

## PEBBLE-HEATER TECHNOLOGY IN METALLURGY PRIMENA "PEBBLE - HEATER" TEHNOLOGIJE U METALURGIJI

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### ABSTRACT

The new type of regenerative heat exchangers, the so-called Pebble-Heater with radial fluid flow, is presented. The given mathematical modelling, as well as experimental and industrial experiences have shown some extraordinary characteristics of that facility, such as: high recuperation efficiency (up to 98%), stable hot gas (product) temperature, low exergy losses (i.e. low temperature difference – as little as 20 K – between heating and heated gas), high temperature gradient inside the pebble-bed (2000 K/m), hot gas (product) temperature of up to 1500°C and at last not the least low investment costs compared to the state of the art. Some applications in the metallurgy have been briefly presented, such as: hot blast supply for blast furnace and other shaft furnaces, post combustion in steel converters, scrap melting with fossil fuels, regenerative burner systems and off-gas cleaning through thermal oxidation.

**Key words:** regenerator, heat exchanger, high-temperature processes, pebble-heater, hot blast stoves, regenerative burners, thermal oxidizers

### IZVOD

U okviru ovog rada prikazan je novi tip regenerativnih razmenjivača toplote koji se nazivaju regenerativni zagrejači sa kugličnom ispunom i radijalnim tokom fluida. Prikazani matematički model, kao i iskustvo koje je stečeno eksperimentalnim radom i u industrijskim pogonima pokazali su izvesne netipične karakteristike ovog postrojenja kao što su: visoka efikasnost rekuperacije toplote (do 98%), stabilna temperatura izlazne tople struje fluida, niski eksergijski gubici (npr. niska temperaturska razlika – čak do 20K – između struja koje zagrevaju i onih koje se zagrevaju), veliki temperaturski gradijent unutar sloja kuglične ispune (2000 K/m), mogućnost zagrevanja struje fluida do 1500 °C, kao i niski investicioni troškovi u poređenju sa savremenim uređajima slične namene. Neke od primena u metalurgiji su ukratko prikazane, kao što su: snabdevanje visokih peći zagrejanim vazduhom, dogorevanje u konvertorima, topljenje otpadnog materijala uz primenu fosilnih goriva, sistem regenerativnih gorionika i prečišćavanje dimnih gasova primenom termičke oksidacije.

**Ključne reči:** Regeneratori, razmenjivači toplote, visokotemperaturski procesi, pebble-heater, kauperi visokih peći, regenerativni gorionici, termička oksidacija.

## INTRODUCTION

The new regenerative heat exchanger is referred to as "Pebble-Heater" - a name already known in technical practice. It is filled with bulk material consisting of spherical pebbles and may operate at high temperatures to heat and cool gaseous media. From that point on there are no further similarities to any known design of a Pebble-Heater.

The differences start with the flow direction: the fluid flows radially through the pebble-bed which is fixed between two concentric, permeable cylinders, referred to as hot and cold grid. All other extraordinary characteristics result from that difference which only appears insignificant at first sight. Higher flow velocity and/or smaller pebble diameters may be used, as there is no danger of fluidization. That provides a very high specific surface (or surface to volume ratio) and consequently an excellent heat transfer. A thermal efficiency of 95 % is easily achieved (without any additional off-gas recuperation for pre-heating combustion air or gas). A unit with a recuperation rate of over 98% is already in operation. In addition, those results are achieved at small exergy losses, i.e. with low temperature difference (as little as 20 K) between heating and heated gas. Moreover, all that takes place at temperatures of up to 1500°C.

Due to the excellent heat transfer, a thin pebble bed (temperature gradient of 2000 K/m) is sufficient in a low or acceptable pressure drop. Finally, that leads to a compact unit with the most important characteristics for every investor: low investment costs.

Such device is interesting for applications in diverse high-temperature industrial processes, especially in metallurgy. Some present and future applications are: post combustion in steel converters, scrap melting with fossil fuels, hot blast supply for blast furnace and other shaft furnaces, regenerative burner systems and off-gas cleaning through thermal oxidation.

## PHYSICAL DESCRIPTION

The Pebble-Heater consists of a cylindrical vessel with two permeable grids and a pebble bed between them. The inner grid, the so-called hot grid, is made of high quality ceramic bricks (almost pure Al<sub>2</sub>O<sub>3</sub>, or mulite) with honeycomb segments set in to prevent the movement of the pebbles. The present design was tested at temperatures of up to 1500°C in a pilot facility (PH 104) and in a laboratory furnace. With improved honeycomb segment quality, it is expected to sustain even higher temperatures, up to 1700°C, which might be of interest for some special applications.

The outer grid, the so-called cold grid, is made of a gas permeable steel construction (e. g. perforated steel plate). The pebble bed is fixed between those two grids, so that there is no possibility for it to fluidize or circulate. The maximal temperature at the cold grid is an important design parameter. It is usually held under 250°C. However, the mean value of the cold grid temperature is considerably lower. That means that the outer shell can be constructed out of conventional steel. There is no need for an outside insulation. Fire-clay elements are only required on the top of the hot grid (so-called dome) and at the bottom, around the hot gas inlet/outlet.

For high temperature applications, the pebble bed consists of alumina pebbles. They can sustain extremely high temperature cycling (even over 400 K) without any damage. For less demanding applications (e.g. thermal oxidizers) other bulk materials may be used, such as fire-clay balls or even river gravels and similar natural minerals.

