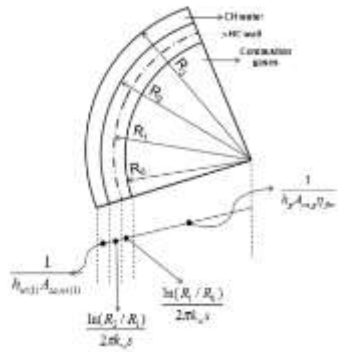

Fig. 6. Modelling of thermal resistances.

The total thermal resistance between the HC wall and the combustion gases and the total thermal resistance between the HC wall and CH water are given as follows;

$$R_{t,g-w} = \frac{1}{U_g A_{sa,g}} = \frac{1}{h_g A_{sa,g} \eta_{fin}} + \frac{\ln(R_1 / R_0)}{2\pi k_w s} \tag{4}$$

$$R_{t,wt(1)-w} = \frac{1}{U_{wt(1)} A_{sa,wt(1)}} = \frac{1}{h_{wt(1)} A_{sa,wt(1)}} + \frac{\ln(R_2 / R_1)}{2\pi k_w s} \tag{5}$$

Two equations are also defined for CH water in one layer of the PHE and DHW in the subsequent layer of the PHE and given below:

$$\rho_{wt} \frac{V_{CHWC}}{l_{PHE}} c_{pwt} \frac{\partial T_{wt(2)}}{\partial t} = -\dot{m}_{wt(2)} c_{pwt} \frac{\partial T_{wt(2)}}{\partial x_1} - 2 \frac{U_{PHE} A_{PHE}}{l_{PHE}} (T_{wt(2)} - T_{wt(3)}) \tag{6}$$

$$\rho_{wt} \frac{V_{DHWC}}{l_{PHE}} c_{pwt} \frac{\partial T_{wt(3)}}{\partial t} = -\dot{m}_{wt(3)} c_{pwt} \frac{\partial T_{wt(3)}}{\partial x_2} + 2 \frac{U_{PHE} A_{PHE}}{l_{PHE}} (T_{wt(2)} - T_{wt(3)}) \tag{7}$$

Total thermal resistance in PHE is given as

$$R_{t,PHE} = \frac{1}{U_{PHE} A_{PHE}} = \frac{1}{h_{wt(2)} A_{PHE}} + \frac{1}{h_{wt(3)} A_{PHE}} \tag{8}$$

3.2. Boundary and Initial Conditions

Finite Element Method is used to discretise the governing differential equations implicitly in order to solve them numerically. Initial conditions for the HC wall, the CH water in HC and PHE, the flue gas and DHW are given below. 10 ˚C is the reference temperature for testing.

$$T_{g,wt(1),w}(y_{1,2},0) = 10\,^{\circ}C \tag{9}$$

$$T_{wt(2),wt(3)}(x_{1,2},0) = 10\,^{\circ}C \tag{10}$$

The BCs of the CH water in HC and in PHE are interconnected and dependent on time. The BCs of DCW and the flue gas are used as constant values. For the combustion gases, adiabatic flame temperature assumption is used. For the BCs of the HC wall equation, convection surface condition is used according to Incropera et al (2006). For wall, because of the second order differential term, there are two necessary BCs.

$$T_{wt(1)}(0,t) = T_{wt(2)}((l_{PHE} / dx_1),t) \quad (11)$$

$$T_{wt(2)}(0,t) = T_{wt(1)}((z / dy_2),t) \quad (12)$$

$$T_{wt(3)}(0,t) = 10\,°C\,(10) \quad (13)$$

$$T_g(0,t) = T_{adia} \quad (14)$$

$$-k_w \frac{\partial T_w}{\partial y_2}\Big|_{y_2=0} = h_\infty (T_\infty - T_w(0,t)) \quad (15)$$

$$-k_w \frac{\partial T_w}{\partial y_2}\Big|_{y_2=(s/dy_1)} = h_\infty (T_\infty - T_w((s/dy_1),t)) \quad (16)$$

4. Evaluation of the Numerical Results

The numerical model was validated with the experiments and established as a general mathematical model for the combi boiler type heating appliances according to Atmaca et al. (2013). Fig. 7 shows the numerical and experimental DHW outlet and inlet temperature difference of 24-plate PHE and the conical HC combination in eco mode at 7 l/min DHW flow rate.

