

Arrangement of reactor-heat regenerator for catalytic combustion of pollutants in air

K. German¹, A. Gawdzik², T. Machej³

¹Institut of Organic Chemistry and Technology, Technical University, 31-155 Kraków, ul. Warszawska 24, Poland

²High Pedagogical School, Opole, Poland

³Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences, Kraków, Poland

Abstract

A dispersive model has been used in the calculations of the operational conditions of the heat regenerators applied in an arrangement of reactor - heat regenerator for catalytic combustion of pollutants in air. It has been studied an influence of selected parameters of the regenerator on the temperature in the combustion zone. Results of calculations have been compared with the experimental results. An example of the industrial application of the method has been given.

Introduction

Combustion of contaminants contained in the air constitutes one of the methods of its purification. At low concentrations of a combusted substance, the enthalpy of the combustion process does not suffice to heat a stream of the purified air to a temperature required by a catalyst to start up the reaction. The consumption of energy supplied from outside can be reduced or eliminated by an appro-

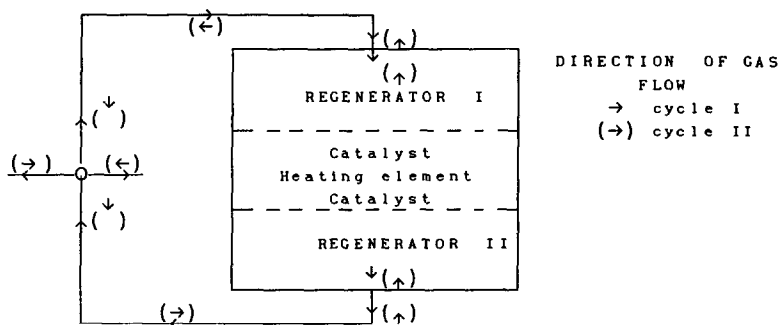


Fig. 1. Scheme of device for the combustion of pollutants under auto-thermal conditions

priate coupling of the reactor with two heat regenerators. The operational principle of the device is explained in Fig.1.

The method consists essentially in a cyclic change in the direction of the gas flow (here the purified air) through the installation and, hence, in a cyclic change of the role played by each regenerator. One of them, regenerator I placed upstream the reactor, gives up heat (previously accumulated), the other, regenerator II placed downstream the reactor, accumulates heat taken from air after the reaction. After the change in the direction of the gas flow, regenerator II assumes a role of regenerator I, whereas regenerator I that of regenerator II. The flow reversals occur periodically, and a period of time between the reversals, called sometime a flow reversal time, has a marked effect on a degree of heat regeneration obtained. The air is heated by an additional heat source until enough heat is accumulated (during the start up of the device).

The conversion degree of the contaminants depends on the temperature in the zone of the catalyst. This temperature in turn depends on the concentration of the contaminants combusted. In the system discussed, this temperature depends also on the efficiency of the regenerators. This efficiency can be regulated by changing the flow reversal time.

Incorporating the heat regenerators into the installation increases the pressure drop (here of the purified air) through the device. The energy consumption by a fan enforcing the flow of a gas stream may be treated as equivalent to the energy consumption due to heating the purified gas with a heating element up to a temperature of the combustion reaction. The exploitation cost of the device depends thus on an adequately chosen balance between the heat efficiency and the pressure drop of the heat regenerators.

Material filling the regenerator should not adsorb the contaminants which would otherwise undergo desorption from its surface to the air after the gas flow reversal.

Analysis of operational conditions of the heat regenerator

Analysis of the operational conditions of the heat regenerators were performed making use in the calculations of a dispersive model [3], [4]. The model implies the following relationship between a

dimensionless variance of heat dispersion, σ_D^2 , and physical parameters of the regenerator:

$$\sigma_D^2 = \frac{6\bar{u}}{5} \frac{\rho_c}{\lambda_s} \frac{c_p}{a_s} \frac{L_p}{H} + \frac{2\bar{u}}{h} \frac{\rho_c}{a_s} \frac{c_p}{H} + \frac{3L_p}{H} - \frac{L_p^2}{2H^2} [1 - \exp(-2H/L_p)] \quad (1)$$

whereby:

$$a_s = (1-\epsilon)/L_p \quad (1a)$$

$$\sigma_D^2 = \sigma^2/\mu^2 \quad (2)$$

where μ is an average heat residence time:

$$\mu = M_s c_{p,s} / F_g c_{p,g} \quad (3)$$

Relationships given in [5] were used to calculate the resistance to flow. A more detailed description of the computing algorithm worked out on this basis is given in [6].

