A pilot plant technical assessment of an advanced in-duct desulphurisation process

F.J. Gutiérrez Ortiz*, Pedro Ollero

*Departamento de Ingeniería Química y Ambiental, Universidad de Sevilla,
Camino de los Descubrimientos s/n, 41092 Seville, Spain*

Abstract

In-duct sorbent injection (DSI) is a well-known, low-cost desulphurisation technology handicapped by its moderate SO_2 removal capacity. Fortunately, there are some technical options for increasing the desulphurisation efficiency without eliminating its inherent advantages. In this experimental study, several improvement design options like the recirculation of reactivated sorbent, the pre-collection of the fly ash and the use of seawater for humidification have been analysed using an extensive parametric testing programme. The effect of the main operating variables directly related to the desulphurisation efficiency has been also tested following a fractional factorial design. These variables were the Ca/S ratio, the approach to the adiabatic saturation temperature and the recirculation ratio of the partially converted sorbent. Other important questions like the use of a high-BET-area lime and the impact of the DSI process on an ESP have been also included in this experimental assessment.

More than 50 experimental tests were carried out in a 3-MWe equivalent pilot plant to assess the different improvement options for in-duct sorbent injection. The results of this study allow us to extract practical conclusions about the devices, equipment and operating conditions as a function of the target SO_2 efficiency, and even enable us to provide an economic assessment. Using the proposed improvement options to process a flue gas with 400–1000 ppm of SO_2 concentration, a 90% sulphur removal with a lime utilisation of 45% was achieved. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Desulphurisation; Sorbent injection; Pilot plant; $Ca(OH)_2$; SO_2

1. Background

The in-duct desulphurisation process involves the injection of a dry sorbent, typically hydrated lime, in conjunction with flue gas humidification achieved by spraying water

---

* Corresponding author. Tel.: +34-95-448-72-60/61/65/68; fax: +34-95-446-17-75.
E-mail addresses: fjgo@esi.us.es (F.J. Gutiérrez Ortiz), ollero@esi.us.es (P. Ollero).

into the ductwork downstream from the air preheater, but upstream from the particulate collection equipment. The main reaction binding SO_2 is a simple acid–base reaction

$$SO_2 + Ca(OH)_2 \rightarrow CaSO_3 \cdot \tfrac{1}{2}H_2O + \tfrac{1}{2}H_2O$$
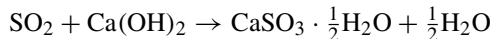
The operating parameters of this simple DSI process are the Ca/S ratio and the approach to the adiabatic saturation temperature. Increasing the Ca/S ratio leads to higher SO_2 removal yields but at the expense of lower sorbent utilisation. On the other hand, decreasing the approach to saturation temperature has a strong positive effect on the SO_2 removal efficiency and sorbent utilisation. However, there is a minimum practical approach temperature of around 8–10°C due to the growing risk of solid deposits on the duct walls and on the internal parts of the process equipment and also due to the corrosion of the material.

The advantages of the DSI process in its simplest form are: low capital cost and low energy consumption; extremely simple installation; low space requirements; short construction time and no wastewater treatment plant. These advantages are offset by several drawbacks that strongly limit the commercial application of the process:

- the removal efficiency of the simple DSI process is in the range of 40–50% at Ca/S ratios of 1–2 and an 11–14°C approach to the saturation;
- the sorbent utilisation is quite low ($<35\%$), which means high lime consumption and a high lime content in the solid waste;
- the fly ash which has a consolidated market is eliminated along with the desulphurisation products and the unreacted lime;
- the total amount of solid waste to be managed and disposed of is high;
- there is a clear risk of solid deposits and accumulation inside the ductwork;
- the particulate emissions from the ESP may increase due to the higher concentration of particulate matter entering the collector.

