NEW EXPERIMENTAL RESEARCH ON RTO PILOT PLANT

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ABSTRACT

Regenerative Thermal Oxidizers (RTO) are extensively used when waste gases containing low solvent mixture concentration, generally between 0.25 and 5.00 gr/Nmc, have to be treated in order to reach established limits.
A lot of manufacturers around the world are involved in this job, but still many factors are unclear, among these are:

- temperature of ceramic packing bed
- temperature difference between gas and ceramic packing along the beds
- heat transfer coefficient
- temperature axial profile in different beds within the same plant
- how a bad distribution of flow affects temperature profiles and consequently the efficiency of plant.

To answer these and other questions, a pilot plant has been built and is actually in operation at the CPTM research center.
Tests of maximum fuel consumption were made with no solvents in the gas stream fed to the plant. Temperature profiles along plant beds were investigated in function of the flow inversion time.
Experimental runs for oxidation efficiency for aliphatic compounds were carried out.

INTRODUCTION AND STATE OF ART

VOCs are defined as volatile organic compounds having a vapour pressure of at least 0,01kPa at a temperature of 293,15K and are the most common pollutants emitted into the atmosphere due to their widespread use in many industrial processes. Thermal oxidation is a process where volatile organic compounds are involved in a combustion reaction with the oxygen contained in the polluted air stream.
There are two types of thermal oxidation systems:

- recuperative;
- regenerative (RTO).

Both systems use the heat derived from the exhaust stream to preheat the incoming gas stream before entering the combustion zone, but each have a different heat recovery system. Selecting the best thermal oxidizer requires a careful analysis of many factors such as: process exhaust gas flow rate and composition, exhaust temperature, space required, secondary heat demand and also capital and operating costs.
RTO essentially consists of three subsystems: burner, combustion chamber and primary heat recovery section. In an RTO system a ceramic packed bed stores heat from hot gases coming from the combustion chamber while another ceramic packed bed releases heat into the cold gases flowing into the combustion chamber. A burner using methane or diesel oil as fuel maintains the temperature of the combustion chamber between 750 – 850 °C. A typical combustion chamber residence time is 0,5-2sec. A stream cycle time commonly used is

between 20sec and 120 sec. The use of RTO systems allows a heat recovery, as defined in [1], of 95 percent. It seems that the use of structured packing provides better thermal efficiency (96,7%) and a lower pressure drop than random ceramic ones. This reduces operating costs even if the initial cost of the packaging increases [2].
In the last few years RTO mathematical models have been elaborated but such mathematical models seem too complex to design an RTO unit.
Steady and unsteady flow fields, distributions of temperature, pressure and compositions of flue gas inside an RTO were simulated by computational fluid dynamics (CFD) [3]. A mathematical model was developed which calculates the temperature throughout the ceramic bed during the operation and can be utilized to minimize the amount of fuel usage.[4].
A computer model for predicting RTO thermal efficiency was developed based on engineering equations from literature. The testing of thermal efficiency was done with a pilot scale RTO system [5].

PLANT DESCRIPTION AND OPERATION

According to the RTO process scheme Fig 1. Pictures of plant are given in fig. 2,3

RTO pilot plant description :

- Two packed beds with 4m of 2” ceramic saddles, 928 mm diameter, 160 mm of inner insulation (fig.4).
- Diesel fuel burner and combustion chamber. Working temperature of up to 950°C, residence time between 0.5 – 2 sec. (depending on the gas feed rate) (fig. 5).
- Two three-way pneumatic valves AV1, AV2, two on/off butterfly pneumatic valves AV3/AV4.
- Instrumentation: diesel fuel rotameter; combustion air rotameter; polluted air vortex flow meter; bed, combustion chamber and chimney thermocouples; DP cell on compensation tank D1; U tube for bed pressure drop;
- RTO pilot plant is equipped with a PLC used for controlling temperatures, polluted air feed rate, cycle time and monitoring process parameters.
- Main fan for the polluted air, 1500Nm3/hr, 7.5KW. Burner fan 200 Nm3/hr, 2 KW
- The columns were equipped with special perforated traps that can put the gas in direct contact with a system for the measurement of the ceramic saddles and gas temperature. It is composed of two thermocouples, one placed in direct contact with the gas, and another imbedded in the ceramic saddle (fig. 6), the system is placed on a steel tube inside the trap. In this way it is possible to measure the stoneware and the gas temperature. The thermocouples are linked to a data logger system connected with a computer. The perforated traps are placed along the bed in correspondence with the plant thermocouples.

