

# **PEBBLE-HEATER TWINS WITH FLUID DYNAMIC VALVE**

## **- an efficient possibility for high combustion air preheating -**

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### **ABSTRACT**

Pebble-Heaters (PH) with radial fluid flow are very effective regenerators for gas preheating at high temperatures. They can reach a regeneration efficiency of up to 98% and the temperature limit nowadays is around 1,400°C. The investment costs are pretty low, due to the usage of a bulk material (usually alumina pebbles) as the heat storage material. With those characteristics they are very attractive for combustion air preheating in the scope of a regenerative burner system. Their biggest disadvantage is that two units, with corresponding hot gas valves, are required for a continuous operation. For smaller capacities, i.e. less than 10,000 m<sub>STP</sub><sup>3</sup>/h, those hot gas valves are in fact the most expensive part of the equipment.

In order to overcome that disadvantage, the so-called Fluid Dynamic Valve (FDV) has been developed. That is a system of channels cast in high quality fire clay, which enables a very fast switching between two hot gas streams. As there are no movable mechanical parts, there is no need for any cooling, so the heat losses are minimal. The application temperature depends on the fire clay quality, so that 1,400°C are achievable. The production costs are extremely low, as all parts are cast in fire clay and enforced outside with a steel shell. The operation of a FDV is based on the interaction between the velocity field, pressure field and flow direction. With a convenient design of the channels it is possible to increase the velocity and to decrease the pressure (and vice versa) at the appropriate positions, so that two hot gas streams flow in different directions. Just by switching a four way valve on the cold side (i.e. after the PH regenerators) it is possible to influence the pressure distribution and correspondingly to change the flow directions of the hot streams.

That principle has been confirmed first by CFD modelling and afterwards by the tests on a pilot scale facility (2,000 m<sub>STP</sub><sup>3</sup>/h, 1000°C). The mixing ratio between two hot gas streams was as low as 2.8%. Moreover, it was very easy to control, so that values of up to 11.6% have been reached without any change of design. In case of a regenerative burner system that means that the off-gas recirculation may be achieved already on the hot side and it could be optimised concerning NO<sub>x</sub> suppression. An industrial project dealing with the application of that system at a steel annealing furnace is in progress.

### **Keywords:**

Air preheating, regenerative burner, heat recovery, regenerators, pebble-heater, fluid-dynamical valve, exhaust recirculation, CO<sub>2</sub> reduction, NO<sub>x</sub> reduction

### **INTRODUCTION**

Many of the conventional industrial furnaces, especially in metal and steel industries, exhaust the products of combustion at levels that are close to actual furnace temperatures (usually between 800°C and 1,400°C). Those products of combustion thus contain considerable sensible heat. One way to offset that energy loss and to increase the furnace efficiency is to preheat the combustion air by utilising the heat of waste gases. The first solution is to use heat recuperators. They may preheat the combustion air up to 600°C, which means that a considerable amount of sensible heat of

exhaust gases still is not used. For higher temperatures and higher furnace efficiencies, heat regenerators based on ceramic elements have to be used. Together with corresponding burners, they are known as regenerative burner systems.

There are several regenerative burner systems on the market. They all have specific pros and cons as well as fields of application. For many applications, a central regenerator is the optimum solution. The number of burners, as well as the burner type are arbitrary, because they are not associated with a regenerator. In that case, even the use of high velocity burners is possible. The exhaust gas can be taken out from the furnace from a place where it is technologically favourable for the process. That enables a better heat transfer, a homogeneous temperature distribution and an increase in capacity. The main problem with the central regenerator is the switching between combustion air and exhaust gas. The solution with two hot blast valves is very costly and energetically not attractive. The water cooling system, necessary for the valves, leads to heat losses of the combustion air and therefore has a negative impact on the total thermal efficiency. A frequent switching between the regenerators reduces the working life of the valves. For that reason the regenerators have to be made very big, what makes such a solution expensive.

One special solution uses a regenerator with rotating bed (*Jasper, 1998*). Due to the sensitivity of the construction the operating temperatures are limited to approx. 1,000°C for the combustion air and to approx. 1,200°C for the exhaust. Therefore this solution is only applicable at furnaces with working temperatures below 1,250°C. Due to the low combustion air temperature only a part of the energy can be saved (heat recovery approx. 80%) and the pay-back period is not very short.

