Applied Thermal Engineering 63 (2014) 218–226

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Analysis of high flue gas recirculation for small energy conversion systems

Ismo Roiha [a,*], Juha Kaikko [a], Keijo Jaanu [b], Esa Vakkilainen [a]

[a] Lappeenranta University of Technology, LUT Energy, P.O. Box 20, FI-53851 Lappeenranta, Finland
[b] Envofire Oy, P.O. Box 142, FI-40101 Jyväskylä, Finland

HIGHLIGHTS

- Simplified approach for obtaining benefits of HiTAC combustion in gas-fired facilities.
- Development of an experimental test facility.
- Promising results for emission reduction.

ARTICLE INFO

Article history:
Received 6 February 2012
Accepted 30 October 2013
Available online 8 November 2013

Keywords:
Flue gas recirculation
HiTAC
Flameless oxidation
Natural gas combustion

ABSTRACT

Restrictions of energy production emissions set new challenges to combustion facilities, and new methods, such as High Temperature Air Combustion (HiTAC) are considered to meet these challenges. In HiTAC, the flue gas is recirculated to the combustion region while preheating the combustion air. The HiTAC combustion is an environmentally friendly and energy-efficient method, but it requires special burner arrangements and additional equipment for air preheating. This work investigates the feasibility to obtain low emissions without preheating the combustion air. Experimental work showed that in this case the applicable flue gas recirculation rates were lower than with conventional HiTAC. Numerical analysis was performed to analyze flow behavior in the combustion chamber. The main contributing factor for combustion stability was found to be pronounced internal recirculation. The flame was forced aside towards the side walls by a back flow in the chamber centerline, which kept the flame stable and attached to the burner. The results suggest that the advantages of HiTAC can be partly achieved without the preheating of combustion air and with moderate flue gas recirculation. This enables a simplified and more economical construction, applicable for instance in small-scale boilers.

1. Introduction

A high amount of flue gas recirculation contributes to lower emissions but increases the risk of combustion instabilities. A discovery was made in England in the early 1970's that stable combustion can be achieved when preheating air during flue gas recirculation [1]. The concept of High Temperature Air Combustion (HiTAC) emerged first in Germany in 1989 during recuperative burner tests. HiTAC, also known as flameless oxidation (FLOX) or flameless combustion refers to a combustion process where regenerative air preheating and high flue gas recirculation is implemented to a burner construction. In the early 1990's, the development of advanced industrial furnaces was promoted in Japan, with a contribution to practical HiTAC applications [2]. Concurrently, a FLOX burner was developed in Germany [3], also for use in power generation systems. Later on, many research institutes and universities have studied HiTAC combustion, its principles, requirements, applications and advantages [4–8]. The experimental studies are mainly related to large-scale furnaces and burners [9,10]; examples of small-scale burners are [11,12]. Computational fluid dynamics (CFD) has been used to analyze flow fields in HiTAC combustion for instance in Refs. [13,14]. Recently, studies have been performed for predicting minor emission species under mean and fluctuating temperature fields [15]. The principle reference book on HiTAC combustion is [16], but the fundamentals of the phenomenon have been described in Refs. [3–5,17] as well.

Research activities on HiTAC have mainly concerned furnace applications where the advantages are most obvious. The focus in this work is on the energy sector, especially household burners and small district heating plant burners. In small-scale applications, simple configuration is a prerequisite for economical feasibility. The

* Corresponding author. Tel.: +358 40 6569884.
E-mail address: ismo.roiha@lut.fi (I. Roiha).

1359-4311/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.applthermaleng.2013.10.062

primary objective of this work is to study whether low emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) can be obtained with no preheating of combustion air. The secondary goal is to determine the operating region for the selected structure where combustion is stable with low emissions. Facility size has an influence on the combustion process as well, but it is not considered in this research.

The study contains an experimental and a numerical part. A laboratory-scale test facility was designed and constructed at Lappeenranta University of Technology (LUT), Finland to investigate the effect of flue gas recirculation on the combustion process and emissions. A commercial gas burner with minor modifications forms the basis for the setup, while multiple amounts of produced combustion gases can be recirculated using an external loop and a blower. After the facility was built, a numerical model was developed with commercial simulation software to examine the inner flow-field in the chamber and analyze factors contributing to burner stability. The novelty of the work is that low emissions and stable combustion can be achieved without air preheating when operating with lower flue gas recirculation rates than with normal HiTAC. The results of the work help to form an overall view on how conventional gas burners could be modified cost-effectively for a lower environmental impact. The findings are applicable also in small scale heat treatment and annealing facilities.