There are different DSI technologies based on three basic process alternatives — slurry injection and dry sorbent injection upstream/downstream from the spray humidification. Besides these general process alternatives, there are still a number of improvement options (Fig. 1) to be considered in a commercial application of DSI technology:

- the use of two particulate collectors — one to capture the fly ash upstream from the sorbent injection location and the other to collect the solid product — makes it possible to separate the collection of saleable fly ash, reduces the amount of final solid disposal and reduces the recirculation, if any, of the spent sorbent;
- the recirculation of the unreacted sorbent improves sorbent utilisation by providing multiple exposure of the sorbent to the flue gas;
- the reactivation of the recycling sorbent by means of grinding and/or humidification may have a strong positive effect on the reactivity of the remaining lime;
- the use of specially-prepared high-surface-area lime and lime compounds like calcium silicate may enhance the reactivity of the sorbent;
- the use of hygroscopic additives such as NaOH, Na_2CO_3 and $CaCl_2$ may be effective in improving SO_2 removal performance. For coastal power stations, an inexpensive means of supplying these types of additives is to use seawater as humidification water.
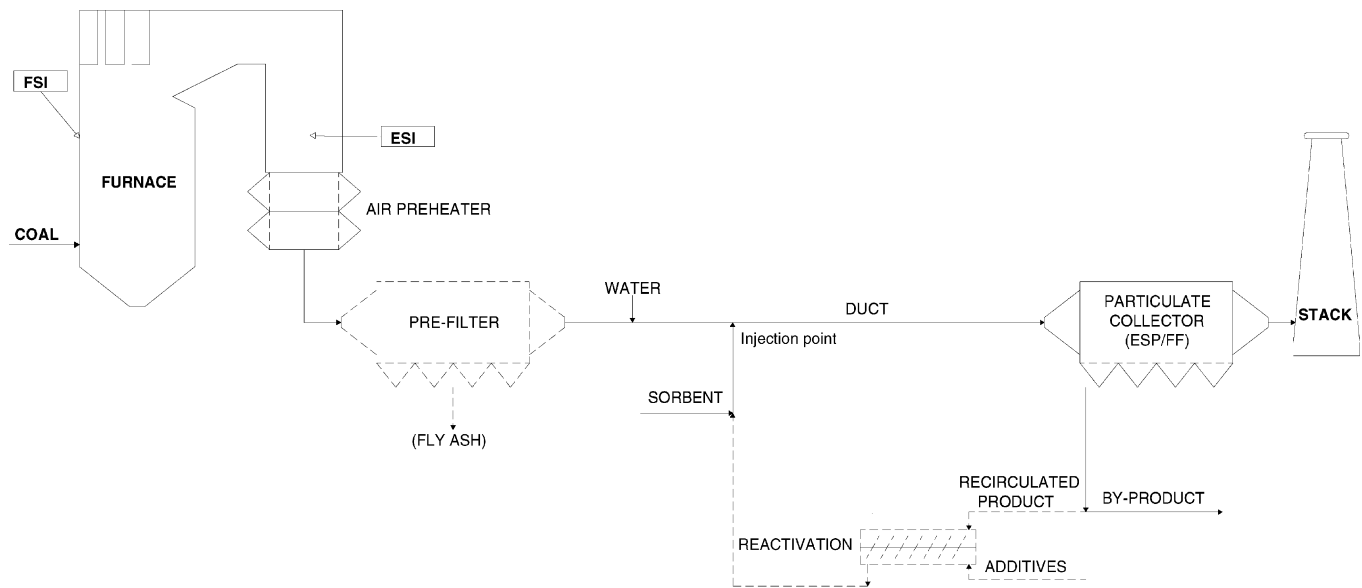
Fig. 1. Flow diagram of the DSI process — parts encircled by broken lines are optional.

2. Literature and technology overview

So far, in-duct sorbent injection technology has been actively developed, mainly in the US, since the mid-1980s. These development efforts include pilot-scale tests, proof-of-concept tests and a few full-scale utility demonstrations. A number of in-duct desulphurisation processes based on calcium hydroxide sorbents have been proposed; some of them are on the market, while others are in different stages of development.

The confined zone dispersion (CZD) process (Pennline and Tice [1]; Battista et al. [2]) uses slurry to inject lime into the ductwork. A 73.5 MWe demonstration was conducted in a US coal-fired boiler, achieving 50% SO_2 removal efficiency at flue gas temperatures of 149–154°C and Ca/S ratios of 2–2.5. According to these data, the sorbent utilisation is less than 25%.