There are two further state-of-the-art regenerative burner systems: the classic regenerative burner design (with integrated regenerator) and the flameless regenerative burner (FLOX). Both systems are not a real alternative to the solution with central regenerators, because two important qualities are missing:

- the optimum place for the off-gas suction cannot be chosen independently of the position of the burner heads
- there is no possibility to use a different type of burner (e.g. a high velocity burner)

A classic regenerative burner system consists of two regenerators with two attached burner heads (*Rich, 1989; Dormire, 2000*). During the heating-up of one regenerator the off-gas is evacuated by the draft fan through the (not operating) burner head, while the second burner is in action. For that reason the system needs the twofold number of burner heads. Because of the small cross section of the burner head, only 85% of the off-gas can be sucked through the regenerator; 15% leave the furnace directly through the chimney. For that reason the total heat recovery efficiency reaches values not higher than 72%.

The so-called FLOX-burners have the advantage of a very low NO<sub>x</sub> emission (*Wünnig & Wünnig, 1996*). Their small ceramic heat storing elements can easily be blocked by dust. Therefore their application is limited to exhaust gases with low dust contents. A further disadvantage is that FLOX-burners have no high-velocity flame. Usually the heat recovery is approx. 65%.

## INNOVATIVE FEATURES OF THE DEVELOPED SYSTEM

The newly developed system consists of two parts: the Fluid Dynamical Valve (FDV) and two regenerators with radial flow direction, the Pebble-Heaters (PH). Compared to the 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. 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 1,400°C) only depends on the refractory material used. Since the FDV consists of a cast refractory part in a steel shell, the manufacturing costs are very low.

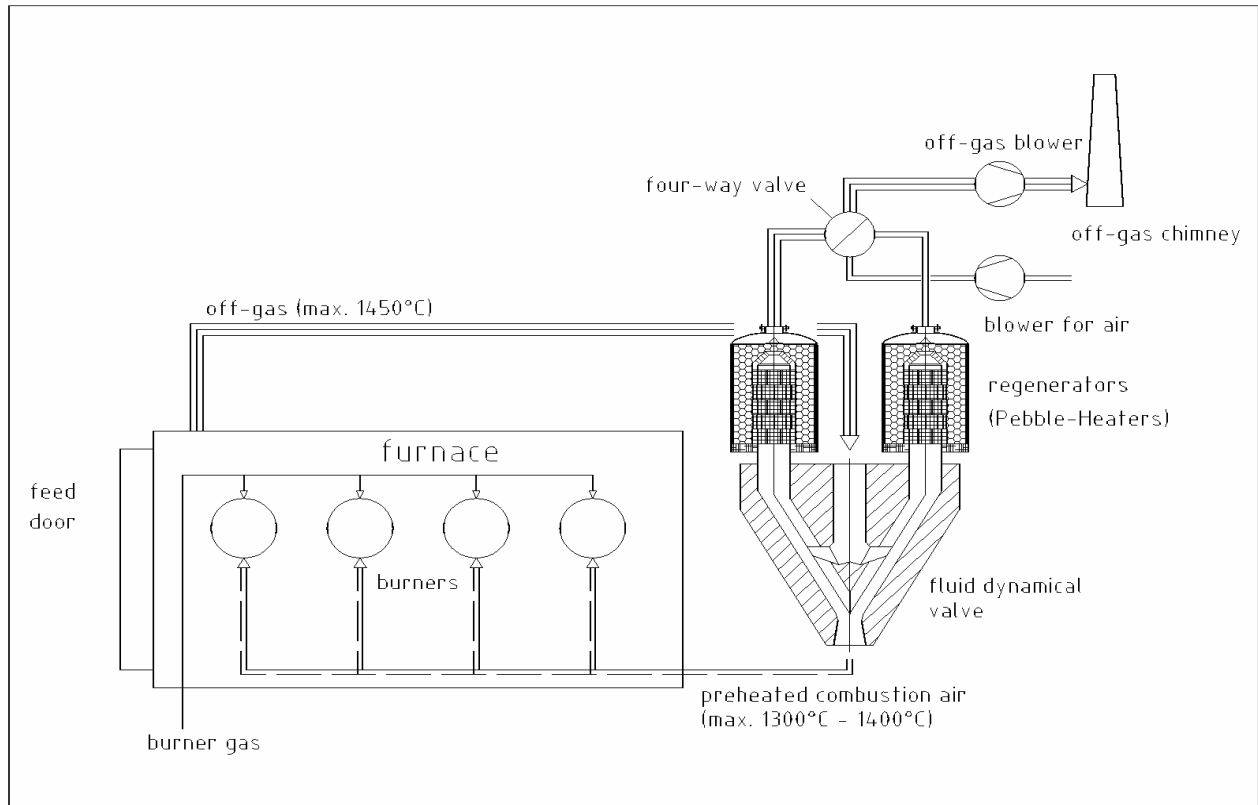
- Due to the radial flow direction, the heat transfer between the gas phase and the storage material in the PH is much more efficient than in regenerators with axial flow. Therefore the temperature difference between off-gas and combustion air is smaller and the heat recovery is better. As the high temperature zone is screened by the storage material (pebble bed), the PH does not need to be insulated on the outer surface. The energy and exergy losses are minimal.

