Control of Catalytic Combustors with Periodical Flow Reversal

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The catalytic reversed flow process is very efficient for the purification of industrial off-gases containing a low concentration of volatile organic compounds (VOCs): part of the catalyst at the two sides of the bed acts as a heat regenerator, making autothermal operation possible even with very lean mixtures (Matros and Bunimovich, 1996). The advantages of the regenerative processes in comparison with alternative solutions such as regenerative thermal oxidation or recuperative catalytic oxidation, and economic aspects, have been discussed recently by Matros and Bunimovich (1995); since part of the catalyst is always at a temperature lower than the ignition temperature, and behaves only as a thermal regenerator, it can be substituted by inexpensive inert material, leaving the catalyst only in the central part of the bed.

Two problems have been noted relative to the operation of this type of apparatus: overheating of the catalyst and extinction of the reaction, which are caused, respectively, by an increase or a decrease in the concentration of the contaminants.

The formation of hot spots, which can lead to thermal runaway of the reactor, has been investigated by several authors (Eigenberger and Nieken, 1988; Sapundzhiev et al., 1993; Purwono et al., 1994; Nieken et al., 1994a,b; Grozev and Sapundzhiev, 1997; van de Beld and Westerterp, 1997); it must be noted that a vicious cycle can be established, since higher temperatures can cause catalyst deactivation, but a lower catalyst activity leads to higher temperatures. Different actions have been proposed to prevent overheating, including hot gas withdrawal from the center of the reactor, and addition of an intermediate heat exchanger, injection of cold gases or water, and addition of air in the feed. None of these control methods proved to be very efficient; the best solution proposed, even if quite complex, seems to be the use of a structured bed, with variable thermal conductivity, and sidestream withdrawal.

Little attention has been focused on the problem of increasing the temperature level in the reactor to avoid extinction, in the case of a reduction of the VOC concentration in the inlet flow: use of auxiliary fuel, or electrical heating, seem to be the best solutions (Nieken et al., 1994a; van de Beld and Westerterp, 1997).

Very little information is available on the open- and closed-loop behavior of the periodically reversed flow combustor, in the presence of disturbances or as a consequence of a change in the set point (or during startup); up to now, a periodic open-loop control policy, with fixed switching time, has been generally considered.

Different control strategies have been discussed for a cooled CO combustor by Budman et al. (1996): they investigated the behavior of a PID feedback loop controlling the outlet conversion by manipulation of the cooling rate (at fixed switching time); a feedforward system was also suggested, that should measure inlet CO concentration and select the optimum frequency and cooling rate on the basis of parametric maps.

Actually, the reversed flow combustor is quite robust, and can operate at a fixed switching time without extinction in a relatively wide range of gas-flow rate and concentration, even if the efficiency of combustion depends on the cycle period (Barresi and Vanni, 2002).

In a previous work the control of another forced unsteady-state combustor, the network of three nonstationary catalytic reactors, has been discussed, showing that a feedback control based on bed temperature measurements can strongly improve the robustness of the control system (Barresi et al., 1999).

The objective of this work is to identify the optimal operating conditions of the combustor with periodic flow reversal in case of fixed switching time, and to compare the performance of the feedback and open-loop periodic control; the scope is to develop a control system capable of keeping the system always close to the maximum of the combustion efficiency, even in the case of variable feed conditions.

Model

An adiabatic catalytic packed-bed reactor, with two large inert sections at both ends has been considered. The same

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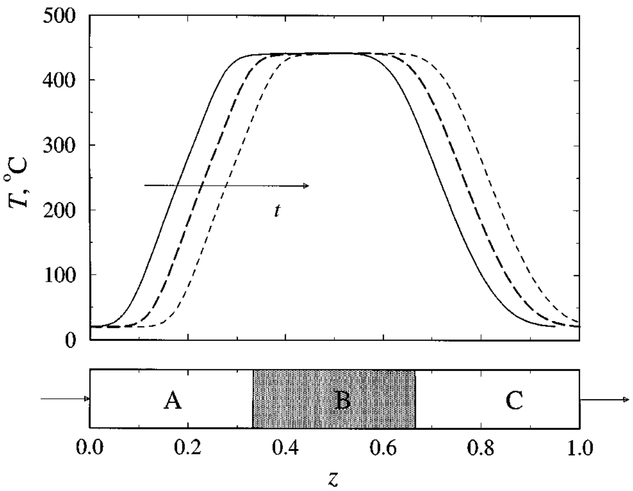

