

# Study on the new aspects in HTAC combustion technology with gaseous fuels

S.Werle<sup>\*1</sup>, R.K.Wilk<sup>1</sup>

<sup>1</sup>Institute of Thermal Technology, Silesian University of Technology, Konarskiego 22,  
PL44-100 Gliwice

## Abstract

The paper presents results of experimental studies on the methane and propane ignition process in various volumetric compositions of oxidizers heated to temperature higher than autoignition point of analyzed fuels (HTAC conditions – High Temperature Air Combustion conditions). The increment of temperature  $\Delta T$  and the ignition delay time  $\tau'$  are parameters characterizing the process of ignition under these conditions. These parameters are the function of air excess ratio  $\lambda$ , temperature of the oxidizer  $t_{\text{oxi}}$  and the volumetric composition of oxidizer. In order to achieve the minimum ignition delay time  $\tau'$  and the maximum increment of the temperature  $\Delta T$ , the oxidizer temperature hadn't be maximize. There is interval of  $t_{\text{oxi}}$  in which analyzed parameters reaches its extreme values.

## Symbols

$\Delta$	Increment
$\lambda$	Air excess ratio
T	Temperature, °C
T	Temperature, K
$\tau'$	Ignition delay time, s
z	Molar fraction of gas, %

## Subscribes

max	Maximal
oxi	Oxidizer

## Introduction

HTAC is the most important achievement of the combustion technology in recent years. This technology is also known as Excess Enthalpy Combustion (EEC) [1] or Flameless Oxidation (FLOX) [2] in Germany or MILD Combustion or Diluted Combustion [3] in Italy.

The basic principles of this technology are as follows [1]:

1. The temperature of oxidizer has to be higher than the autoignition point of the combustible mixture. In such conditions the phenomenon of combustion is in its character similar to a volumetric and flameless combustion. Thanks to this, the temperature level inside the combustion chamber is relatively uniform, and temperature peaks ( $t \geq 1400^{\circ}\text{C}$ ) at which thermal nitrogen oxides are formed, can be avoided.
2. The fuel nozzles are positioned away from the air nozzles supplying the gas fuel into hot flame gases.
3. Strong recirculation of hot exhausted gases to reaction chamber is required.

The main advantages of applying HTAC technique are as follows [1]:

1. Thanks to the strong recirculation of combustion gases, HTAC burners permit to increase the average temperature in the

combustion chamber and a more equalized, avoiding temperature peaks and thermal  $\text{NO}_x$  formation.

2. The intensive circulation of hot combustion gases reduces the local concentration of oxygen, retards mixing of fuel with the oxidizer, so that the formation of prompt  $\text{NO}_x$  and via  $\text{N}_2\text{O}$  may be prevented.
3. The heat radiation is more effective.
4. The increase of the average temperature in the combustion chamber and the heat radiation improves the thermal efficiency of the system and thus also reduces the consumption of fuels and the emission of  $\text{NO}_x$  and  $\text{CO}_2$ . The final results are a reduction of the operating cost.
5. The construction of the combustion chamber is very compact; in comparison with a classical combustion system it is much smaller, thanks to which also capital costs are not so high.

The HTAC technology has been introduced so far for furnaces gas combustion only. Furthermore, it was also proved that in similar way, it may be used for combustion of liquid fuels [4]. Further on, first trials has been made to burn solid fuels in a chamber of several MW of power with very good results and ultra low  $\text{NO}_x$  emission [5]. HTAC technology is still a new and promising combustion technology so the HTAC technology is still a subject of scientist's research all over the world.

The present paper deals with the results of experimental investigations concerning the ignition of methane and propane in various volumetric compositions of superheated oxidizer in a combustion chamber with a constant volume (constant volume bomb CVB). Experiments in a co-flow reactor (CFR – an attempt to create real furnace conditions) to compare results with CVB were also done.