As shown in Figure 1, the hot grid together with the dome may expand upwards freely. That eliminates all sealing problems between metal and ceramic parts. Moreover the hot grid stays free of stresses.

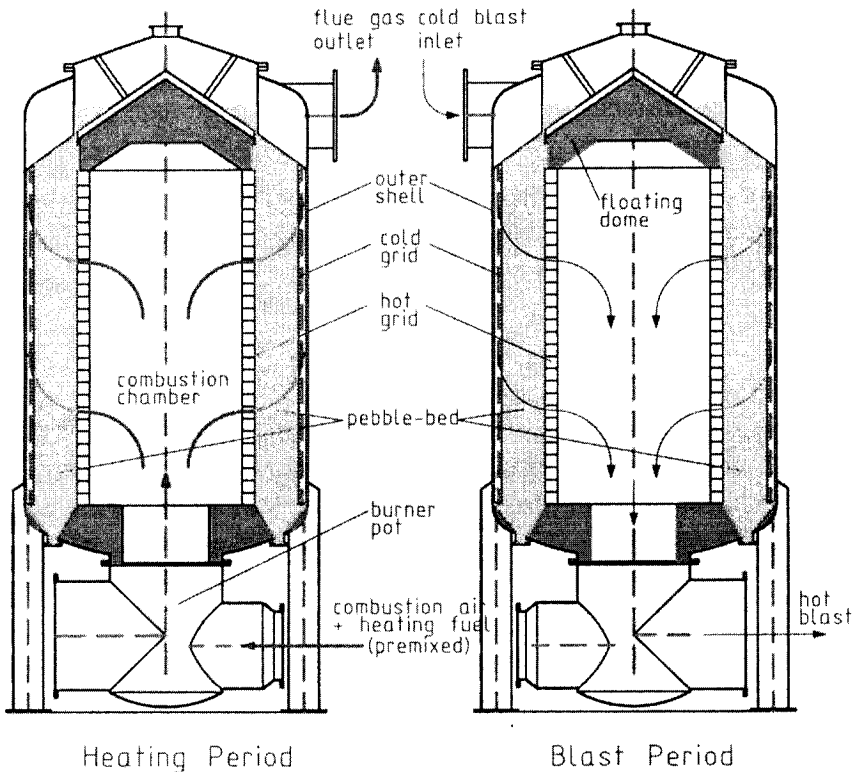


Figure 1: Pebble-Heater with radial fluid flow

## OPERATION

The Pebble-Heater is a regenerative heat exchanger, which means at least two units are required for a continuous flow. While one is in the heating phase, the other produces hot gas. After a certain period of time, they will switch and exchange their phases of operation.

Figure 1 explains the operation of the Pebble-Heater during those two phases. The combustion chamber is placed inside the hot grid. The premix burner is using combustion gas with high (natural gas) or low (BFG) heat value. During the heating phase, the mixture of combustion air and fuel enters the burner pot and ignites. Due to good premixing, the flame is very short and without temperature peaks. Combustion products enter the pebble bed through the hot grid. When reheating the bed, exhaust gases are cooled down and leave it at a low temperature. They pass upwards through the distributing gap between the cold grid and the outer shell and exit the heater toward a stack..

When the Pebble-Heater is reheated, the burner stops and after pressurizing the cold blast enters in reversed direction. It is distributed around the pebble bed and passes through it. During that "blowing phase", the heat is transferred in opposite direction, from the pebbles to the gas phase. The hot blast is collected in the combustion chamber and leaves the Pebble-Heater through the hot blast main.

Instead of combustion products, some hot gas may be used during the heating phase. In that case, the Pebble-Heater recuperates the waste heat from that gas for preheating air or some other gas.

## MATHEMATICAL MODELLING

The mathematical model and respective numerical code have been developed for the simulation of a Pebble-Heater operation. That model and corresponding numerical code have been used to perform various numerical experiments in order to get the first confirmation of the expected extraordinary characteristics. With some small changes they are used nowadays for design optimization of newly developed technology.

The physical model of the pebble-heater consists of a combustion chamber in the centre and a hollow cylinder filled with pebbles around it. The heater is axial-symmetric and the upper and bottom walls are adiabatic, so the heat is transferred just in radial direction. Due to a very high specific surface available for the heat transfer (usually between 500 - 1000 m<sup>2</sup>/m<sup>3</sup>, depending on the bulk

material), the temperature difference between gas and solid phase is very low, i.e. negligible compared to the whole temperature change. In such cases the so-called "homogeneous" model for the pebble-bed may be used [1]. Respectively, just one energy balance equation may be used. The original equation of *Vortmeyer & Schäfer* [1] was derived for a cylindrical pebble-bed with axial flow. It had to be rewritten for the radial geometry in the form:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( r \Lambda_r \frac{\partial T}{\partial r} \right) = \frac{\partial}{\partial r} (m_o c_{pf} T) + [(1-\psi) \rho_s c_s + \psi \rho_f c_{pf}] \frac{\partial T}{\partial t} \quad (1)$$

with the following notation:

$r$  - radial coordinate

$t$  - time

$\Lambda_r$  - "effective" heat conductivity

$T$  - temperature

$m_o$  - mass flux of gas

$\psi$  - void fraction (i.e. bed porosity)

$c_s, c_{pf}$  - specific heat of solid and gas phase

$\rho_s, \rho_f$  - density of solid and gas phase.