Adjustment of selected parameters of the regenerator

Effect of a calorific value of the combusted contaminant

Fig. 2 compares plots of temperature attained in the zone of the catalyst as a function of the flow reversal time, when carbon monoxide or toluene are combusted in a device equipped with regenerators of an average heat residence time of 560 s. Toluene and carbon monoxide differ considerably in their calorific values. Combustion of e.g. 2 g of toluene contained in 1 m³ of air, according to the stoichiometric equation:



yields 81.8 kJ of heat. In consequence, the temperature of air will increase by about 40°C. Toluene belongs to substances of high calorific values. If 2 g of carbon monoxide contained in 1 m³ of air is combusted, the temperature will increase merely by about 10°C. The figure reveals that the combustion of 0.25 g/m³ of toluene allows to attain easily the temperature 350 - 400°C, whereas the same temperature may be attained only with the help of an extra heating element, when the same amount of carbon monoxide is combusted. Even if the concentration of carbon monoxide is increased to 0.5 g/m³, the temperature of 400°C can be attained at a very short flow reversal time. At the same concentration of toluene and at short flow reversal times, the temperature of the catalyst will considerably exceed 1000°C which can affect adversely the catalyst. The calculations ha-

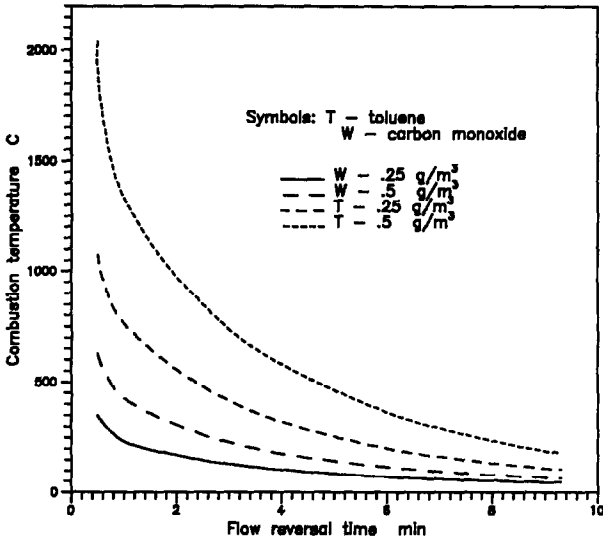


Fig.2 Temperature obtained on combustion of carbon monoxide and toluene under constants conditions of regenerator operation

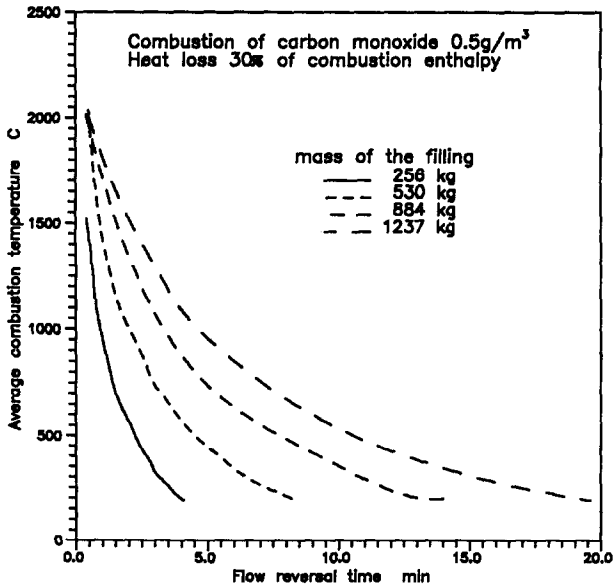


Fig. 3 Effect of mass of the filling on average reaction temperature

ve been performed on the assumption that 30% of heat evolved on the combustion is lost through the walls of a device.

Effect of average heat residence time.

The average heat residence time, is a basic parameter of the regenerator. It determines (equation 3) a ratio of heat capacity of the regenerator to heat capacity of the gas stream flowing through the regenerator. The same heat residence time can be achieved in regenerators differing in volume and height to diameter ratio, by choosing the filling material of various volume density and specific heat. These parameters have a significant effect both on thermal efficiency of the regenerator (equation 3) and on porosity of the bed, and hence both on temperature attained in the zone of the catalyst and the resistance to the gas flow.

Effect of specific density of material filling the regenerator.

The effect of change in the average heat residence time of the regenerator, obtained by varying the specific density of the filling, on the temperature - flow reversal time plots is illustrated in Fig.3. The specific density of the filling (beads of small diameter) was varied in the range from 1450 kg/m^3 (e.g. a ceramic material) to 7000 kg/m^3 (e.g. steel beads).