<sup>\*</sup>corresponding author: sebastian.werle@polsl.pl  
Proceedings of the European Combustion Meeting 2009

## Experiment

Experimental matrix for both types of experiments is presented in Table 1. Methane and propane (in CVB experiment) and propane (in CFR experiment) were used as fuels. Main properties of investigated fuels are presented in Table 2. Eighth different values of air excess ratio were investigated ( $\lambda=0.7; 0.8; 0.9; 1.0; 1.1; 1.3; 1.6; 2.0$ ). Various oxidizers were taken into consideration: air ( $z_{O_2}=0.21$  and  $z_{N_2}=0.79$ )-in both experiments, oxidizer1 ( $z_{O_2}=0.15$  and  $z_{N_2}=0.85$ ), oxidizer2 ( $z_{O_2}=0.10$  and  $z_{N_2}=0.90$ ) and oxidizer3 ( $z_{O_2}=0.05$  and  $z_{N_2}=0.95$ ). Oxidizers were initially preheated up to pre-set temperatures  $t_{oxi}$  (in CVB: in the case of methane  $t_{oxi}=687\div 961^\circ\text{C}$  and in the case of propane  $t_{oxi}=530\div 782^\circ\text{C}$  and in CFR:  $t_{oxi}=530\div 630^\circ\text{C}$ ). The lowest values of those intervals of  $t_{oxi}$  are higher than the autoignition temperature of the combustible mixture (see Table 2). This fundamental experimental assumption indicates the main of the requirements of HTAC technique, which demands preheating the oxidizer above autoignition point and strong gas recirculation (low level of volumetric composition of oxygen) into the combustion chamber.

Table 1. Experimental matrix

$\lambda$	CONSTANT VOLUME BOMB-CVB				CO-FLOW REACTOR - CFR	
	Methane		Propane		Propane	
	$t_{oxi}, ^\circ\text{C}$	oxidizers	$t_{oxi}, ^\circ\text{C}$	oxidizers	$t_{oxi}, ^\circ\text{C}$	oxidizers
0.7	687	Air	530	Air	530	Air
0.8	716	oxidizer1	560	oxidizer1	560	
0.9	732	oxidizer2	580	oxidizer2	580	
1.0	761	oxidizer3	610	oxidizer3	610	
1.1	782		630		630	
1.3	812		660			
1.6	831		687			
2.0	861		716			
	913		732			
	933		761			
	961		782			

Table 2. Main properties of investigated fuels [6]

	Methane	Propane
Chemical formula	$\text{CH}_4$	$\text{C}_3\text{H}_8$
Flammability limits in the air mixtures, % vol.	5.0-15.0	2.0-9.5
Autoignition temperature of the combustible mixture with air, $^\circ\text{C}$	595.0	493.0

### Experimental rigs-CVB

Figure 1 shows the diagram of the stand for experimental investigations of the ignition of gaseous fuels and its fundamental elements [7]. Gases from the gas cylinders (1) through reducing valve (2), electric valve (3) and removable conduit supplying are passed into the reaction chamber (5). The cylindrical reaction chamber (5) with the total volume approximately  $400\text{ cm}^3$  is the main element of the installation. In the upper cover, there is a safety vent (11) as well as two holes, through which two thermoelements (12) type S (PtRh10-Pt) are installed. The thermoelements are

connected with a digital recorder (10). The reaction cylinder is heated by heating coils (7) with the total heating power of 1.7 kW. The temperature inside the reaction chamber is controlled by a microprocessor control unit (9) integrated with a thermoelement of the type K (NiCr-NiAl). The chamber is insulated with ceramic fibre (8).

