Robust recuperators for the preheating of exhaust air in thermal post-combustion plants for long-term applications

0. Management Summary

Recuperators for the preheating of exhaust air in thermal post-combustion plants serve to reduce additional fuel and are particularly efficient when situated directly downstream from the combustion chamber. However, they are then subject to a high level of thermal stress, so that gas-tightness must be absolutely ensured. If welding seams tear, e.g. as a result of differential expansion being obstructed, raw gas constituents are converted into pure gas, so that emission values that have been defined for the TPC plants may be exceeded.

Several decades of trouble-free operation in many plants and different applications using surface reactors and tubes bent into a lyra-shape in areas of high thermal stress, have shown that this particular design variant can withstand occasional extreme strain (high preheating temperatures, high exhaust air loads and fluctuations, pre-reactions on the exhaust air side, etc.), if these are adeptly constructed and manufactured to high standards.

1. Introduction

Thermal post-combustion is a reliable procedure used throughout the world for the treatment of flue gas with organic constituents. Applications based on processes in which organic solvents, for example, are processed through to post-combustion zones in waste incineration plants. In this process, the essentially toxic organic substance C_xH_y is converted by oxidation into the non-toxic substances CO_2 and H_2O – insofar as this involves a so-called “pure” hydrocarbon:

$$C_xH_y + \left(x + \frac{y}{4}\right) O_2 \rightarrow xCO_2 + \frac{y}{2} H_2O \qquad (1)$$

If chlorine, sulphur, nitrogen, etc. are organically bound to a relevant extent in hydrocarbon, secondary pollutants are generally formed, which must be removed using facilities that are situated downstream from combustion (e.g. in the case of sulphur and chlorine), or whose formation (for example in the case of nitrogen) can be influenced by measures based on combustion technology.

Fig. 1 [1] demonstrates the development of the emissions of volatile organic compounds (with the exception of methane) in Germany. These are dominated nowadays by industrial processes and are interrelated with the use of organic solvents [1]. It is mostly drying processes in which the organic solvents pass through to the gas phase and – in most application cases – together with ambient air, are fed to a treatment process.

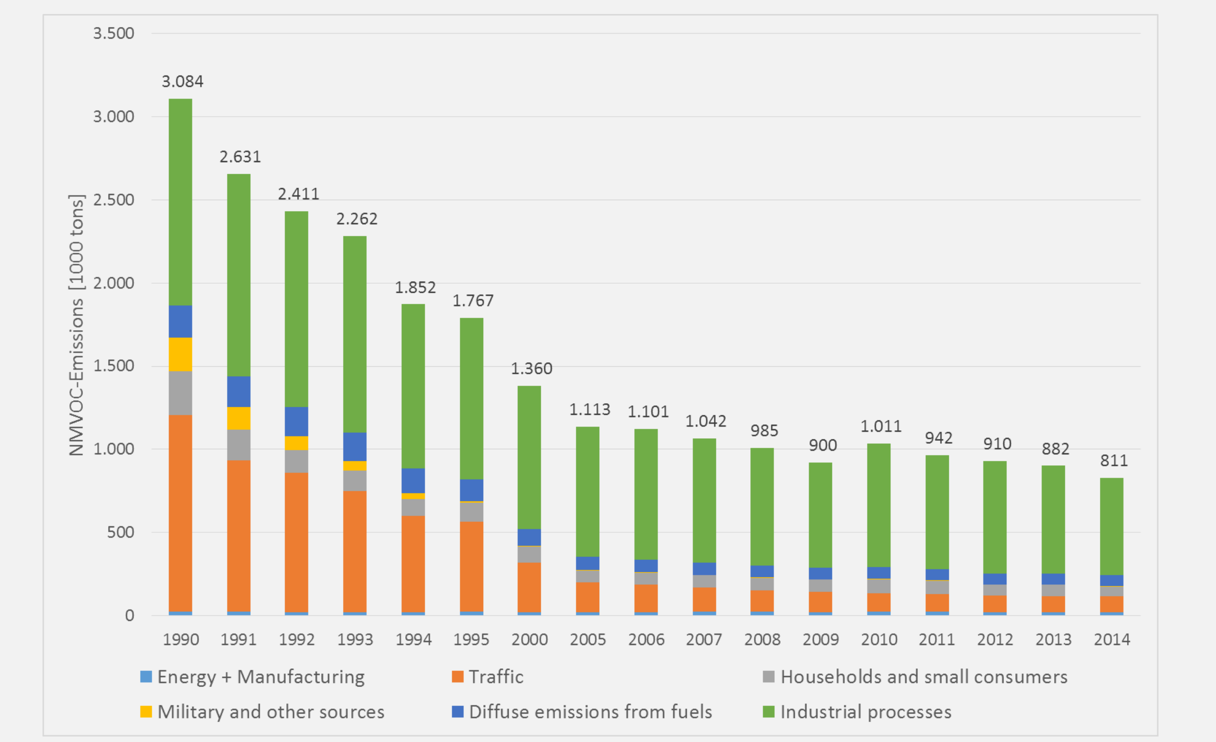

Fig. 1: Emissions of volatile organic compounds with the exception of methane (NMVOC) according to source categories [1].

