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Comparison of two numerical approaches to the domestic hot water circuit in a combi boiler appliance

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ABSTRACT

This study mainly touches on natural gas fueled combi boiler appliances having space and water heating functions. The hot water demanded in any type of building for daily activities such as personal hygiene, cleaning, and bathing is referred to as *domestic hot water (DHW)*. Since high efficiency targets have been already reached with respect to the space heating, most of the research and development activities are now focusing on the DHW heating function. Therefore, the subject of this study is concerned with only DHW heating function and the basic objective is making a comprehensive comparison between two mathematical models via different approaches for the same DHW circuit. In the first approach, basic heat transfer equations for DHW heating function are established by means of one-dimensional and time dependent differential equations. Later on, those transient energy equations were discretized by finite-difference method implicitly and solved simultaneously in Matlab®. The second model has been constructed with the help of commercial software, Flowmaster® which is one-dimensional thermo-fluid simulation tool. Then, the numerical results have been compared with the experimental data and the validity of the models has been discussed separately on the basis of the agreement between them. The advantages of both models have been evaluated as the distinctive contributions to the literature from DHW circuit modeling viewpoint. Among the intensive research and development activities of the combi boiler manufacturers to achieve high DHW comfort scores for high selling rates in the market, decreasing the time and money spent on the laboratory tests of the appliances is a challenging issue. Number of the laboratory tests is proposed to be decreased due to the preliminary results obtained from properly working numerical models for the performance analyses of completely new appliance concepts or design modifications on the regular appliances.

1. Introduction

Combi boilers which are dual function heating appliances to be used for space and DHW heating are one of the indispensable appliances in every residence. Another aspect resulting in widely use of these integrated space/water heaters is the availability of the natural gas commonly consumed by the boilers as their energy source. As to these respects, there is a dramatic increase in the product scope of the combi boiler manufacturers.

Besides, accompanying research and development activities are of primary importance to the manufacturers to serve appliances providing high comfort levels and efficiency values as most as possible. Prior to displaying an appliance in the market, the background laboratory testing to certify the basic characteristics such as efficiency value, comfort level, etc. is a long period and requires a huge budget especially in terms of prototype costs and labor of the engineers and the technicians. Therefore, modeling studies are utterly essential for the development activities to reduce time, energy, and money spent on the laboratory works and prototypes. Within the content of this study, two numerical models are built up only for the DHW heating function to investigate the performance thoroughly by means of the comparisons between the theoretical calculations at issue and the experimental data.

A typical commonly used combi boiler appliance has two basic components, namely the primary and secondary heat exchangers, as shown in Fig. 1. The primary heat exchanger is responsible for

Abbreviations: CH, central heating; DHW, domestic hot water; DCW, domestic cold water; PHE, plate heat exchanger; HC, heat cell.

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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_o	Heat transfer area to the surrounding air, m^2
A_{PHE}	Heat transfer area of each plate, m^2
h	Convective heat transfer coefficient, W/m^2 K
U	Overall heat transfer coefficient, W/m^2 K
l_{PHE}	Length of the PHE, m
s	HC height, m
t	Time
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
$y_{exp,i}$	ith experimental datum
$y_{theo,i}$	ith calculated value
RE_i	ith calculated relative error
RE_{ave}	Average relative error
N	Number of the observed data (experimental or theoretical)

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

heating up the system water which is called the central heating (CH) water circulating through the radiators to give its energy to the surrounding air. Then, it cools down and turns back to the primary heat exchanger to be heated up again. This simple operation order is the summary of the space heating function.

In a combi boiler appliance, when users create DHW demand, space heating is stopped since both of the functions cannot be activated at the same time. At the time of DHW request, the diverter valve changes its direction and the water heated up by the primary heat exchanger is sent through the secondary heat exchanger instead of the radiators. Therefore, the domestic cold water (DCW) is heated to produce DHW requested by the users. As the main target of this study, the simple working algorithm of the DHW circuit will be created with two different modeling approaches to yield the heat transfer rates to CH water and DHW separately at different operation conditions.

The route-map of the study contains three steps in main: (i) theoretical model including energy transfer equations, (ii) simulations via commercial software, and (iii) experimental validation of both models. Firstly, the primary and the secondary heat exchangers are modeled according to the thermodynamics laws and their working order in DHW mode are explained by means of the governing differential equations. Next, a commercial one-dimensional thermo-fluid simulation tool is used to create the model of the same circuit. As the last step, experiments are conducted to present a comparative discussion regarding heat transfer rate calculations of DHW and CH water sides in order to validate both of the theoretical models established by the commercial software and the proposed algorithm of the differential equations.

The transient regions especially in DHW outlet temperature presented as heat rate profiles in this study have an effective role on the comfort level of the appliances to be declared to the consumers. The importance of the transient region investigations becomes apparent especially for the DHW requests at some flow rates causing modulation in the appliance power. The direct response of this power modulation in the DHW outlet temperatures are given in Fig. 2 for 5 and 7 l/min hot water requests. The power modulation data and corresponding DHW outlet temperature profiles are directly recorded from the appliance at the above-mentioned DHW requests.

Making elaborative parametric analyses concerning both the operation and design, mathematical models are required to avoid from the money and time spent on the developments tests and prototypes. Subsequently, there are numerous modeling studies with various simulation tools in the literature as given below. The previous researches are categorized in three groups; (i) experimental and numerical heat exchanger studies, (ii) combi boiler studies, and (iii) the models including Flowmaster®.

Although heat exchangers have been studied for so long, they have been still researched from various aspects, i.e., optimization algorithms via different methods, transient response investigations, and analyses of different applications, etc. Mishra et al. [1] investigated the transient temperature response of the cross-flow heat exchangers numerically when perturbations were created both in temperature and flow. Conservation of the energy was applied to the wall and two fluids and the equations were discretized using the implicit finite difference technique. Sarraf et al. [2] numerically investigated the relation between the flow structures and friction coefficients. Firstly, a general agreement between the numerical and experimental data was obtained for the model verification. The numerical simulations were conducted with the computational fluid dynamics (CFD) software STARCCM+®. Mota et al. [3] worked on the optimization of the heat exchange area of the plate heat exchangers using the screening method. Finding the configuration of the lowest number of the plates for a given process and the type of the plate was the main target of the proposed algorithm. The major contribution of the study is that there is no need to use additional software. Differential equations of the system were solved analytically and the algorithm under question was validated through a case study from the literature. Tiwari et al. [4] made a numerical investigation on the heat transfer and fluid flow characteristics of a single pass counter-flow chevron corrugated plate heat exchanger employing the nanofluids. The agreement between the numerical results and the experimental data showed that the established model can be used to calculate performance characteristics of the plate heat exchangers under consideration. Korzen and Taler [5] described a new equation set to analyze the dynamics of the plate fin and tube heat exchangers using the finite volume method. The model was constructed for a car radiator and examined experimentally with the help of the water and air outlet temperature comparisons. Yang et al. [6] made a comparison among the four modeling methods, i.e., (i) the unit model, (ii) the periodic model, (iii) the porous model, and (iv) the whole model for a rod-baffle shell-and-tube heat exchanger. The first two approaches modeled only a small subsection of the heat exchanger, whereas the third one considered the heat exchanger as a porous medium. Lastly, the fourth one created the model of the heat exchanger using CFD.