Figure 1. Behavior of the reverse flow reactor.

conditions adopted for the network of reactors described in the previous work (Barresi et al., 1999) have been adopted to make a comparison of the performance of the two devices possible (see also Barresi et al., 1997); the large inert fraction of the network (80% of the bed) is quite unusual for the reverse flow combustor, but it has been shown that, with the inert, a stronger dependence of temperature profiles and conversion on a cycle period occurs (Nieken et al., 1994b; Fissore and Barresi, 2002). Thus, a 9 m bed, with the same amount of catalyst and inert of the three beds of the network studied in the previous work (3 m long each) has been modeled; shorter beds, corresponding to the volume of only one and two beds of the network, have been also considered.

The heterogeneous 1-D mathematical model used here is the same previously described; the differential balance equations for catalytic and inert sections, as well as the values of the physical parameters, are the same as reported by Barresi et al. (1999) for the network of reactors. The method of solution is described by Brinkmann et al. (1999).

Results

The mechanism of operation of the combustor can be explained by making reference to Figure 1. The cold gases entering the reactor are heated by the inert section A. When they reach the catalytic section B, their temperature is above the ignition point and combustion takes place. The heat released allows the central zone to remain hot and makes the temperature of section C increase. At the same time, the temperature of part A becomes lower, because of the flow of cold gas. As a result, a temperature front moving in the gas flow direction is created, whose velocity is very small as compared to the gas velocity: the feed must be reversed before the hot front exits the combustor to avoid extinction; thus, it is necessary to fix the switching frequency in advance, or set up an automatic controller.

In order to start up the combustor, the gases must be fed in a preheated system; in this work the uniform initial temperature $T_{ph} = 257°C$ has been considered. As discussed in another article (Cittadini et al., 2002), different initial temperature profiles do not modify the final periodic state of operation for this system, provided that T_{ph} is sufficiently high.

Open-loop control

Figure 2 shows the performance of the combustor in the case of open-loop control, that is, with the period of each semicycle (t_{csp}) fixed in advance; at the end of each semicycle, the direction of the flow is reversed, and, once the final pseudo steady state is reached, in the absence of disturbances, the same conditions are periodically obtained in the reactor every two semicycles.

It can be noted that there exists a wide range of t_{csp} in which the conversion is independent of the reactor length, even if the maximum temperature is different. The longer the reactor, the wider is the range of cycle periods that supports stable autothermal operation. Note that, with a 3-m long reactor, stable operation does not occur in the considered range.

The range of operating conditions of the reactor is limited by two factors: at short cycling periods, wash out effects become important with emissions of untreated gas at each switch. On the other hand, at very long cycle periods, the thermal front exits from the reactor, leading to the loss of the heat contained in the bed and to extinction.

Figure 2 shows that an optimum switching frequency exists at which conversion is the highest, and that longer reactors allow better optimal performances, even if the improvement

