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Experimental and numerical investigation of a micro-CHP flameless unit

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ABSTRACT

A numerical and experimental investigation of a system for the micro-cogeneration of heat and power, based on a Stirling cycle and equipped with a flameless burner, is carried out with the purpose of evaluating the system performances with hydrogen-enriched fuels. The numerical model of the combustion chamber gave significant insight concerning the analysis and interpretation of the experimental measurements; however it required considerable efforts, especially regarding the definition of proper boundary conditions. In particular a subroutine was developed in order to couple the oxidation process to the overall operation of the micro-cogeneration unit. This procedure was proved to perform satisfactory, providing values of the heat source for the Stirling cycle that lead to expected thermal efficiencies in agreement with those indicated in the literature for similar systems. The importance of a proper turbulence-chemistry interaction treatment and rather detailed kinetic schemes to capture flameless combustion was also assessed. A simple NO formation mechanism based on the thermal and prompt routes was found to provide NO emissions in relatively good agreement with experimental observations when applied on thermo-fluid dynamic fields obtained from detailed oxidation schemes.

1. Introduction

Combined heat and power generation (CHP), or cogeneration, has recently received particular attention as an alternative to conventional methods of producing heat and electricity separately.

In particular, the continuous fluctuations in energy price and the uncertainty in fuel supplies have determined a growing interest for the use of micro-cogeneration in the residential sector. In fact, micro-CHP systems are characterized by very high conversion efficiencies (over 80%) with respect to fossil fuel fired electricity generation systems. Moreover, distributed generation in decentralized systems is very appealing to reduce greenhouse gases emissions and to exploit the new opportunities offered by alternative fuels, such as hydrogen-based fuels obtained from biomass (and coal) thermal conversion processes.

Onovwiona and Ugursal [1] recently carried out a literature review on residential cogeneration systems, taking into account four different technologies: reciprocating internal combustion engines, micro-turbines, fuel cells and Stirling engines. The authors discussed the development stage of the technologies, indicating environmental benefits, performances and installation costs. As a result, the privileged choice for residential application appeared to be the reciprocating internal combustion engines (ICE), due to their robustness, reliability and reasonable costs. However, the "maturity" of the ICE technology is also responsible of the poor performances of such systems from the environmental point of view, e.g. CO and NO_x emissions, although improvements have been recently made for micro-CHP applications [2]. On the other hand, innovative technologies such as Stirling engines are characterized by emissions about 10 times smaller [1] than those of Otto engines with catalytic converters and they offer more flexibility from the point of view of fuel nature.

A recent life cycle assessment [3] analysis on micro-cogeneration has indicated micro-CHP systems are superior in terms of GHG emissions to both average electricity and heat supply as well as to separate production of electricity in gas power plants and heat in condensing boilers. Among the existing possibilities (i.e. fuel cells, micro-turbines), cogeneration systems based on Stirling cycles appear particularly appealing, as they ensure high efficiency, fuel flexibility, low emissions, low noise/vibration levels and good performance at partial load [1]. Since the combustion process takes places outside the engine, different fuels may be used; moreover the combustion process can be controlled independently from the engine operation. Besides, the maintenance of Stirling engines is less critical compared to other reciprocating internal combustion engines, because of fewer moving parts leading to quieter and smoother operations. The versatility regarding the fuel topology is extremely important as it implies that non conventional fuels such as biomasses and low-calorific gases enriched with hydrogen could

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Nomenclature

CI	confidence interval
C_p	specific heat, J kg^{-1} K^{-1}
$\tilde{E}$	error associated to the numerical simulations
F_s	safety factor
GCI	Grid Convergence Index
k	turbulent kinetic energy, m^2 s^{-2}
k_R	recirculation degree
h	grid spacing, m
n	number of experimental replicates
$\dot{m}$	mass flow rate, kg s^{-1}
P_{He}	helium operating pressure, Pa
$\dot{Q}_{rem}$	heat removed in the flue gases/helium heat exchanger, W
$\dot{Q}_{in}$	burner input power, W
$\dot{Q}_{air}$	air preheating power, W
$\dot{Q}_{fg}$	power recoverable from the exhaust gases, W
r	radial coordinate, m
r_{hc}	grid coarsening ratio
r_{hf}	grid refining ratio
s	sample standard deviation
T	temperature, K
$t_{\alpha/2,\nu}$	quantile of the measured population
x	axial coordinate, m
y_m	predicted variable
$\bar{y}_e$	measured variable
Y	mass fraction
U_e	experimental uncertainty
U_{sver}	solution uncertainty
$\dot{W}_{el}$	electric power, W

