Numerical assessment of a gas-fired condensing boiler model for residential buildings application

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Abstract. According to the official statistical reports, gas-fired boiler units still remain to be one of the main equipment types for meeting the space heating and daily hot water demand of the residential dwellings across the European Union. Due to the prevalence of the natural gas grid and performance stability, gas-fired boilers are considered to remain as one of the standard energy sources. On the other hand, even though gas-fired water heating technology is a well-known concept, existing numerical models found in the literature are often case-specific with poor reusability mostly reflected in fitted efficiencies. Algorithms behind these models usually require the input of large amount of hardly attainable design characteristics of the units. In this paper, a modelling method for acquiring the performance of a heating gas-fired condensing boiler unit will be shown. The model is based on the limited input data available in the official characteristics of the units issued by the relevant manufacturers. The simulations are programmed by using the programming language Modelica and the software tool Dymola. The model is based on the fixed natural gas intake which combusts into a stable mixture of the combustion gases that further heat the circulating water. During the heat transfer process inside the condensing boilers there is a possibility for condensate formation out of the water vapour of the combustion gases which increases the efficiency of the unit. The formation of condensate, however, is depending on the return water temperature of the unit which has to be lower than the dew point temperature of the combustion gases. The goal of this research is to determine how accurate can performance indicators of gas-fired boilers be attained with the use of a limited amount of available input data together with clearly defined assumptions that follow the modelling methodology.

1. Introduction
With the energy use share of 25.71%, residential buildings are the biggest energy users in the European Union (EU) after transport [1]. In the year 2018, natural gas accounted for the share of 32% of the final energy use in the EU’s households. Inside the residential buildings, the highest energy user is the equipment used in space heating and domestic hot water systems with the total share of 78.4% [2]. In Belgium alone, natural gas is responsible for meeting 47% of the heating energy use of the residential dwellings [3]. Despite the growing awareness of the harmful consequences against the environment brought by the direct exploitation and use of fossil fuels, the use of natural gas is foreseen not to diminish quickly. The reasons for such predictions are most of all the developed gas piping network, price ranges
and performance stability of gas burning through water heating boilers. Moreover, most of the recently sold residential heating boilers are gas-fired condensing boilers. With their ability to use the latent heat of condensing the water vapor of combustion gases, condensing gas boilers achieve very high efficiencies with low losses [4]. Nonetheless, the decrease of the natural gas use will be inevitable in the years to come. However, the use of technologies such as biogas and hybrid systems which involve the use of gas boilers as backup heaters of alternative technologies like heat pumps, will certainly be of interest for further analysis and proper integration. In order to accurately predict the energy demand of residential dwellings, increased attention is paid to the performance assessment through transient detailed modelling simulations. The improvement in overall energy use assessments will secure the future energy provision and thus meet the essential energy needs of the population.

Therefore, easily parametrized models of building systems units are needed. In the literature, water heating boiler models mostly differ from case-specific, design based models [5,6], to the ones that are purely based on the detailed experimentally obtained performance maps [7]. These models are finding hard reusability for general application. In the contrast, the goal of this article is to present an easily parametrized gas-fired condensing boiler model which brings reliable performance prediction within the context of the work.

2. Methodology

In this chapter, a gas-fired condensing boiler modelling methodology will be discussed. The methodology is based on the parameters available in the official brochures of the relevant manufacturers. Special attention is paid to the consistent use of the laws of thermodynamics and clear list of the adopted assumptions:

- Combustion process is complete and without thermal losses;
- Combustion gasses are ideal gases;
- Combustion air is the wet ambient air;
- Reference thermodynamic conditions are temperature of 15°C (\(T_0\)) and pressure of 1.01325 bar (\(P_0\));
- Nominal heat input, design temperature regime, dry weight and water volume are available in the list of the characteristics of the units.

2.1. Nominal performance and parameter estimation of the gas-fired heating boiler

At first, parameter identification analysis is made on the available performance characteristics at the nominal non-condensing and condensing performance regime. Figure 1 represents the thermodynamic scheme for the chosen control volumes (burner, gaseous and water side of the heat exchanger) of the process.