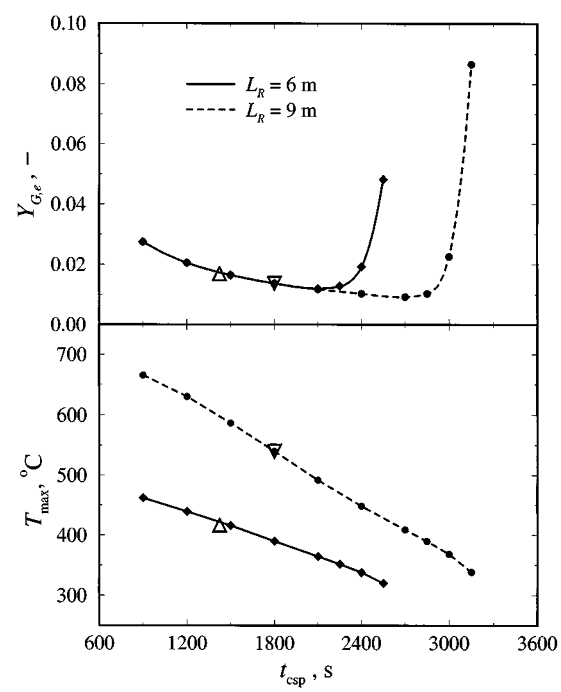

Figure 2. Dimensionless outlet VOC average concentration (top) and maximum temperature (bottom) in reactors of different length, as a function of the cycle semiperiod (open-loop control), with the final pseudo steady state.

The triangles indicate the values obtained in the case of closed loop (one-point control; $T_{sw} = 257°C$).

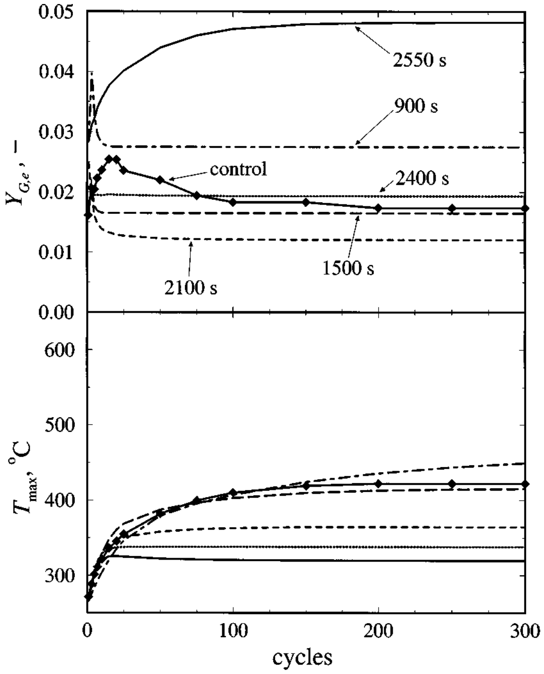

Figure 3. Behavior of the fixed period control (t_{csp}) and feedback control (one point control logic: T_{sw} = 257°C) during startup.

$L_R = 6$ m.

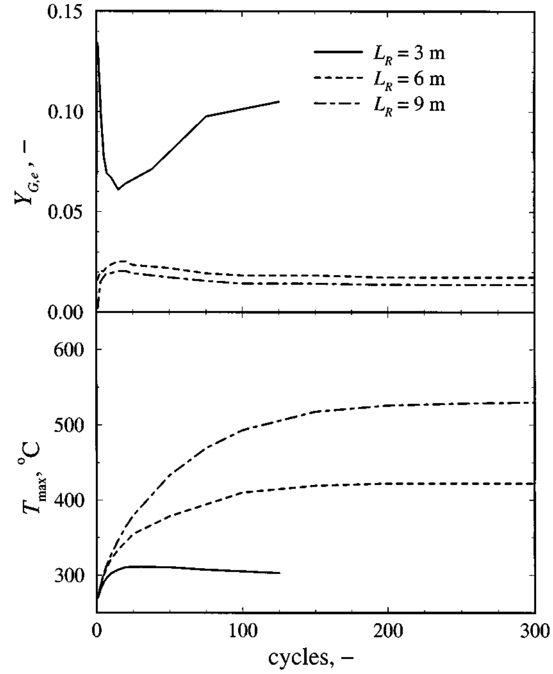

Figure 4. Dimensionless outlet VOC average concentration (top) and maximum temperature (bottom) during the startup in reactors of different length.

Closed-loop control, one point control logic: T_{sw} = 257°C.

is relatively small. Figure 2 also shows clearly that the optimal value is very close to the stability limit, and that cycle periods which are slightly higher than the optimum lead to a strong reduction of the system performance. The maximum temperature decreases monotonically when the cycle period increases, and its values are also largely affected by the reactor length.