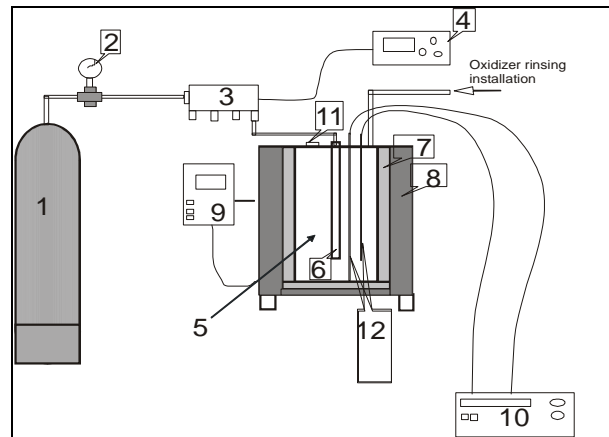


Fig.1. Diagram of the installation for experimental investigations of the ignition of gaseous fuels-CVB, 1- gas cylinders, 2- reducing valve, 3- electric valve, 4- electric valve control system, 5- reaction vessel, 6- conduit supplying the gas, 7- heating coils, 8- thermal insulation, 9- recorder controlling the temperature of the air, 10- temperature recorder with thermocouples, 11- safety vent, 12- thermoelements.

### Experimental rigs-CFR

Scheme of CFR reactor is presented on the Figure 2. Main element of the rig is reaction vessel (1), heated by heating coils with the total heating power of 1.7kW. Air from the laboratory air network is flowing in the pipe inside the vessel and preheating up to pre-set temperature.

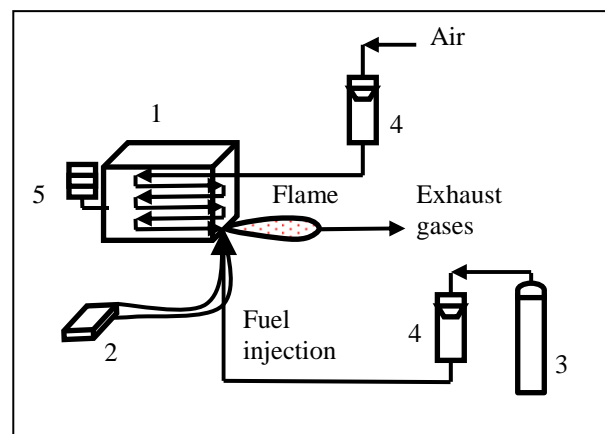


Fig.2. Diagram of the installation for experimental investigations of the ignition of gaseous fuels-CFR reactor; 1-reaction vessel; 2, temperature recorder; 3- gas cylinder, 4-rotameters, 5, temperature recorder,

Gas from the cylinder (3) is injected into the stream of hot air. Temperature of the mixture is controlled by recorder (2) and temperature of the air is controlled by regulator (5).

### Definition of main parameters

Majority of results are presented for CVB reactor, because experiments with CFR were performed to verify results from CVB.

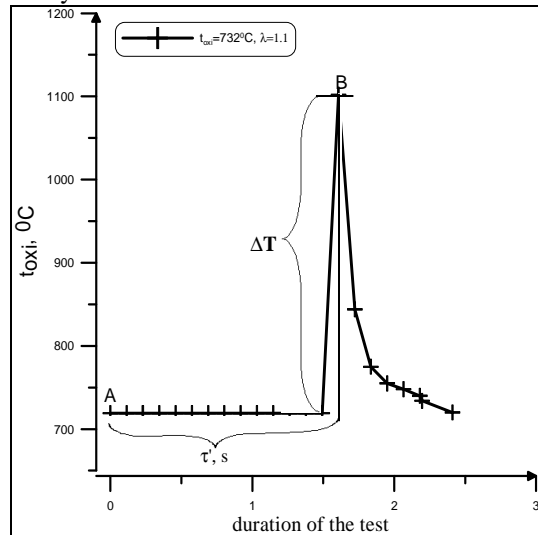


Fig.3. Example of the increment of the temperature  $\Delta T$  and the ignition delay time  $\tau$ , as a function of the duration of the test; methane;  $t_{oxi}=732^{\circ}\text{C}$ ;  $\lambda=1.1$ .