Since the switching element (four-way valve, see the following *Figure 1*) 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  $\epsilon = 0.90$ , a value much higher than in other systems, the energy consumption can be lowered and the CO<sub>2</sub> emission can be reduced respectively. The new regenerative burner system allows using 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 1* 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 (before a chimney) evacuates hot exhaust (max 1,450°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 1*). 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 1*). The air is preheated up to max. 1,300–1,400°C and led through the FDV in the direction of the burners.

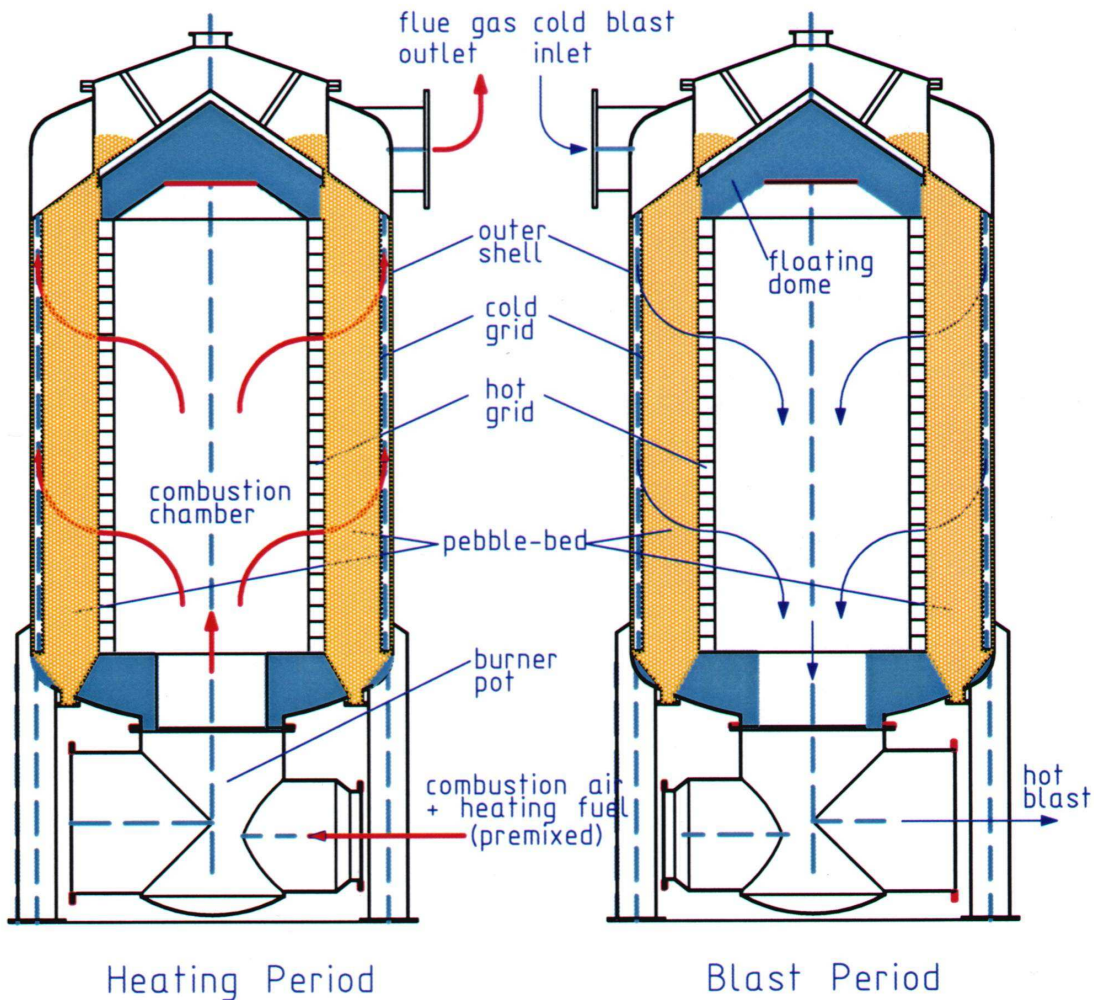


**Figure 1** New developed regenerative burner system

By fast-changing the position of the four-way valve the conditions (pressure and velocity fields) inside the FDV are changed instantaneously. Then the off-gas flows 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 as the four-way valve is placed on the cold side of the system.