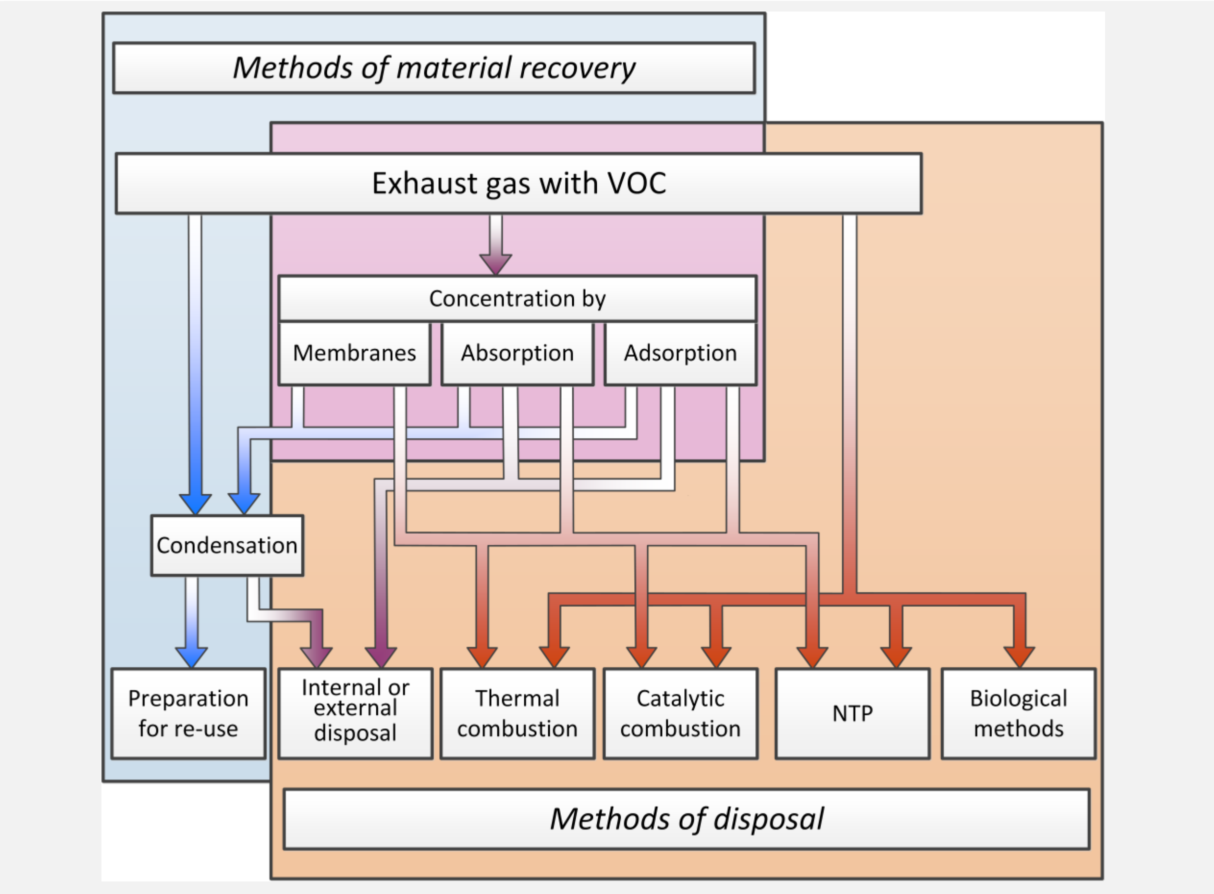

Fig. 2: Procedure for the treatment of flue gases with organic substances [2].

However, the thermal post-combustion process, which is the focus in this case, is not the only means of removing flue gases from organic substances (Fig. 2). If the flue gas has a small number of solvent components and a high solvent mass flow, a substance recovery process can be deployed through which concentration using membranes, adsorptive or absorptive processes mostly proves useful for the realisation of condensation at temperatures that are not excessively low. Generally the condensate must be processed in order to reuse the recovered substances in the process from which they have been derived.