Analytical instrumentation :

- FID, portable analyser for VOC TOC. Portable flue gas monitoring for CO, CO_2, NO, NO_2, SO_2, O_2.

RTO pilot plant operating :

The plant columns operate alternatively in regeneration and heating phases. The polluted air enters the ceramic bed at the bottom of the column during the regeneration phase (fig.1) and

crossing over the warm bed, is preheated from the inlet temperature up to 600-850°C (depending on the operating conditions).
VOCs start to oxidise from about the middle of the column and are completely oxidated in the combustion chamber. The heat coming from fuel and VOC combustion is then released to the second column bed, crossing over the burned gas from the top to the bottom. During this phase the hot gases pass from the temperature of the combustion chamber to that of the chimney's low temperature which is 50-160°C higher than the inlet temperature.
The two beds are alternatively in regeneration and heating phases by the flow of the gas for a fixed time period (cycle time or flow inversion time) in one direction and then in the opposite direction. This is ensured by two three-way on/off connected valves as shown in fig.1 (AV1, AV2). The valve plates close the duct to the chimney or the fan throughput linking the bottom of the columns with the chimney or with the fan periodically.
During the air flux switching (AV1 and AV2 plates move in a second) the fan is directly linked to the chimney. Moreover, the two columns have the same pressure at the bottom inlets, so the air can't flow into them and it is completely conveyed to the chimney by the fan. After the air flow switching, a limited amount of dirty air trapped in the pipes and in the void space of the bed, which was previously in regeneration is conveyed directly to the chimney. For these reasons AV3 and AV4 valves are present. The valves' cycle is the following:

1) Valve AV4 closes the chimney beginning a second before the AV1 and AV2 action, avoiding gas discharge, at the same time AV3 opens, linking the columns with the compensation tank D1 and allowing the gas reflux.
2) AV1, AV2 switching
3) A few seconds after the gas flow inversion, AV3 closes and AV4 opens.

In this way we avoid conveying primary air directly to the chimney because it is closed and we can reflux the dirty trapped gas to the combustion chamber where it is destroyed (by the gas reflux).

EXPERIMENTAL RESULTS

A lot of experiments without VOC pollutants in the primary air were carried on in order to characterize fluid dynamic behaviour and heat exchange performance. Axial and radial bed thermal profile, chimney temperature, fuel consumption, drop in pressure, ceramic and gas temperature are measured at different process conditions. Heat transfer coefficient was determined. Experiments with aliphatic VOC were carried out to determine the abatement efficiency.

Bed thermal profiles and heat transfer coefficient

RTO pilot plant works with different bed thermal profiles depending on the total gas feed rate (primary air + combustion air). Three gas feed rates are investigated 570,1070,1600 Nm3/hr corresponding to the gas superficial velocity in the bed 0.70,1.32,1.97 Nm/sec. It was clear that higher feed rates affect lower beds and lower chimney temperatures. (fig.7). The behaviour of the RTO bed temperatures is related to the heat transfer coefficient, related to the gas superficial velocity. It was possible to determine the heat transfer coefficient based on the findings of the ceramic bed and gas temperatures logged with the system described above (fig.6). The figures (fig.12,13,14) show the thermal profile over time (stationary conditions) for the gas and the ceramic situated at 58 and 345 cm from the bottom of the bed.

During the bed heating phase, the hot combustion gases cross over the bed with a higher temperature than the ceramic temperature. The gas releases its heat to the ceramic that in turn increases in temperature. The gas rises in temperature over time because the bed also increase in temperature and the gas gives less warmth to it. The phenomenon proceeds until the inversion of the gas flow. After inversion the bed enters into the regeneration phase and to the contrary of the previous step, heats the gas. So, The bed temperature decreases in time because of the cooling effect of the fresh gas that flows into it.
The graphs (fig.12,13,14) show clearly that the range of temperature variation and gas-ceramic temperature difference is higher at the bottom of the bed. It can bee seen that the temperature variation (gas and ceramic) and the temperature difference between gas and ceramic are accentuated by the gas superficial velocity increase.
The different behaviour in terms of temperature variations is explainable by the difference in the heat transfer coefficient. Two thermal balances were made for the three gas superficial velocities, the only unknown variable is the heat transfer coefficient **U**:

