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# Effect of relative humidity in the efficiency of condensing gas water heater appliance

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## HIGHLIGHTS

- Effect of relative humidity is correlated with boiler efficiency.
- Simplified mathematical model was used to assess boiler efficiencies.
- Condensing and non-condensing boiler efficiencies were analyzed.
- Non-condensable gases model was considered for heat exchangers with condensation.
- Relative humidity impact on efficiency is significant for low loads.

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ABSTRACT

In the present work a simplified mathematical model for a condensing gas water heater appliance was built to evaluate the impact of relative humidity (RH) on the appliance. Validation was performed considering experimental results from condensing and non-condensing appliances. The mathematical model was solved using an improved Broyden method. Analytical results are in good agreement with experimental results.



## 1. Introduction

The high efficiency of condensing gas water heater appliance (>90%) and the alarming rise on gas prices makes condensing gas water heater appliance more attractive to consumers even if they still cost more than conventional water heaters since consumers not only buy these appliances for water heating but also tend to buy them for low-temperature demand domestic heating. On the cost side, governments have been making laws and/or special programs for consumers to opt for condensing gas water heater appliance and boilers. The heating equipments are classified accordingly to their efficiency following standard test procedures that have some degree of freedom in the process of measuring some parameters.

In the United States of America the CFR Part 430, Point 6.2.2.2 – Test Procedure Rule from the Department of Energy (U.S. – D.O.E.) is used and in Europe the EN 297, EN 483, EN 15417 for boilers up to 70 kW of different types (central heating only or with Domestic Hot Heating or condensing) from CEN (Comité Européen de Normalisation). Both these standards specify reference conditions for ambient air temperature and pressure and for cold water inlet and return (not relevant for water heater appliances). Regarding the air humidity the European standard EN 15417 specifies a reference value of 10 g/kg of moisture in the air and proposes for condensing water heating appliances or boilers a correction of −0.08% in the efficiency for an increase of 1 g/kg in the ambient air, while the U.S. standard does not specify any reference for relative humidity (RH) nor its control during the tests. For steam generating boilers the ASME standard PTC-4.1 considers the influence of moisture but this was not adapted for small scale boilers.

Another important difference between the standards is related to the reference of the calorific value of the fuel that is the HHV (Higher Heating Value) for the American and the LHV (Lower Heating Value), used in the standards for Europe. Because of this, in USA the efficiency does not surpass 100% and in Europe it can.

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The main objective of the present paper is to present a numerical model that is able to predict the influence of the water heater geometric and operational characteristics, including the ambient conditions and in particular the moisture in the ambient air. To get insight into the problem with typical conditions (e.g. 25 °C, 50% relative humidity, atmospheric pressure) the moisture content is the reference 10 g/kg that represent an additional in reactants flow. For methane stoichiometric combustion the molar fraction of products has 20% water vapor: 18.7% from hydrogen combustion and 1.4% from the air moisture. The later value represents 7% of the total moisture and this fraction increases with excess air and is a larger fraction of the water vapor that is condensed.

The explanation for the increase in efficiency decreasing air moisture is that there is possibility to condense more water vapor formed from the hydrogen combustion and that the difference in energy from the air moisture related to the hydrogen from the methane leads to the negative correction proposed in the European standard. On the other hand for a reference composition of the dry gases the increase of moisture in the air increases the total gas flow through the installation decreasing the efficiency. This effect is ignored in the standards as it is expected to have smaller influence and affects also the units without condensation.

The importance of the test conditions and the accurate measurement of the parameters that affect efficiency are discussed in detail by De Paepe et al. [5] who present an uncertainty analysis on tests and compared results in a Round Robin test. Results obtained in 1991 showed a reproducibility of 4% for full load and 6% for 30% boiler load for a 20 kW boiler and these were improved to 2% and 5.9% for a 30 kW test presented. This reproducibility is important since the classification of the boilers according to efficiency have intervals of 3–4%.

The development of water heating appliances is mainly proprietary and there are few papers presented in the scientific literature. The main issues are related with heat transfer, namely condensation, combustion efficiency and emissions. To access efficiency calculation models should address heat transfer and this may be evaluated with different levels of approach. The most detailed is based on CFD (Computational Fluid Dynamics), intermediate models are based on zones and the simplest ones are based on black box models that ignore the actual geometry of the boiler.