Closed-loop control

To realize a closed-loop control, a temperature sensor is located at either end of the catalytically active portion; the feedback controller reverses the flow direction when the prescribed condition is fulfilled by the measured temperatures. The simplest control logic (one point controller) takes into account only the temperature measured by the sensor located close to the inlet at the end of the first inert section: the flow is reversed when this temperature falls below a fixed value (T_{sw}).

Figure 3 shows an example of the evolution of the system during the startup using the previous control logic, compared to the case of open-loop control. The dynamics is quite similar concerning obtaining the maximum temperature in the reactor, while it takes many more cycles for the system with feedback control to reach the final pseudo steady-state conversion. The outlet concentration initially increases, then slowly decreases. When a fixed switching time is adopted, a transient maximum in the emission can be observed, but the final value is obtained in few tens of cycles.

Figure 4 compares the behavior of reactors of different length. If stable operating conditions can be reached, the maximum temperature increases monotonically up to the asymptotic value. The conversion passes through a minimum, and the final value is different for the two reactors; this behavior is different from that in the case of open-loop control. In Figure 4 the initial behavior of the shortest bed (3 m) is also shown for comparison; the temperature slowly decreases after a few initial cycles, as the conversion and the reactor finally extinguishes.

The cycle period is variable during the startup, as shown in Figure 5; initially, it decreases, then increases to reach in this case the final value in about 200 cycles. Note that the final

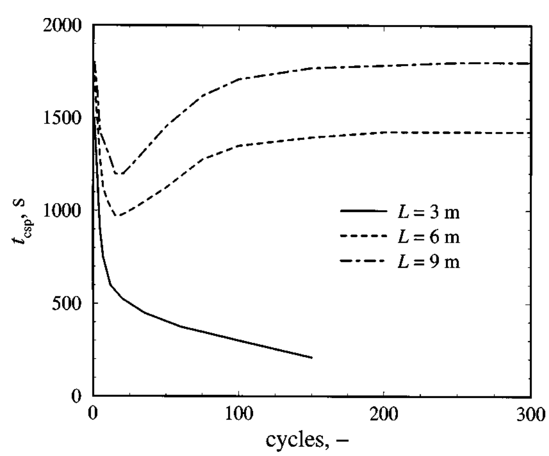

Figure 5. Variation of the cycle period during the startup.

Closed-loop control, one point control logic: T_{sw} = 257°C.

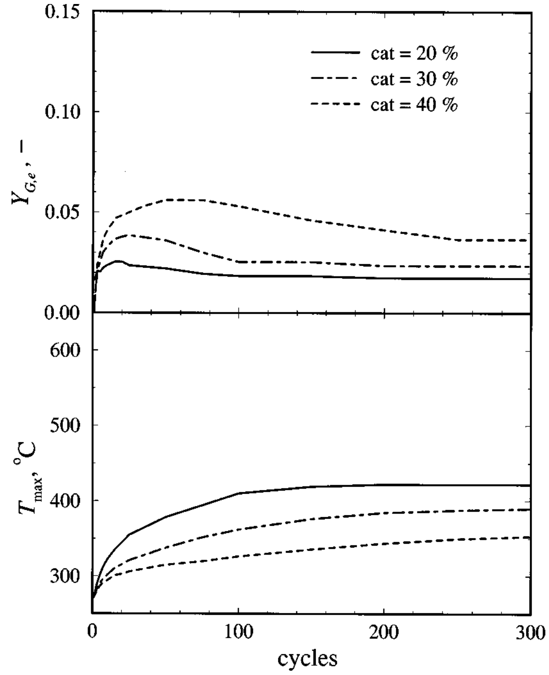

Figure 6. Dimensionless outlet VOC average concentration (top) and maximum temperature (bottom) during the startup in reactors with different fraction of catalytic material (cat).

$L_R = 6$ m; closed-loop control, one point control logic: $T_{sw} = 257°C$.

