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Natural ventilation of a room with an atmospheric-vent water heater in both on- and off-states

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ABSTRACT

Instantaneous or tankless gas-fired water heaters are widely used in residential buildings to heat water for domestic use. For the combustion can process properly, a minimum amount of air is required, which can be obtained directly from outdoors or from inside the room. This latter case corresponds to the operation mode of the atmospheric-vent water heater, which is one of the most frequently encountered appliances to heat domestic water. As the room where the water heater operates is generally a living area, the installation design should account for the health and comfort requirements. Increasing the room airflow rates reduces the risk of harmful products from incomplete combustion but, as counterpart, important impacts on the thermal and energy performance of the room can occur. In this paper the natural ventilation conditions of a room with an atmospheric-vent water heater are investigated. Moreover, the effects on energy demand for thermal comfort are assessed. The study was conducted through the EnergyPlus simulation program, whose applicability to the problem was first tested. The results obtained are consistent with the expectations, allowing for a better insight into the level of compliance of the combustion air requirements and respective impacts on energy performance.

1. Introduction and background

Instantaneous or tankless gas-fired water heaters are very common appliances in residential buildings to heat domestic water. Although in modern and new homes instantaneous water heaters are being abandoned in favour of water boilers of greater capacity with storage tank, which have the double function of heating water for domestic use and for space heating, the instantaneous solution of heating water continues to be the most popular in traditional dwellings. Technological advances in recent years have led to an increasing performance and sophistication of gas-fired water heaters in terms of energy efficiency, functionality and secure use. Due to the combustion reactions involved in the normal operation, safety is a very important issue in the manufacture of these equipments and in their installation on site. Gas-fired water heaters are factory-equipped with devices to control operating temperatures and combustion products concentrations, cutting-off the gas supply when predefined limits are exceeded. In a combustion reaction enough oxygen must be present to completely burn the gas and prevent the release of harmful products. This means that the way how air is supplied to a gas-fired water heater is a fundamental component of the design, which should be carefully studied to mitigate risks for human health. In this context, essentially three categories of gas units can be found in the market: (i) atmospheric-vent water heaters, that use room air for combustion and a chimney or flue to expel the released products by natural draught (open-flue appliance); (ii) direct-vent or "sealed combustion" water heaters, that draw all air for combustion from the outside atmosphere, rather than inside the room, and discharge all flue gases to the outside atmosphere, usually with the aid of a blower; (iii) power-vent or fan assisted water heaters, that are the same as the atmospheric models, but with a blower installed to assist the expulsion of combustion by-products.

With respect to the atmospheric-vent water heater, to which this paper is devoted to, the ventilation of the installation room should be carefully planned to account for the minimum amount of fresh air required for complete combustion. If such minimum is not obtained severe indoor air conditions can arise, unless the appliance has a device to automatically interrupt the current operation when abnormal concentrations of combustion products occur. A gas-fired water heater should be installed in compliance with national regulations and its operating conditions should be periodically inspected by a qualified professional. The requirements are very strict and specific and are addressed to the appliance installation as well as to the ventilation rates that should hold for complete combustion. In case of an atmospheric-vent water heater a permanent opening area in the installation room is generally required, irrespective of the window openable area, to make ventilation conditions independent of the user's interference.

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Nomenclature

A	opening area (m^2)
AF	air–fuel mass ratio (–)
A_r	relative atomic mass (–)
C	discharge coefficient (–)
c_p	specific heat (J/kg/K)
EA	excess air (–)
f	Fanning friction factor (–)
g	acceleration of gravity (m/s^2)
H	height (m)
$\bar{h}$	average convection heat transfer coefficient ($W/m^2/K$)
h_c	heating value (J/kg)
k	thermal conductivity (W/m/K)
L_1,L_2	lengths (m)
$\dot{m}$	mass flow rate (kg/s)
$\overline{Nu}$	average Nusselt number (–)
P_n	rated input power (W)
P	heat source power (W)
Q_f	flue gas losses (W)
Q_i	heat input rate (W)
Q_r	heat losses to the surrounding room (W)
Q_w	heat transfer rate to domestic water (W)
Ra	Rayleigh number (–)
S	cross section area (m^2)
T	temperature (°C)
T_c	adiabatic combustion temperature (°C)
T_f	combustion temperature (°C)
U	overall heat transfer coefficient ($W/m^2/K$)
x	spatial coordinate

Greek symbols

γ	radiation–convection loss factor (–)
η	thermal efficiency (–)
ρ	density (kg/m^3)