The increment of temperature  $\Delta T$ , ignition delay time  $\tau$ , volumetric fraction of oxygen in the oxidizer  $z_{O_2}$  and kind of the gas are parameters characterizing the process of ignition under conditions of superheating of oxidizer. These parameters are the function of air excess ratio  $\lambda$  and the temperature of the oxidizer  $t_{oxi}$ . Figure 3 provides an example of the increment of temperature  $\Delta T$  and the way of determining the ignition delay time  $\tau$  [8]. Similar diagrams have been plotted for other temperatures of oxidizers  $t_{oxi}$  as well as for other values of air excess ratio  $\lambda$ . Point A is interpreted as the moment of the gas injection (the moment of the opening of the electric valve) and the start of ignition (beginning of the process). The stretch between point A and the point B is determined as the increment of temperature  $\Delta T$ . The time from the moment of opening the electric valve (point A) to the achievement of the maximum temperature (point B) is called the ignition delay time  $\tau$ .

### Results

Figure 4 illustrates the dependence of the increment of temperature  $\Delta T$  as a function of the air excess ratio for various values of volumetric composition of oxidizer (both for methane and propane). Four cases are presented in this Figure – the results with four different values of volumetric fraction of oxygen in superheated oxidizer. There are only two examples ( $t_{oxi}=861^{\circ}\text{C}$  in the case of methane and  $t_{oxi}=660^{\circ}\text{C}$  in the case of propane)

but similar diagrams have been plotted for other temperatures of oxidizers for both gases.

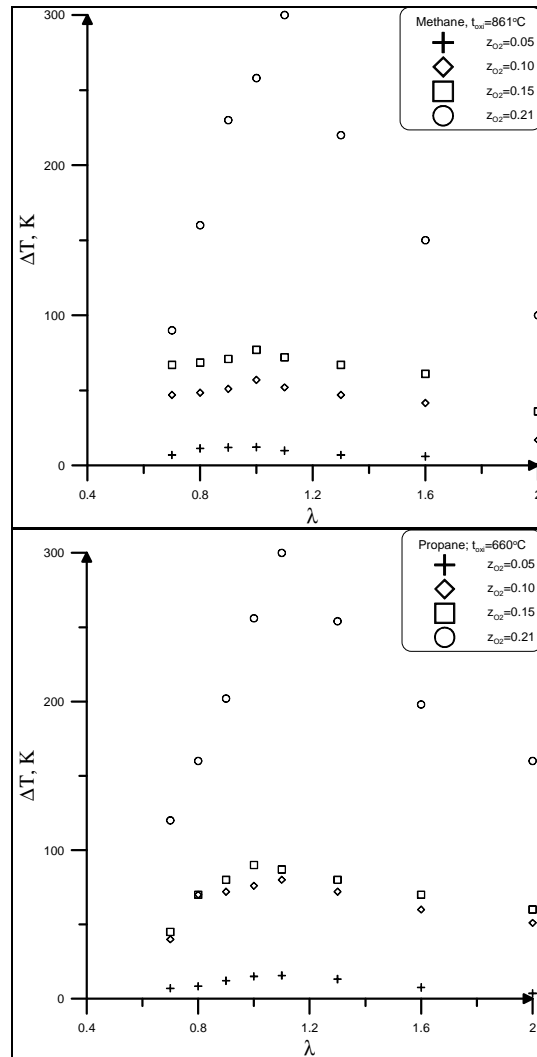


Fig.4. Dependence of the increment of the temperature  $\Delta T$  as a function of the air excess ratio  $\lambda$  for various volumetric composition of oxidizer; methane and propane

The highest values of the increment of temperature are for interval of air excess ratio equal to  $\lambda=1.0\div 1.1$ . On the one hand, it was ascertained that the highest values of  $\Delta T$  were achieved for test with volumetric fraction of oxygen equal to  $z_{O_2}=0.21$  and on the other hand, the lowest values of  $\Delta T$  were for  $z_{O_2}=0.05$ . This is caused by low concentration of oxygen and high level of mixture dilution. It worth to point that, irrespective of the volumetric composition of oxidizer, the ignition reaction always takes place. Irrespective of considered cases, there is an interval of air excess ratio ( $\lambda=1.0\div 1.1$ ) in which the increment of temperature reaches its maximum.