It can be concluded from Fig.3 that in theory the temperature in the combustion zone does not depend on the average heat residence time of the flow reversal regenerator. In a limit, at a very short flow reversal time, the same temperature is obtained (it depends only on the level of heat losses of the installation to the environment). In practice, however, there exists a limit, a certain minimal flow reversal time. An attempt to diminish it further leads to a de-regulation of the system in which the pseudo-stationary state cannot be maintained. Fig.3 reveals that the effect of the average heat residence time on the temperature is twofold:

- at the same flow reversal time, the higher the mass of the filling (the higher the average heat residence time), the higher temperature will be reached in the combustion zone,
- the higher the mass of the filling, the higher the precision with which one can control the temperature in the combustion zone, the higher the flow reversal time necessary to attain the same tempe-

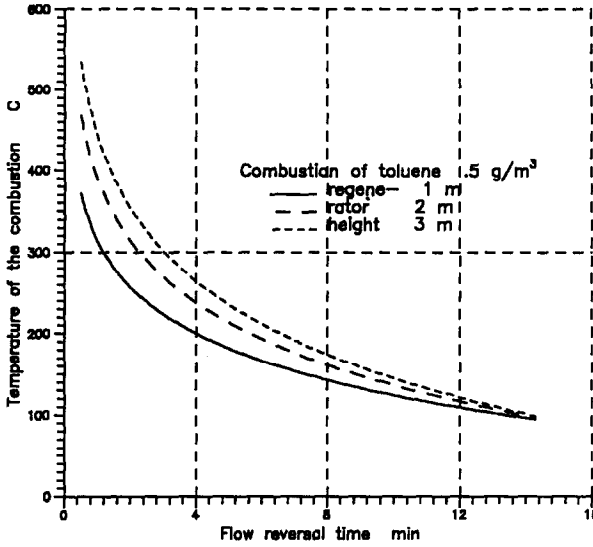


Fig.4 Effect of proportions of the regenerator on temperature in the combustion zone at a constant volume of regenerator, $V = 3 \text{ m}^3$. Air flow 2000 m³/h

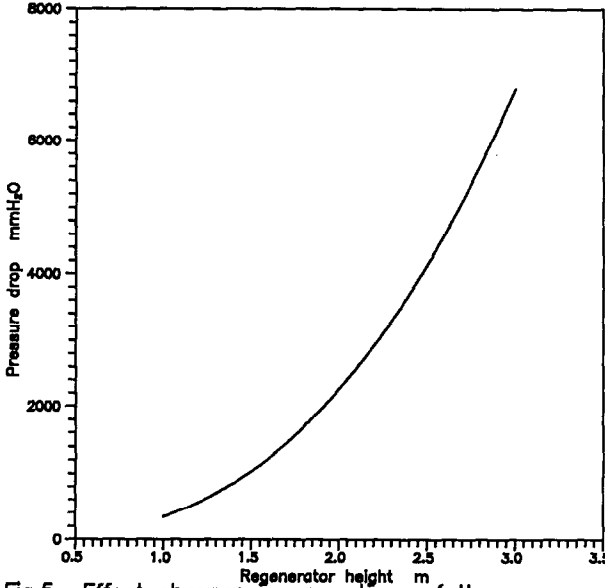


Fig.5 Effect changes in proportions of the regenerator of a constant volume $v = 3 \text{ m}^3$ on magnitude of pressure drop

perature.

To give an example from Fig.3: at a flow reversal time of 3 min. and a low mass of the filling (256 kg), the average temperature in the combustion zone is 318°C, at a high mass of the filling (1237 kg), the temperature increases to as high as 934°C, at heat losses to the environment being as high as 50% of heat evolved during the combustion. The same temperature of 400°C is obtained at the flow reversal time $t = 2.5$ min for the mass of filling of 256 kg and $t = 11$ min for the mass of 1237 kg.

In the considerations presented, the increase in the heat capacity of the filling material, and hence the increase of the average heat residence time, is obtained by increasing mass of the filling. Analogous conclusions are also valid for variations in heat capacity obtained by changing the specific heat of the material of which the elements of the filling are produced.

Effect of proportions of the heat regenerator.

The same volume of the regenerator can be obtained for various proportions of its dimensions, i.e. for various ratios of its height to diameter, H/d_R . An appropriate transformation of equation (1) to the form:

$$\sigma_D^2 = \frac{24F_g c_p L}{5\lambda_s a_s \Pi d_R^2 H} + \frac{8F_g c_p g}{h a_s \Pi d_R^2 H} + \frac{3L}{H^2} - \frac{L^2}{2H} [(1 - \exp(-2H/L_p))] \quad (5)$$

indicates that the first and the second components of the sum, determining the variance, do not depend on the proportions of the regenerator and merely on its volume. In turn, the third and the fourth components of the sum, do not depend on the volume, but on the height of the regenerator, hence, at constant volume, on the proportions of the regenerator.

Effect of the proportions of a regenerator on the temperature reached in the combustion zone is illustrated by the results of calculations shown in Fig.4. The calculations have been performed for a regenerator of the volume of 3 m³ and the flow of the purified air of 2000 m³/h (0.55(5) m³/s), containing 0.5 g of toluene/m³.