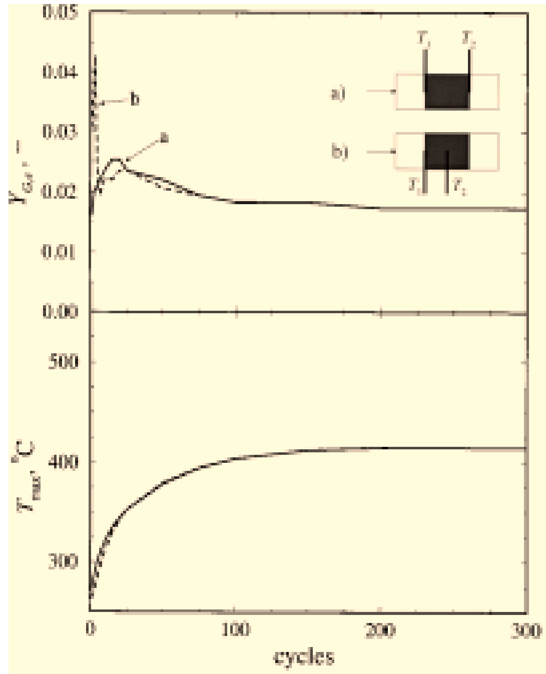

Figure 7. Dimensionless outlet VOC average concentration (top) and maximum temperature (bottom) during the startup.

$L_R = 6$ m; two-points control logic: $T_{sw1} = 257°C$; $T_{sw2} = 262°C$.

value depends on the reactor length, and it is significantly different in the two cases considered: this is the reason for the difference in the final pseudo steady-state conversion observed (compare Figure 2 and Figure 4). For the shortest reactor, the switching frequency continues to increase until it extinguishes.

The performance of the reactor depends on the choice of the temperature set point: the minimum value for stable operation depends on the ignition temperature. Thus, it is characteristic of the catalyst and of the VOCs considered; while increasing this value, the maximum temperature in the reactor and the switching frequency increase.

The performance depends also on the relative amount of catalyst and inert material, but an increase of the amount of catalyst does not necessarily improve the conversion. As shown in Figure 6, while the volumetric fraction of catalyst increases from 20% to 40%, the maximum temperature decreases as expected, but the averaged VOC concentration at the exit increases. The reason for this surprising result is that, with the feedback control, the final period of the semicycle decreases when the fraction of catalyst increases, thus leading to lower final conversions: in the case considered t_{csp} reduces from 1,425 s to 1,050 s and 750 s when the catalyst fraction increases from 20% to 30% and 40%, respectively.

A two-point control logic has been considered as well, taking into account the values of temperature measured at both the beginning and the end of the catalytic bed: the flow is reversed if $T_1 < T_{sw1}$ and $T_2 > T_{sw2}$ (see Figure 7). The use of the second sensor has little influence; the behavior is almost identical to that with one point control, and the final conversion is just slightly higher. In the case shown, T_{sw2} has been chosen slightly greater than T_{sw1}: no improvements can be obtained choosing higher values of T_{sw2}; on the contrary, if $T_{sw2} > T_{ph} + \Delta T_{ad}$, no switch occurs after the first cycle, and extinction takes place.

A different configuration has also been tested where the second sensor is positioned in the middle of the bed; this arrangement is still a two-point control, but its practical realization requires three sensors (one in the middle and two at the two ends, of which only the one close to the inlet is considered in each semicycle). Figure 7 shows that the second switching condition is influent at the beginning of operation only. After a few cycles, the same performance as before is obtained; also in this case, the choice of an higher value for T_{sw2} can lead to extinction.

Conclusions

It has been shown that a feedback control can operate effectively for the reverse flow reactor. Such a control reverses the flow direction when the temperature at the inlet of the catalytic section falls below a prescribed value. The feedback control is particularly suited in case of large variations of the flow rate, because the cycle period is automatically set and the conversion is only slightly lower than the optimal one.

Acknowledgments

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Notation

t = time, s
t_{csp} = cycle semiperiod, s
T = temperature, °C
T_{max} = maximum temperature in the reactor, °C
T_{ph} = preheating temperature, °C
T_{sw} = set point temperature for switch, °C
$Y_{G,e}$ = dimensionless outlet concentration ($= y_{G,e}/y_{G,0}$)

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