Along with the possibility of substance recovery, the procedures for disposal or detoxification illustrated in Fig. 2 can be deployed with a concentration partly applied upstream – for the improvement of economic operations – insofar as this has not already been realised within the production process. In the case of biological procedures, the organic substances are initially bound in the aqueous phase, where they are aerobically broken down or metabolised by bacteria. Biological procedures are mainly deployed in the area of low hydrocarbon concentrations and for odours. This also applies – with some exceptions – to the non-thermal plasma (NTP), which has the function of ionisation of the gas to be treated. According to [2], an NTP can be created, for example, through electromagnetic radiation or electrically induced discharging processes. NTP plants usually also contain process combinations with adsorptive, catalytic or biological phases.

In the case of catalytic combustion, it is advantageous to reduce the activation energy for the oxidation according to equation (1) so that the reaction can take place at significantly lower temperatures compared with thermal combustion, ranging between 250 °C and 450 °C, depending on substance and catalyst. However, the extent to which catalyst poisons can cause deactivation and thus irreversible damage must be taken into consideration in each individual case.

In contrast, thermal combustion or thermal post-combustion (TPC) is a less sensitive process with regard to unwanted concomitant substances in the flue gas to be treated. The reaction temperature level begins at approx. 750 °C (given the existence of a so-called "ignition pill" to ensure initiation of the reaction); higher temperatures from approx. 850 °C are required for purely independent gas phase oxidation. This applies equally, for example, to the oxidation of halogenated hydrocarbons. However, the economically expedient deployment of a TPC usually requires a case-related modified utilisation concept for the highly tempered enthalpy flow from the combustion chamber system.

2. Waste heat utilisation categories for thermal post-combustion plants

Thermal post-combustion differentiates according to categories A to C. The criterion for the differentiation is the ratio of thermal output $\dot{Q}$ to exhaust air volume flow $\dot{V}$ (in standard conditions):

$$\varphi = \frac{\dot{Q}}{\dot{V}} \, in \, \frac{kWh}{m_n^3} \qquad (2)$$

In category A, the feeding of exhaust air to an existing firing system instead of the combustion air, φ reaches maximum value (Fig. 3).

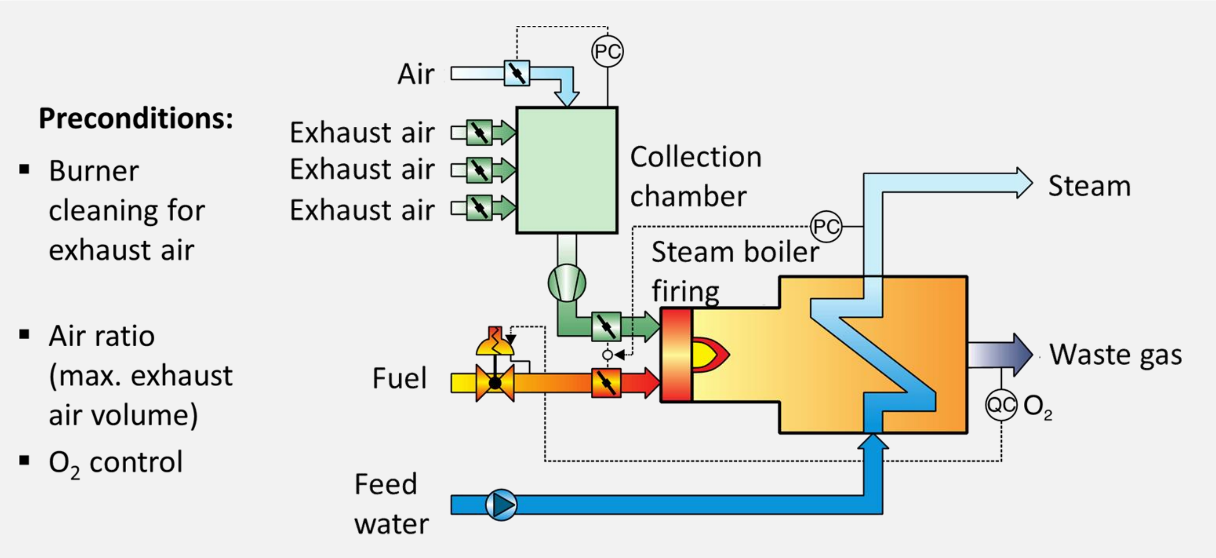

Fig. 3: Feeding of exhaust air into an (existing) boiler [3].

In this process the boundary conditions explained in Fig. 3 must also be observed:

- The burner must be suitable; the flame monitoring system in particular, must not be cooled using (polluted) exhaust air.
- As the combustion chamber is generally cooled so that heat from the reaction zone is decoupled, only limited air ratios (empirical values to $\lambda = 1.5$) can be represented without risking a complete burn-out.
- Combustible substances are now fed to the firing system via the “air pathway”. The bond between air and fuel must now be corrected, for example using oxygen control, unless a change to substoichiometric operation, caused for example by a low concentration of hydrocarbon in the exhaust air, can be entirely ruled out.

