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Numerical and experimental investigation of a mild combustion burner

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Abstract

An industrial burner operating in the MILD combustion regime through internal recirculation of exhaust gases has been characterized numerically. To develop a self-sufficient numerical model of the burner, two subroutines are coupled to the CFD solver to model the air preheater section and heat losses from the burner through radiation. The resulting model is validated against experimental data on species concentration and temperature. A 3-dimensional CFD model of the burner is compared to an axisymmetric model, which allows considerable computational saving, but neglects some important burner features such as the presence of recirculation windows. Errors associated with the axisymmetric model are evaluated and discussed, as well as possible simplified procedures for engineering purposes. Modifications of the burner geometry are investigated numerically and suggested in order to enhance its performances. Such modifications are aimed at improving exhaust gases recirculation which is driven by the inlet air jet momentum. The burner is found to produce only 30 $\mathrm{ppm_V}$ of NO when operating in MILD combustion mode. For the same air preheating the NO emissions would be of approximately 1000 $\mathrm{ppm_V}$ in flame combustion mode. It is also shown that the burner ensures more homogeneous temperature distribution in the outer surfaces with respect to flame operation, and this is attractive for burners used in furnaces devoted to materials' thermal treatment processes. The effect of air excess on the combustion regime is also discussed.

Keywords: MILD combustion; Flameless; Burner; CFD

1. Introduction

The improvement of combustion efficiency to reduce fossil fuel consumption and carbon dioxide emission is a key issue in combustion research. Therefore, the achievement of high-energy-efficiency processes through advanced heat recovery systems is desirable even if the increase in process temperature arising from air preheating generally leads to very large NO_x emissions. However, NO_x emissions are regulated in many countries with increasingly stringent laws because of their adverse impact on the environment (climate change, acid rains, photochemical smog). Thus, the development of a combustion technology able to accomplish large energy savings with very low pollutant emissions has become a primary concern.

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Nomenclature

A	area	m^2
$A_{\mathrm{air,in}}$	air inlet cross-sectional area	m^2
Da	Damkohler number	–
e	emissivity	–
e_{air}	air excess	–
F	view factor	–
k_{ins}	insulation layer thermal conductivity	$\mathrm{W\,m^{-1}\,K^{-1}}$
k_{prompt}	kinetic constant of prompt NO	$\mathrm{s^{-1}}$
k_{R}	recirculation degree of burnt gases into the reaction region	%
k_{R0}	parameter in Eq. (12)	–
k_{thermal}	kinetic constant of thermal NO	$\mathrm{m^{1.5}\,K^{0.5}\,mol^{-0.5}\,s^{-0.5}}$
$\bar{k}(T)$	kinetic constant integrated over a PDF of temperature, arbitrary units	
L_{em}	emitter length	m
$\dot{m}$	mass flow rate	$\mathrm{kg\,s^{-1}}$
PDF(T)	probability density function	–
$\dot{Q}$	irradiative heat flux	W
$\dot{Q}_{\mathrm{in}}$	burner load	W
$\dot{Q}_{\mathrm{rec}}$	heat flux exchanged in the air preheater	W
r	radial coordinate	m
R	radius	m
T	temperature	K
$\dot{w}$	reaction rate	$\mathrm{kg\,m^{-3}\,s^{-1}}$
W	molecular weight	$\mathrm{kg\,mol^{-1}}$
x	axial coordinate	m
X	molar fraction	–
[ ]	molar concentration	$\mathrm{mol\,m^{-3}}$

Greek symbols

η	efficiency	–
ρ	density	$\mathrm{kg\,m^{-3}}$
σ	Boltzmann constant, $\sigma = 5.67 \times 10^{-8}\ \mathrm{W\,m^{-2}\,K^{-4}}$	
τ_{c}	chemical timescale	s
τ_{t}	turbulent timescale	s

Subscripts

1	radiant tube
2	Inconel shield
$2'$	internal insulation layer of the Inconel shield
$2''$	external insulation layer of the Inconel shield
3	water heat exchanger
A	air
EG	exhaust gases
F	fuel
max	maximum
mix	mixture
rad	radiant tube
reaction	reaction region
rec	heat recovery section
Δk	parameter in Eq. (12)

In this framework, MILD combustion appears interesting, as it may ensure high combustion efficiencies with low pollutant emissions [1,2].

Such a combustion regime needs the reactants to be preheated above the self-ignition temperature and enough inert combustion products to be entrained in the reaction region. The former requirement ensures high thermal efficiency, whereas the latter allows diluting the flame and reducing the final temperature well below the adiabatic flame temperature. As a result, a flame front is no longer identifiable, so that MILD combustion is often denoted as flameless combustion. Moreover, it has been observed that ignition and extinction phenomena do not occur in MILD combustion because of the small temperature difference between burnt and unburnt gases.

Among the advantages associated with this combustion technology, one is that flame stabilization occurs naturally as the reactants' temperature exceeds the self-ignition temperature. Therefore a large degree of freedom in the choice of the fluid dynamical configuration of the combustion chamber is allowed. Moreover, the temperature field homogeneity and reduced gradients allow better control of maximum temperatures with beneficial effects on materials.

Importantly, NO_x emissions are greately reduced because of the limited temperature increase. Soot formation is also suppressed, because of the lean conditions in the combustion chamber, due to the large dilution levels. In addition, the large CO_2 concentration due to the recirculation of combustion products has a beneficial effect of soot suppression [2].

Therefore, MILD combustion poses itself as a technology combining high efficiencies, because of the strong preheating, with low pollutant emissions.

All these aspects make MILD combustion worthy of further investigations and attention, even though, to date, several studies have been devoted to understanding its operational conditions [3] as well as its mechanisms and critical parameters [4]. An extensive review on MILD combustion features considering physical, chemical, and thermodynamic aspects has been provided by Cavaliere and de Joannon [2].

From a technological point of view, the first requirement for MILD combustion, reactant temperature above the self-ignition temperature, may be