In the 'HALT' process (Babu et al. [3]), the sorbent is injected downstream from the water spray after droplet evaporation. Results obtained in a 5 MWe 'halt' pilot unit show a sulphur dioxide removal efficiency of 52.9% at an average Ca/S ratio of 2.05 and 11°C approach to saturation temperature. Thus, the sorbent utilisation is also quite low (<26%).

The 'Coolside' process (Stouffer et al. [4]) involves the injection of calcium hydrate as a dry powder upstream from the water spray. This technology has been demonstrated in a 105 MWe coal-fired power station. The tests showed SO_2 removals of 70% at a Ca/S molar ratio of 2 and an 11°C approach to adiabatic saturation temperature. However, the sorbent activity in these tests was enhanced by dissolving sodium hydroxide or sodium carbonate in the humidification water up to a Na/Ca ratio of 0.2. Thus, this process achieves a sorbent utilisation of around 35% but it requires the consumption of an expensive sodium compound.

The 'Advanced Coolside' process (Withum et al. [5]) is a significant step toward the achievement of the high performances needed to satisfy existing and coming environmental regulations. This technology has demonstrated SO_2 removals and sorbent utilisations exceeding 90 and 60%, respectively, at a fairly small (0.3 MWe) pilot plant. This process operates at higher flue gas humidity and more fully exploits the potential of sorbent recycling than the previously described processes. The key to this developing technology is a gas/liquid contacting device, downstream from the air preheater, that serves two purposes: to remove most of the coal fly ash from the flue gas and to nearly saturate the flue gas with water.

In the ARA process (Khinast et al. [6], Khinast [7]), the SO_2 removal takes place in two stages. Limestone is injected into the coal boiler where only 40–50% of desulphurisation is achieved at Ca/S ratios between 3 and 4. The unreacted CaO is collected in a cyclon and reactivated with steam in a fluidised bed reactor. The reactivated sorbent, mainly $Ca(OH)_2$, is reinjected into the gas duct upstream from the cyclone. The claimed advantages of the ARA process are removal efficiencies of more than 90%, low operating costs due to the use of limestone instead of lime and that there are not wet parts that may cause corrosion because the required relative humidities are quite low (30–50%).

Recently, Sorbent Industries Corporation (USA) (Nalbandian [8]) demonstrated the feasibility of achieving ≥80% SO_2 removal in dry, duct sorbent injection with the use of "fluesorbents" which are granular solids with a large internal surface area coated with hydrated lime. A pilot plant (2 MWe) was constructed to demonstrate this technology and

achieved relative success. In this plant, a new hybrid collector (based on a baghouse) was integrated.

The new integrated desulphurisation process (NID) (Nalbandian [8]), developed by ABB, integrates the flue gas cooling and the SO_2 removal by means of sorbent injection into the functions of a fabric filter system. In a ductwork system designed specifically for the NID process, at the Laziska Power Station in Poland, high SO_2 removals were obtained.

3. The pilot plant

The pilot plant (Figs. 2 and 3) is located in southern Spain at the Los Barrios Power Plant and was built over an existing desulphurisation pilot plant constructed for two past semi-dry desulphurisation projects (Ollero et al. [9] and Gutiérrez et al. [10]). The power plant has one 550 MWe unit and burns Colombian and South African coal with a sulphur content of less than 0.7%. The pilot plant is made up of three integrated main units: a spray dryer designed by ABB-Fläkt, a circulating fluidised bed of our own design, and an electrostatic precipitator also of our own design. There is a long gas duct upstream from the precipitator to provide enough residence time for in-duct desulphurisation (Table 1). A set of butterfly valves allows us to assemble these main units in different ways to emulate several semi-dry desulphurisation processes. This multipurpose pilot plant can process up to 12,000 N m^3/h of flue gases which are withdrawn upstream and/or downstream from the power plant precipitator at 130–150°C. This allows us to mix flue gases with or without fly ash in any proportion, thus simulating the performance of an ash pre-collector located upstream from the desulphurisation unit. There is also an SO_2 injection unit to increase the SO_2 gas concentration from 350 to 3000 ppm. The pilot plant is fully instrumented with wet and dry temperature sensors, flow rate and pressure measurement devices, and an SO_2 analyser

