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

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Abstract

A model for the prediction of air entrainment in a full-premix, atmospheric, ejector-pump like gas burner is derived. The model expands upon current knowledge by including the effects of combustion and the buoyancy of the hot combustion products in the air entrainment mechanism, and predicts the λ ratio (excess air relative 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 used to experimentally calibrate and validate the model. The prototype burner combustion products were analyzed with a CO_2 sensor, the λ ratio was determined experimentally and compared with the model's predictions. A good agreement is achieved between the model's predictions and the experimental results, both qualitatively and quantitatively. After validation, some guidelines that may help during future burners development are stated.

Keywords: combustion modeling, air entrainment, atmospheric, ejector-pump, burner

1. Introduction

During combustion, 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 during combustion, but nowadays special attention is being given to the formation of pollutants such as CO and NO_x. Atmospheric full-premix burner technology is in vogue nowadays, as it represents a viable, low-cost way of obtaining very low NO_x emissions. References such as [1] and [2] are excellent sources of information on the working principles of many different burner designs, but the focus of study is on full-premix burners where the oxidizer is regular ambient air. In full-premix burners, all the oxidizer needed to complete combustion is mixed with the fuel before the flame. Usually in this type of burner the fuel is mixed with more air than what's strictly necessary to complete combustion ($\lambda > 1$), leading to lower flame temperatures and lower NO_x emissions. Full-premix combustion is however very sensible to the λ ratio, and either too much air and too little air will lead to high CO emissions. The obtaining of a good burner design is facilitated by a good understanding of the mechanism of air entrainment, and the topic of predicting air entrainment in various kinds of burners and ejector-pumps by means of simple 1D models is not new in the bibliography. The simplest 1D model might be by [3] and it aims to predict the primary aeration for a typical cooking stove burner. If the reader is capable of reading portuguese he may be also interested in referring to [4] and [5], the two of them aiming to predict the primary aeration for various kinds of burners encountered in gas appliances for the heating of domestic waters. Also in portuguese, [6] develops a dynamic model of a domestic water heater and in such model it also delves in the topic of air entrainment prediction. [7] also derives a model for the prediction of air entrainment in a burner used a gas domestic water heater, but his work is written in english. For burners akin to ejector-pumps, like the one being modeled in this study, [8] derives a model for the primary air entrainment. All this sources sport models of similar simplicity and assumptions, and many of the models seem to be a direct application of the theory derived in [1]. Very important phenomenon derived from combustion like the buoyancy of hot gases and secondary ambient air entrainment due to pressure differentials seem to be purposefully disregarded or not mentioned at all, and when referring to burners used in the water heating industry the very important effect of the heat-exchanger (as it constitutes a barrier to the flow after the burner) is almost always never mentioned or included. The more sophisticated model derived in this work aims to fill those gaps in modeling the combustion phenomenon.