T.B. on the gas : $$Gg \cdot Cpg \cdot (T1 - T2) = U \cdot A \cdot (\Delta Tgas\_cer) \qquad \text{(eq.1)}$$

T.B. on the ceramic bed : $$Mc \cdot Cpc \cdot \Delta Tcer = U \cdot A \cdot (\Delta Tgas\_cer) \cdot \theta cycle \qquad \text{(eq.2)}$$

The calculations result in U obtained with the two equations (eq.1, eq.2) are compared to each other and with the heat transfer coefficient calculated with the correlation “packed bed to fluid heat transfer coefficient” very old indeed [6] (Perry’s).
The experiment results (eq.1,eq.2) agree with the Perry’s correlation, and indicate in the strong change of the heat transfer coefficient one of the principal cause of the different gas/ceramic temperature behaviour with diverse gas superficial velocity (fig.8).

Radial temperature profile of the bed
Radial bed temperature profiles were measured for the feed rate indicated previously (fig10,11). A significant temperature radial profile appears at a low feed rate with a maximum localized on the bed axes. This profile becomes flatter as the feed rate increases.
The behaviour of the system is justified with the bad gas distribution at low feed rates, under these conditions the gas tends to pass through preferential ways close to the bed axes.
The effect it’s probably enhanced because of the big size of the bed saddles.

Influence of process parameters, RTO optimization
The parameters “gas feed rate” and “cycle time” have a considerable importance on the RTO thermal efficiency. The thermal efficiency increases with higher fluid superficial velocity and consequently specific diesel fuel consumption decreases (fig.9). This aspect is explained by the higher heat transfer coefficient and flat radial thermal profile at high superficial gas velocity. The thermal efficiency can be represented by the difference between chimney and inlet temperature, in fact, the fuel consumption will be correlated with the discharge temperature or in other terms with the ability of the RTO to regenerate. In the fig.15 the chimney/inlet temp. difference (mean) instead of the process parameters are represented. It can be noticed that chimney temperature decreases as the gas feed flow rate increases but it is also clear that the temperature depends on the cycle time with no-monotone trend. For every

superficial velocity there is a minimum value of the chimney temperature with a definite cycle time. The "optimum cycle time" value is different for diverse gas superficial velocities.
Also the chimney temperature oscillates between a minimum reached after the flow inversion and a maximum immediately before the successive inversion (fig16). When the cycle time increases the mean value of the chimney temperature decreases but when the cycle time is too long, the behaviour of the system goes in the opposite direction (fig.15). Such behaviour is the same if "gas ceramic temperatures difference" are considered (fig.17) It is necessary to go deeper into the study to explain such a behaviour.

Generalization to RTO systems, RTO design and optimization
The thermal efficiency and the operating conditions of an RTO unit are strongly influenced by the process parameters. To generalize to RTOs systems we have to consider the effect of process parameters on another variable: the gas ceramic bed temperature difference (fig. 17). Observing the graph (fig.17) it's clear that the absolute value of the mean gas ceramic temperature difference has a behaviour similar to the mean chimney temperature behaviour (fig 15). However, in this case, corresponding to the optimum cycle time, there is the maximum ΔTceramic/gas. Hence ,we have the minimum specific fuel consumption and the best RTO thermal efficiency for maximum ΔTceramic/gas.
A new and important result comes from correlating the mean chimney temperature and ΔTceramic/gas (fig.18). The graph is built with the measurement of stationary temperature profiles, with different operating conditions each represented by a point on the graph. Every point lies on a curve, every RTO process condition is described by the same curve that correlates thermal efficiency (chimney temperature) and ΔTceramic/gas.
The thermal efficiency of RTO plant depends on the difference in temperature between the gas and the ceramic bed.
Thus, for a specific type of packed bed with a fixed chimney temperature, the temperature difference between gas and ceramic it is immediately known. Then choosing the process conditions we want to create ("gas feed rate" and "cycle time"), it would be possible to design the RTO system.
Using some of the previous experimental data it was possible to design RTO systems.