The "effective" heat conductivity, as well as all other physical properties, is a function of the temperature and thus of the radial coordinate (temperature strongly depends on radial position). The mass flux of gas is also a function of the radial position, due to a change in the flow cross section. The "effective" heat conductivity in radial direction ( $\Lambda_r$ ) encounters the heat conductivity of fluid and solid, the convective heat transfer between fluid and solid, as well as the effect of radiation between solid particles (pebbles). In the literature there are several correlations for those terms. The correlations given in [2] and [3], which are valid up to a *Péclet* number of  $Pe = 30$  are used here. For some very specific applications there is a need for correlations in the region of  $Pe > 30$ . As it is not available in the literature, an experimental facility for its evaluation has been used.

For solving the partial differential equation of second order (1), it is necessary to know one initial and two boundary conditions. Some known temperature distribution over the radius has to be given as initial condition. Heat fluxes on the hot and cold end (i.e. hot and cold grid) are the required boundary conditions.

The partial differential equation (1) can not be solved analytically, first of all because the “effective” heat conductivity and gas flux are not constant. That type of equation (basically *Fourier*-equation) has been effectively solved in [4] using the Crank-Nicolson numerical method. Its main advantage is implicitity, i.e. it enables pretty high time steps without disturbing the calculation stability. A numerical code based on that method has been developed for simulating the Pebble-Heater operation. A typical result of the code with the characteristic temperature profile through the pebble-bed is given in Figure 2.

Simultaneously with solving the energy equation (1), the numerical code calculates the pressure drop through the pebble-bed by integrating the equation:

$$\frac{dp}{dr} = \frac{1}{\psi^2} \mu \xi \frac{\rho w_o^2}{2D_c} \quad (2)$$

with newly introduced parameters:

$p$  - pressure

$\mu \xi$  - friction and path factor

$w_o$  - gas velocity

$D_c$  - equivalent pebble diameter.

For the friction and path factor  $\mu \xi$  the famous Ergun equation [5] may be used. It was found that the correlation of *Kast* [6] gives better results. However, the best results were achieved with own correlations based on own measurements. That was especially the case when the shape of the pebbles deviates from ideal balls.

The temperature profile inside the bed is S-shaped, as presented in Figure 2. That is a very important and extraordinary characteristic of the Pebble-Heater. It is the result of intensive heat transfer and consequently a low temperature difference between gas and pebbles. While the pebbles in the middle of the pebble bed experience a temperature change of 400 K, the hot grid (distance between -10 and 0 on the graph) always stays at a high temperature.

The hot blast temperature stays constant during two thirds of the blast period. Only during the last third of the blast period does this temperature have a somewhat more intensive drop ( $\Delta T = 30-100$  K, depending on design requirements and operational conditions). The temperature changes on the cold grid are also relatively small ( $\Delta T = 100-150$  K), which results in a low average temperature of the exhaust gas and thus a low exit loss.

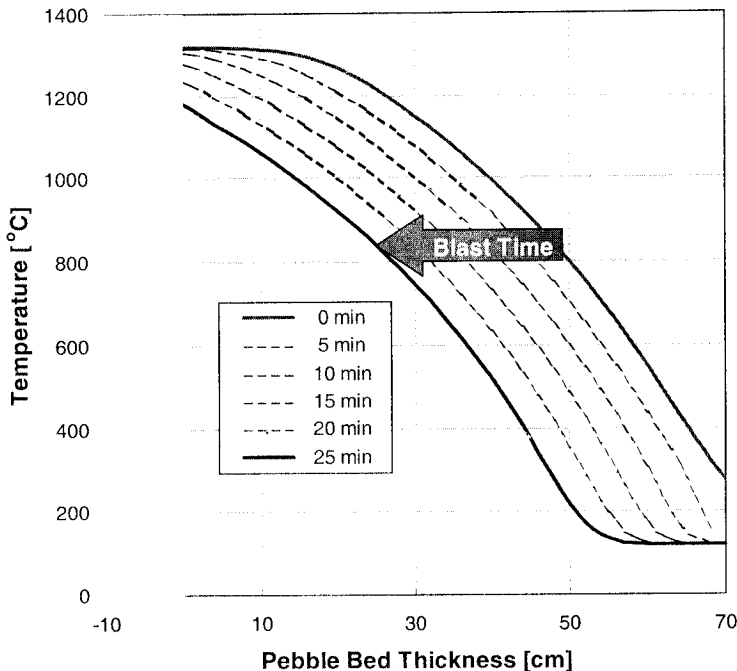


Figure 2: Typical S-shape temperature distribution inside the pebble-bed

### EXPERIMENTAL PERFORMANCES

Those extraordinary characteristics have been verified on the experimental, pilot and industrial facilities, as well. In 1991, a pilot Pebble-Heater designed according to the described principles was erected. This research project on a 10.000 Nm<sup>3</sup>/h unit was an extensive test series on the pilot unit PH 104, which has clearly demonstrated the following advantages of this new regenerator concept:

- very high thermal efficiency between 92 and 95%
- ability to operate at high flame temperature
- stable outlet temperature of hot wind.

During the test series the blast rate, cycling time and flame temperature were varied, in order to obtain the representative data for the whole spectrum of possible operating conditions. The achieved thermal efficiency is far better than the efficiency of the modern stoves with recuperative heat exchangers for pre-heating combustion air and/or fuel gas.