2. Background

2.1. Burner geometry

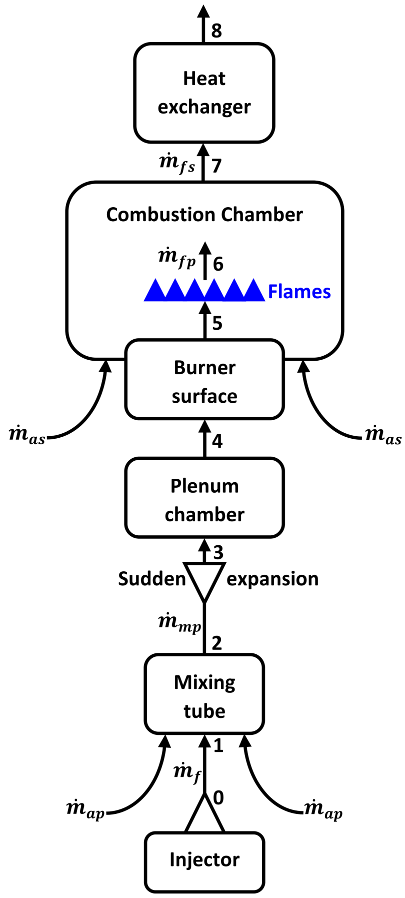

Figure 1: Diagram of the modeled ejector-pump burner

The ejector-pump burner considered in this work is comprised of the following elements depicted in Figure 1: **(0)** Injector, which discharges a mass flow $\dot{m}_f$ of gaseous $C_xH_yO_z$ fuel into the entrance of a mixing tube **(1)**; **(1 to 2)** Mixing tube of circular cross section, where the entrained flow of primary ambient air, with a mass flow $\dot{m}_{ap}$, 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 **(2)** and the plenum chamber entrance **(3)**; **(3 to 4)** Plenum chamber of rectangular cross section, consisting simply of an empty volume; **(4 to 5)** Perforated burner surface, where the flame is anchored; **(5 to 6)** Premix lean flame, where the air/fuel mixture is burned, changing its composition and forming a mass flow rate $\dot{m}_{fp} = \dot{m}_{mp}$ of primary combustion products; **(6 to 7)** Rectangular combustion chamber, where combustion ceases to occur; **(7 to 8)** Heat-exchanger, where part of the heat released during combustion is recuperated into the water flow circulating inside a hydraulic circuit. The ensemble of the burner **(1 to 6)** and the combustion chamber **(6 to 7)** forms the so-called "heat-unit". A gap between the periphery of the plenum chamber and the combustion chamber may exist, allowing the entrainment of a secondary mass flow of ambient air $\dot{m}_{as}$, which does not participate in the combustion. The mixture between the primary flue gases and the secondary airstream is assumed to be perfect at **(7)**, originating a new gaseous mixture of secondary flue gases with mass flow $\dot{m}_{fs}$. The existence of 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 the model is to determine the amount of air that is being entrained into the burner (both primary and secondary streams), in the cold firing case (combustion is not occurring) and in the hot firing case (combustion is occurring), as a function of burner geometry, ambient conditions, type supplied gas and burner firing rate. To do so, some assumptions and simplifications are made throughout this work, so as to allow the development of a simple 1D model bearing a scalar solution for the mass of entrained air. The model assumptions are: **1)** steady-state regime; **2)** all the gases obey the perfect gas law; **3)** the Mach numbers throughout the burner are too small for compressible effects to be considered; **4)** the flow is adiabatic all the way up to the flame, meaning that any eventual preheating effects are absent; **5)** the mixing tube is long enough in order to allow a perfect mixture between the air and fuel; **6)** the flow is one-dimensional, i.e., properties change only along the longitudinal direction; **7)** changes in potential and kinetic energies can be ignored; **8)** the combustion products are CO_2, H_2O and N_2, except for a lean mixture in which case, in addition to the previous products, there is O_2; **9)** combustion is complete; **10)** the air/fuel mix is stoichiometric (no excess air is present, $\lambda = 1$) or lean (some amount of excess air is present, $\lambda > 1$); **11)** all the air necessary for combustion is already present before the flame (the burner is of the full-premix type); **12)** water resulting from combustion remains always at vapor state, i.e., no condensation occurs inside the burner; **13)** the air involved in combustion is dry air, i.e., ambient humidity is negligible. Regarding preheating effects, when burners are firing they tend to heat up, especially near full power operation, and the unburned air/fuel mix tends to heat up as well, causing an increase in flame temperature and changing the air entrainment and the performance of the burner. Studies on the preheat effect ([9], [3] and [10]) show that increasing air temperature decreases primary aeration.

2.3. 1-D burner model

The obtaining of the 1D model is mostly dependent on 6 key equations/principles:

(1) Conservation of mass:

$$\rho_1 A_1 V_1 = \rho_2 A_2 V_2 \tag{1}$$

(2) Conservation of momentum:

$$\begin{aligned} &p_1 A_1 + \rho_1 A_1 V_1^2 + g\mathcal{V}\left(\rho_{atm} - \overline{\rho}_{12}\right) = \\ =&p_2 A_2 + \rho_2 A_2 V_2^2 \end{aligned} \tag{2}$$

(3) Generalized Bernoulli's law:

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2 + g\rho\Delta h_{12} \tag{3}$$

