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1D model for a low NO_x ejector-pump like burner

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ABSTRACT

This work is about a model for the prediction of air entrainment in a full-premix, atmospheric, ejector-pump like gas burner, used for domestic water heating purposes. The model improves current knowledge by including the effects of combustion and buoyancy on the air entrainment mechanism. It predicts the λ ratio (excess of air in relation to stoichiometry) as a function of ambient conditions, burner geometry, type of hydrocarbon fuel and burner firing rate. A prototype burner with variable geometry was assembled to calibrate and validate the model. The combustion products were analyzed with a CO_2 sensor and the λ ratio was compared with model's predictions, showing good accuracy. A parametric study was done to ascertain the impact of key geometric parameters on burner aeration.

1. Introduction

During a combustion reaction, solid, liquid or gaseous fuels react with an oxidizer (typically ambient air) to form CO_2 (except for H_2 fuel) and H_2O, whilst releasing heat. A large number of other compounds can also be formed, but nowadays special attention is given to the formation of pollutants such as CO and NO_x. In an attempt to reduce pollution levels during combustion, the atmospheric full-premix burner technology is becoming widely used, as its ability to control lower flame temperatures (when compared to partial diffusion burners) allows for a viable and low-cost way of achieving very low NO_x emissions. References such as [1,2] are excellent references for information on the working principles of many different burner designs, this study being nonetheless focused on burners of the ejector-pump type, not mentioned in the previous references. The case in analysis throughout this work uses the technique of full-premix atmospheric combustion with ambient air as oxidizer. In “full-premix” burners, all the oxidizer needed is mixed with the fuel before the flame, whilst in an “ejector-pump like” burner, the region where the fuel is injected into the burner consists of an ejector-pump. An extensive bibliography is available for this type of device, common in atmospheric burning applications due to its simplicity. Finally, an “atmospheric burner” is a burner operating at or very near atmospheric pressure. Rather than using forced convection systems with moving parts such as fans or turbines, as in the case of pressurized burners, the air rises in the burner by natural convection due to the buoyancy originated from the hot combustion products. An important parameter in all burner types is the excess of air in relation to stoichiometry, defined as $\lambda = (AF)/(AF)_{st}$, with AF being the air/fuel ratio on a mass basis and the subscript “*st*” standing for “stoichiometry”. Usually for the types of burner specified in this study, the fuel is mixed with more air than strictly required to complete combustion ($\lambda > 1$), leading to lower flame temperatures and lower NO_x emissions. However, full-premix combustion is very sensible to the λ ratio, and either too much or too little air leads to high CO emissions. The design of an efficient burner therefore requires an accurate prediction of air entrainment, this issue being treated with 1D models in many types of burners and ejector-pumps. The simplest ones are mentioned in [3], aiming to predict the primary aeration for a typical stove burner, and [4], aiming to determine the range of design parameters for a biogas burner. Refs. [5–7] (written in Portuguese) address the same issue for domestic water heating. Likewise, Ref. [8] refers to ejector-pump type burners and [9] describes a model for primary air entrainment as well. All the aforementioned studies disregard two important issues: (i) the buoyancy of hot combustion products and the secondary ambient air entrainment due to pressure gradients; (ii) the energy dissipation due to the heat-exchanger, for burners used in domestic water heating, since it interferes with the outflow of combustion products. Ref. [10] presents a 1D model for the entrainment of air in the flame region of a stove burner, taking into account the effects of buoyancy, however, the goal is not the parametric study of a burner used in water heating.

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Nonetheless, it highlights the need for including the effects of buoyancy. The model derived in this work aims to fill these gaps by: (i) including the effects of combustion, i.e., accounting for the change in temperature, density, velocity, pressure and chemical composition of the flow after the flame; (ii) including the buoyancy forces acting on the hot combustion products; (iii) considering the local changes in temperature, density, velocity and pressure through the heat-exchanger, as well as the wall shear stress.

2. System layout and modeling

2.1. Burner's geometry

The ejector-pump burner considered in this work consists of the following elements (Fig. 1):

- **0** Injector, which discharges a mass flow $\dot{m}_f$ (the subscript "f" standing for "fuel") of gaseous $C_xH_yO_z$ fuel from a reservoir (gas manifold) into the inlet of a mixing tube at **1**;
- **1** to **2** Mixing tube of circular cross-section, where a mass flow $\dot{m}_{ap}$ of primary ambient air mixes with the fuel, originating a homogeneous mixture at **2** with mass flow $\dot{m}_{mp}$;
- **2** to **3** Sudden expansion between the mixing tube end at **2** and the plenum chamber inlet at **3**;
- **3** to **4** Plenum chamber of rectangular cross-section, consisting only of an empty volume;
- **4** to **5** Perforated burner surface, where the flame is anchored;
- **5** to **6** Lean premix flame, where the air/fuel mixture is burned, changing its composition and originating a mass flow $\dot{m}_{fp}$ of primary flue gases, but keeping the mass flow rate constant, i.e., $\dot{m}_{fp} = \dot{m}_{mp}$;
- **6** to **7** Combustion chamber with rectangular cross-section;
- **7** to **8** Heat-exchanger, comprised of a series of thin parallel fins cooled by water flowing inside a hydraulic circuit, where part of the heat released during combustion is recovered.

