Fuel 261 (2020) 116449

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

A numerical study of confined turbulent jets for homogeneous combustion with oxygen enrichment

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ARTICLE INFO

Keywords:
Confined turbulent jets
Furnace
Homogeneous Combustion
Industrial
Jet momentum
NOx

ABSTRACT

Homogeneous Combustion (HC) and its variants (MILD, FLOX, CDC etc.) have emerged as attractive techniques to abate NOx emissions. The underlying theory is the arrest of *Damköhler number* (*Da*) to values close to unity by intense dilution (internal or external) of the reactant streams. The main research problem addressed in this work is the attainment of HC with enriched oxidizers ($X_{O2} > 21\%$). The complex and three-dimensional in-furnace flow is described by breaking it down into a set of canonical flows and using parameters related to the latter. Further, jet-momentum ratio and stagnation length are used to characterize the flow-field and their effect on NOx emissions is explained. Unlike oxidizer-jet momentum, fuel-jet ($< 5\%$ inert content) momentum is seen to have a nuanced effect on reaction zone homogeneity and NOx emissions; while reactant inlet temperature is seen to have little effect. Stagnation distance is also suggested as a length scaling parameter to describe arrangements with multiple confined turbulent jets. It is shown to perform well for flows under the jets by yielding velocity curves which are independent of chemistry. CO and hydrocarbon emissions are found to be dependent only on equivalence ratio. Volumetric standard deviation of Heat Release Rate is used to quantify the tendency of transition to the conventional mode of combustion due to oxidizer enrichment.

1. Introduction

A substantial portion of literature discussing efficient and low pollutant emission combustion systems comprises of Homogeneous Combustion (HC) or its variants (MILD, FLOX, CDC, HiTAC etc.) [1–6]. Qualitatively, they have a homogeneous reaction zone (small gradients of temperature and composition) and an absence of visible (or audible) flame fronts. Quantitatively, *Damköhler* number (*Da*) is controlled to be of the order of unity [4]. Industrial heating is often accomplished by using "enriched" oxidizer streams ($X_{O2} > 21\%$) to attain high temperatures with reduced fuel consumption. Extending the concept of HC to industrial heating applications (e.g. glass melting furnaces) is a challenging task. Higher concentration of reactant species (oxygen) would accelerate reaction rates, thus increasing *Da* and causing a shift to conventional combustion with high NOx emissions. Additionally, less momentum being injected via the oxidizer stream (due to higher oxygen concentration) would reduce mixing rates; thus increasing *Da* further. This calls for suitably modifying the flow to keep $Da \sim 1$.

With the notable exception of a few [7,8], a majority of studies reporting oxy-fuel combustion in the HC regime do not use methane/natural gas as fuel. Biogas [9,10], propane [11], light oil [12], and most prominently, coal [12–15] have been investigated with different levels of oxidizer enrichment by researchers. Methane (natural gas) is the most industrially relevant fuel (especially in the US [16]) and thus, further investigations are needed with industrial feasibility kept in mind. Sánchez et al. [7] reported very low NOx emissions with X_{O2} up to 40% for a 20 kW regenerative burner. The burner had a sophisticated "switching" mechanism in which the same set of nozzles operated alternatively to inject oxidizer and extract exhaust for 30 seconds each. Such an arrangement, coupled with the cordierite honeycomb regenerators can be challenging for industrial settings due to cost and maintenance downtime concerns. Moreover, the heat load was imposed via cooling pipes running through the furnace chamber. This is more like a boiler and unlike industrial furnaces where the load is kept at one end of the furnace (generally acting as one of the "boundary walls" for the gaseous chamber). A similar heat extraction strategy was employed by Li et al. [8] who utilized external dilution of the reactants with CO_2 for a 13 kW burner; and in some test cases completely replaced N_2 in the oxidizer with CO_2. External dilution is an excellent way to reduce *Da* and achieve HC [8,17,18] as increased inlet jet momenta aid mixing

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https://doi.org/10.1016/j.fuel.2019.116449
Received 22 August 2019; Received in revised form 10 October 2019; Accepted 17 October 2019
Available online 30 October 2019
0016-2361/

Nomenclature

Acronyms

CDC	Colorless Distributed Combustion
EDC	Eddy-Dissipation Concept
FLOX	Flameless Oxidation
HC	Homogeneous Combustion
HiTAC	High Temperature Air Combustion
HRR	Heat Release Rate
MILD	Moderate or Intense Low-oxygen Dilution
NOx	Nitrogen Oxides
RANS	Reynolds-Averaged Navier Stokes
TCI	Turbulence Chemistry Interaction
THC	Total Hydrocarbons
WSGGM	Weighted Sum of Gray Gases Model