Figure 5 illustrate the dependence of the increment of temperature  $\Delta T$  as a function of the initial oxidizer temperature  $t_{oxi}$  for various volumetric composition of oxidizer. There are only two examples – for  $\lambda=1.0$  for

both gases. The same dependences have been tested for remain values of air excess ratio.

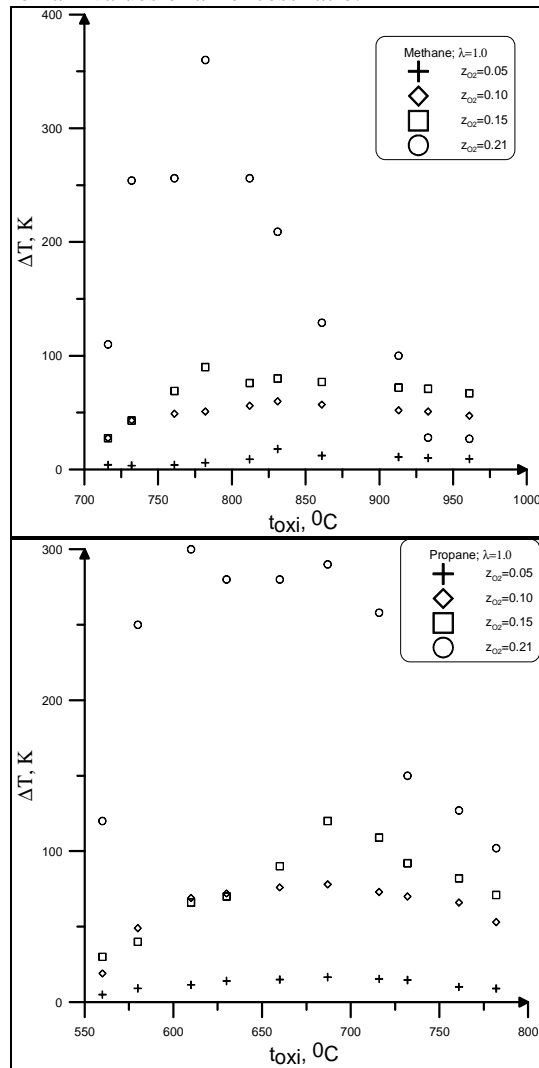


Fig.5. Dependence of the increment of the temperature  $\Delta T$  as a function of the air temperature  $t_{oxi}$  for various volumetric composition of oxidizer; methane and propane

There is an interval of the oxidizer temperature (in the case of methane  $t_{oxi} \approx 780 \div 850^\circ\text{C}$  and in the case of propane  $t_{oxi} \approx 630 \div 680^\circ\text{C}$ ), in which the increment of temperature reaches its maximum. And, similar the Figure 4, the highest values of  $\Delta T$  are for volumetric fraction of oxygen equal to  $z_{O_2}=0.21$  and the lowest for  $z_{O_2}=0.05$ . The difference between those maximum values is quite high. Nevertheless, irrespective of considered cases, the clear ignition effect was achieved.

Next Figure (Fig.6.) illustrates the dependence of the ignition delay  $\tau'$  as a function of the air excess ratio  $\lambda$  for various volumetric composition of oxygen in preheated oxidizer. The ignition delay time  $\tau'$  depends parabolically on air excess ratio. The lowest measured values of the ignition delay time are observed-independently of considered cases-for the air excess ratio equal to  $\lambda=1.0-1.1$ . Analyzing these diagrams, it has been noticed that the lowest values of the ignition delay time  $\tau'$  are for tests with volumetric fraction of

oxygen in the oxidizer equal to  $z_{O_2}=0.21$ , but it is very important, the differences between values of  $z_{O_2}=0.21$ ,  $z_{O_2}=0.15$  and  $z_{O_2}=0.10$  are not as strong as in the case of the  $\Delta T=f(t_{oxi})$  (Fig.5.). It is probably caused by comparable values of reaction rate in these three cases. In the case of propane, the ignition delay time is a little bit lower than for methane. It is connected probably with the reactivity of propane, which characterising in, for example, the much lower the autoignition temperature and more complex molecule structure in comparison with methane.