Subscripts

0	reference condition
a	air, ambient
f	flue
g	gas
in	inlet
ou	outlet
s	stoichiometric condition
w	wall

From the above, the ventilation conditions of a room where an atmospheric-vent water heater operates is an important topic of study, with implications in building design, energy efficiency and indoor air quality. Most of the research works related to boilers or water heaters are centred on the equipment's ability to burn the fuel and transfer the resulting heat to water [1–3]. Usually, in this type of studies the air mass flow rate is treated as an input for the heating appliance that is not impacted by the room characteristics but rather obtained from the stoichiometric balance of the combustion process. Fewer studies examined how interaction between heating appliance, room, and flue or chimney affects the mass flow rates. In an early work, Benett and Purkis [4] studied the flue gas flow from gas appliances using constant coefficients for heat and friction losses. Farías et al. [5] analysed theoretically and experimentally the natural draught in a chimney with multiple flues using a control volume model for the temperature and pressure distributions. In these works the interaction with the room ventilation conditions was not considered. Warren and Webb [6] developed a more elaborated model of the flue behaviour of domestic appliances that, accounting for the room openings and outdoor conditions, allowed the assessment of room ventilation. The effect of the gas appliance operation on the air change rate of the installation room and its relationship with the nominal heat output was also investigated through a CFD study carried out by Barna and Goda [7]. The CFD simulation was also used to analyse the carbon monoxide concentration in an enclosed room, as result of poor ventilation, produced by a natural gas water heater [8]. Measurements of the characteristics of the gas flow in chimneys for specific appliances have also been made by some authors [5,9].

The main goal of the present paper is to use multizone airflow to investigate the ventilation performance of a room with an atmospheric-vent water heater connected to a chimney for diluting and exhausting the combustion by-products. The ventilation levels for the on- and off-states of the appliance are predicted and the impacts on the energy needs for thermal comfort assessed. The study was conducted using the EnergyPlus program [10], which is a dynamic building energy simulation tool widely accepted in scientific communities. The fundamental concepts and model assumptions underlying the study are presented in the following sections.

2. Combustion process and energy balance

The fired-gas water heater has a combustion chamber where the supplied gas is burnt and reacts with the oxygen (O_2) of the atmospheric air, releasing heat and producing carbon dioxide (CO_2) and water (H_2O). The atmospheric air is essentially composed of oxygen and nitrogen (N_2) with a ratio of nitrogen to oxygen of 3.76 on a volume basis. During a combustion process, nitrogen behaves as an inert gas and does not react with other elements. The minimum amount of air required for complete combustion is called stoichiometric air. Assuming natural gas and that is composed of 100% methane (CH_4), the stoichiometric equation for the combustion of natural gas is:

$$CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \quad (1)$$

Once the relative atomic mass (A_r) of each element is known, the mass ratio of air to fuel (air–fuel mass ratio, AF) for the complete combustion of natural gas is, from Eq. (1):

$$AF_s = \frac{\dot{m}_{a,s}}{\dot{m}_g} = \frac{2 \times [2 \times A_r(O) + 3.76 \times 2 \times A_r(N)]}{A_r(C) + 4 \times A_r(H)} \quad (2)$$

where $\dot{m}_{a,s}$ is the stoichiometric mass flow rate of air and $\dot{m}_g$ is the mass flow rate of natural gas. Knowing that $A_r(O) = 16$, $A_r(N) = 14$, $A_r(C) = 12$ and $A_r(H) = 1$, the result of Eq. (2) gives $AF_s = 17.2$.

To ensure that the gas is totally burnt, the amount of air supplied is typically greater than the stoichiometric value. Excess combustion air dilutes the combustion products, which is desirable, but lowers the temperature of combustion, which leads to a decrease in efficiency. However, the reduction of the risk associated with insufficient combustion, which can result in the formation of harmful by-products, is a priority and thus should prevail over efficiency considerations. The quantity of air supplied in excess of stoichiometric air is called excess air (EA) and is defined by the following equation:

$$EA = \frac{\dot{m}_a - \dot{m}_{a,s}}{\dot{m}_{a,s}} = \frac{AF}{AF_s} - 1 \quad (3)$$

Another parameter of interest in this study is the combustion temperature (T_f), which is the temperature that results from the conversion of the heat released during combustion in enthalpy of the discharge gas. It is called adiabatic combustion temperature or adiabatic flame temperature (T_c) when the heat of combustion is