The process can also be of interest following a concentration.

In the case of category B, an (almost) adiabatic combustion chamber is principally resorted to, so that considerably higher air ratios can be realised compared with category A. Fig. 4a illustrates a system in which a steam boiler with feed water preheater is situated downstream from the combustion system. Systems of this kind are frequently found in the chemical industry. If less process heat (in this case in the form of steam) is required, exhaust air preheaters can be deployed to reduce the ratio φ (Fig. 4b). If process heating requirements fluctuate due to production factors, recuperator 3 can be avoided with the help of a bypass, so that an increased process heat flow is available in the event of greater fuel deployment. The energy flow diagrams outlined below the charts illustrate the respective energetic circumstances.

If no or little process heat is needed, a regenerative thermal post-combustion concept is recommended (category C, Fig. 5).

This is a system with heat storage beds (nos. 2, 3, 4), which are cyclically switched: in each case one bed (regenerator) preheats the exhaust air (no. 2), one bed cools the pure gas (no. 3) and a third bed (no. 4) is flushed before the switchover from exhaust air to pure gas operation (in this case with fresh air in underpressure operation, whereby the ventilator is positioned on the pure gas side; in the case of overpressure operation (the ventilator is positioned in the exhaust air) pure gas is sucked through the regenerator to be flushed, contaminated in the process and fed to the exhaust air).