The asymptotic shape of the curve indicates a DT ceramic./gas greater than 2 Nm/sec in order for solutions to have a lower chimney temperature. This implies that the best thermal efficiency is obtainable with a high superficial velocity and consequently with higher drop in pressure. Fig. 19 show how pressure drop increases with gas superficial velocities for the RTO pilot plant.
A benefit obtainable with a better heat exchange coefficient is to accomplish higher pumping costs.

The experimental work will be completed using 1 inch bed ceramic saddles.

VOCs abatement
Experiments with aliphatic compound were carried out with a primary gas VOC concentration between 200 and 1500 mg/Nm^3. VOC, and CO, NO, NO2 were measured at the chimney with the instrumentation mentioned above. The superficial velocity conditions adopted for the experiments are three: 0.7,1.32,1.97 Nm/sec, the cycle time: 60,120 sec.

In all of the experiments the RTO pilot plant was able to destroy most of the VOCs with a pollutant concentration at the chimney always less than 5 mg/Nm3.
Traces of NO, NO2 and CO were detected at the chimney.

CONCLUSIONS

1. Influence of the process parameters on RTO thermal efficiency and fuel consumption were showed
2. Temperature differences between ceramic and gas was studied for different process conditions.
3. Axial and radial bed thermal profile were determined for different process conditions
4. Heat transfer coefficients for different gas feed rate were determined
5. RTOs have low regenerative efficiency with low gas flow. This is justified with the lower heat transfer coefficient and with a worse gas distribution
6. Every RTO process condition is described by a curve (the size of the saddles was fixed) that correlated "the temperature difference between chimney and inlet" and "the temperature difference between gas and ceramic on whole bed". This new important finding allowed the design of an RTO unit using empirical measurements.

SYMBOLS

Gc : gas feed rate Nm^3/hr;
Cpg : Gas heat capacity $Kcal/Nm^3K$;
T1,T2 : High and low temperature of the bed °C (industrial thermocouples, fig.1);
A : heat exchange area of the bed m^2;
ΔTgas_cer : mean difference of temperature between gas and ceramic for the bed included by the two thermocouples high and low;
Mc, Cpc: mass and specific heat of ceramic bed between the two thermocouples kg, kcal/kgK;
ΔTcer: mean temperature variation of the bed between the two thermocouples ;
θcycle :cycle time in hours .

Nm/sec : this unit is defined as the ratio between the feed rate in Nm^3/sec and the void bed section m^2

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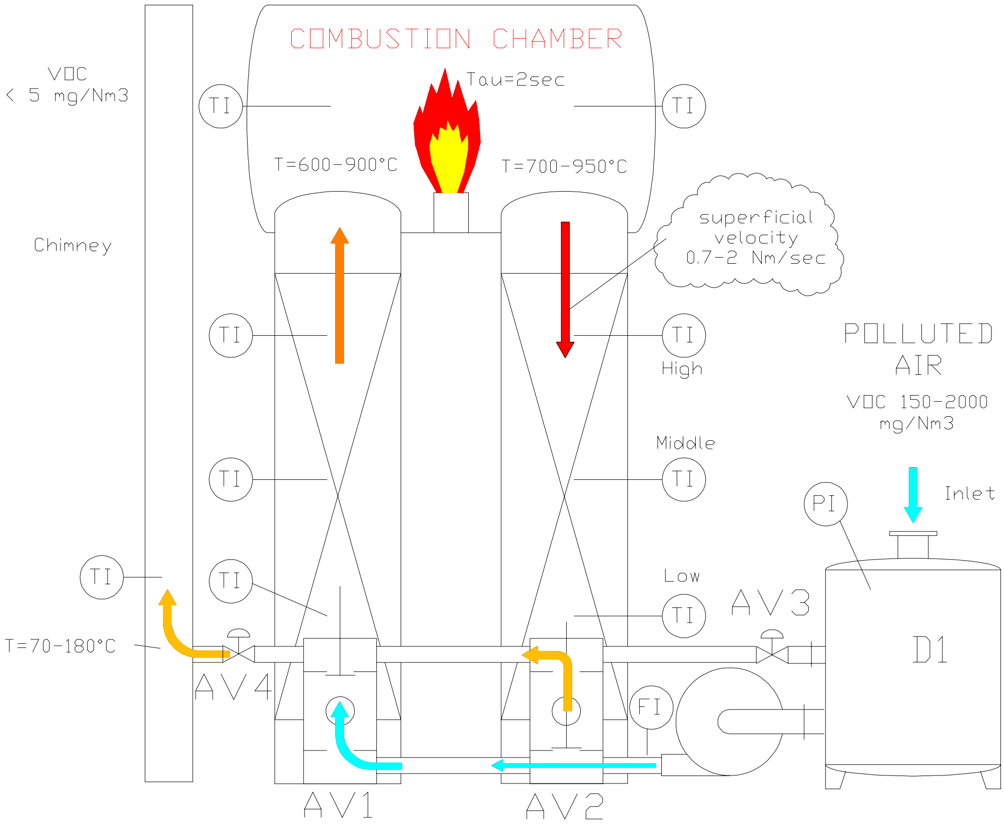