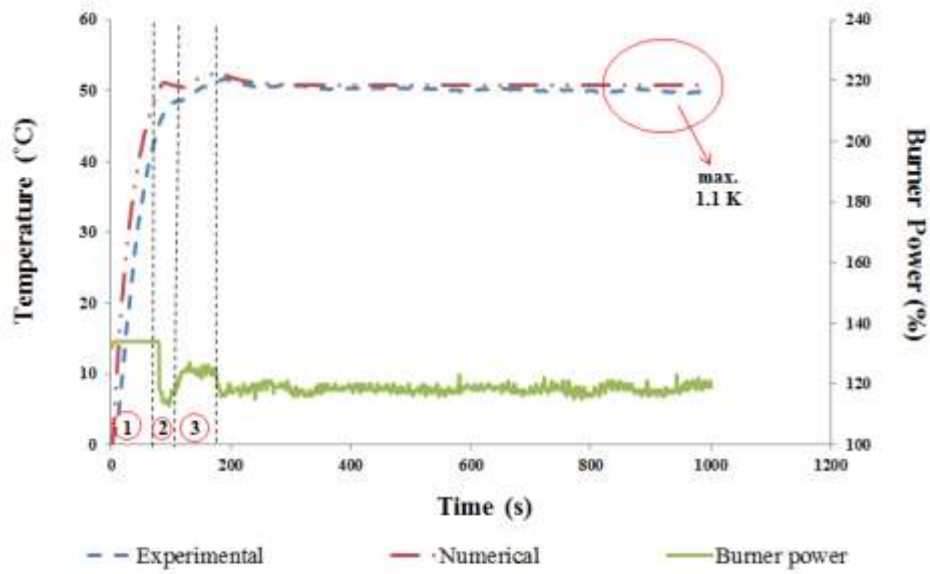

Fig. 7. Eco mode simulations for 7 l/min DHW tapping request.

Furthermore, Fig. 8 displays the numerical and experimental DHW outlet and inlet temperature difference of 24-plate PHE and the conical HC combination in comfort mode at 7 l/min DHW flow rate.

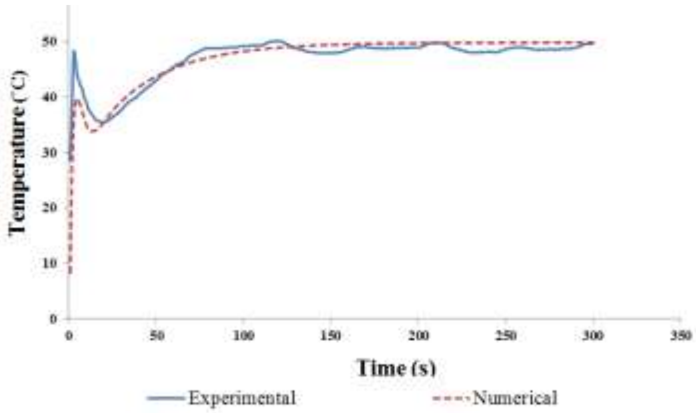

Fig. 8. Comfort mode simulations for 7 l/min DHW tapping request.

5. Parametric Investigation

The effects of various HC wall materials and different CH water channel depths around the HC have been investigated. All the effects of the changes are compared as the differences on DHW outlet temperature.

First change is made on the HC wall material. Three alternatives are presented as pure aluminum, aluminum alloy (Alloy 2024-T6, 4.5 % Cu, 1.5 % Mg, 0.6 % Mn), and carbon steels (Mn≤1%, Si≤0.1%). Because of the change in density, the mass varies according to material type for the same volume as displayed in Table 1.

Table 1. Comparison of various wall materials.

HC wall material	**Density (kg/m^3)**	**Mass (kg)**	**Specific heat, c_p (J/kgK)**	**Thermal conductivity, k (W/mK)**
Pure Aluminum	2702	8.5	903	237
Aluminum alloy (Alloy 2024-T6, 4.5 % Cu, 1.5 % Mg, 0.6 % Mn)	2770	8.7	875	177
Carbon steels (Mn≤1%, Si≤0.1%)	7854	24.7	434	60.5

Fig. 9 shows the effects of different HC wall material types on the DHW outlet temperature of the reference combi boiler.