The mean flame temperature was in the range of  $1.175^{\circ}\text{C} - 1.353^{\circ}\text{C}$ . The hot blast temperature was very stable during the whole blast period (Fig. 3). The maximal off-gas temperature was never higher than  $210^{\circ}\text{C}$  (Fig. 4). Mean values were between  $88^{\circ}\text{C}$  and  $137^{\circ}\text{C}$ , which explains the very high efficiency achieved during the trials. The exit losses were always lower than 8 %.

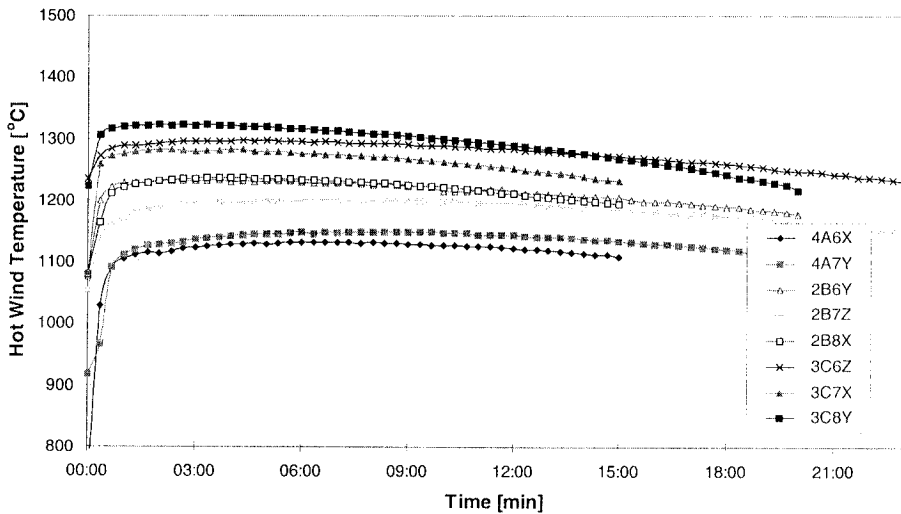


Figure 3: Hot blast temperatures

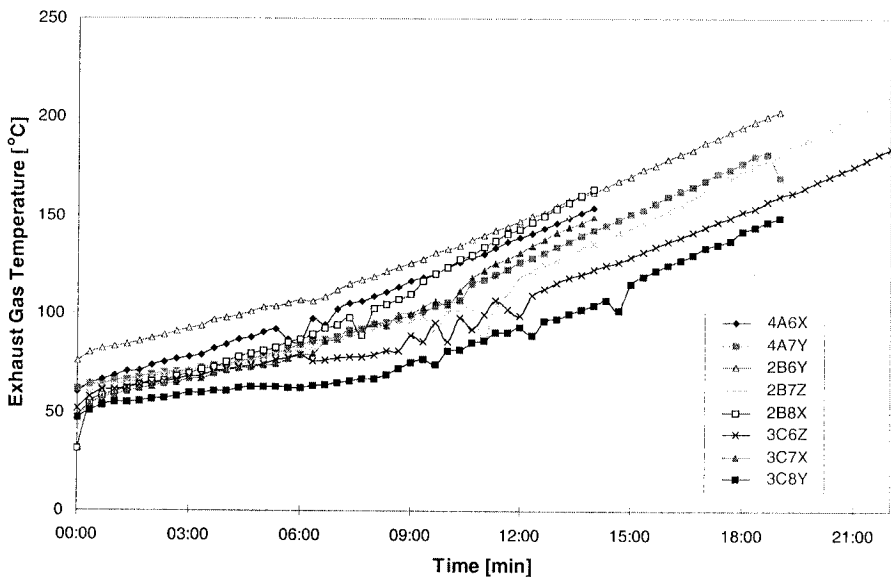


Figure 4: Off-gas temperatures



### COMPARISON PEBBLE-HEATER : CLASSICAL STOVE

The following table shows a comparison between the parameters of a Pebble-Heater and a classical hot blast stove.

Parameter	Pebble Heater	Stove	Ratio
Equivalent diameter of a heat storage material	4,5 mm (Pebbles)	36 mm (Checker-work)	1 : 8
Specific heat transfer surface	$800 \frac{m^2}{m^3}$	$40 \frac{m^2}{m^3}$	20 : 1
Heat transfer coefficient	$1,5 \frac{W}{m^2 \cdot K}$	$1,0 \frac{W}{m^2 \cdot K}$	1,5 : 1
Bulk density of heat storage material	$2200 \frac{kg}{m^3}$	$1300 \frac{kg}{m^3}$	1,7 : 1

This comparison explains the following advantages of the Pebble-Heater:

- volume of heat storage material is 6-7 times smaller (at the same capacity and switching times)
- temperature changes of the heat storage material are about 4 times higher
- temperature difference between gas and solid phase is 4-5 times smaller, resulting in a lower temperature difference between the flame and the hot blast temperature.

This drastic reduction of the heat storage volume leads to a compact design of the Pebble-Heater. Figure 5 presents two Pebble-Heaters in front of two existing stoves they will replace. The smaller internal volume will minimize the jolts occurring during pressurizing /depressurizing.