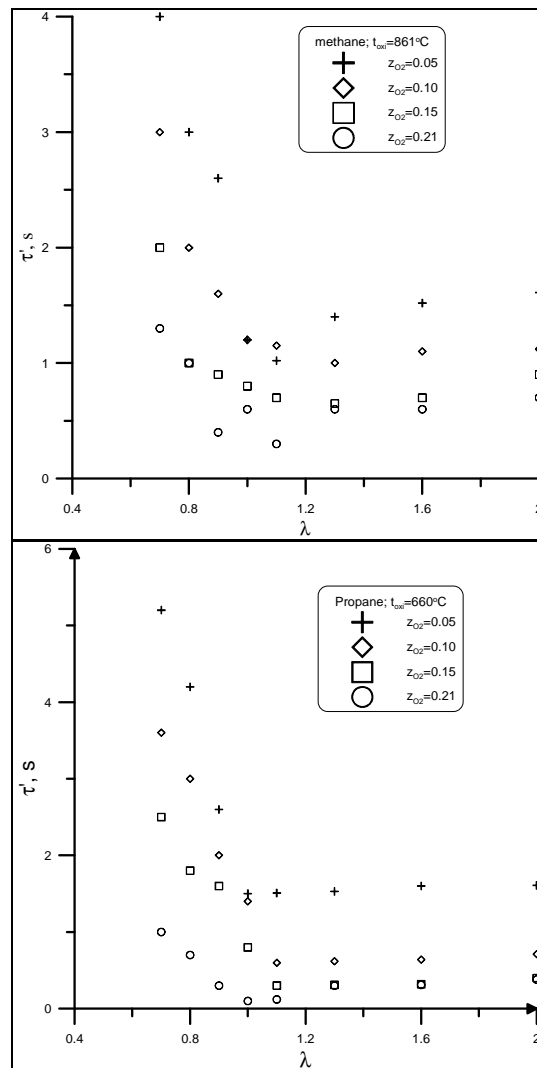


Fig.6. Dependence of the ignition delay time  $\tau'$ , as a function of the air excess ratio  $\lambda$  for various volumetric composition of oxidizer; methane and propane

Figure 7 illustrates the dependence of the ignition delay time  $\tau'$  as a function of the oxidizer temperature  $t_{oxi}$ . There is an interval of the oxidizer temperature (in the case of methane  $t_{oxi}=850-890^\circ\text{C}$  and in the case of propane  $t_{oxi}=650-675^\circ\text{C}$ ) in which the ignition delay time reaches its minimum. Analyzing these diagrams it has also been found that the lowest values of the ignition delay time  $\tau'$  are for tests with the volumetric fraction of oxygen in the oxidizer equal to 0.21, and also

differences between the values of the ignition delay for  $z_{O_2}=0.21$ ,  $z_{O_2}=0.15$  i  $z_{O_2}=0.10$  are rather low.

