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# Highly flexible burner concept for research on combustion technologies with recirculation of hot combustion products

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ABSTRACT

This paper reports the development and testing of a research coflow burner that generates laminar flames in a hot and diluted environment, which is adequate for studying the operating conditions found in practical combustors that use flue gas recirculation techniques. The burner has two flame zones; the first is an annular laminar premixed flat flame stabilized by a perforated plate, which generates a hot oxygen-rich flue gas mixture. The second is a non-premixed laminar flame, which uses the hot oxygen-rich flue gas mixture as an oxidizer. A methodology based on coflow calculations, which is the most significant component, was designed to provide different temperatures and dilution levels. The burner was built based on this design and tested using both intrusive and non-intrusive measurement techniques. The device emulated several features of practical combustor systems but with a simpler geometry, well-defined boundary conditions and using the simplest configuration found in literature (laminar flames). In a preliminary study, the MILD combustion regime was emulated by generating methane laminar non-premixed flames at oxygen concentrations between 3% and 9% and temperatures between 973 K and 1173 K.



## 1. Introduction

Combustion processes have been long-standing topics of scientific and technological interest because of their impact on the optimization, efficiency and economy of energy conversion systems. Recently, the strong dependence of industry and finance on fossil fuels initiated a new phase of investigation in the field of combustion in which the development of advanced combustion technologies has been a high priority issue. Several current studies have shown that such developments can be achieved much faster, more cheaply and more precisely if adequate computational tools and combustion models were available [1,2]. However, in spite of significant advances in computational tools, the modeling of advanced combustion techniques still represents great challenges because the chemical and fluid-dynamic phenomena that occur in these devices are highly complex. The chemistry, fluid-dynamics, heat transfer and mass transport interact in a practical combustor. These phenomena are highly sensitive to parameters such as the temperature, gas composition, turbulence level and dilution levels [3]. Studying advanced combustion regimes in burners that allow the control of these parameters while maintaining the physical phenomena of interest might yield valuable information. For example, in a review by Masri et al. [4], the authors argue that laminar flames stabilized in this type of burner could be suitable for studying chemical kinetics, flame extinction limits, soot formation, and thermal radiation.

The recirculation of combustion products is one of the most significant combustion techniques that have been extensively studied over the past two decades. However, few studies had attempted to model the chemistry of recirculation prior to the last decade [5]. In addition to fluid-dynamic and chemical challenges, the limited optical access found in most flue gas recirculation equipment complicates the implementation of nonintrusive diagnostic techniques, especially those used to develop and validate combustion models.

The emergence of technologies like MILD combustion [6,7] has motivated the study of the impact of the addition of diluents to laminar non-premixed flames. Because $CO_2$ and $N_2$ are two of the main combustion products, many studies have been conducted to analyze the effects of these species on the properties of non-premixed laminar flames, such extinction limits, flame length, and pollutant emission [8,9].

McEnally et al. [5] presented a coflow burner with a simple geometry and unconfined reaction zone. The burner generated atmospheric, axisymmetric non-premixed laminar flames. By using

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intrusive (thermocouple techniques) and nonintrusive diagnostic techniques (Rayleigh scattering), they attempted to validate a chemistry model that simulates soot formation in aircraft turbines. The fuel (ethylene diluted with nitrogen) emerged from a vertical brass tube in the burner, and the oxidizer (air) emerged from the annular region between this tube and a 50 mm diameter concentric tube. This work was the first attempt to validate a detailed chemistry model that incorporated a multiple section soot growth model in a flame with well-defined boundary conditions. However, this experimental setup does not emulate the operating conditions of many practical combustor devices in which the fuel is discharged into a hot mixture of oxidant and combustion products. More recently, Min et al. and Guo et al. [10,11] used a confined co-flow burner to experimentally and numerically study the influence of air dilution on laminar non-premixed methane flames. The flames were generated in a combustion chamber with square cross-sectional area, a side length of 25 cm and a height of 80 cm. The fuel (methane) flowed into the reaction zone through a round tube, which was mounted at the center of the chamber bottom. The oxidant emerged from the space between the fuel tube and the inner wall of the combustion chamber. They used a flexible experimental setup that simulates the vitiated environment of a recirculation burner by adjusting the flow rate ratio between air and diluents ($CO_2$ and $N_2$), but at lower temperatures than that found in a practical combustor.