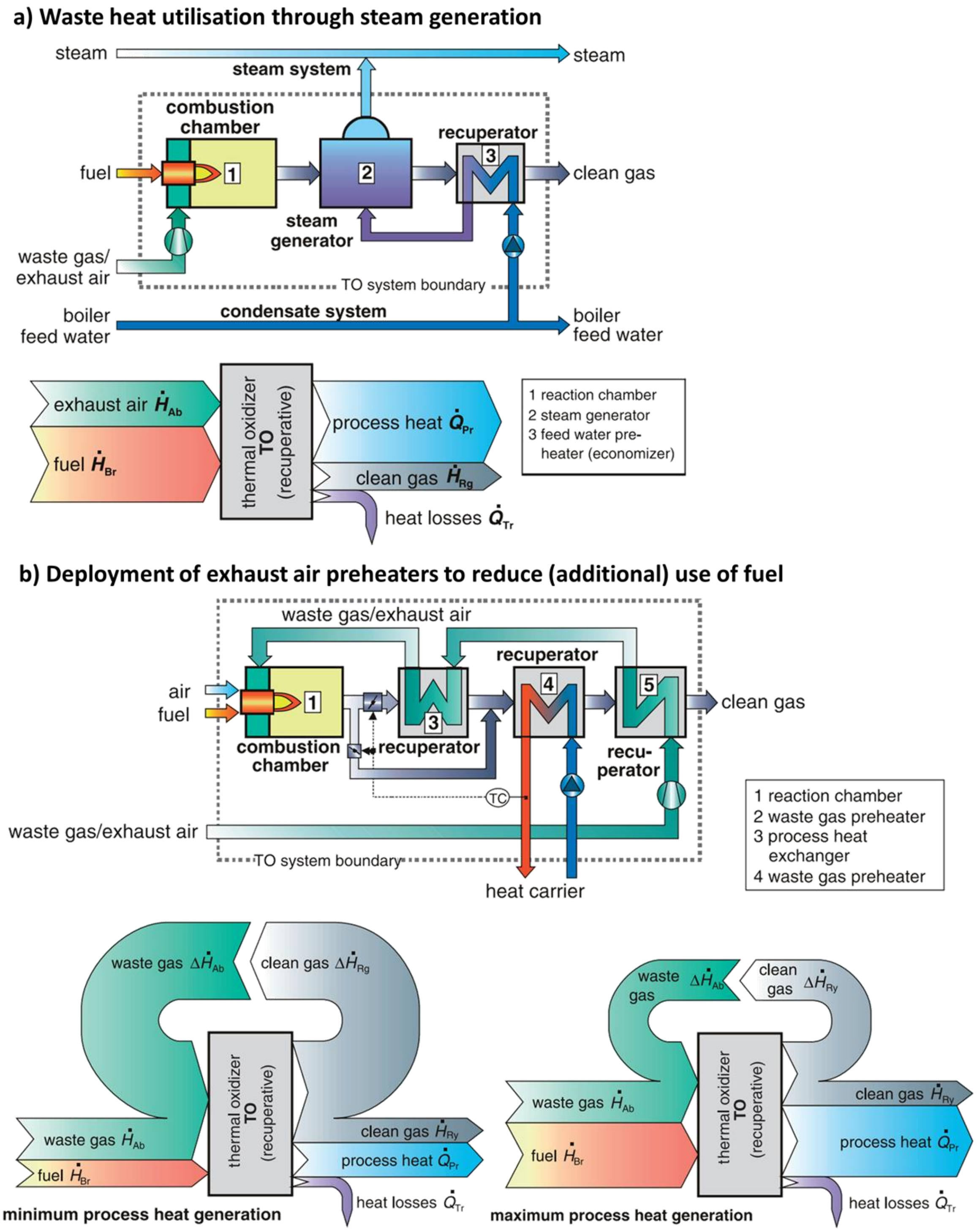

Fig. 4: Recuperative thermal post-combustion systems [3]:
a) Waste heat utilisation through steam generation;
b) Deployment of exhaust air preheaters to reduce (additional) use of fuel
$(\dot{H}: Enthalpy\ flow\ ; \dot{Q}: Heat\ flow; Indices: Ab: Exhaust\ air, Br: Fuel, Pr: Process, Rg: Pure\ gas, Tr: Transmission)$

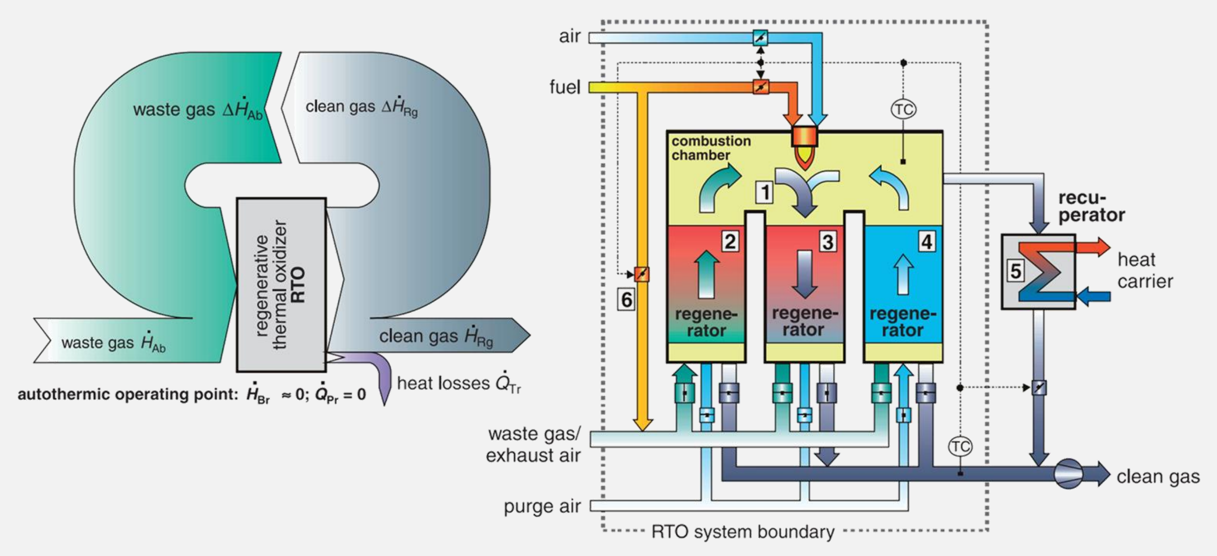

Fig. 5: Regenerative thermal post-combustion (simplified) [3].

Recuperator no. 5 serves to decouple process heat, insofar as the exhaust air contains relatively high organic loads (so-called super-autothermal operation). Because they reach extremely high preheating temperatures, such systems can manage with solvent loads of (0.5...2) g/m^3_n without additional fuel (autothermal operation). The burners (Fig. 5) are run in sub-autothermal operation without primary air; For safety reasons, air is absolutely necessary during the start-up procedure (not shown in Fig. 5).

A comparison of the ratios φ for the categories A to C described above is illustrated in Fig. 6 [3].