Fig. 1 : process scheme

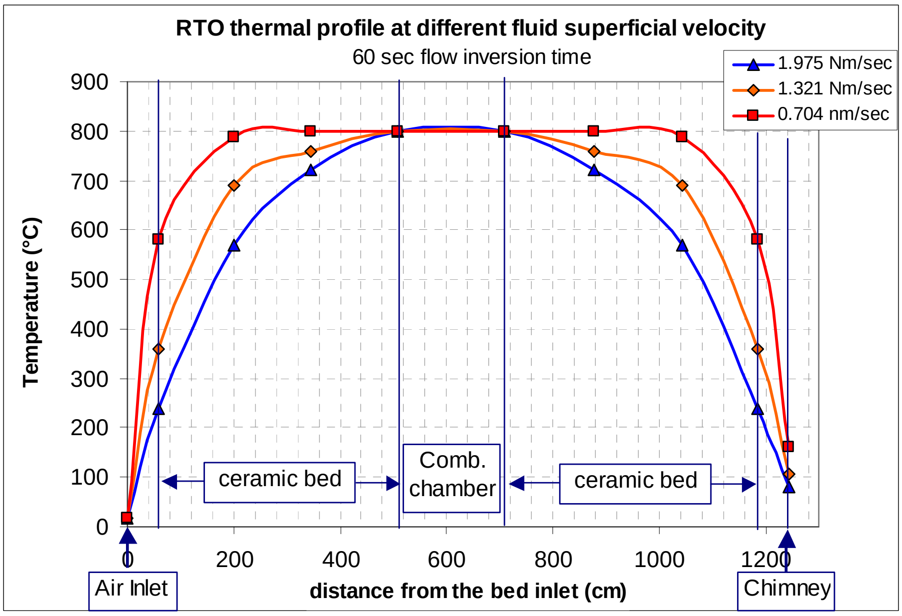
Fig.2: plant view

Fig.3: plant installation

Fig.5: combustion chamber

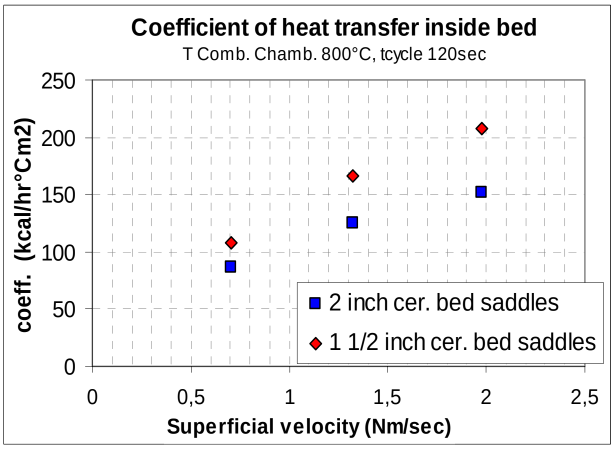
Fig.4: cer. packed bed

Fig.6: gas & cer. thermoc.



