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Dynamic Model of a Boiler Adaptable to Green Fuels for a Heating System

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ABSTRACT

A mathematical model of a fuel combustion boiler suitable for system level studies of a heating system and adaptable to different combustible fuels is presented. The model considers the thermophysical properties of the flue gas and of the heat transfer fluid, mass flow rates and temperatures. To provide confidence into the modelling approach, the model was built in MATLAB/ Simulink and simulation results were compared with results obtained with Apros. Results exhibited a good agreement between both software platforms under different mass flow rate conditions when methane and hydrogen were employed as fuels.

Keywords: Dynamic model, gas boiler, green fuels, combustion, heat transfer.

NOMENCLATURE

Abbreviations	
HTF	Heat transfer fluid
Subscripts	
$ad, stoic$	Adiabatic, stoichiometric
fg	Flue gas
h, c	Hot, cold stream
j, n	Cell number, total number of cells
s, t	Shell, tubes (heat exchanger)
i	Input
Symbols	
A	Heat transfer area (m^2)
A_t	Area of all tubes (m^2)
$A/F,\ \emptyset$	Air-fuel ratio, equivalence ratio
c_p	Specific heat (J/kg°C)
e	Excess air (%)
h_f	Enthalpy of formation (J/mol)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
ρ	Density (kg/m^3)
T	Temperature (°C)
U	Heat transfer coefficient ($W/m^2°C$)
v	Mean velocity (m/s)

1. INTRODUCTION

Energy demand and environmental awareness have increased in past years, leading to a widespread adoption of low carbon energy resources and thus affecting the way energy is converted and consumed. However, these resources are critical to meet policy targets on reduction of carbon emissions. Robust strategies considering all energy sectors and their interdependencies are in turn required. The heating sector will play a crucial role to achieve decarbonisation of energy systems, where the adoption of low carbon heat sources and replacement of fossil fuels with green fuels is seen as the future [1].

Mathematical models should be tailored to the application and the physical phenomenon to be studied. For a heating system, detailed models of individual components have been developed. These are used for detailed heat transfer or hydraulic studies, but they tend to be complex [2]. Steady-state models enable operation scheduling and system optimisation; however, models considering a dynamic regime are required to guarantee the effective operation of a system and to maximise its performance [3]. Component representations suitable for control system design and for system level studies are less common, although models of heat exchangers and thermal energy storage units are available [4, 5]. Availability of dynamic models for heat sources such as gas boilers, due to their complexity, is limited.

Most references on dynamic models of boilers focus on a specific type of boiler or on detailed representations including chemical processes [6, 7]. In addition, water is usually converted into steam, which implies steam is the end-product [8]. However, heating systems of public facilities (e.g. civic buildings, hospitals) use gas boilers to meet heat demands for space heating and hot water.

This paper presents a dynamic model of a fuel combustion boiler. The model is adaptable to consider different types of fuels, such as biofuels, methane, and hydrogen. The combustion process is represented using

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a stoichiometric relation and the model of a counter-flow heat exchanger is adopted to represent the heat transfer between the flue gas and the heat transfer fluid (HTF). Although the model is simple, it considers fundamental variables such as mass flow rate and temperature, and thermophysical properties of the flue gas and the HTF. The simplicity of the modelling approach makes the presented model suitable for system level studies of heating systems.

2. DYNAMIC MODELS

2.1 Representation of the boiler

The fuel combustion boiler [9] is modelled as a heat source with two main subsystems: the combustion chamber and the heat transfer process from the flue gas to the HTF (see Fig. 1).

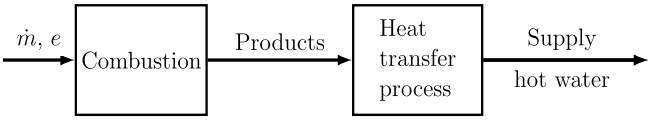

Fig. 1. Block diagram of the fuel combustion boiler: combustion and heat transfer processes.

2.2 Operating principle of the combustion chamber

The thermal energy used to heat water is obtained by burning a combustible material (e.g. a fossil fuel) in the combustion chamber. This process is an exothermic chemical reaction between the fuel and an oxidiser (air) [10]-[12]. In the model developed (see Fig. 1), the inputs to the combustion chamber are the mass flow rate of the fuel and the percentage of excess air. The hot flue gas products of the combustion process exit the combustion chamber. The output variables of interest are the mass flow rate and the temperature of the flue gas.

2.3 Modelling of the combustion chamber

To demonstrate the modelling approach, methane (CH_4) is used—the largest component of natural gas and biogas mixtures. Methane is combusted in the presence of air, which contains 21% of oxygen and 79% nitrogen.

For simplicity, it is assumed that the combustion is a stoichiometric reaction. In general, for a hydrocarbon fuel (C_xH_y) this is expressed as [12]:

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + (y/2)H_2O + 3.76aN_2 \quad (1)$$

where $a = x + y/4$. To determine the air required for complete combustion the air-fuel ratio is used. The stoichiometric air-fuel ratio is calculated as

$$(A/F)_{stoic} = \left(\frac{m_{air}}{m_{fuel}}\right)_{stoic} \quad (2)$$

Let the equivalence ratio be defined as:

$$\emptyset = \frac{(A/F)_{stoic}}{(A/F)} \quad (3)$$

If insufficient air is provided into the combustion chamber some fuel will not burn. This is known as a fuel-rich mixture and $\emptyset > 1$. On the other hand, the provision of excess air may lead to an inefficient operation, resulting from a fuel-lean mixture where $\emptyset < 1$. When $\emptyset = 1$, the mixture is known as stoichiometric.

The actual air-fuel ratio (A/F) is determined as [13]

$$A/F = (1 + e) \times (A/F)_{stoic} \quad (4)$$

where e is the percentage of excess air. Mass balance is used to determine the masses of substances. Hence,

$$\dot{m}_{air} = (\dot{m}_{fuel}) \times (A/F) \quad (5)$$

$$\dot{m}_{fg} = \dot{m}_{air} + \dot{m}_{fuel} \quad (6)$$

The adiabatic temperature of the combustion products is determined through an energy balance. Assuming a process with constant pressure and an initial temperature of 25°C, this is defined as [12]

$$\sum_{\text{reactants}} N_i h_{f,i} = \sum_{\text{products}} N_i\left[h_{f,i} + c_{p,i}(T_{ad,i} - 25)\right] \quad (7)$$

where N is the number of molecules. The enthalpy of the products considers the specific heat (in J/mol°C) and the temperature difference brought by the combustion. T_{ad} is the temperature of the flue gas which is injected to the heat transfer process in the next stage of the boiler model (see Fig. 1).

Fig. 2 shows a screenshot of the implemented Simulink subsystem for the combustion chamber, which considers equations (2)–(7). To determine T_{ad}, a look-up table is implemented.

Although the model of the combustion chamber has been formulated for hydrocarbon fuels, it is easily adaptable to green fuels such as hydrogen. In this case, the stoichiometric relation is expressed as [14]:

$$H_2 + b(O_2 + 3.76N_2) \rightarrow cH_2O + dO_2 + 3.76bN_2 \quad (8)$$

where b, c, and d are calculated by balancing the atoms in the combustion reaction.

2.4 Heat transfer between the flue gas and the HTF

The heat transfer process from flue gas to the HTF is represented using the model of a shell and tubes counter-flow heat exchanger (see Fig. 3). A cell division method is adopted to consider the energy balance over hot and cold streams [4]. This way, ordinary differential equations are developed for each cell j as follows:

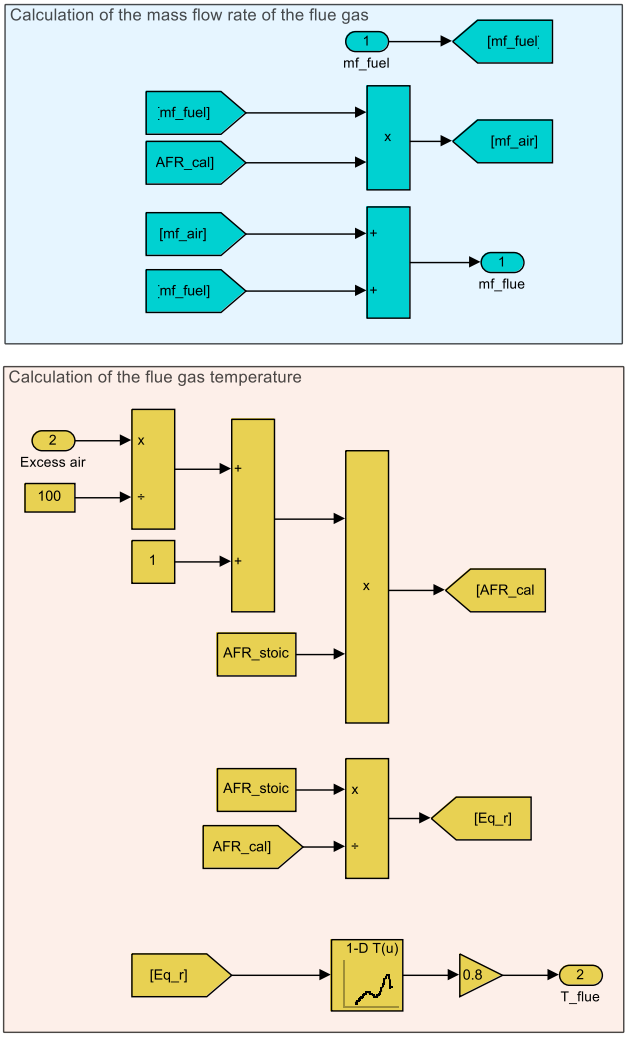

Fig. 2. Combustion chamber subsystem.

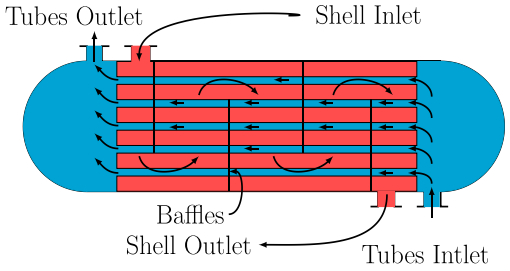

Fig. 3. Counter-flow shell and tubes heat exchanger [2].

$$m_{hj}c_{ph}\dot{T}_{hj} = \dot{m}_h c_{ph}\left(T_{h(j-1)} - T_{hj}\right) + U_j A\left(T_{cj} - T_{hj}\right) \quad (9)$$

$$m_{cj}c_{pc}\dot{T}_{cj} = \dot{m}_c c_{pc}\left(T_{c(j+1)} - T_{cj}\right) + U_j A\left(T_{hj} - T_{cj}\right) \quad (10)$$

where n is the number of cells. The masses of the hot and cold fluids, m_{hj}, m_{cj}, depend on the dimensions of the heat exchanger. The heat transfer coefficient U_j is obtained by calculating the mean velocity, Reynolds number and Nusselt number for each fluid as in [4]. However, since the procedure in [4] considers incompressible fluids such as water, it is thus necessary to incorporate a correction factor f to account for the effect of gas compressibility. This is included in the calculation of mean velocity through the tubes of the heat exchanger:

$$v = \dot{m}_h / f\rho A_t \quad (11)$$

where the value of f depends on the type of gas.

2.5 Limitations and assumptions of the model

Although the modelling approach is suitable for different types of fuels, the reaction in the combustion chamber is assumed as complete. A constant air-fuel ratio has been adopted, which could be achieved with a suitable control scheme, but this is not modelled.

For the complete boiler model, a gas is used in the tubes of the heat exchanger subsystem. Given that the characterisation of the compressibility of the fluid is out of the scope of this work, correction factors f of 0.38 and 0.36 in (11) have been employed for methane and hydrogen, respectively. These values were obtained heuristically to ensure a good agreement between the results obtained with MATLAB and Apros.

3. SIMULATION RESULTS AND DISCUSSION

3.1 Counter-flow shell and tubes heat exchanger

The model of the heat exchanger was built in MATLAB/Simulink. Simulation results are compared with results obtained with Apros to provide confidence into the modelling approach. Apros is a commercial software where high-fidelity mathematical models of thermal systems including heat exchangers are available [15], but not of a suitable fuel combustion boiler.

