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CFD analysis of exhaust gas recirculation in a micro gas turbine combustor for CO_2 capture

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The aim of this paper is to numerically investigate the effects of CO_2 dilution on the operation of an industrial micro gas turbine combustor in order to assess the possible application of exhaust gas recirculation (EGR) for post-combustion CO_2 capture. A complete 3D model of the combustion chamber has been developed, taking into account the conjugate heat transfer (CHT) and radiation effects, and a detailed chemical mechanism has been employed in the framework of the Flamelet Generated Manifolds approach to model the combustion process. The importance of including the effects of conjugate heat transfer in the model has been demonstrated for both air-fired and EGR conditions. Also, combustion with EGR resulted in lower temperature levels with respect to the air-fired case and thus in reduced NO_x production. Further, the increased presence of carbon dioxide has been observed to have an impact on both the flame speed and the flame stabilization mechanism.

According to the numerical results, EGR can be a viable way to increase the CO_2 content in the flue gas of dry low-emissions (DLE) combustors, and therefore enhance the efficiency of post-combustion carbon separation. At the same time, due to the reduced temperature levels within the combustion chamber, it is possible to attain lower NO_x emissions without compromising the combustion efficiency under the considered EGR levels.

1. Introduction

A number of measures aimed at reducing greenhouse gas emissions from the energy sector have been proposed to tackle global warming and, at the same time, do not compromise economic growth. These measures include boosting the use of low-carbon power generation (nuclear, renewables), enhancing the efficiency of fossil fuel usage, reducing the energy demand through energy efficiency and deploying Carbon Capture and Storage (CCS). Among these possible solutions, CCS is particularly attractive because it allows us to preserve the economic value of fossil fuel reserves and infrastructures and also it is applicable to reduce industry-related emissions [19].

Although gas-fired power plants are less carbon-intensive than other forms of fossil fuel power generation, e.g. coal, gas is not a zero-emission fuel and therefore the application of CCS to gas-fired power plants has to be taken into account. Among all the possible carbon capture technologies that are suitable for gas-fired power generation, post combustion combined with exhaust gas recirculation is regarded as the most feasible in the short-term [21]. The application of EGR results in a higher concentration of carbon dioxide in the exhaust gas and in a lower exhaust mass flow, which improves significantly the efficiency of the post-combustion capture process [23].

From the combustion process point of view gas turbine operation with EGR differs from conventional air-firing, and this is mainly due to the increased CO_2 presence in the combustion environment. The presence of carbon dioxide has a significant impact on the combustion process in terms of temperature levels, heat transfer, flame stability and pollutant emissions [25].

The impact of carbon dioxide on the combustion process is due to both thermal and chemical effects [16]. The thermal effects are related to the higher heat capacity of CO_2, which implies a reduction in the adiabatic temperature with respect to conventional air combustion. The chemical effects are related to the chemical reactivity of carbon dioxide and result both in a direct participation in elementary reactions and in an involvement in termolecular reactions as a third body with a higher efficiency with respect to nitrogen. It has been observed [26] that the impact of the presence of carbon dioxide on the combustion chemistry is mainly due to the reaction:

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Nomenclature

c	progress variable (–)	Z	mixture fraction (–)
$\dot{m}$	mass flow rate (kg/s)	*Greek letters*	
R	EGR ratio (–)	δ_L	laminar flame thickness (m)
T	temperature (K)	ϕ	equivalence ratio (–)
X_i	mole fraction of species i (–)		

$$CO + OH \leftrightarrows CO_2 + H \tag{1}$$

Let us consider the single most important chain-branching step in hydrocarbon combustion, i.e.:

$$H + O_2 \leftrightarrows OH + O \tag{2}$$

This reaction is fundamental since it generates the OH and H radicals necessary for the oxidation of fuel molecules. It can be seen that carbon dioxide decreases the production of these radicals by consuming the hydrogen radical available for reaction (2) via the reverse of reaction (1).

Andersson and Johnsson [2] performed an experimental investigation in a 100 kW test facility, using an oxidizer consisting of a mixture of oxygen and carbon dioxide for two different compositions (the first with 21% O_2 and the second with 29% O_2) and the results obtained have been compared with a reference air-combustion case. In the 21% oxygen case, significantly lower temperature levels with respect to the reference air-fired case were observed, and this is mainly due to the higher heat capacity of carbon dioxide. In general, the lower temperature can be related also to an increase in radiation losses caused by the higher emissivity of carbon dioxide; the importance of radiative heat losses depends on the radiative characteristics of the considered flame. In the 29% O_2 case, the overall combustion process resulted in similar species concentrations and temperature levels as those observed in the air-combustion case. An increase in the flame radiation intensity up to 30% has been registered in this case compared to the baseline air-fired condition, despite the fact that the two cases were characterized by similar values of the temperature.