### PEBBLE-HEATER (PH)

At ATZ-EVUS the new concept of a regenerator, the so-called Pebble-Heater, has been developed (Fassbinder, 1996). The main difference lies in the flow direction: gas flows radially through the pebble-bed, which is fixed between two coaxial cylindrical grids (Figure 2). The inner grid, the so-called hot grid, is made of porous ceramic bricks. The outer grid, referred to as cold grid, is made of a gas permeable steel construction (e.g. perforated steel plate). All other extraordinary characteristics result from that at first sight small difference. 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. That results in a high recuperation efficiency, as defined in Stevanovic, 2001 (units with more than 98% are in operation) and a temperature gradient in the range of 1500 – 2000 K/m. The pebble-bed does not have to be thick in radial direction, so that the pressure drop is also low. In the end, that leads to a very compact unit at low investment costs. That new technology has been developed primarily to substitute the technology of hot wind stoves (Cowpers) for supplying blast stoves with hot blast (Brotzmann & Stevanovic, 1998). Another very successful application is in the field of off-gas cleaning through thermal oxidizers (Stevanovic & Fassbinder, 2000; Stevanovic et al., 2001).



**Figure 2** Pebble-Heater with radial fluid flow

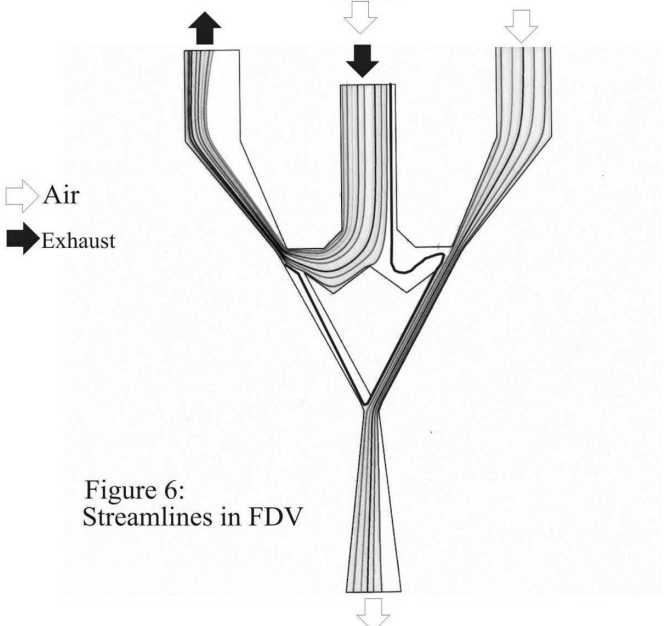
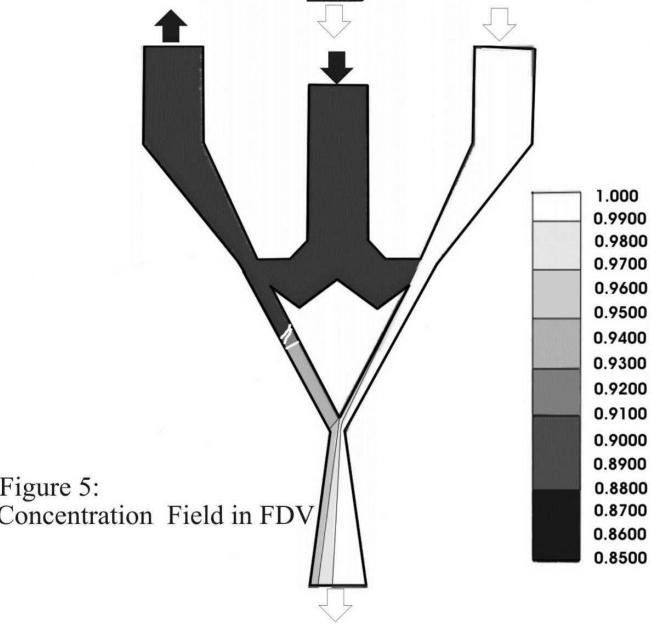
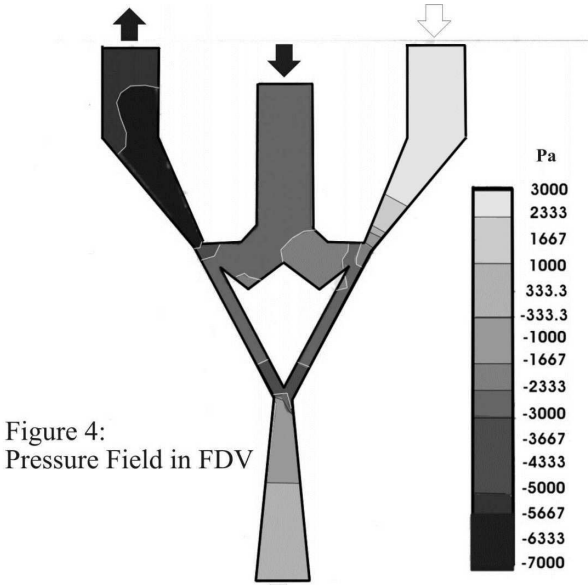
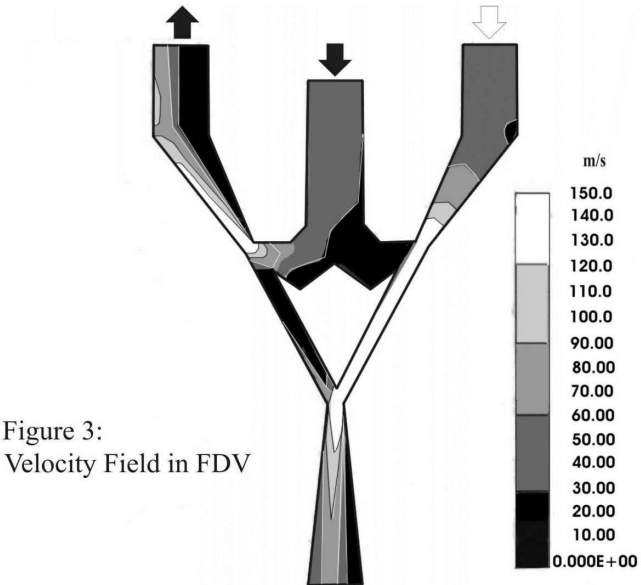
### FLUID-DYNAMIC VALVE (FDV)