In this initial exercise, water was used as the fluid in both streams of the heat exchanger. Constant mass flow rates for the tubes (25.42 kg/s) and for the shell (35.60 kg/s) and a constant inlet temperature of the tubes ($T_{tI} = 90°C$) were used. The inlet temperature of the shell was varied throughout the simulation. Parameters of the heat exchanger are provided in Table 1.

Table 1. Heat exchanger parameters

Variable	Description	Value
n	Number of cells	5
N_t	Number of tubes	7000
L_t	Length of tubes	2 m
L_s	Length of shell	2.175 m
r_i	Inside radius of tubes	16.60 mm
r_o	Outside radius of tubes	19.00 mm
A	Heat transfer area	557.10 m²

Simulation results are shown in Fig. 4. Prefix 'M' is adopted for the MATLAB model, while results from Apros are labelled with prefix 'A'. As it can be seen, a change in the shell's inlet temperature correspondingly reflects in the outlet temperature. In addition, results obtained from both software engines show a good agreement.

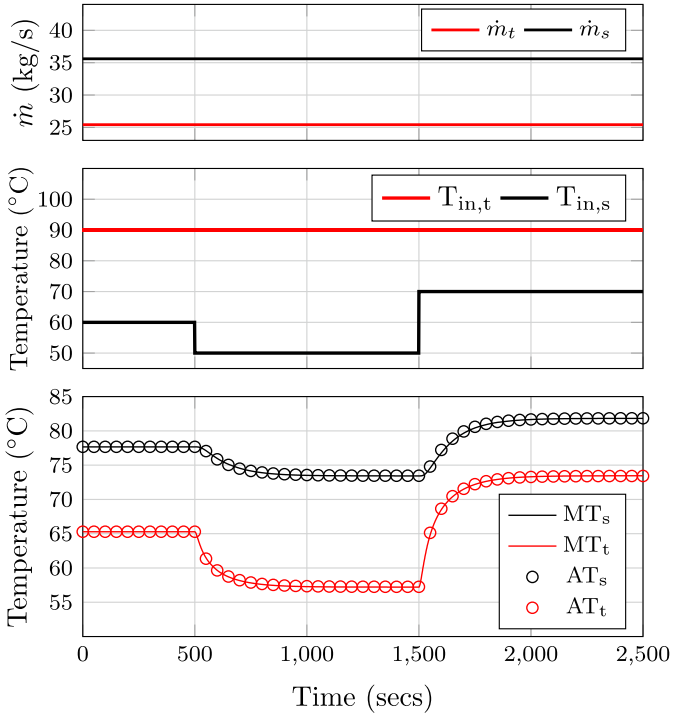

Fig. 4. Simulation results for MATLAB/Simulink and Apros models of the counter-flow shell and tubes heat exchanger.

The heat exchanger subsystem accurately captures the transient response resulting from the change in operating conditions. This is critical to analyse the boiler representation for different operating points.

3.2 Coupling of the combustion chamber and heat exchanger subsystems

As discussed in Section 2, combustion occurs in the combustion chamber and the flue gas from combustion is used to heat water. To represent heat transfer, the flue gas passes through the tubes (and not water as in Section 3.1) and water flows through the shell. The temperature of the flue gas calculated using equation (7) is the inlet temperature of flue gas in the heat exchanger model.

Simulations are conducted considering hydrogen and methane as fuels. These start with the boiler running at its maximum capacity (100%). The mass flow rate of the fuel is reduced every 500 s, which in turn changes the mass flow rate of the flue gas. The output power rating correspondingly reduces by 25% until a rating of 50% is reached. Tables 1-2 show the system parameters and Tables 3-4 show the simulated operating conditions.

Table 2. Combustion chamber parameters

Variable	Description	Value
$\dot{Q}$	Output power rating	2.6 MWth
η	Efficiency of combustion process	80%
e	Excess air rate	15%

Table 3. Operating conditions for methane

Boiler capacity (%)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{flue}$ (kg/s)	$\dot{m}_s$ (kg/s)	T_{tI} (°C)	T_{sI} (°C)	$\dot{Q}$ (MW)
100	0.066	1.38	70.42	1562	75	2.604
75	0.049	1.02	70.42	1562	75	1.95
50	0.031	0.66	70.42	1562	75	1.3