Greek symbols

α	desired level of confidence
ΔT_{max}	maximum temperature rise, K
ε_{AIR}	air excess
ε	kinetic energy dissipation rate, m^2 s^{-3}
$\eta_{th,St}$	thermal efficiency of the Stirling engine
η_{reg}	regenerator efficiency
ν	degrees of freedom

Subscripts

0	at ambient conditions
air	air
b	base grid
c	coarse grid
e	electrical
f	fine grid
f_g	flue gases
$f_{g,R}$	recirculating flue gases
fuel	fuel
k	species index
m	mixed value, referred to the mixing process of fresh and flue gases
out	value at chimney
th	thermal
tot	overall

Abbreviations

BC	boundary condition
CHP	combined heat and power generation
EDC	Eddy dissipation concept
HITAC	high temperature air combustion
MILD	moderate or intense low-oxygen dilution
PDF	probability density function
WSGG	weighted sum of gray gases

be effectively exploited, without damaging the engine. Indeed, the performances of the combustion system in terms of efficiency and pollutants emissions need to be assessed when working with non conventional fuels.

Thomas [4] recently performed a benchmark testing of four micro-CHP units in the range of 5–9 kW electric power, two of them based on Stirling engines and two Otto CHP units. The systems were compared on the basis on the German environmental regulation which fixes the admissible performances of CHP systems from the point of view of electrical, thermal and overall efficiencies, NO_x and CO emissions. Results of the benchmark clearly showed that the only unit able to meet all the regulation requirements was a SOLO Stirling unit [5], equipped with a flameless burner.

The implementation of flameless burners in micro-CHP units represents a very attractive solution, due to the great potentials of the flameless technology to deal with complex fuels. Flameless combustion [6], or MILD [7,8] of HITAC [9–11] has received particular attention in the last years due to its ability of combining high combustion efficiencies with extremely low pollutant emissions. Such combustion regime is based on the modification of the traditional flame structure: the system is driven towards homogeneous (temperature and species) conditions, by means of a massive recirculation of exhaust gases in the reaction region. As a result, the system approaches perfectly stirred reactor conditions and temperature increase due to combustion is diluted over a wider reaction zone. The volumetric nature of the combustion process allows achieving very high combustion efficiencies ensuring near zero CO emissions in the exhausts. Moreover, NO_x emissions are largely suppressed, even when large air preheating is applied, because of the reduced temperature peaks.

The latter effect appears particularly beneficial for controlling NO_x formation and shows potentials for limiting the reactivity of hydrogen-based fuels. The effectiveness of flameless combustion with hydrogen-based fuels has been recently demonstrated [11–15].

The present paper aims at investigating a flameless system for the micro-CHP of heat and power based on a Stirling cycle, with the purpose of evaluating its performance with hydrogen-enriched fuels. A joint experimental and modeling activity has been carried out to gain insight into the main features of the system, which shows complex geometry, due to its industrial characteristics, and operation, due to the coupling between the combustion process and a Stirling cycle. The available experimental data are, then, crucial for a constructive validation of the computational approach, with particular attention to oxidation kinetic schemes and pollutant formation models.

2. The burner

The investigated micro-CHP system[1] [5], is able of providing 2–9 kW of electricity and 22–30 kW of thermal power, with an electrical efficiency of 22–24% and a total efficiency larger than 90%. The system is equipped with a flameless burner for the oxidation of the gaseous fuel and a finned heat exchanger is placed inside the combustion chamber to supply power to a Stirling cycle operated with a different medium (i.e. helium). The CHP unit is designed to burn

[1] SOLO Stirling 161 Cogeneration Unit by SOLO® installed at the ENEL Ricerca facilities of Livorno, Italy.