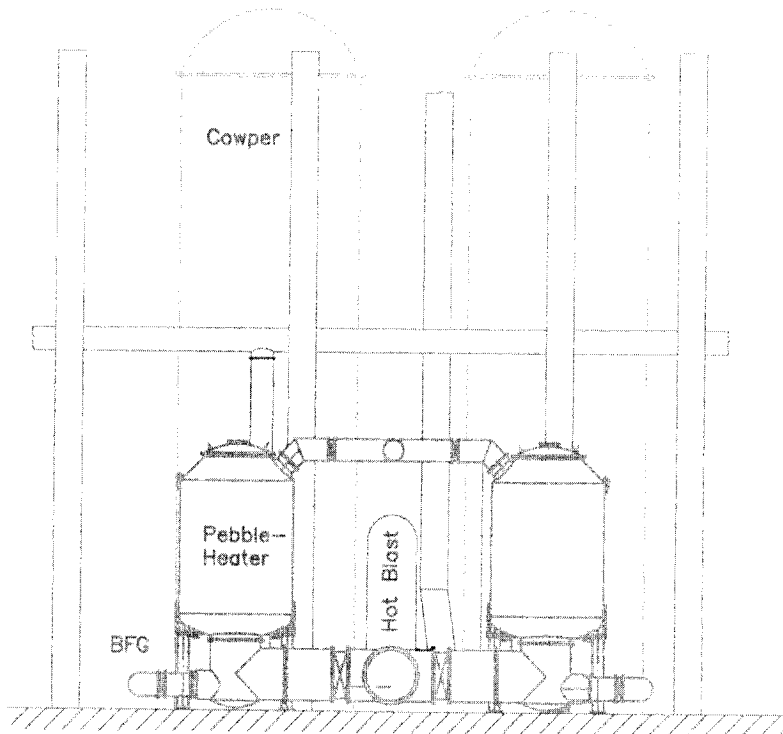
Size reduction leads to cost reduction. The investment in a Pebble-Heater is much lower than in a modern stove, even when considering that the peripheral equipment, like hot valves, hot main, automation etc., is the same. The costs for a Pebble-Heater can vary significantly according to local conditions, but in general are around one half of the costs for a comparable stove.

Another considerable advantage of the Pebble-Heater lies in the short construction and delivery time. The majority of the components may be pre-fabricated and only the hot grid has to be built on site. Filling a regenerator with pebbles takes no more than one day.

## APPLICATION WITH STEEL CONVERTERS

Hot blast jets supplied by a Pebble-Heater may be used very effectively in the steel converters and in the electric arch furnaces [7, 8]. Through the post combustion of the process gas inside a converter, its chemical energy may be used directly inside the converter for melting the scrap or at least for increasing the scrap ratio for about 170 kg/t steel. The phenomena of the heat transfer from an oxidizing flame to the bath were explored in great detail during the development of the HIs melt process [9, 10]. Substantial advantages over the post combustion by oxygen jets were demonstrated. The post combustion degree (PCD) of up to 70% and the heat transfer efficiency (HTE) of up to 85% have been achieved. By adding additional fossil fuel energy, the complete melting of the scrap has been achieved in a 10 t test converter.

Following very thorough tests in industrial conditions, some long-term industrial applications are planned in the next period.



*Figure 5: Size and volume comparison between Pebble-Heaters and classical stoves*

## APPLICATION WITH BLAST FURNACE

This new generation of Pebble-Heaters was developed mainly for applications in the steel and iron industry. As mentioned before, the most important application for big units is as a hot blast stove [11]. However, due to very high capacities, those facilities are very big and investment intensive, so that even longer operation experience is required before a first big unit will be erected. The installation of a Pebble-Heater facility brings about the following advantages in comparison to a classical stove system for the hot blast supply of a blast furnace:

### 1. Investment cost savings

Savings in investment costs through the installation of a complete facility for the hot blast supply are roughly 30% - 50% (strongly dependent on local conditions). The relative savings may be even higher in case an outdated stove has to be replaced, but the hot blast valves, mains and control and regulation may be taken over.

### 2. Energy cost savings due to higher efficiency

The thermal efficiency of a Pebble-Heater is higher than of most stoves. When an outdated stove has to be replaced, this could lead to an efficiency increase of even more than 20%.

### 3. Savings in operational costs due to higher wind temperature

The higher wind temperature allows for an additional substitution of coke by PCI (pulverized coal injection) and simultaneously reduces the total energy consumption of a blast furnace. The savings again strongly depend on the local conditions. An example of the coke consumption reduction and the reduction of energy costs (for the given local conditions) is given in Figure 6.

### 4. Increasing the oxygen concentration in the blast

The design of the Pebble-Heater and the application of high quality ceramic parts enable a further increase in the oxygen concentration in the blast. This leads to additional savings in operational costs.

The pilot facility of  $10.000 \text{ m}_{\text{STP}}^3/\text{h}$  (Figure 7) has been in operation since 1992. In several different test campaigns, it was in operation for more than 8.000 hours. It was designed for  $1.200^\circ\text{C}$  nominal hot blast temperature, but even  $1.350^\circ\text{C}$  have been achieved.