Baltasar et al. [4] investigated the effects of EGR on the flame characteristics and pollutant emissions in a gas-fired laboratory furnace. The recirculated flue gas has been cooled down and the condensate water has been removed before its injection into the burner.

Three different values of the excess air have been considered, varying the EGR ratio from zero to the blow-off limit. The EGR ratio, R, is defined as

$$R = \frac{\dot{m}_{rec}}{\dot{m}_{air} + \dot{m}_{fuel}} \tag{3}$$

where $\dot{m}_{rec}$ is the mass flow rate of the flue gas being recirculated.

As reported in several other studies, e.g. Røkke and Hustad [25], ElKady et al. [13], Tanaka et al. [29], a noticeable decrease in nitrogen oxides emissions can be obtained by recirculating the flue gas into the burner for all the excess air levels considered, the reduction being more significant for larger values of R. This is mainly due to the lower combustion temperature observed with EGR, and the consequent reduction of the thermal NO_x production. Flame blow-off has been observed to occur at an EGR ratio of about 0.3 for this particular furnace, regardless of the excess air level.

The effects of EGR in a DLE research combustor slightly modified from the version actually used in industrial gas turbines have been investigated by ElKady et al. [13]. The oxidizer stream, consisting of an air/CO_2 mixture, is preheated to a temperature of 700 K at an inlet pressure of 10 atm. The aim was to demonstrate the feasibility of EGR in an existing DLE combustor in order to increase the carbon dioxide content in the flue gas to reduce the cost of the post-combustion CO_2 capture process. It has been demonstrated that an EGR ratio up to 35% (corresponding to a carbon dioxide content in the oxidizer and in the flue gas of about 3% and 10%, respectively) can be employed with minor changes in the combustion design with a significant reduction in NO_x emissions with respect to air-fired operation and slightly higher, but still acceptable, values for carbon monoxide emissions.

The feasibility of EGR in another industrial gas turbine combustor has been assessed by Tanaka et al. [8] with the aim of reducing NO_x emissions for Mitsubishi Heavy Industry's ultrahigh-temperature gas turbine (1700 C-class). Because, due the thermal NO_x formation path, nitrogen oxides production increases dramatically as the combustion temperature increases, NO_x production is a major issue for ultrahigh-temperature gas turbines. Under these conditions, EGR can be employed to reduce NO_x production by lowering the temperature in the combustion region. To investigate the effects of EGR on the NO_x formation, two different levels of oxygen in the oxidizer stream were considered: a high (19.6%) inlet O_2 concentration (corresponding to a 10% EGR ratio) and a low (17.0%) O_2 inlet concentration (corresponding to a 26.6% EGR ratio). A substantial decreasing in NO_x formation has been observed in the latter case, the nitrogen oxide production with a 26.6% EGR ratio being equal to 23% of that with 10% EGR ratio. No substantial differences in CO emissions have been observed between the two cases, and the CO levels were measured to be below the target of 10 ppm in both configurations.

Given the fact that EGR has a substantial impact on the combustion process, it is of paramount importance to evaluate the effects when considering its application to existing industrial gas turbine combustors. Due to the complexity of industrial configurations, experimental measurements within the combustion chamber are often not feasible (e.g.: Boudier et al. [7]). For this reason, the development of accurate numerical models of the combustion process is essential in order to assess the possibility of operating the existing industrial gas turbine combustors with EGR.

In this paper, a molar concentration of 4% of CO_2 in the oxidizer stream (corresponding to an EGR ratio of about 35%) of the micro gas turbine Turbec T-100 combustion chamber has been considered, with the aim to evaluate the operation of this device in combination with EGR. The effects of carbon dioxide on the combustion process in terms of flame stability, heat release and pollutant emissions have been investigated, and a comparison with the operation of the same device without EGR has been performed.

2. Combustor description and numerical grid

The Turbec T-100 is a micro gas turbine system for the combined generation of heat and power [1]. The nominal electrical power output is 100 kW and the corresponding thermal power output is about 165 kW, with an electrical efficiency of about 33% and a 80% overall efficiency. This micro gas turbine employs a reverse flow DLE combustor. NO_x emissions are reduced by controlling the combustion temperature by means of a highly air-diluted lean premixed combustion process. Further, a