Temperat. in °C at 3 gas super. vel. Nm/sec			
L (cm)	0,704	1,321	1,975
0	18	17	18
58	580	360	240
200	787	690	570
345	800	760	723
508	800	800	800
708	800	800	800
878	800	760	723
1043	787	690	570
1185	580	360	240
1243	160	105	81

Fig. 7 : stationary RTO thermal profiles



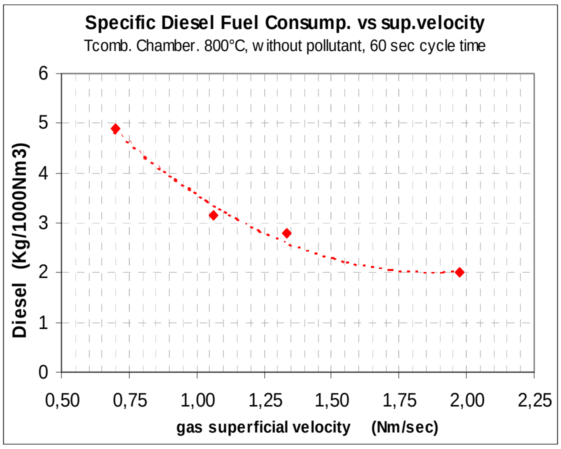
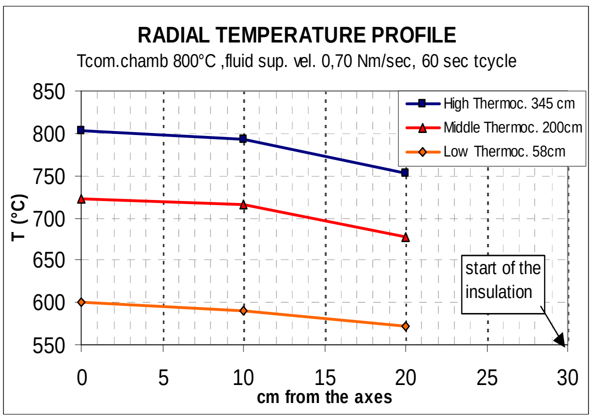


Fig. 8 : heat transfer coefficient

Fig.9 : RTO Specific Diesel Fuel Consumption



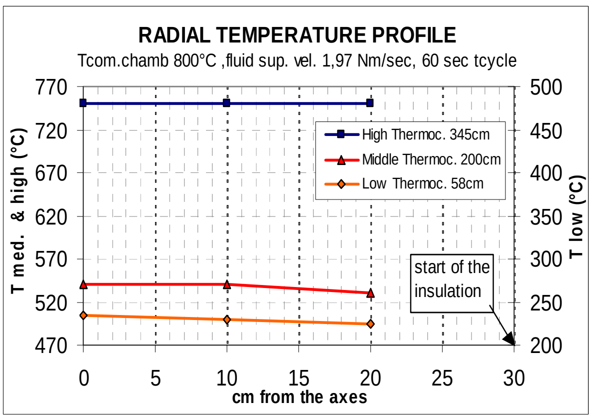
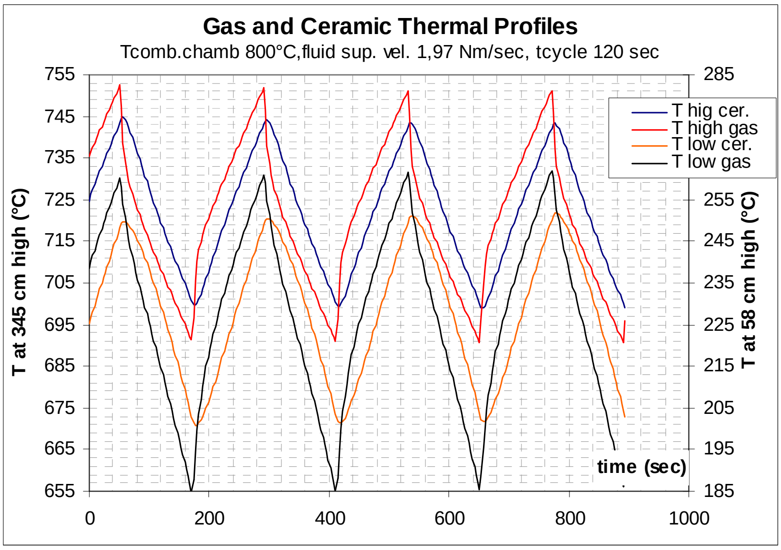
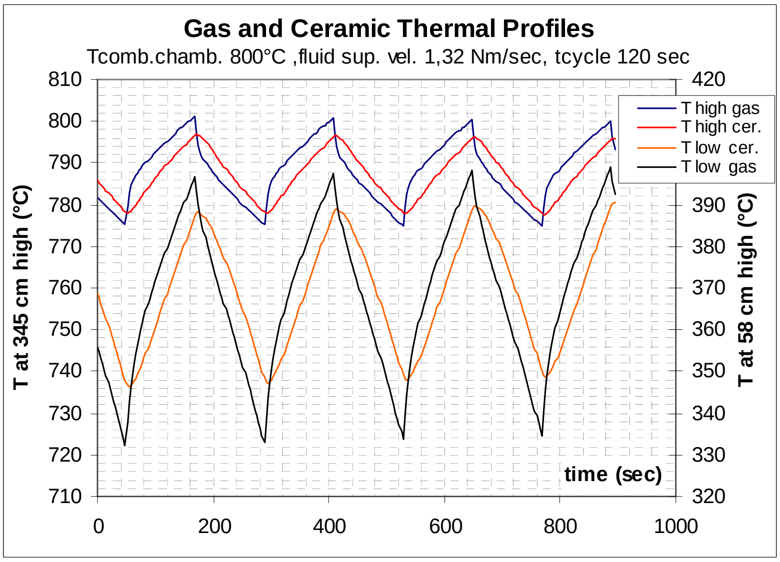