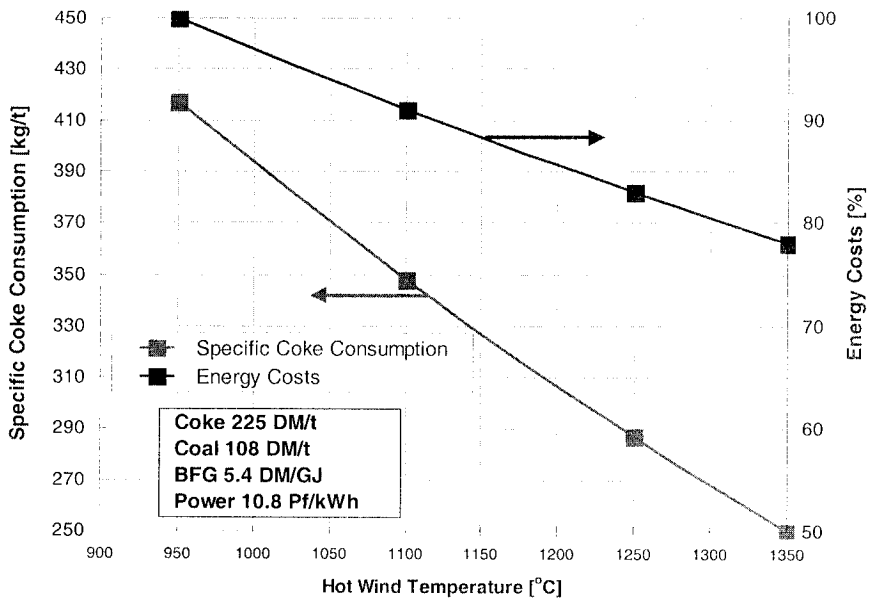


Figure 6: Effect of the blast temperature on the reduction of the coke consumption and energy costs

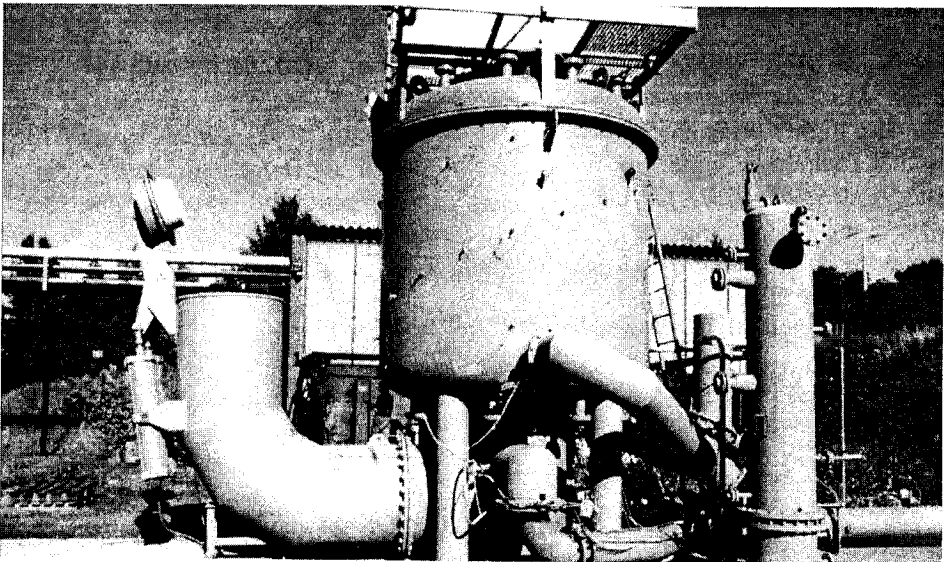
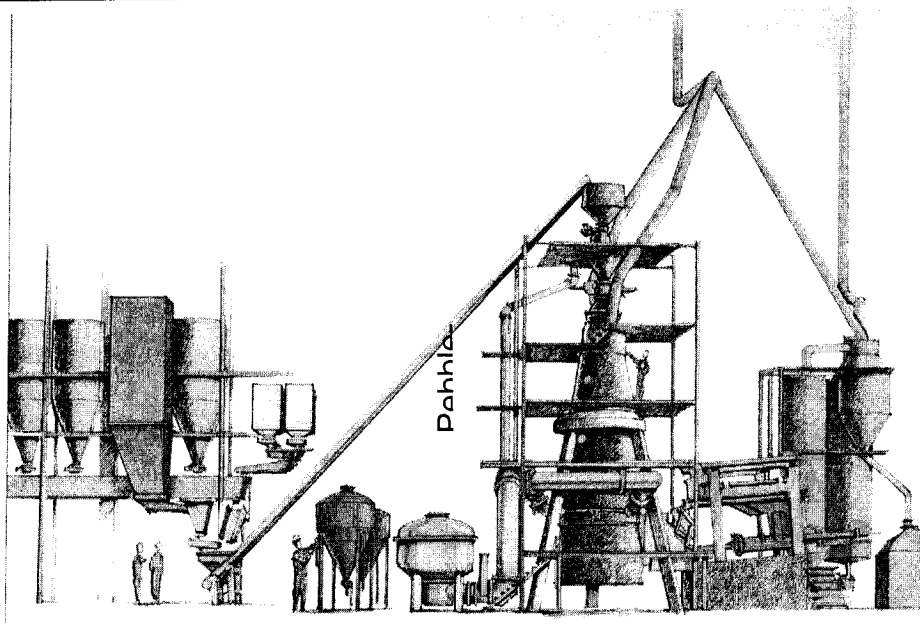


Figure 7: Pilot facility PH104 for  $10,000 \text{ m}_{\text{STP}}^3/\text{h}$  of hot blast at  $1,300^\circ\text{C}$



*Figure 8: Experimental blast furnace at MEFOS equipped with two Pebble-Heaters*

The experimental blast furnace at MEFOS (Luleå, Sweden) is equipped with two Pebble-Heaters. The furnace has the useful volume of  $8,4 \text{ m}^3$  and a hearth diameter of  $1,2 \text{ m}$ . As some tests with  $1300^\circ\text{C}$  mixed blast temperature were planned, the Pebble-Heater was designed for  $1400^\circ\text{C}$  hot blast outlet. That facility (sketched in Figure 8 – notice that dimensions are considerably smaller than those of the blast furnace itself!) has been in campaign operation since November 1997.