The usage of a FDV makes it possible to achieve a rapid switching between two hot gas streams (above 1,000°C) without movable mechanical parts (*Fassbinder & Stevanovic, 1999*). The principle is based upon the interaction between the velocity and pressure field in a fluid duct. With a suitable design of the flow ducts it is possible to increase the velocity and to decrease the pressure (and vice versa) at certain positions, so that two hot gas streams flow in different directions, without considerable mixing. By switching just one four-way valve on the cold side (e.g. after a regenerator) it is possible to influence the pressure field in the FDV in a way that the flow directions are suddenly changed. Such equipment operates faster and more reliably (without movable mechanical parts) and is simpler and cheaper to manufacture than a conventional one. It can operate even in cases when the pressure levels of two gas streams deviate from each other (up to about 100 mbar).

The plausibility of that principle has first been demonstrated through 2D and 3D numerical simulations. With a commercial CFD code the proposed duct geometry and flow conditions have been modelled. Resulting fields of velocity, pressure and concentration, as well as streamlines, are presented in *Figures 3, 4, 5 and 6*, respectively. In all cases the exhaust enters through the central

pipe on the top, turns left and leaves through the left pipe (direction PH in heating phase). The preheated air (coming from the second PH) enters through the pipe on the right side and flows downwards, leaving the FDV through the lower central pipe.

Figure 3 shows that the preheated air velocity rises from the entrance value of 40 m/s to over 140 m/s after the contraction. The last part of the preheated air duct (outlet) is designed as a diffuser. Thus the velocity drops again to less than 60 m/s. Figure 4 shows that a pressure difference of 60 mbar exists between the entrance of preheated air (+3,000 Pa) and the entrance of hot exhaust (-3,000 Pa). However, due to a velocity increase through the contraction, the relative pressure of preheated air drops toward -3,000 Pa, so that at a position where there is a contact to the space of the exhaust, the pressure difference between the two practically disappears. Afterwards, the pressure of preheated air rises again in the diffuser, but due to the irreversible pressure drop it just reaches +300 Pa.