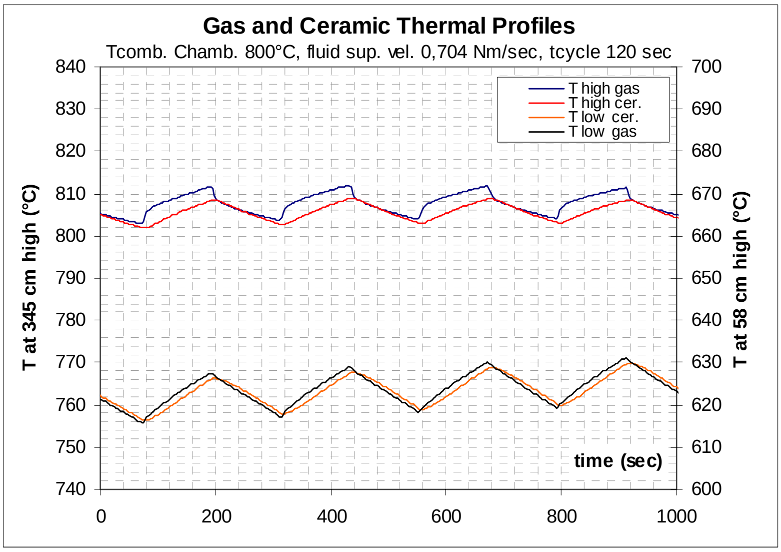
Fig. 10 : radial thermal profile

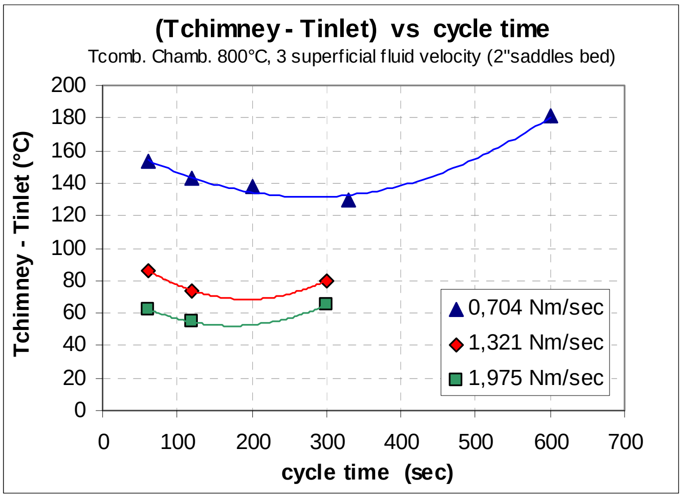
Fig.11 : radial thermal profile

Fig. 12,13,14 : Gas and Cer. thermal profiles at 0.70, 1.32,1.97 Nm/sec gas super. velocity