Symbols

ϕ	Equivalence ratio (global)
σ	Standard deviation
$C_{1\epsilon}$	$k-\epsilon$ model constant
C_τ	Time scale constant (EDC)
C_ξ	Volume fraction constant (EDC)
d	Diameter
Da	Damköhler number
J	Jet momentum = mU_{av}
l_{stag}	Stagnation length
m	Mass flow rate
M_r	Momentum ratio = J_o/J_f
U	Velocity component along the axial direction
X	Mole Fraction
Z	Axial distance downstream from nozzle exit

Subscripts

av	averaged property
c	property in the axial direction along nozzle axis line
f	property at fuel nozzle exit
max	maximum
o	property at oxidizer nozzle exit

and reduced reactant concentrations reduce reactivity. CO_2 is a better diluent than N_2 as it (a) has a higher specific heat (b) lowers N_2 content available for NOx formation (c) radiates away heat and cools the reaction zone (d) promotes NO reduction [19]. The furnace used for [8] was pressurized to avoid air ingress. This is also unlike industrial combustors which are operated at a pressure slightly lower than atmospheric due to safety considerations. Air ingress is a source of NOx emissions even if the inlet streams have no nitrogen content; as was observed by Krishnamurthy et al. [11] (2–3 ppm NOx with pure propane and oxygen). Commercially available natural gas generally has an appreciable nitrogen content. As listed by Wünning et al. [2], pure reactant streams (no nitrogen content), and perfect sealing (to avoid air ingress) are hard and costly to implement in practical systems. Furthermore, practical implementation of external recirculation of high temperature exhaust gas or displacing N_2 with CO_2 in the reactant streams at industrial scales is also difficult and costly. Relevant to practice, it must be emphasized that this study reports on a 91.7 kW furnace which would be easier to scale up as compared to the ones reported in [7,8].

Based on the discussion above, it can be seen that there is a need to study/develop oxy-fuel HC systems which are industrially feasible. Also, since such systems would be expected to work with fuels and oxidizers having considerable nitrogen content, flows in these combustors would need proper engineering to ensure suppression of NOx forming and promotion of NOx reburning reactions. Consequently, understanding the complex, turbulent flow (driven by high-momentum inlet jets) in the reaction zone is important. This study is rooted in the conclusions presented in [8,20] where it was found that externally premixing the fuel with inert gas helped achieve MILD conditions. The effect of increasing fuel-jet momentum in enhancing internal dilution and thus potentially reducing NOx emissions is tested here. There appears to be a lack of reports on the effect of fuel-jet momentum on HC. There have been studies on the effect of oxidizer jet momentum [21,22], premixed jet momentum [23,24] and diluted fuel jet momentum (with CO_2, N_2) [8,25] but limited information is available about "pure" (as available commercially) fuel-jets. For this study, fuel

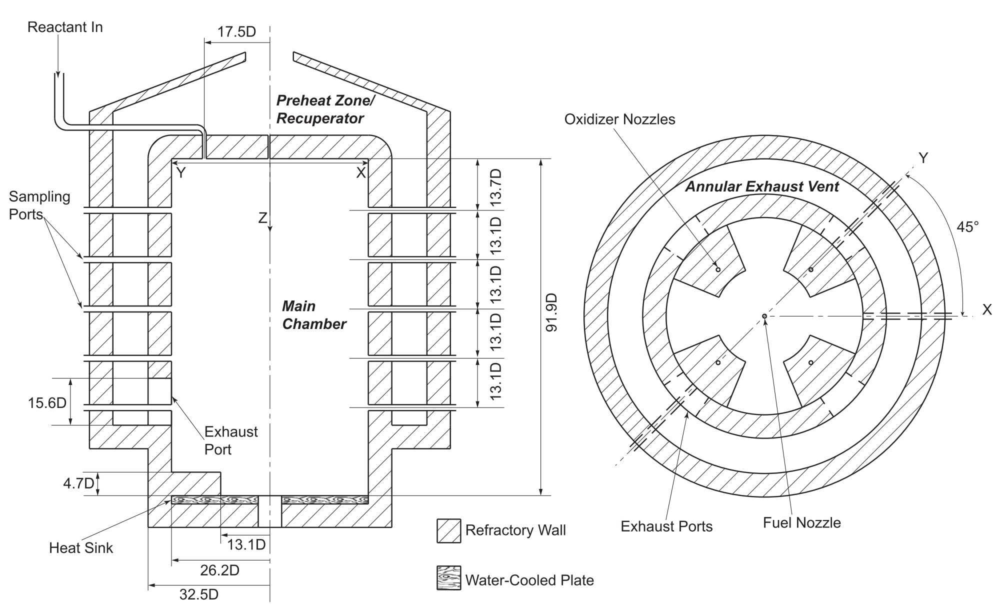

Fig. 1. Furnace geometry ($D = d_o = 16mm$). Only a quarter of the main chamber is simulated.