Table 4. Operating conditions for hydrogen

Boiler capacity (%)	$\dot{m}_{fuel}$ (kg/s)	$\dot{m}_{flue}$ (kg/s)	$\dot{m}_s$ (kg/s)	T_{tI} (°C)	T_{sI} (°C)	$\dot{Q}$ (MW)
100	0.026	1.07	70.42	1751	75	2.604
75	0.019	0.79	70.42	1751	75	1.95
50	0.013	0.52	70.42	1751	75	1.3

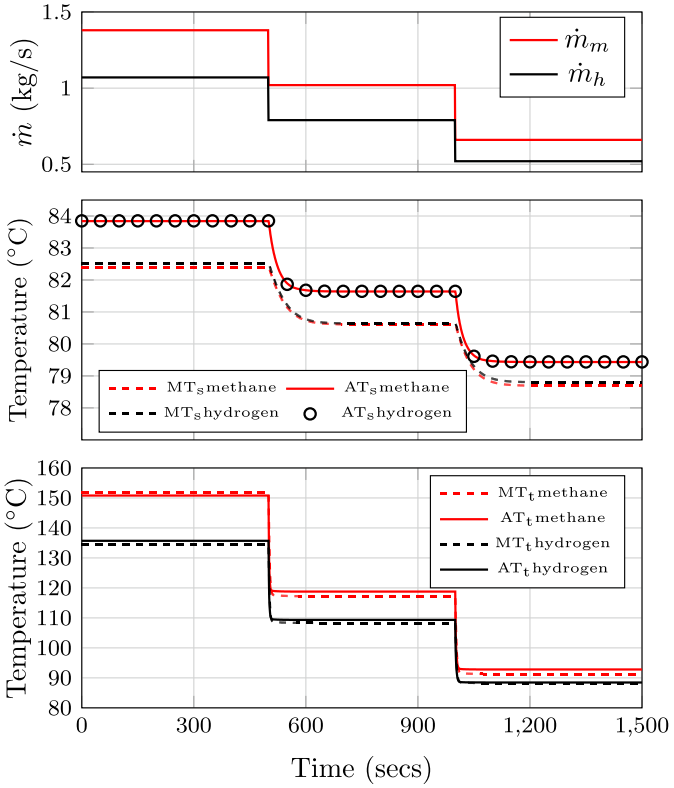

Fig. 5. Mass flow rate (top plot). Supply water temperature (middle plot). Exhaust gas temperature (bottom plot).

Simulation results are shown in Fig. 5. It can be seen from Tables 3 and 4 that the adiabatic flue gas temperature of hydrogen is 1751°C compared to 1562°C for methane. Therefore, a higher mass flow rate of methane is needed compared to hydrogen for a similar power output from the boiler, as shown by the top plot

(note that the volume flow is lower due to the lower density of hydrogen).

It can also be observed in the middle plot of Fig. 5 that the output temperature of the water (shell side) rises to 84°C at maximum boiler capacity for either fuel when Apros is employed, which means an increment of 9°C. For a mass flow rate of water of 70.42 kg/s, the maximum power capacity is thus achieved $\left(P = \dot{m}c_p\Delta T = 2.59\ \mathrm{MW}\right)$. Notice there is a slight discrepancy with the results obtained with MATLAB (i.e. 82.5°C), but this is deemed acceptable for a heating system.

From the bottom plot of Fig. 5, it can be observed that the exhaust gas temperature is higher when methane is employed as opposed to hydrogen, with simulations results from MATLAB and Apros showing agreement. This is consistent with the mass flow rates of the fuels shown in the top plot.

4. CONCLUSIONS

A mathematical model of the thermal behaviour of a fuel combustion boiler suitable for heating applications was presented. Despite its simplicity, the model considers the temperature dependence of the thermophysical properties of a fluid and the dynamic computation of the overall heat transfer coefficient. It thus enables the analysis of fundamental variables of the process such as mass flow rate (fuel and flue gas) and temperature (combustion and HTF).

With the presented dynamic model, it is possible to assess the thermal transient response of the boiler, which is critical to conduct system level studies of a heating system where operating conditions may change and effective control systems are required to maximise system performance. A key attribute of the model is its adaptability to any type of combustion fuel, including green fuels, which is attractive to study heating systems featuring low carbon heat sources.

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