2. High Temperature Air Combustion

In conventional combustion systems, a steady and visible flame front is formed by the fuel and combustion air. As a result, a sharp temperature gradient with high local flame temperatures and large amount of OH radicals occur. Flame stabilization is usually provided by recirculating the combustion products internally and/or using a swirl plate [18]. HiTAC avoids the formation of a flame front by a high combustion temperature and a large amount of inert gases in combustion, and has consequently two main requirements. First, the temperature level in the chamber must be well above the self-ignition temperature of the fuel (lowest temperature at which the fuel-air mixture ignites spontaneously in normal atmosphere without an external spark or flame). For instance, for natural gas with the self-ignition temperature of 630–650 °C, the temperature level must be 800–850 °C. The temperature limit exhibits a hysteresis of 20–50 °C, depending on whether the chamber is heated or cooled. Secondly, high flue gas recirculation is required to decrease the oxygen (O_2) concentration to a sufficient level. The flue gas recirculation rate R is determined as the ratio of recirculated and produced flue gas mass flow rates [16].

$$R = \frac{q_{\mathrm{m,rec}}}{q_{\mathrm{m,a}} + q_{\mathrm{m,f}}} \tag{1}$$

In typical HiTAC applications, R is in the range 4–5. The decreased O_2 decelerates the reactions, and thus they take place in a wider space. This has an effect on the flame via temperatures and reaction times. An increase in the initial temperature of the air and fuel mixture expands the combustible limits significantly, as can be seen in Fig. 1. Without preheating the air, the flame becomes typically unstable at an R exceeding 0.3 [16,19].

The temperature field in HiTAC is uniform, producing lower temperature gradients and lower maximum temperatures than in conventional combustion. As a result, the formation of NO_x and CO is reduced significantly. Other advantages compared to the conventional combustion mode are for instance reduced noise levels and equipment size [19]. HiTAC combustion requires special arrangements for the burners, as well as additional equipment for air preheating and flue gas recirculation. The omission of a visible flame, UV emission or ionization poses challenges for operational safety.

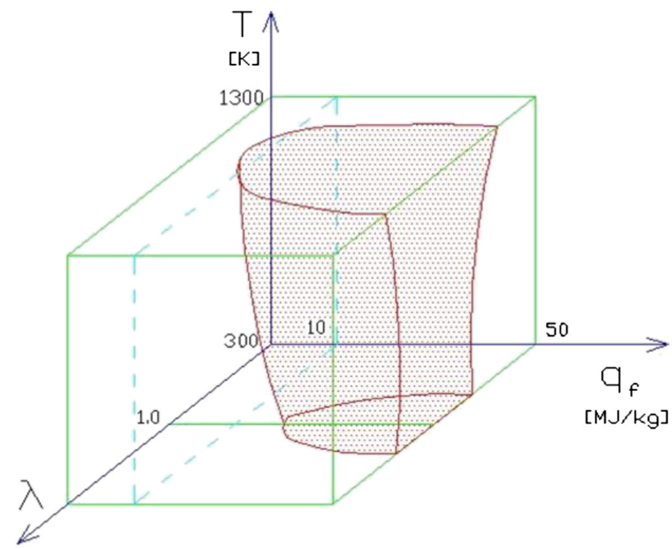

Fig. 1. Flammable domain as a function of the heating value of fuel q_f, initial temperature of air–fuel mixture T and air ratio λ. Adapted from Ref. [16].

Thermal NO_x emissions increase when the temperature in any part of the combustion chamber exceeds 1000 °C. On the other hand, CO formation increases rapidly below 800 °C. The CO emission is also highly dependent on the time available for the reactions [20]. This must be taken into account when sizing the combustion chamber. Altogether, the emissions and combustion stability are mainly affected by the used fuel, burner structure and power level, as well as the combustion air staging and temperature. A HiTAC burner is normally started up in a conventional flame mode with no flue gas recirculation. To avoid instability, the combustion chamber must be heated up properly before recirculation can be started and increased to yield the HiTAC conditions. Fig. 2 shows a schematic presentation of allowed operational areas as a function of chamber temperature and R for conventional combustion (region A) and HiTAC combustion (region C). This work investigates the applicability of region B, and especially the marked Research area in Fig. 2 for safe and low-emission operation. This area is designated as the pre-HiTAC region below.

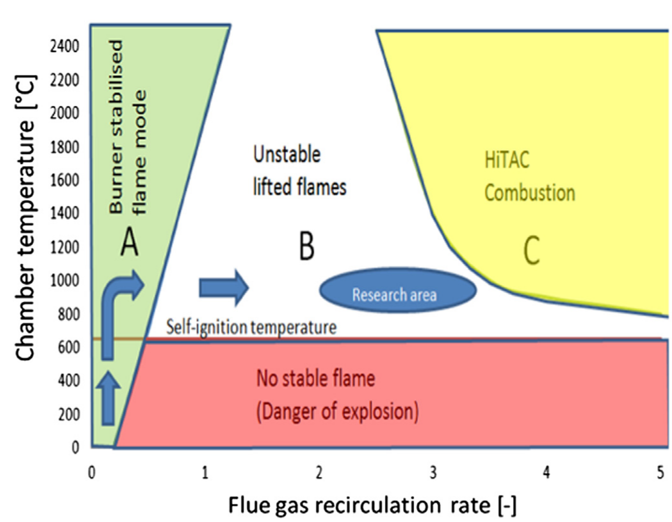

Fig. 2. Scheme of combustion regimes, adapted from Ref. [3].