Hanby [9] presents a black box model assuming instantaneous combustion and then heat transfer is characterized by heat transfer capacity (AU) of main sections without any information of the actual geometry. The only factor that is considered is that this heat transfer capacity is proportional to the gas flow rate with a power factor of 0.67 that is a reasonable assumption for the convection heat transfer but it has no relevance for the main part of heat transfer by radiation within the combustion chamber. For condensation the main mechanism does not depend on the gas flow rate, although it has an influence on film condensation based correlations. In summary the model presented is rather empirical and its use requires the determination of parameters to be derived from experimental results including intermediate temperatures in the heating appliance and tests are required for conditions with and without condensation in the flue gases. Makaire [19] further developed this black box model dividing the condensing section in several sections again without any reference to the actual geometry but just for the solution of the equations. The heat transferred in each of these sections is the maximum from the values calculated considering the flue gases completely wet or completely dry. This method is used to apply the effectiveness model for cooling towers and cooling coils and is a crude approximation since condensation depends mainly on the surface temperature. This type of black box models is still useful to analyze the performance of the boiler as it can fit the data between the experimental values used to fix the parameters. Further the model does not include any influence of the moisture content except in the condensation section. The presence of moisture in the combustion air affects the global flow rate, radiation heat transfer and condensation.

Idem [12] implemented a model for a condensing boiler using a ceramic fiber matrix burner that is the base of a rectangular combustion chamber with a multi-pass heat exchanger promoting the condensation of water vapor. The combustion chamber is calculated with radiosity equations applied to the surfaces with participating gas and the performance of the heat exchanger is described by convection coefficients obtained experimentally in a wind tunnel. The agreement with test data was good and could be improved using more accurate surface emissivity.

To analyze combustion, heat release and pollutant formation one dimensional flame models were developed by Miranda et al. [20] that allowed them to calculate the height of the combustion chamber and the production of $NO_x$ and CO. The combustion chamber included heat transfer by convection and radiation. The model was applied to non-condensing water heaters and it was observed that the convection on the primary heat exchanger was important and that it increased with the water mass flow to be heated. Jeong et al. [14] developed models for the condensation section of boilers to calculate temperature and the condensation flow rate, as a function of the mass flow of the cooling water and the flue gas flow rate. The model was implemented numerically discretizing the condenser heat transfer area in 1000 cells and applied to an experimental test section with 6 heat exchangers, with the objective of representing the exhaust of an industrial boiler.

From the literature review it can be noted that most studies consider heat transfer correlations with condensation developed for specific geometries. In the present work we propose the use of correlations from literature for heat transfer and the calculation is integrated with the model for radiative heat transfer in an enclosure with participating media. The motivation of the work was the evaluation of the effect of the water vapor content in the air on the boiler efficiency at different loads. The water vapor effect on boiler efficiency could, in humid climates, help to promote a reduction on gas consumption. Other aspect is how much influence the water vapor has on the boiler efficiency when no substantial condensation occurs. The main result however is the comparison of the model predictions with test data from several units including condensing and non-condensing water heaters. Following this introduction Section 2 presents the numerical model developed, followed by the results in Section 3 and conclusions.

## 2. Model

For modeling the condensing gas water heater appliance was conceptually divided into 4 zones for the energy balances as illustrated in Fig. 1. The first zone is the combustion zone, the second the combustion chamber zone, the third zone is the primary heat exchanger zone and the fourth is the condenser(s) zone. Gas temperatures are indicated as $T_{gi}$ and denote the same position as $h_{gi}$. On the condenser(s) the index $i$ can go up to 9.

The combustion zone corresponds to a plane surface at a temperature that is the result of the energy balance considering complete and instantaneous combustion with heat losses to the combustion chamber zone above. The gas composition is calculated from the test conditions based on the gas fuel composition and the carbon dioxide fraction measured in tests on dry basis that allows the definition of the excess air. The water vapor in the combustion air is considered on the products of combustion increasing the total gas flow and lowering the adiabatic flame temperature. The burner temperature that is the temperature in the bottom surface of the combustion chamber zone is obtained from: