ADIABATIC COMBUSTION PROCESSES IN POROUS INERT MEDIA AT THE LEAN FLAMMABILITY LIMIT

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Abstract

In order to study adiabatic combustion processes in porous inert media experimentally, a porous burner chamber was built, in which the behavior of different porous media could be investigated by measuring the temperature- and the emission-profiles. The attention was focused on the stabilizing behavior of the combustion wave in the range of high excess-air-ratios λ, and the influence of air preheating. The results indicate that stabilized porous media combustion leads to a significant rise of the thermal heat load, e.g. the flame velocity, and to a larger stability range of premixed combustion.

1 Introduction

Flame propagation and heat transfer through porous media have already been investigated by several scientists The experiments of *Babkin et al* (1991) resulted in the following limiting modified Peclet number for flame propagation in porous media:

$$Pe \geq 65 \qquad (1)$$

where:

$$Pe = \frac{S_L d_m c_p \rho_G}{\lambda_G} \qquad (2)$$

and S_L is the laminar flame velocity, d_m the equivalent porous cavity diameter, c_p the specific heat capacity, ρ the density, and A the thermal conductivity of the gas mixture. If $Pe \leq 65$ the flame structures extinguish (quenching), since heat is transferred to the porous matrix at a higher rate than it is produced

The characteristic cooling time of hot gases in a packed bed was calculated by *Lyamin and Pinaev* (1986, 1987) The cooling time multiplied by the flame front propagation velocity resulted in a characteristic cooling distance < 5 mm for all known experimental cases. The recorded flame front thickness in such experiments (*Konhavin et al* (1982)) was several centimeters. This means that the chemical transformation and cooling of the combustion products proceeded simultaneously in each section of the porous material. Cooling of the combustion products terminated in practically the same section where the chemical reactions vanished.

The studies in this field known from literature deal with unsteady combustion and flame propagation in inert porous media (*Kauffman et al* (1982), *Pinaev and Lyamin* (1989), *Yoshida et al (1990)*), with heat transport in packed beds *(Gnielinski* (1978, 1982), *Tsotsas and Martin* (1987)), with surface radiant burners (*Sathe et al* (1990), *Tong and Sathe* (1991), *Hammura and Echigo(1991)*), with the so-called superadiabatic combustion in porous media (*Hanamtira et al* (1993), *Hsu et al* (1993)), and also with steady catalytic chemical conversion in porous media (*Emonts and Brockerhoff* (1996)).

In the present work, a burner concept is used, which functions on the basis of steady combustion inside inert porous media without catalysts. The principle design of such a burner has been described by *Trimis and Durst* (1996). In order to ignite, stabilize and operate a burner based on combustion in inert porous media under steady state conditions, the combustion region had to be stabilized at a definite position of the porous matrix. The stabilization of the combustion region inside the porous material was obtained with the design shown in Fig. 1. The premixed gas flows through the porous medium region A with an equivalent diameter d_m of the porous cavity space, which is less than the quenching diameter for these flow conditions. At the position where the flame front should be located, a steep gradient in the pore size of the porous medium is realized, resulting in cavity space diameters larger than the quenching diameter. In other words, a porous medium region C, with a d_m larger than the quenching diameter, follows the region A. Flame propagation is only possible in region C, where $Pe > 65$, and is stabilized by local quenching at the interface to region A where $Pe < 65$ The different Peclet numbers are obtained by changing the size of the porous cavity spaces. A change in the load of the combustor does not affect the combustion region location but only changes its length, starting always from the edge of region A. The stabilization of the combustion zone under steady-state conditions is strongly dependent on the heat transport properties of the porous material in the regions A and C. These can be adjusted, additionally to the size of the porous cavity spaces, through the porosity, the emissivity and the thermal conductivity of the ceramic porous material in such a way, that a high power modulation range can be applied without stabilization problems.

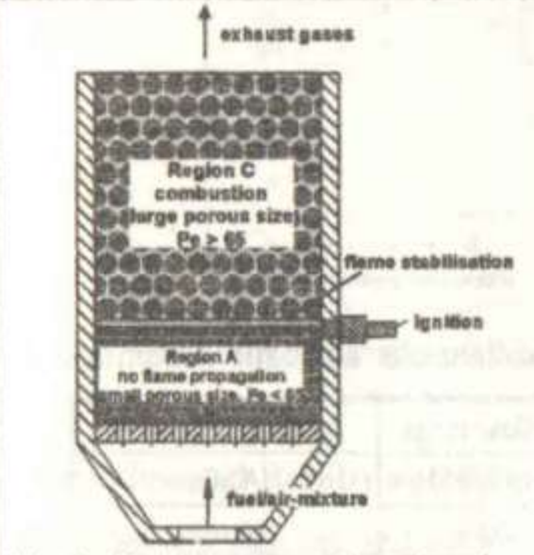

Fig. 1 Stabilization of combustion zone in porous media

The main advantages of steady combustion in inert porous media may be summarized as follows:

- The large inner surface of the porous medium results in high heat transport between the gas phase and the porous medium (quasi-equilibrium).
- The superior heat transport properties of the porous medium result in:

- higher combustion velocities (higher power density)
- better control of the reaction zone temperature
- the high heat capacity of the porous medium ensures a high combustion process stability against changes in thermal load and excess air ratio.

The aim of the present study is to study adiabatic combustion processes at high excess air ratios in the burner configuration described above. Such processes are interesting for several industrial applications like gas-turbine combustion chambers at partial load, incinerators etc.

2 Experimental Setup

A porous burner was designed and built, in which the behavior of different porous media could be investigated by measuring the temperature- and the emission-profiles The burner guaranteed almost adiabatic conditions for the combustion process. Methane-air mixtures at different excess-air ratios were used

Ceramic foams with 10 ppi (pores per inch) made of SiC, Hiflow rings and spheres made of Al_2O_3, as well as a wire mesh made of Aluchrom PS-1, were investigated in the combustion region. The specifications of the used porous media are summarized in Table 1.

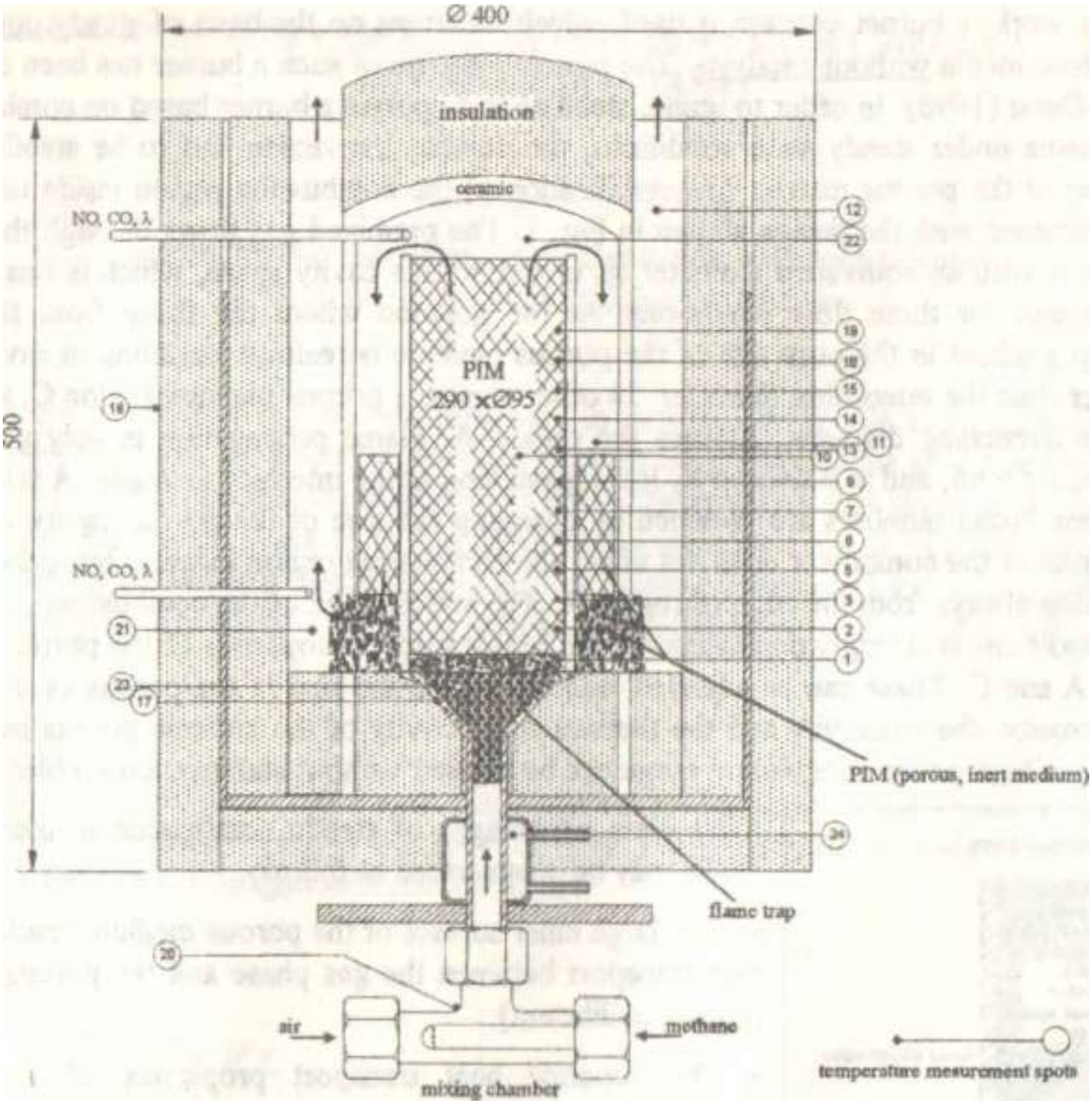

Fig 2. Burner for the investigations of the behavior of porous inert media under adiabatic conditions

	Unit	wire mesh	ceramic foam	Hiflow-rings	packing of spheres
material		Aluchrom	SiC	AL_2O_3 95%	Al_2O_3
type		PS-1	10 ppi	20/4	16 mm
density	kg/m^3	7100	2300	2700	3900
packing density	kg/m^3	180	430	600	1700

specific surface	m^2/m^3	209	750	280	210
porosity	-	0,97	0,76	0,72	0,45
mass in the combustion chamber	kg	0,34	0,82	1,15	3,17
material thermal- conductivity at 1000°C	W/mK	13	19	5,5	6,15
material heat-capacity at 1000°C	J/kgK	500	840	1050	1050
radiation coefficient at 1000°C	-	(≈ 0.8)		(≈ 0,4)	0,3

Table 1 Specifications of the used porous media

The burner shown in Fig 2 was used in a thermal power range between 2 kW and 20 kW with and without air preheating. During the tests the burner was first heated up using an air ratio of 1,4 to 1,6. After a steady temperature field was reached, the air ratio was increased stepwise. Each setting was kept until a steady state was achieved. The excess air ratio as well as the concentrations of carbon- monoxide and nitrogen-raonoxide were measured for each steady state. It was possible to detect the limit excess air ratio up to which the combustion was stable in the porous medium by using the temperature profile measurements and also to some extent by the increasing concentration of carbon-monoxide. As soon as a steady state was reached in the combustion area, a new setting for the fuel- air mixture was adjusted. The temperature profile of the steady state was used to find the limit excess air ratio. The plot of the steady temperatures of an experiment is shown in Fig 3. The limit excess air ratio which causes a blow-off of the burner can easily be detected by the temperature profiles. In the shown experiment, a stable combustion was possible up to an excess air ratio of $\lambda = 2,7$ (full line).

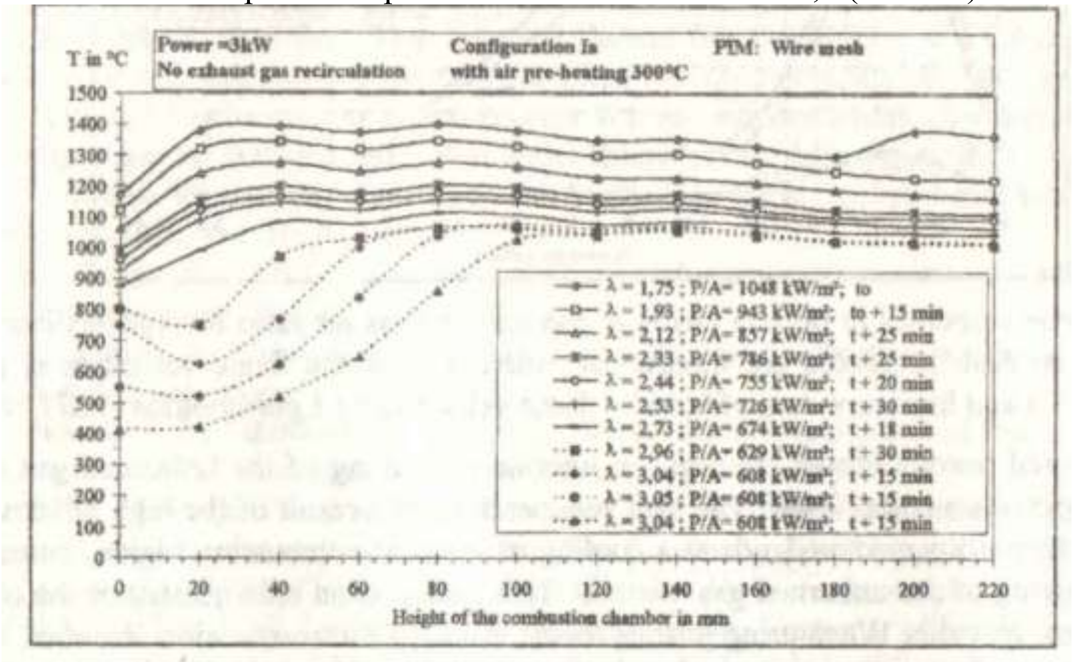

Fig. 3 Plot of the measured steady and unsteady temperature profiles

3 Experimental Results and Discussion

The attention was focused on the stabilizing behavior of the combustion in both the range of high excess air ratios λ and the influence of preheating the air. By analysis of the obtained data, it was possible to estimate the flame velocity of a methane-air mixture at the limit excess air ratio in a adiabatic porous burner. A theoretical estimate of the flame velocity based on the thermal theory of Mallard and Le Chatelier under the assumption that the porous combustor is pseudo-homogeneous and that no catalytic effects occur, was also performed. According to these estimates, the flame velocity inside of the porous medium is about eight to ten times higher than it is for free flames.

Under the simplified assumption that a combustion temperature of 900°C is the minimum for a selfsustained combustion process of methane and air, the maximum excess air ratio (limit excess air ratio λ_G) could also be estimated by an energy budget.

In the various experiments performed, the excess air ratio and the flow velocity in the combustion chamber was increased stepwise at a given thermal power until the combustion extinguished. At extinction, the flow velocity exceeded the flame velocity and/or the energy balance became negative. The flow velocity of the gases in the combustion chamber just before extinction can be assumed to be roughly equal to the flame velocity at these conditions.

In Fig 4, the experimentally determined flame velocities, and the theoretical estimates are presented. The discrepancies between the measured velocities of the flame inside of the porous body and the predicted values can be explained by the turbulent flow structure and the high amount of heat recuperation, which was caused by the burner design itself.

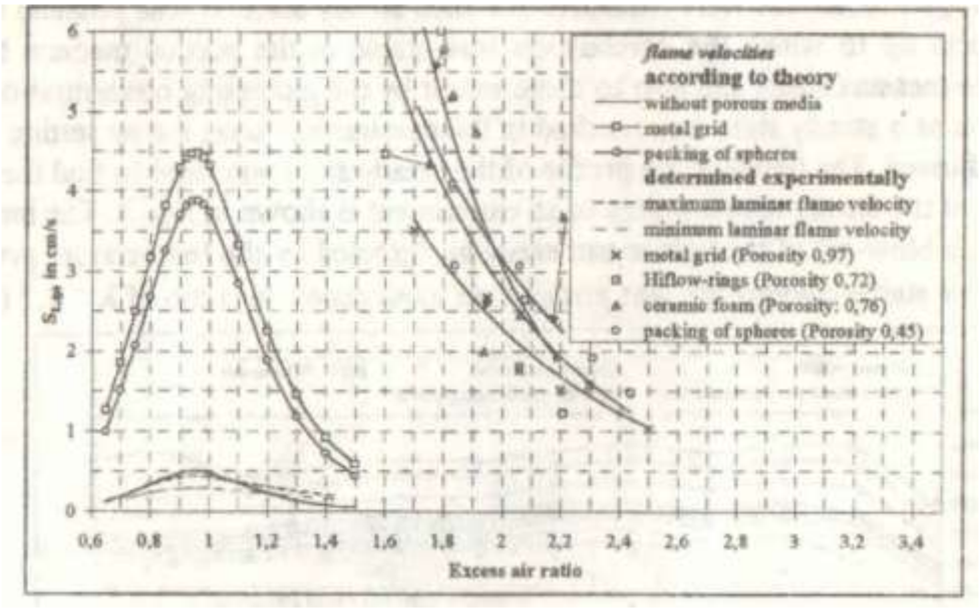

Fig 4 Flame velocities in porous media at the limit excess air ratio for various configurations. Also presented are theoretical estimations of the flame velocities in porous media and literature data of laminar flame velocities by *Egolfopoulos et al* (1989).

With the presented porous burner concept, an internal preheating of the unburned gas mixture is achieved by the porous medium itself. The heat recuperation as a result of the high effective thermal conductivity of the porous medium leads to a cooling of the post-combustion region, combined with an internal preheating of the unbumed gas mixture. This results in an enlargement of the operational range of the excess air ratio. When using porous media inside of the combustion chamber, the excess air ratio limit increases by approximately $\Delta\lambda$ = 0,3 for a methane-air mixture without additional heat recuperation. More detailed results were reported by *Trimis and Kesting* (1996).

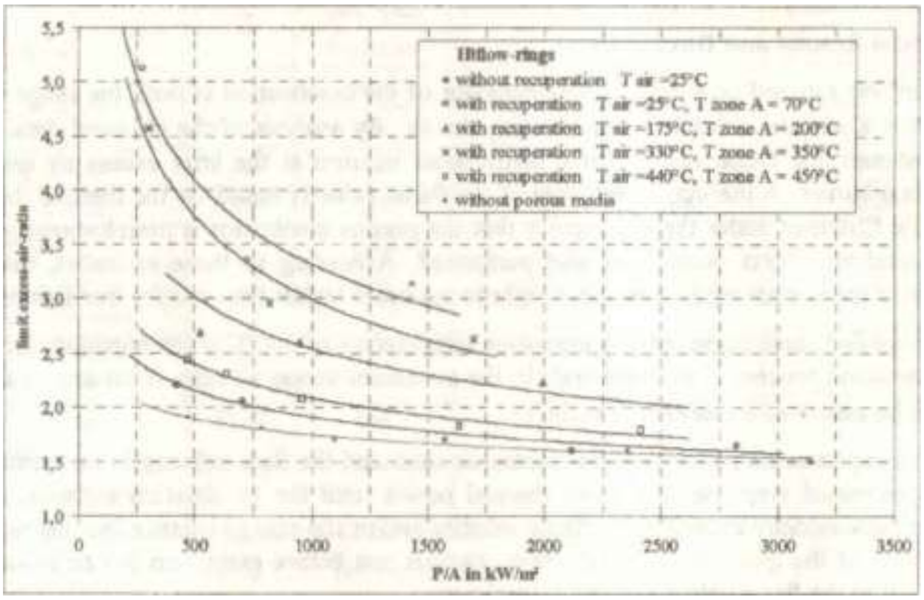

Fig 5 Limit excess-air-ratio as function of the heat load at various air preheating temperatures

4 Future Work

The potential of this burner technology with respect to applications like gas turbines at partial load, incinerators, etc., is an interesting task for future investigations. In this respect, experiments dealing with adiabatic combustion processes in porous inert media under pressure are planned.

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