![Figure 1. Thermodynamic scheme of the gas-fired condensing boiler.](image-url)
The combustion modelling method is based oncombusting the known natural gas fuel composition with the certain excess air amount which can vary according to the power load of the unit. Such input parameters allow the conduction of molar and mass analysis on the formed combustion gases thus leading to the complete set of the different compound properties. The combustion gases are formed at the adiabatic flame temperature $T_{\text{adiab}}$ and further brought to the heat exchanger of the unit. Inside the heat exchanger, the heat transfer process occurs from the combustion gases to the circulating water. If the return water temperature is lower than the dew point temperature of the combustion gases, the condensation of the water vapor inside the combustion gases can evolve. Thus, the mass balance for the gaseous side of the heat exchanger is:

$$m_{\text{ex}} = m_a + m_f - m_{\text{cond}}$$  

(1)

where $m_a$ and $m_f$ represent the mass flow rates of air and fuel and thus the mass flow rate of the combustion gases $m_g$, while $m_{\text{ex}}$ and $m_{\text{cond}}$ represent the flow rates of the exhaust gases and condensed water respectively. Equation (2) represents the complete steady-state energy balance for the nominal condensing regime of the unit referenced to the standard reference conditions:

$$m_{\text{ex}}[h_{\text{ex}}(T_g) - h_{\text{ex}}(T_0)] = m_g \cdot [h_g(T_{\text{adiab}}) - h_g(T_0)] \cdot (1 - f_{\text{env}}) - m_{\text{cond}}[h_{\text{cond}}(T_{\text{cond}}) - h_{\text{cond}}(T_0)] - m_w \cdot [h_w(T_{\text{w, out}}) - h_w(T_{\text{w, in}})]$$  

(2)

where $h_{\text{ex}}$ represents the enthalpy of the exhaust gases at the exhaust gas temperature $T_g$, $h_g$ the enthalpy of the combustion gases while $h_{\text{cond}}$ and $h_w$ represent the enthalpies of the condensed water and circulating, heated water at the temperatures of condensation $T_{\text{cond}}$ and water supply $T_{\text{w, out}}$ and return water $T_{\text{w, in}}$ respectively. The last term of equation (2) represents the heat capacity of the unit which is considered to be a known parameter in nominal working conditions accessible in open source brochures.

Due to their hard experimental attainability, the envelop losses are assumed to be a fraction of the load power input to the unit ($f_{\text{env}}$) and hence the first fitting parameter proposed by this modelling method. Therefore, the unknown variables of equation (2) are the temperature of the exhaust gases and the amount of formed condensate. In a condensing boiler, the condensation only occurs if the return water temperature is lower than the dew point temperature of combustion gases. In this model, the previous condition is evaluated with the comparison between the partial pressure of water vapor of the combustion gases and saturation pressure of a specific temperature called the temperature of condensation $T_{\text{cond}}$. The temperature of condensation is assessed through the second fitting parameter called the heat exchanger condensation effectiveness (characteristic of the heat exchanger) which specifies the part of the combustion gases that comes in contact with the wall of the heat exchanger thus forming condensation. The envelop losses and heat exchanger effectiveness values are assessed for the experimentally issued values over the exhaust gas temperature and mass flow rate of condensate in nominal working conditions by the standard EN15502 [8]. Equation (2) is solved iteratively for the exhaust gas temperature value. The nominal overall heat transfer coefficient is determined by the use of logarithmic mean temperature difference for the known temperatures.

2.2. Part-load performance of the gas-fired heating boiler

The full dynamic model is made for the metal heat capacity, based on the known dry weight and the water content given by the volume capacity of the unit. The boiler unit is controlled by a feedback controller which compares the supply water temperature against the water set supply temperature. In this way, the signal from the feedback controller is representing the firing rate of the burner which further sets the required mass flow rate of fuel. In the off-design performance regime of the unit, the energy balance is solved for the double iteration process on the exhaust gas temperature and the supply water temperature for the known return water temperature and water mass flow rate $\dot{m}_w$ (given by the coupled heating system).
3. Results
The numerical modeling and simulations were performed in the programming language Modelica and software tool Dymola [9]. In order to construct the performance efficiency map, the complete model is tested at the nominal and 15% firing rate for reaching the steady-state conditions. The return water temperature was varied between 20°C to 70°C. The tested unit has the nominal capacity of 26.5kW in the condensing and 24kW in the non-condensing working regime. Figure 2 shows the results of the analysis.

![Efficiency of a gas-fired heating boiler for the varying return water temperature.](image)

The results show a clear difference between the condensing and non-condensing working regime in the case of the nominal firing rate of the unit. The obtained efficiencies are within the expected range. The nominal efficiencies deviate less than 1.5% from the three measured steady-state values for the same unit as issued by the official conformity institute [10].

4. Conclusion
Residential buildings claim a significant share of the total energy use. Most of the today’s households are equipped with a heating boiler using natural gas. In this article, an overview of a thermodynamically consistent gas-fired heating boiler has been shown. With the use of the clearly adopted assumptions and input parameters available in the open-source brochure of the manufacturers, the presented model shows expected efficiency results for the reach of the steady-state performance under different operating conditions. The modelling methodology suggest integration of the nominal steady-state exhaust gas temperature and mass flow rate of the condensate values obtained under the official performance assessments methods to become a standardized part of the issued performance characteristics of these units.

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