Those two facilities have accomplished some 20.000 operation hours (cumulative), so that a new, fully industrial facility for some  $40.000 \text{ m}_{\text{STP}}^3/\text{h}$  hot blast is planned.

### **APPLICATION WITH REGENERATIVE BURNERS**

A system of Pebble-Heaters may be used for regeneration of off-gas sensible heat and combustion air preheating, especially in diverse furnaces used in steel and iron industry, where the off-gas temperature lies mostly at above  $1000^\circ\text{C}$  [12]. The newly developed system consists of two parts: the Fluid Dynamical Valve (FDV) and two regenerators with radial flow direction, the Peb-

ble-Heaters (PH). Compared to the state-of-the-art systems described above, there are important advantages:

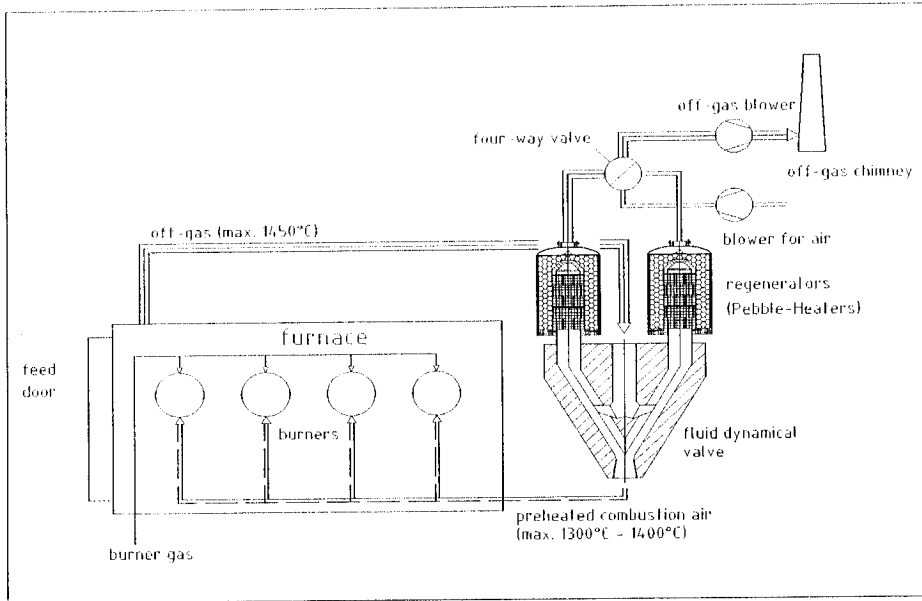
- The principle of the FDV is based on the interaction of velocity and pressure field in a flow [13]. If the layout of the flow channels is done appropriately, the two hot gases flow through the valve in different ways. By switching on the cold side, the pressure field is influenced in a way that the directions of the hot gas flows are changed. As it has no movable mechanical parts, no cooling is necessary and therefore the heat losses are very small. The operation temperature (up to 1400°C) depends only on the refractory material used. Since the FDV consists of a cast refractory part in a steel shell, the manufacturing costs are very low.

- Due to the radial flow direction, the heat transfer between the gas phase and the storage material in the PH is much more efficient than in regenerators with axial flow. Therefore the temperature difference between off-gas and combustion air is smaller and the heat recovery is higher.

Since the switching element (four-way valve, see the following Figure 9) is placed on the cold side, it is cheap and has a long working life, even when it is operated frequently. The short switching times allow a compact (and cheap) construction of the regenerators. The FDV as well as the PH enable a very high preheating of the combustion air. They have small energy losses and the investment costs are low.

With an attainable air preheating number above  $\varepsilon = 0.90$ , a value much higher than in other systems, the energy consumption can be lowered and the CO<sub>2</sub> emission reduced respectively. The new regenerative burner system allows the use of high velocity burners, because the exhaust gas is not evacuated through the burner heads. Together with an internal off-gas recirculation in the FDV, the NO<sub>x</sub> concentration can be reduced to a value below 200 mg/m<sub>STP</sub><sup>3</sup>. The position of the exhaust gas suction can be chosen in a way to optimise the circulation of the furnace atmosphere. The result is a more homogeneous temperature field and an increase in the furnace capacity.

Figure 9 shows the flow diagram of the whole regenerative burner system, including the furnace. A draft blower located on the cold side of the exhaust gas stream (in front of a chimney) evacuates hot exhaust (max 1450°C) from the furnace at an optimised position. The exhaust gas enters the FDV and due to pressure and velocity fields inside the valve, flows in the direction of one Pebble-Heater (left one in Figure 9). That PH is reheated, while off-gas is cooled down. The cold off-gas leaves the PH through the four-way valve and flows in the direction of the chimney, due to the action of the draft fan. Simultaneously, a cold air fan blows the cold ambient air through the same four-way valve in the direction of the second PH (right one in Figure 9). The air is preheated up to max. 1300–1400°C and led through the FDV in the direction of the burners.