The ensemble of the burner from sections **1** to **6** and the combustion chamber from sections **6** to **8** forms the so-called "heat-cell". A gap of area A_s between the plenum chamber and the combustion chamber may exist, allowing the entrainment of a secondary mass flow of ambient air $\dot{m}_{as}$, which is not involved in the combustion since it mixes with $\dot{m}_{fp}$ only after the flame. The mixture between the primary flue gases and the secondary airstream (which in the 1D model is assumed to be homogeneous throughout the cross-section) originates a mass flow $\dot{m}_{fs}$ of secondary flue gases at section **7**. This secondary air entrainment is paramount, since it affects the primary air entrainment and, therefore, the performance of the burner as a whole.

2.2. Assumptions and simplifications

The objective of this 1D model is to determine the amount of air $\dot{m}_{ap}$ (as well as $\dot{m}_{as}$ when $A_s > 0$) being entrained into the burner, as a

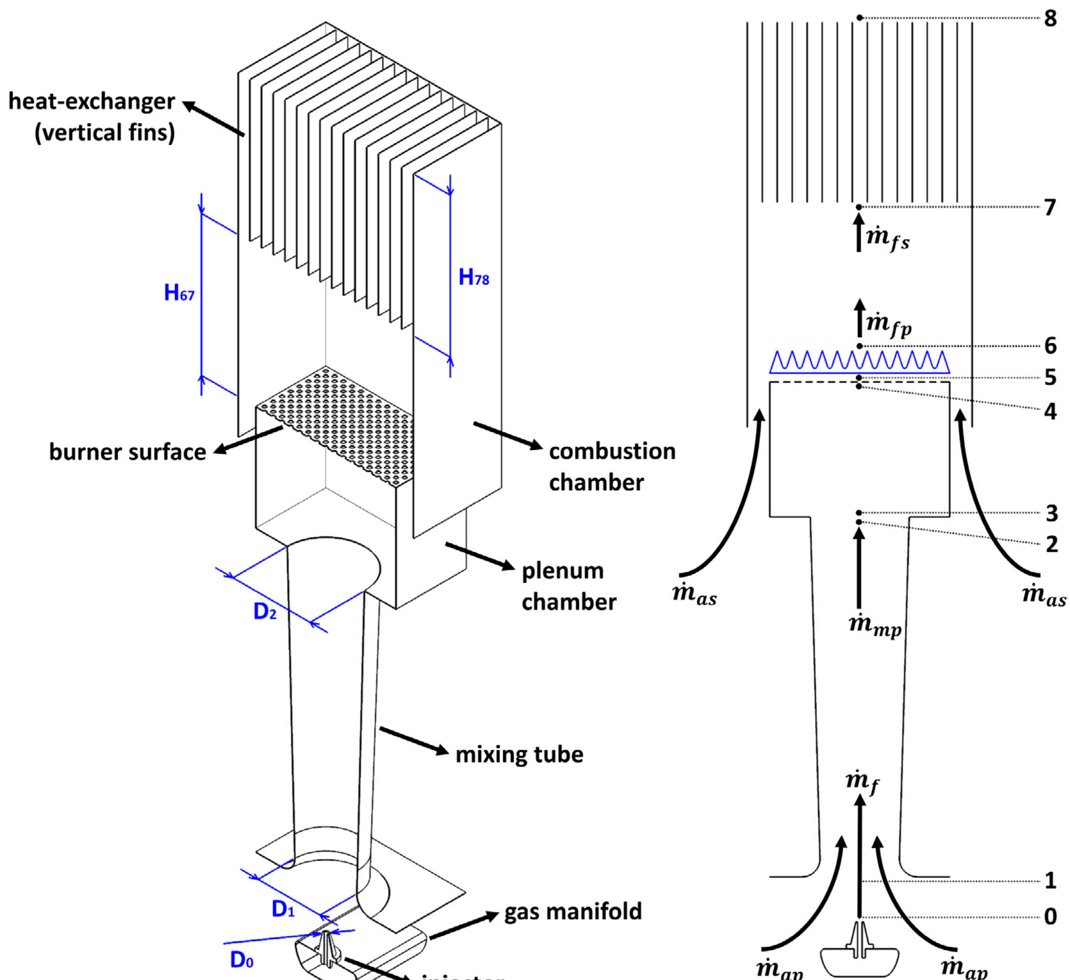

Fig. 1. Diagram of the modeled ejector-pump burner geometry.