Several recent studies have been performed in burners similar to those discussed above. Most of these studies first noted that a co-flow burner, especially a vitiated co-flow burner, allows the study of the recirculation process without complex recirculating flows. Its simplified geometry provides data and boundary condition information sufficient to validate numerical simulations. Second, there is a renewed interest in laminar non-premixed flames. Understanding the transport and chemical reaction process in these flames can improve the models of combustion under various conditions. Some authors have highlighted that laminar non-premixed flames can be considered "adequate tools" [12] or as "benchmark test" [13] to validate the accuracy of numerical models.

A laboratory scale burner to analyze the effects of both co-flow temperature and dilution level on the properties of non-premixed laminar flames was developed based on a hot coflow burner. This burner is similar to that used by McEnally et al. [5], but it features a secondary burner in the coflow, which stabilized a lean laminar premixed flame that provides oxygen-rich combustion products where the laminar fuel jet is discharged. The temperature and oxygen concentration of the co-flow can be modulated to provide a wide range of operating conditions to be investigated. In this paper, we show some details of the design and operation of this burner. To corroborate the great flexibility of this device, experimental results that demonstrate its performance under MILD combustion conditions are presented.

## 2. The vitiated hot coflow laminar burner

The main characteristic of the burner is the possible of generating atmospheric, axisymmetric non-premixed laminar flames in a vitiated and hot environment where the temperature and dilution level can be controlled. It consists of a central non-premixed laminar flame (primary burner) surrounded by oxygen-rich combustion products that comes from a lean premix flat flame (secondary burner), which is stabilized on a porous surface. Fig. 1 shows a schematic representation of the burner.

From Fig. 1:

- In the primary burner the fuel flows into the reaction zone from a stainless steel tubing with inner and outer diameters of 5 mm and 6 mm, respectively. The tubing passes through the mixing chamber and the secondary burner to finally inject the fuel in the center of the oxygen-rich combustion products by an interchangeable nozzle.
- In the mixing chamber, the fuel, oxidizer and inert enter separately in adequate proportions to guarantee the desire temperature and air dilution in the coflow. The mixing chamber is made of a stainless steel round tube. Inside the mixing chamber there are two flame arrestors to prevent accidents. Before the zone where the flame arrestors are located, there is a laminarization system which consists of an annular honeycomb body.
- In the coflow, to stabilize the premixed flat flame we use a perforated plate with diameter ($D_{coflow}$) and porosity of 40.9 mm and 27% respectively. This perforated plate is designed to be easily interchangeable. Additionally, a water cooling circuit was implemented to refrigerate the burner plate and the walls that protect the flat flame from the influence of the surrounding air.

## 3. Methodology

### 3.1. Design and operation methodology

An iterative procedure was implemented to design and operate the secondary burner, which probably is the most relevant

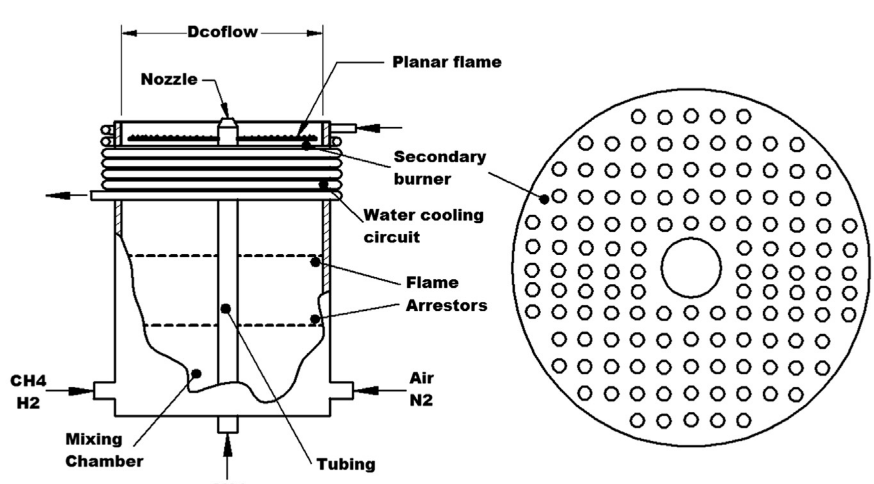


**Figure 1.** Schematic representation of the burner.