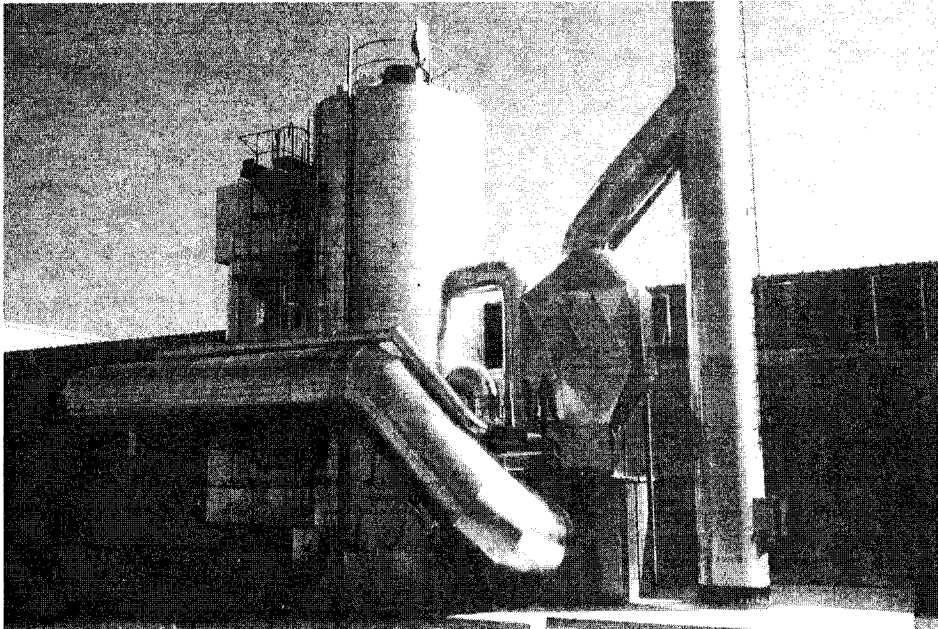
*Figure 9: New developed regenerative burner system*

By fast-changing the position of the four-way valve the conditions (pressure and velocity fields) inside the FDV are changed instantaneously. The off-gas flows then through the PH on the right side, while the air is preheated in the left one. That alternating change may be done very often, e.g. once per minute since the four-way valve is placed on the cold side of the system.

The tests on a facility with real high-temperature conditions have proved the results achieved by CFD simulations. The first long-term test campaign in real industrial conditions is to be started.

## APPLICATION FOR THERMAL OXIDIZERS

In general, the Pebble-Heater technology has achieved its widest industrial application as very effective equipment for off-gas cleaning through the thermal oxidation [14, 15]. The same type of Pebble-Heater is applied in the units of regenerative thermal oxidizers for thermal destruction of volatile organic compounds (VOC) and/or carbon-monoxide in different off-gases. Such units incorporate two big and one small Pebble-Heater in the same cylindrical casing. Regenerative thermal oxidizers are used for cleaning the exhaust gas of different industrial furnaces. They are demanded more and more as the environmental regulations become stricter. On the other hand, there is a steady effort to develop systems with lower investment and especially operational costs.



*Figure 10: Thermal oxidizer (30.000 m<sup>3</sup> STP/h) based on the Pebble-Heater technology*

The new Pebble-Heater technology with annular beds and radial fluid flows has been used as a basis for developing a system of a regenerative thermal oxidizer which can meet the market requirements. Theoretical studies and numerical simulations have shown that an extremely effective heat transfer at *Péclet* numbers around  $Pe=30$  in granular beds of natural materials/minerals (like quartz-gravels, volcanic stones or fire-clay) is possible. Temperature gradients of more than 20 K/cm have been realized, so that the required bed thickness may be as low as 35 cm. That also results in lower pressure drop. Those studies have shown that under optimized conditions the natural materials/minerals are much more effective than artificial forms (ceramic rings, saddles, honeycombs...) developed especially for heat regenerators. The price ratio between the two is more than 1:100, of course in favour of natural minerals.

The realized facilities have justified the expectations. A heat recovery degree of more than 98% (!) has been achieved, with a total pressure drop of about 18 mbar. The next best system on the market has at least 100% higher energy (gas/oil) consumption and about 50% higher fan power consumption. Some other characteristics of the new system have also shown important improvements for the process. The bigger volume of the hot chamber (reaction zone at 800°C) results in a longer residence time (1,5 - 1,7 seconds), so that the destruction of different pollutants (aldehyds, benzols, phenols...) and carbon-monoxide is more effective. The measured emission values are far beyond the limits set by



the regulation authorities. The realized facilities have capacities in the range of 1.000 - 45.000 m<sup>3</sup><sub>STP</sub>/h.

The first realized facility (see Figure 10) is in operation since August 1996. In the beginning, those facilities have been applied mainly in ceramic industry. Now, there is an increasing demand to apply them in the iron and steel industry, for cleaning the off-gases from foundries, electric arch furnaces, sinter plants, etc.

## CONCLUSION

Numerical simulations, as well as thorough experimental and industrial experiences have shown that the new developed Pebble-Heater with radial fluid flow is a very interesting technology for high-temperature applications. Very high heat recuperation efficiency, together with a simple and robust design makes it attractive mostly for metallurgical processes. Some applications are already proved in the long-term industrial operations, while the others are short before a wider market penetration. Steadily new application possibilities for diverse high temperature processes occur.

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