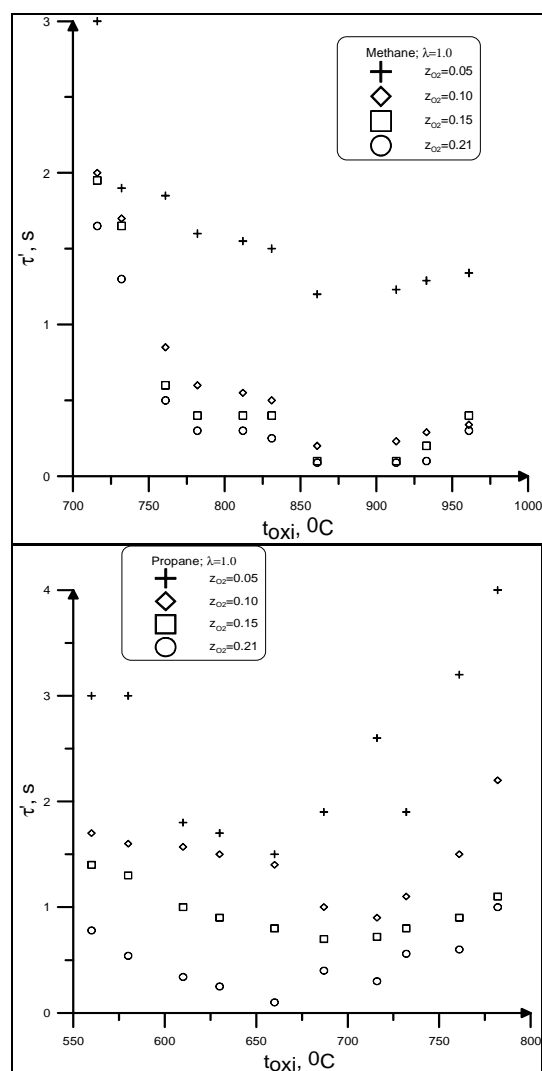


Fig.7. Dependence of the ignition delay time  $\tau'$ , as a function of the oxidizer temperature for various volumetric composition of oxidizer; methane and propane

### CVB versus CFR reactor

The comparison between some results achieving in CVB reactor and CFR were presented on the Fig.8. As mentioned in experimental matrix, propane as a fuel was investigated. Wide interval of air preheating temperature was investigated. Analyzing this figure, it can be seen that the increment of temperature for CFR reactor is higher due to higher level of homogeneity of mixture. It is observed in the Figure that it is possible to compare results achieved in CVB and CFR reactor and confirms the similar tendency of interdependence between increment temperature and air excess ratio.

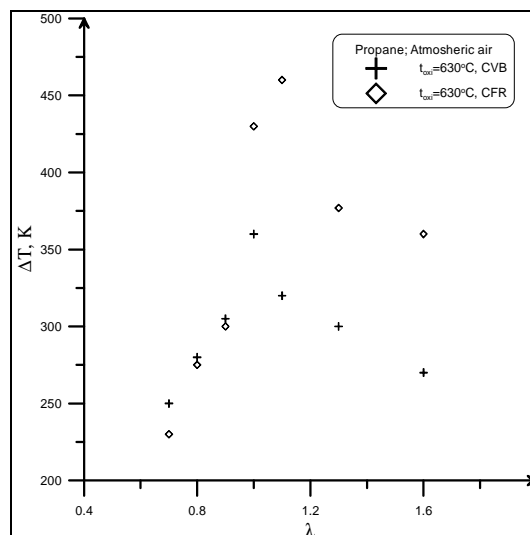


Fig.8. Comparison of the results for CVB and CFR reactor

### Conclusions

In order to achieve the minimum ignition delay time  $\tau'$  (the maximum reaction rate) and the maximum of increment of temperature  $\Delta T$ , the oxidizer has to be preheated to a temperature of  $t_{oxi}$  about 780-890°C (in the case of methane) and 630-680°C (in the case of propane). It seems that preheating of the oxidizer above this interval is unsubstantiated. Additionally it is important to keep interval of air excess ratio approximately equal to 1.0÷1.1.

Beyond this interval of  $t_{oxi}$  and  $\lambda$  in which  $\tau' \rightarrow \min$  and  $\Delta T \rightarrow \max$ , analysed parameters are going to increase ( $\tau'$ ) or to decrease ( $\Delta T$ ). It is mainly caused by the dilution of reagents.

The optimum value of the oxidizer temperature is probably a function of the combustion chamber type, the intensity of mixing and other factors. However, experiment in CFR reactor gives possibility to say that it is possible to transfer results from CVB reactor into really installation.

### Acknowledgements

The paper has been prepared within the frame of the statute research of the Institute of Thermal Technology, Silesian University of Technology – BK-219/RIE6/2007.

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