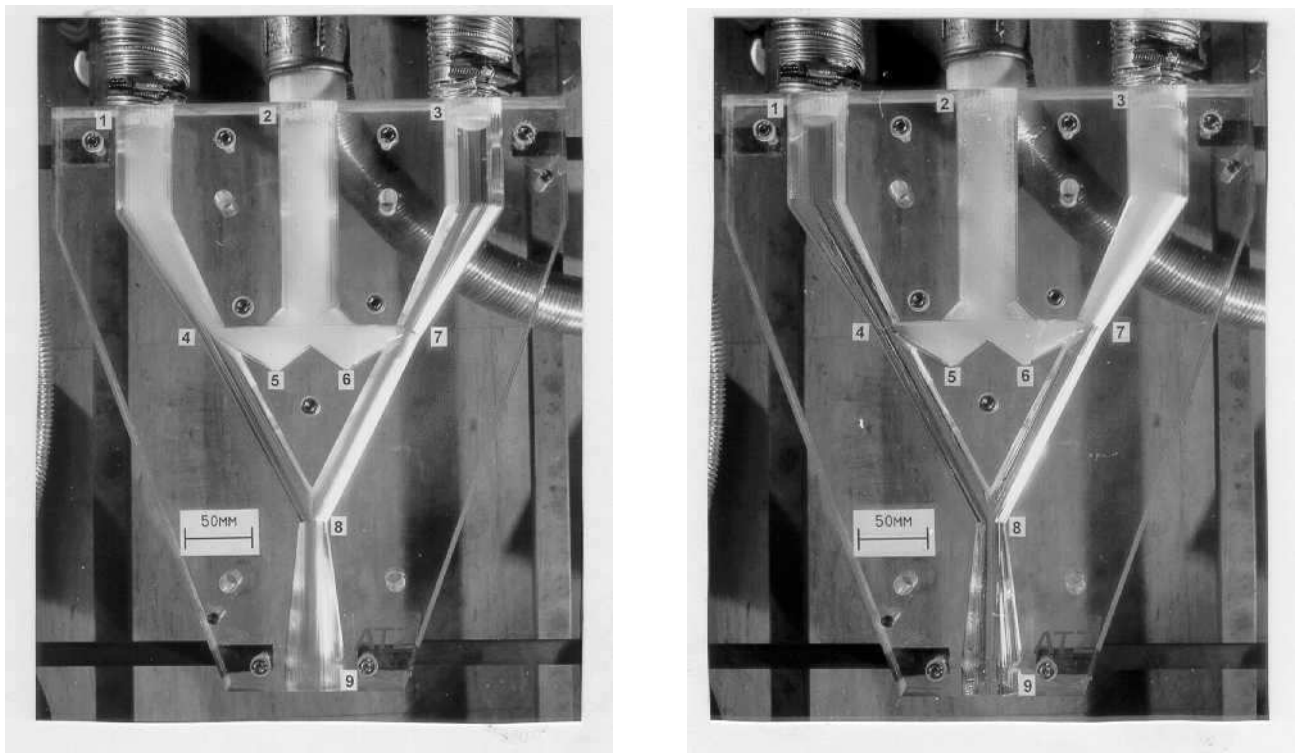
Despite a fairly high pressure difference between the two hot gas streams at the entrance, the mixing between them is minor, due to the increase in velocity and pressure decrease in the preheated air at the potential mixing zone (end of contraction). *Figure 5* shows the air concentration field inside the FDV. At the entrance of the preheated air it is composed of 100 % air. At the outlet it is 98.3 % air (mean value) and 1.7 % exhaust. From *Figure 6*, which presents the streamlines through the FDV, it is again clear that the mixing is very slight. Just one streamline of exhaust overflows to the preheated air duct, but afterwards, before the diffusor, it flows back to the duct of exhaust gas.

The second demonstration of the FDV principle was done in a cold model made of plexiglass. As presented in *Figure 7*, the “exhaust” (air mixed with disco-fog) entered the FDV always through the same central pipe at the top. The pure cold air ( 100 m<sup>3</sup><sub>STP</sub>/h) entered through the pipe on the right or on the left, depending on the position of the four-way valve. Respectively, “exhaust” was evacuated through the pipe on the left, or on the right. Visually it was not possible to notice any mixing between the two gas streams.

The same plexiglass model has been used to precisely measure the mixing ratio, defined as the ratio between the volumetric (STP conditions) flow-rates of the exhaust gas contained in the outlet hot air ( $V_{exh/ha}$ ) and the total hot air flow ( $V_{ha}$ ):

$$Mix = \frac{V_{exh/ha}}{V_{ha}}$$

Air and nitrogen have been used for that. By measuring the oxygen concentration at the “hot air” outlet, the mixing ratio was estimated. After some small changes in the geometry, the preceding mixing ratio of 13% has easily been reduced to 5.5%.