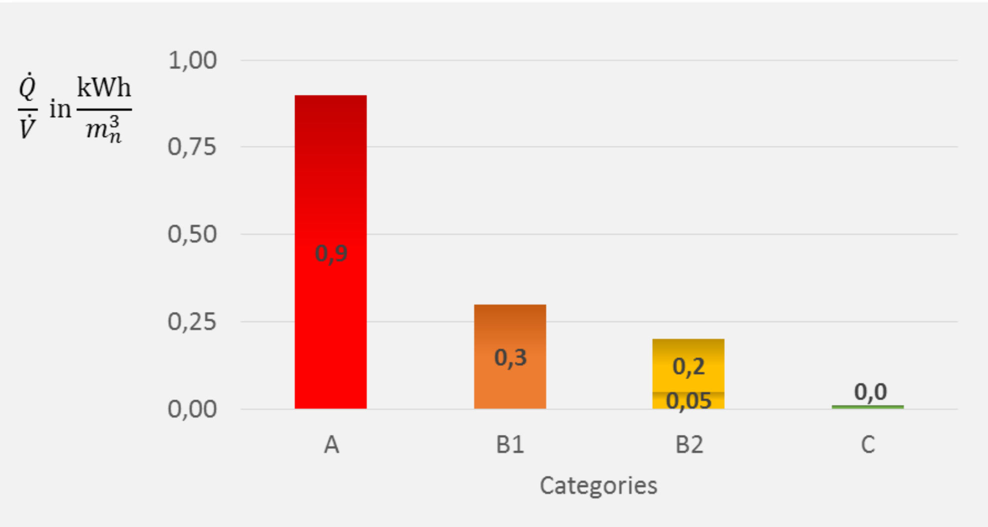

Fig. 6: Ratio $\varphi = \frac{\dot{Q}}{\dot{V}}$ for different categories of thermal post-combustible plants [modified according to 4].

In this case recuperators would be used as exhaust air preheaters in category B2, whereby the degree of exhaust air preheating is based on the respective process heat flow to be decoupled. For example, if the exhaust air volume flow to be treated is $\dot{V}$ = 10,000 m$_n^3$/h, it would be possible to provide process heat of $\dot{Q}$ = (0.5...2) MW. The enthalpy flow from the combustion chamber at a reaction temperature of 800 °C amounts to around

$$\dot{H}_B = \dot{V}_n \cdot c_{pn,0\to B} \cdot \delta_B \cdot \approx 3.2\ MW \qquad (3)$$

where

$\dot{H}$: enthalpy flow

$c_{pn,0\rightarrow B}$: average specific, on the basis of standard volume, heat capacity at a constant pressure between 0 °C and δ_B

δ_B: combustion chamber temperature

Theoretically, a maximum value of

$$\dot{H}_B - \dot{Q} = (3.2 - 0.5)MW = 2.7\ MW \qquad (4)$$

is available for exhaust air preheating. The real value is smaller, as the temperature of the exhaust air to be treated generally has a value greater than 0 °C and defined temperature differences between exhaust air and pure gas must to be taken into account.

However, one crucial aspect should be pointed out: the exhaust air preheating recuperators (in Fig. 4, no. 3 and no. 5) must be absolutely gas-tight; otherwise unburned gas will mix with the pure gas caused by pressure differences between exhaust gas and pure gas, with the result that the statutory emission values will be quickly exceeded, which would mean that the TPC plant would be operating illegally. However, for economic fuel-saving reasons, it is not viable in the large majority of application cases to dispense with exhaust air preheating recuperators, so that an extremely robust design is of vital importance.

3. Surface recuperators[1] as robust exhaust air preheaters

Fig. 7 shows two different types of TPC plants:

- the compact plant
- the component plant

In the *compact plant*, exhaust air in cross-flow countercurrent reaches the pure gas in the device with circular cross-section and is recuperatively heated. (A: circular disc recuperator as exhaust air preheater). Via burner B, the preheated exhaust air (2) finally reaches the reaction chamber R, in which the detoxification of the hydrocarbons takes place through oxidation. The pure gas formed in this way flows back through the annular gap in the direction of the burner and cools down after renewed deflection, in the pipes of recuperator A, before leaving the device as pure gas. Flap no. 4 allows hot pure gas in the bypass to pass by recuperator A, in order to increase the pure gas temperature level at the apparatus outlet if required.

[1] The suspended pipe bundles of the recuperator are not located in a subsurface channel, but in a separate housing above.