(4) Perfect gas law:

$$p = \rho\left(\overline{R}/M\right)T \tag{4}$$

(5) Energy conservation:

$$\begin{aligned} &\sum_i^{React} \dot{n}_i \left[\bar{h}_f^o + \int_{T_{ref}}^{T_1} c_p(T)\, dT\right]_i = \\ =&\sum_j^{Prod} \dot{n}_j \left[\bar{h}_f^o + \int_{T_{ref}}^{T_2} c_p(T)\, dT\right]_j - \dot{Q}_{12} \end{aligned} \tag{5}$$

(6) Lean combustion equation:

$$\begin{aligned} &\dot{n}_f\, C_x H_y O_z + \lambda w\left(O_2 + 3.76 N_2\right) \longrightarrow \\ \longrightarrow &a\, CO_2 + b\, H_2O + c\, O_2 + d\, N_2 \end{aligned} \tag{6a}$$

$$\dot{n}_f = \dot{m}_f / M_f \tag{6b}$$

$$w/\dot{n}_f = x + y/4 - z/2 \tag{6c}$$

$$\lambda = \frac{\dot{m}_{ap}}{w M_{air}} \tag{6d}$$

$$a/\dot{n}_f = x \tag{6e}$$

$$b/\dot{n}_f = y/2 \tag{6f}$$

$$c = w(\lambda - 1) \tag{6g}$$

$$d = 3.76 w\lambda \tag{6h}$$

The full derivation of the model won't be done here.

3. Implementation

The derived mathematical model has a somewhat circular nature to it: one frequently needs the value of $\dot{m}_{ap}$ to be able to determine $\dot{m}_{ap}$. One example of such situation is depicted in equation 6a, where λ appears as a variable. To deal with the circularity of the derived 1D mathematical model, an iterative algorithm was developed to allow for the computation of λ. The algorithm relies on a 1^{st} guess for λ, and the successive iterations rely on the previous iteration air entrainment value λ^{n-1} to compute the current iteration value for the air entrainment λ^n. The algorithm stops when $|\lambda^{n-1} - \lambda^n|/\lambda^{n-1} < \epsilon_\lambda$. The stopping criteria ϵ_λ was set at 0.1%, usually ensuring convergence in λ within a dozen iterations of the algorithm.

4. Results

To validate and calibrate the derived 1D mathematical model, experimental test resorting to a prototype burner with a modular nature (allowing for easy and quick changes in burner geometry) were done. Burners of various geometries were utilized to experimentally determine the effects of changing the following key geometrical aspects of the burner on the burner air entrainment performance: injector diameter, mixing tube diameter and type of entrance, burner surface permeability/porosity, combustion chamber height and finally the number of fins (and consequently, the heat-absortion efficiency) at the heat-exchanger. The experimental tests consisted of varying the firing rate Q of the burner from the minimum burner output up to the burner nominal output Q_n, and for select firing rates, the combustion products were sampled at the top of the heat-exchanger at **(8)** by a probe located at the geometrical center of the burner. Ambient conditions were controlled and not allowed to vary during the test. The composition of the combustion products was determined by a Horiba PG350 gas analyzer (details available in [11]), and readings for $\%CO_2$, $\%O_2$, $\%CO$ and $\%NO_x$ were taken.

4.1. Comparison between experimental results and model predictions

It is observed that, for all the burner configurations used throughout this work, a good correspondence (both qualitatively and quantitatively) between the 1D model's predictions and the experimental results is observed. All (or almost) experimentally verified effects of changing the burner geometry (for the key parameters studied) on burner aeration are being captured by the model. It is also important to note that the geometry of the burner is not the only major factor at play at setting the burner aeration. The primary burner aeration is highly depended on burner output, with higher λ ratios being observed for low burner outputs and vice-versa.

4.2. A correlation for the predicted λ vs. Burner Output

Interestingly, the model's predictions for λ_{ap} vs. Q/Q_n correlate very well with the inverse hyperbolic co-secant function, in an expression of the form:

$$\lambda = \alpha + \beta\, \mathrm{csch}^{-1}\left[\gamma + \delta\left(\frac{Q}{Q_n}\right)^{\varphi}\right], \tag{7}$$

where the parameters α, β, γ, δ and φ are dependent on burner geometry.