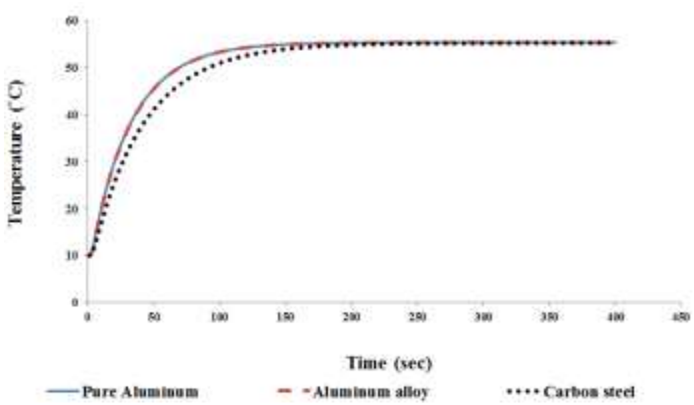

Fig. 9. Effect of the different HC wall materials on DHW outlet temperature of a combi boiler.

Second parametric study is about the CH water channel depth around the HC. The water mass is also affected by the depth of the channel. The changes in the water channel depths creates very little effects on the HC mass, but it is at ignorable levels as shown in Table 2. Different cross-section area of water flow causes the changes in flow characteristics which is strongly affected by the convective heat transfer coefficient. Table 2 summarizes all resultant changes according to the variations in water channel depth.

Table 2. Resultant changes for different water channel depths around the HC.

Water channel depth (mm)	Hydraulic diameter (mm)	Water volume capacity (m^3)	HC mass (kg)	Convective heat transfer coefficient of the water (W/m^2K)
6.8	10.9	0.7796	8.4683	16198
7.3	11.5	0.8370	8.5	14632
7.8	12.2	0.8943	8.5317	13326
8.3	12.7	0.9516	8.5634	12221

Fig. 10 shows the effects of different water channel depths on the DHW outlet temperature of the reference combi boiler.

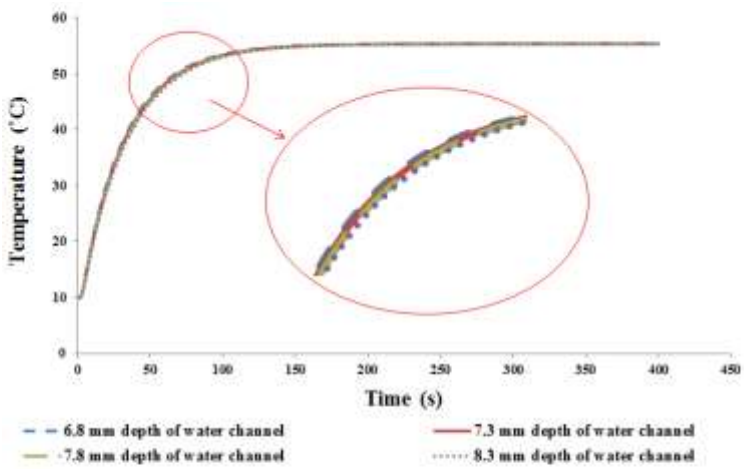

Fig. 10. Effects of different water channel depths on the DHW outlet temperature of the standard combi boiler.

6. Conclusion

Finally a mathematical model has been obtained to test any changes on regular appliances or completely new design concepts, even if they are only idea, with computer simulations thereby decreasing the cost, time, and energy spent on the trial-and-error phases of the laboratory works.

As the main objective, via the constructed mathematical model, the parametric investigation has been carried out on the primary heat exchanger of a standard combi boiler appliance and the effects of the variations in the HC wall material and water channel depths have been discussed.

Transient duration in DHW outlet temperature is smaller if Aluminum or its alloy is used when compared to the carbon steel because of the higher thermal conductivity and lower density. Smaller water depths are preferred for high rate of the heat transfer since smaller hydraulic diameters result in better convective heat transfer coefficients for CH water side. The changes in the CH water channel depths investigated within the concept of this study have minor effects on the DHW outlet temperature, but it is useful to observe the main tendency.

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