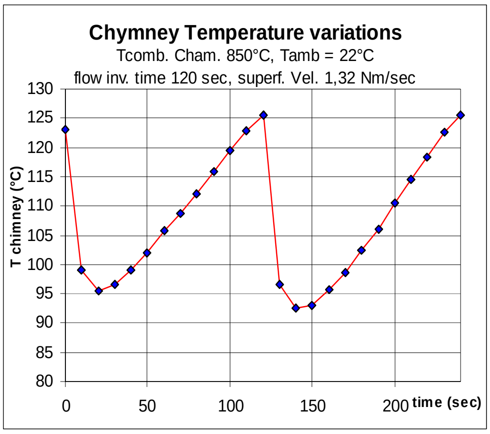
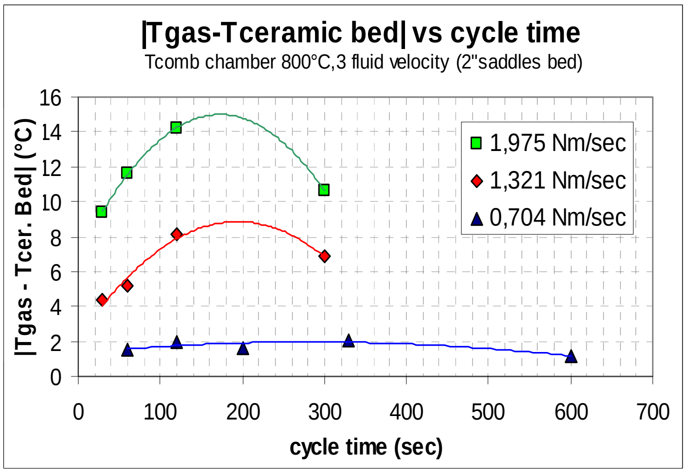


Fig 15: DTchimney/inlet vs. process parameters

Fig.16: Chimney temperature



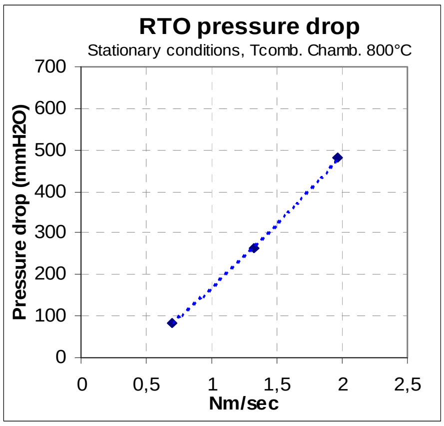


Fig 17: DTcer./gas vs. process parameters

Fig. 19 :pressure drop

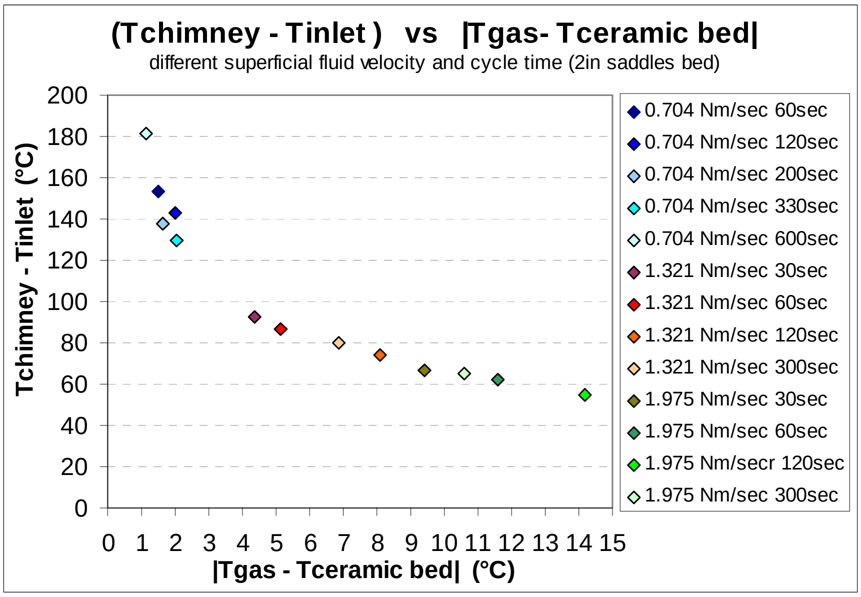


Fig 18: DTchimney/inlet vs. DTcer./gas