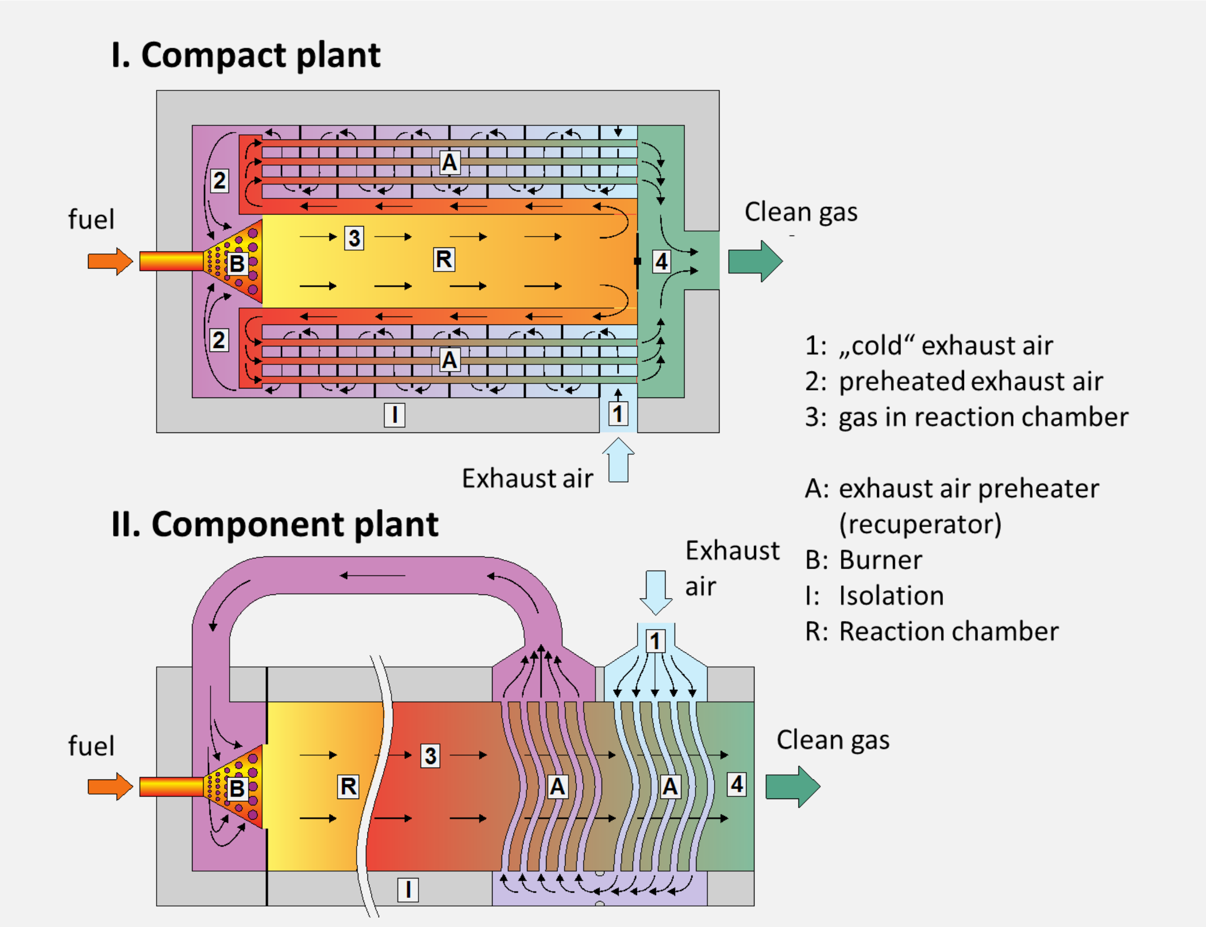

Fig. 7: Equipment-based design variants of TPC plants [5].

An equipment-based separation of combustion chamber R and exhaust air recuperator A has been realised in the case of the *component plant*. As a rule, the combustion chambers and the channel for the heat transfer pipe bundles (therefore the much-used name channel recuperator) are lined on the inside with ceramic material, so that the steel housing remains “cold” on the outside and no relevant thermal expansion occurs. The exhaust air heats up in the cross-flow, whereby the pipe bundles should be arranged in counterflow, resulting in cross-counter flow. The combustion chamber design may deviate from the design illustrated in Fig. 7. For example, a so-called (flat) U-arrangement is possible, so that the path of the preheated exhaust gas up to the combustion chamber can be reduced to a minimum.

Table 1: Properties of the TPC design variants

Compact plant	Component plant
• small size • low weight • frequently presented as all-steel apparatus; temperature-sensitive • pipe bundles not interchangeable • more suitable for small to medium-sized exhaust air loads and lower reaction temperatures	• larger installation space • greater weight • as a rule ceramic inner lining, low temperature-sensitivity • pipe bundles individually interchangeable • also suitable for greater exhaust air loads and higher reaction temperatures

The properties of both TPC design variants are presented in Table 1. It is clear that both concepts have been designed for different areas of application. If strongly alternating loads combined with peak concentrations and temperatures and/or pre-reactions are expected in the exhaust air preheater, the component plant should be the preferred choice. In this case, the compact plant (realised mostly as an all-steel concept), would have a limited service life, whereby a change of construction type at a later stage is usually difficult to implement due to the diversity of overall construction sizes and layouts. Therefore very careful consideration must be given in advance to the choice of model.

The design of a surface recuperator must also take into account aspects which can influence its service life. These are focused on two central questions:

1. How is differential expansion between the pipe rows that are arranged perpendicular to the direction of the pure gas flow (RR 1 to RR 9 in Fig. 8) compensated? (Compensation direction A according to Fig. 8)
2. How is differential expansion within a row of pipes compensated? (Direction of compensation B according to Fig. 8)

Answers to these questions are particularly important in the case of the pipe rows facing the combustion chamber.