5. Conclusions

This thesis proposed the development of a 1D mathematical model for the air entrainmet prediction of a full-premix, atmospheric, ejector-pump like gas burner. The primary aeration of an atmospheric burner is a consequence of its geometry, burned fuel, firing rate and ambient conditions, and it's a critical parameter for the obtaining of a good combustion in terms of NO_x and CO emissions. Regarding the 1D model, by comparing the model's predictions with the experimental results, one can conclude that the mathematical model derived in the present work is accurately depicting the general working of the modeled burner. Generally one notes a good qualitative and quantitative agreement between the model's predictions and the observed experimental results, and the main effects of changing burner geometry (for the studied parameters) on burner aeration are almost all being captured by the model.

5.1. Achievements

In the present work, three major achievements occurred. First, a 1D mathematical model for the prediction of air entrainment in an ejector-pump like burner was developed. Second, the developed 1D model was calibrated and validated with the used of experimental testing on a prototype burner. Finally, with the validated and calibrated 1D model of the burner, some guidelines on the effects of changing key geometrical parameters on burner air entrainment performance were devised. The 1D mathematical model developed in this work can constitute a framework for newer, more complex models pertaining the inner workings of atmospheric gas burners.

5.2. Future Work

It would be interesting to include detailed chemical kinetics in the developed model, to try to explicitly predict CO, NO_x and eventually other pollutant emissions, instead of just having to rely on a prediction of the λ ratio and from that try to infer the expected levels of these pollutants on the combustion products. Also, the inclusion of a model of the preheat effect would benefit the accuracy of the model and would allow the capturing of non-steady phenomena occurring on an operating burner, something that the current model cannot achieve. Finally, additional work on the performance of an ejector-pump as a function of its geometry would certainly benefit these kind of 1D models, as this is a key geometrical aspect of the burner in study, as well as on numerous other industrial or engineering applications.

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References

[1] Charles E Baukal Jr. *Industrial Burners Handbook*. CrC press, 2003.

[2] Joseph Colannino. *Modeling of combustion systems: A practical approach*. CRC Press, 2006.

[3] Apinunt Namkhat and Sumrerng Jugjai. Primary air entrainment characteristics for a self-aspirating burner: Model and experiments. *Energy*, 35(4):1701 – 1708, 2010.

[4] Roberto Manuel Silva Magalhães. Estudo do comportamento de um esquentador estanque de 22 kw. Master's thesis, Universidade do Minho, 2014.

[5] Manuel António Ribeiro Lopes. Estudo do elemento de um queimador de chama pobre com estabilização por chama piloto para queimadores de baixo nox de 19 kw. Master's thesis, Universidade do Minho, 2012.

[6] Joo Tiago Corredeira Calejo Rodrigues. Modelo dinmico de um esquentador. Master's thesis, Instituto Superior Tcnico, 2012.

[7] José Teixeira, Luis SB Martins, Manuel Lopes, Senhorinha F Teixeira, and Manuel E Ferreira. Two stage atmospheric burners: Development and verification of a new mass-energy balance model. In *ASME 2014 International Mechanical Engineering Congress and Exposition*, pages V06AT07A047–V06AT07A047. American Society of Mechanical Engineers, 2014.

[8] CJ Lawn. A simple method for the design of gas burner injectors. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217(2):237–246, 2003.

[9] Apinunt Namkhat and Sumrerng Jugjai. The effect of primary air preheat on the primary aeration of a self-aspirating burner. In *The First TSME International Conference on Mechanical Engineering*, pages 20–22, 2010.

[10] Apinunt Namkhat and Sumrerng Jugjai. Prediction of total equivalence ratio for a self-aspirating burner. *Journal of Research and Applications in Mechanical Engineering (JRAME)*, 1(2):31–6, 2012.

[11] Horiba PG350 gas analyzer. `http://www.horiba.com/process-environmental/products/combustion/transportable/details/pg-300-portable-gas-analyzer-14647/`. Accessed: 2016-12-30.