As one can see in Fig.4, a required average heat residence time (represented here by a constant volume and porosity of the filling bed) can be secured in the regenerators of possibly high ratio of

height to diameter. The higher the regenerator, the higher its maximum efficiency. For the case taken above as the illustration, the temperature in the reaction zone does not practically reach 400°C for a regenerator 1 m high, but 550°C is reached in a regenerator 3 m high. This temperature difference decreases however with increasing flow reversal time.

It should be born in mind, however, that the higher the ratio of height to diameter, the higher the resistance to gas flow which is proportional to a square of the linear gas flow velocity. The increase of the pressure drop in the regenerator of the volume given above (Fig.3), expressed as mm H_2O is illustrated in Fig.5.

Comparison of energy consumption by a heating element and a fan

As already mentioned, energy consumption by a fan enforcing gas flow through the heat regenerators cannot exceed energy consumption by an electric heater. The pressure drop depends on one hand on the length of a regenerator, on the other hand on the specific packing of the filling material which accumulates heat. Fig.6 shows increase in the energy consumption necessary to maintain a required temperature in the zone of the catalyst, or a constant flow of the purified air, for the filling materials of various specification, determined by ratio of the specific surface area of the filling to its mass per unit of volume. The lines (solid and dashed) in Fig.5 show results of calculations performed for the model described. The points marked refer to a parallel results of the experimental measurements carried out to verify the model. The figure points to a very good agreement between the model calculations and the experimental results.

Application of the method

The presented method of purifying air and the model for the calculations have found wide application in the practice. Results obtained with the industrial installation are given as an example in table 1.

The installation purifies the waste gas from painting box for care spare parts. The waste gas contained organic pollutants o-, m- and p-xylenes, ethylglycol and cyclohexanol. The minimal energy for the autothermal operation was equal to $21\text{-}25 \text{ kJ/m}^3$, which is equivalent

to 0.5-0.6 g of xylene/m³. The amount of gas to be purified was 4300 m³/h.

Table 1. The degree of purification versus temperature of catalyst for the industrial installation Gas flow of 4300 m³/h

Temperature °C	Concentration of organic pollutants g/m ³	Degree of purifi- cation %
320	0.65	96.3
340	0.65	97.2
360	0.68	98.0
380	0.82	98.6

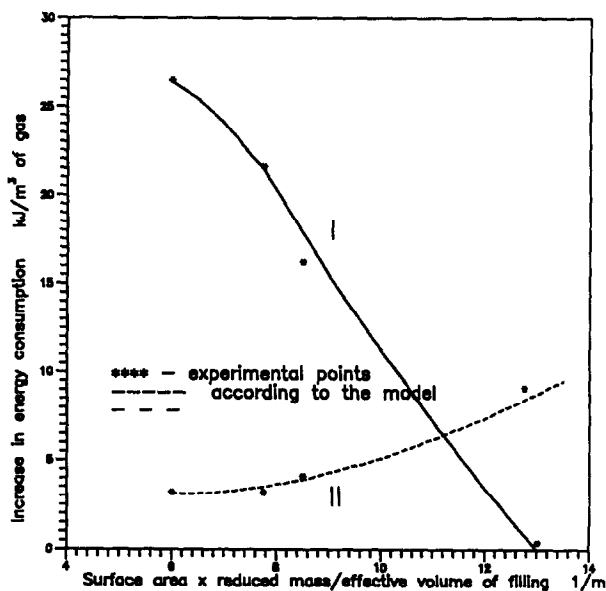


Fig. 6 Effect of specific packing of the filling material on increase in energy consumption in order to attain I. required reaction temperature II. required gas flow

Symbols

a_g - specific surface area of a material filling the regenerator

[m / m]

$c_{p,g}, c_{p,s}$ - average specific heat of gas and material filling the regenerator	[kJ/kg K]
d_R - regenerator diameter	[m]
F_g - mass velocity of the purified gas	[kg/s]
F_v - volume velocity of the purified gas	[m ³ /s]
G - mass stream of the gas flow	[kg/m ² s]
H - regenerator height	[m]
h - heat exchange coefficient solid state - gas	[W/m ² K]
L_p - linear parameter of elements filling the regenerator	[m]
M_s - mass of material filling the regenerator	[kg]
u_g - average linear gas flow velocity	[m/s]
ϵ - porosity of the filling bed	
η - heat efficiency of the regenerator	
λ_s - heat conduction coefficient of the material filling the regenerator	[W/mK]
ρ_g - gas density	[kg/m ³]
μ - average heat residence time	[s]
σ^2 - variance	
σ_D^2 - dimensionless variance, defined by equation (2).	

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