One solution which has been tried and tested for decades, including in TPC plants, is to fit the particular pipe bundle facing the combustion chamber, which is subject to strong thermal stress, with lyra-shaped bundled pipes (see also Fig. 7 and Fig. 9). In this way, differential expansion can be compensated by stronger or less pronounced deflections, without excessive force fields having to be coupled into the tube plate.

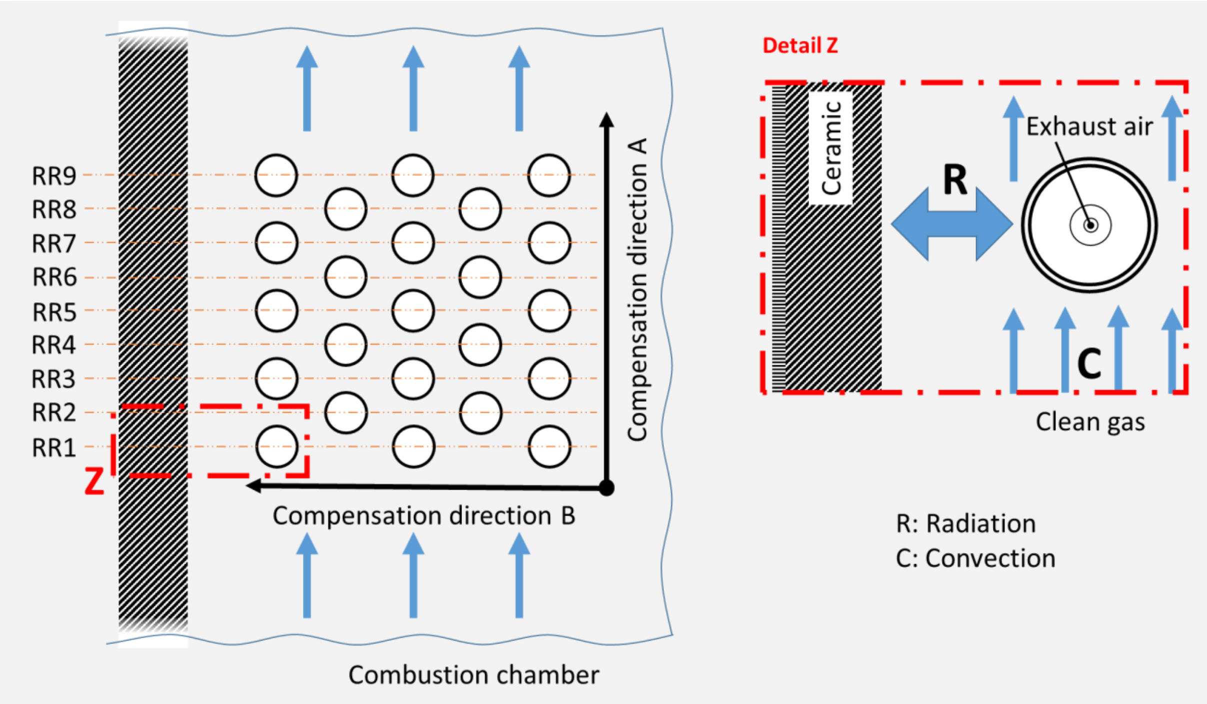

Fig. 8: Relating to the question of differential compensation.

Fig. 9: Lyra-shaped formation of recuperator pipes [6].

Particularly high differential expansion occurs as shown in Fig. 8, detail Z, at the pipes that are in the proximity of the hotter ceramic cladding, in particular in the area close to the combustion chamber. These pipes are located in the area of influence of the thermal radiation of the wall or combustion chamber and – in contrast to most of the other pipes – are for the most part not exclusively heated convectively, so that their medium pipe wall temperature must be set to a higher value. The pipe geometry in this case is in contrast to the plate-shaped ideal form, especially as it allows the deflection and therefore the purposeful expansion compensation that is appropriate to operational demands.

If high concentrations of hydrocarbon continue to be found in the flue gas or exhaust air to be treated, pre-reactions may be expected on the exhaust air side and therefore in the heat exchange pipes, which can lead to an additional (including in the adjacent pipes) varying temperature increase. Here also, the lyra-shaped pipe deflection has shown itself to be an ideal individual pipe compensator.

Furthermore, it should be taken into consideration during construction of the surface recuperators at TPC plants, that mechanical decoupling takes place between recuperator and recuperator housing (=pure gas channel). In this way damage due to mechanical stress and subsequent release of exhaust air or pure gas can be avoided.

4. Literature

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