a) air on the right side

b) air on the left side

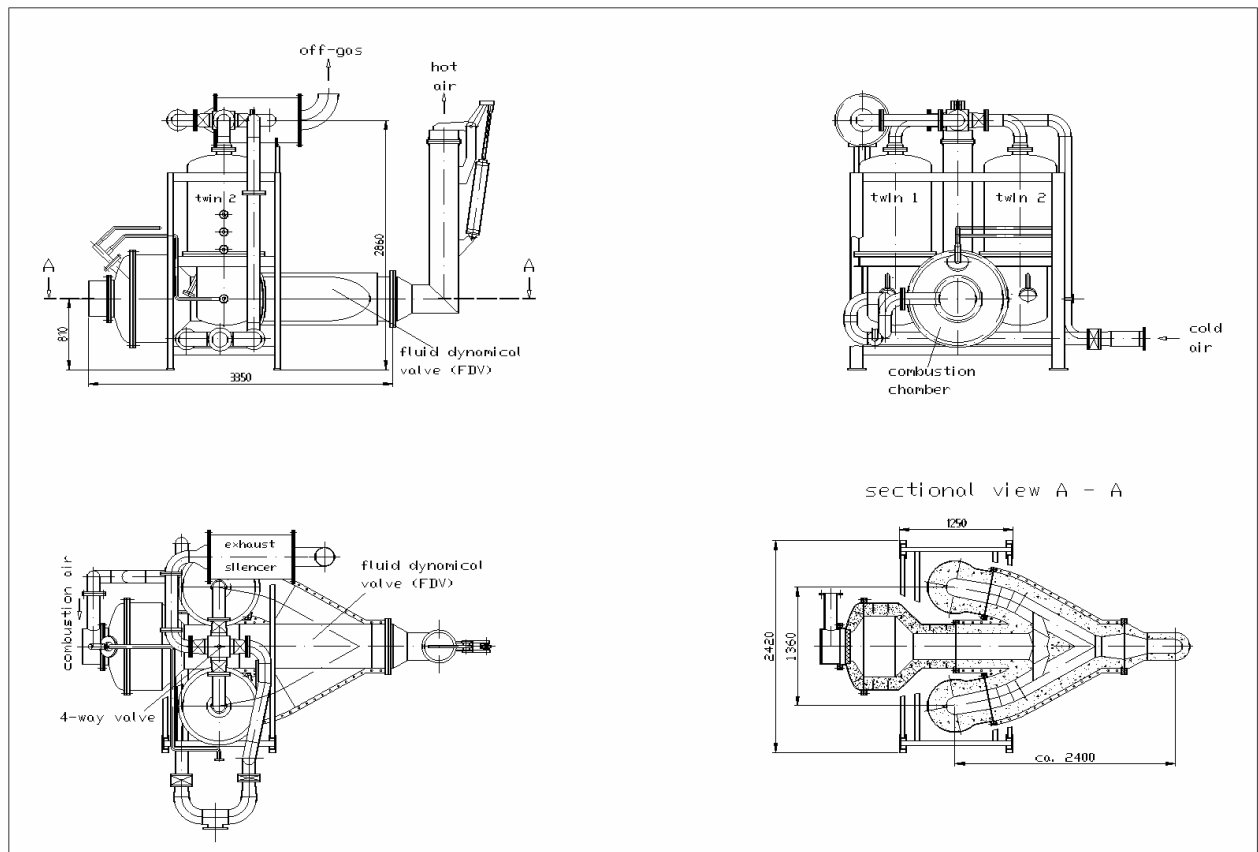
**Figure 7** Cold FDV model made of plexiglass (“exhaust” enters through the central pipe on the top)

## TEST FACILITY

The final demonstration of the plausibility of the FDV connected with PHs was carried out at a high temperature test facility (nominal  $2,000 \text{ m}^3_{\text{STP}}/\text{h}$ ,  $1,000^\circ\text{C}$ ). As shown in *Figure 8*, the facility was not connected with a furnace, but with a separate combustion chamber. The preheated air was just blown into the atmosphere. The combustion and preheating air were supplied from a compressed air pipe ( $1 \text{ bar}_g$ ), but before usage the pressure was reduced to about ambient level. In several tests, the flow rate of the preheated air was in the range  $1,400\text{--}2,100 \text{ m}^3_{\text{STP}}/\text{h}$ , at temperatures between  $830^\circ\text{C}\text{--}1,030^\circ\text{C}$ .

Here, the mixing ratio was estimated by measuring the  $\text{CO}_2$  concentrations in hot air ( $^{ha}$ ), atmosphere ( $^{atm}$ ) and exhaust gas ( $^{exh}$ ). According to the balance of  $\text{CO}_2$  it is possible to deduce the mixing ratio as:

$$Mix = \frac{CO_2^{ha} - CO_2^{atm}}{CO_2^{exh} - CO_2^{atm}}$$



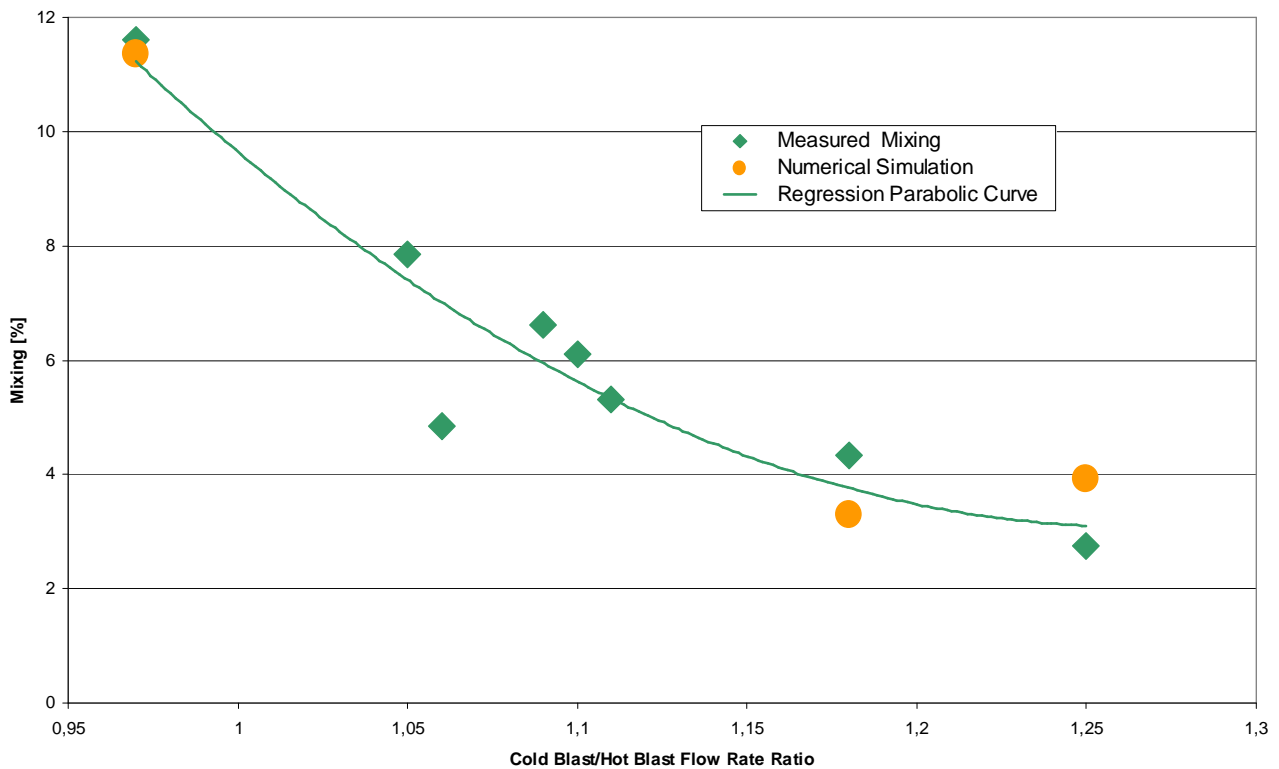
**Figure 8** High temperature test facility (nominal  $2,000 \text{ m}^3_{\text{STP}}/\text{h}$ ,  $1,000^\circ\text{C}$ )

The tests have shown that the mixing ratio may easily be adjusted (without changing the geometry) by changing the ratio between the flow rate of cold air and hot (i.e. preheated) air. Normally it is 1, but with regulation valves it is possible to force it to be higher or lower than 1. When it is higher than 1, the flow rate of air is constant up to the FDV, but then some amount is forced to overflow towards the exhaust, so that the flow of preheated air at the outlet is reduced. In that case it is possible to further reduce the mixing. That is of interest when industrial gas has to be preheated and its purity has to be preserved. On the other hand, it is possible to increase the mixing by reducing



the ratio between the flow rate of cold air and hot air to below 1. In that case, some amount of exhaust is forced to overflow to hot air. That may be used as some kind of in-situ or internal recirculation of exhaust, which may be of interest for regenerative burner systems for the control of  $\text{NO}_x$  emissions. *Figure 9* shows that during the tests a mixing ratio between 2.8 and 11.6 % was achieved. The points presented by circles were obtained by CFD concentration modelling and are in good agreement with measured values.

The overall thermal efficiency was around 70% during those tests. However, the exhaust gas losses were low (max. 12%), what means that the efficiency of the PH system was over 88%. The wall heat losses of the FDV were predominant. The reason lies in the low quality and insufficient thickness of the insulation used for that test facility. The intention was not to prove the high thermal efficiency (it is known that for PH systems it lies usually between 92% and 98%, see *Brotzmann & Stevanović 1998, Stevanović & Fassbinder 2000, Stevanović & al. 2001*), but the effectiveness of the FDV as a hot gas valve. In the industrial applications much better insulation will be used in aim to reach the overall efficiency of at least 85%, probably even above 90%.



**Figure 9** *Mixing as a function of the cold air/hot air flow ratio*

## FUTURE ACTIVITIES

Some of the advantages have already been demonstrated by the measurements on the test facility. The others will still have to be demonstrated by the operation at a real industrial furnace. That will be the subject of a new EU project, with several international partners, which will start soon. The system will be tested in operation at several furnaces in a steel industry.

Further, a very high preheating temperature (up to 1,400°C) makes this system interesting for the recent developments regarding ultra-low-NO<sub>x</sub> burners with direct fuel injection into the high temperature furnace atmosphere.

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