Table 1
Technical characteristics of the pilot plant units used in this work

Duct sorbent injection	
Diameter (m)	0.44
Length (m)	50.00
Pugmill volume (m^3)	0.10
Lime conveyor (kg/h)	140
Solid recirculation rate (kg/h)	2600
Water flow rate (kg/h)	700
SO_2 injection (kg/h)	22
Electrostatic precipitator	
Number of electrical fields	3
Effective height (m)	2.2
Effective length (m)	2.0
Plate spacing (mm)	300
SCA (s/m)	20
Peak voltage (kV)	120
Maximum effective voltage (kV)	78
Maximum effective intensity (mA)	42
Gas velocity (m/s)	0.8–1.8

Fig. 2. View of the Los Barrios pilot plant.

with three measuring probes located at the pilot plant inlet, after the desulphurisation units and downstream from the electrostatic precipitator at the pilot plant outlet. The signals from these sensors are processed in a data acquisition system using SCADA software.

The sorbent injection process tested in our pilot plant is as follows. The flue gas at 140–150°C is first humidified by spraying it with water to reduce its dry temperature to 10–15°C above the adiabatic saturation temperature. The sorbent, actually a mixture of fresh lime and recirculated product which may be humidified with liquid water, is injected downstream from the humidification chamber into the very humid flue gas. In this way, the slaked lime is very reactive for SO_2 capture, and high efficiencies are possible. The SO_2
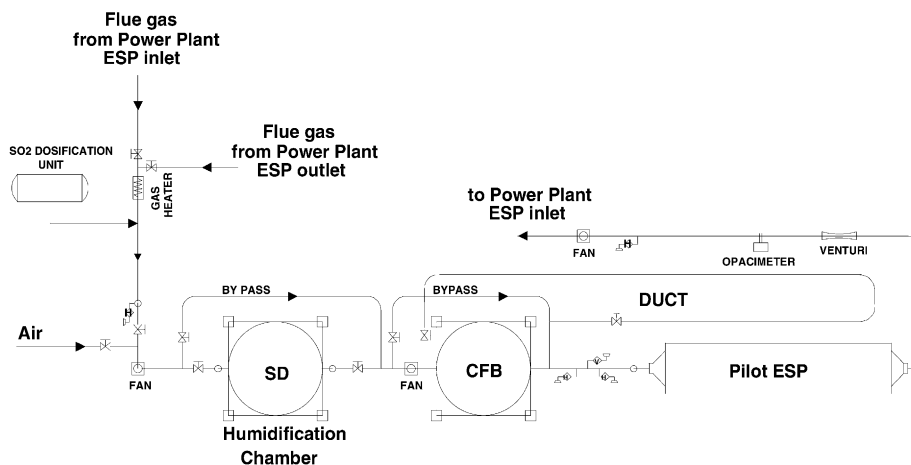
Fig. 3. Pilot plant flowsheet.

is removed in the duct but also in the ESP, which contributes significantly to the global yield thanks to the long gas residence time and the presence of unconverted lime. The dust collected in the ESP is conveyed to the product hopper by means of a pneumatic device. Both the fresh lime and product hoppers discharge through rotary valves into an air slide where both products are mixed. The air slide in turn discharges the mixture into a pugmill, where it is eventually sprayed with water.

4. Experimental results

The experimental programme was designed to evaluate the performance of the process with respect to the main operating variables: Ca/S ratio, approach to adiabatic saturation temperature (AST), SO_2 flue gas concentration (SO_2) and flue gas flow rate (FR), as well as the use of the improvement options.

The assessment was performed by conducting 58 large-scale experiments with two nominal levels of SO_2 concentration (400 and 1000 ppm), two different Ca/S ratios (1.5 and 2.0), two approach temperatures (10 and 15°C), two gas flow rates (6000 and 10,000 N m³/h), with ($Z \approx 0$ g/dN m³) and without ash pre-collection ($Z \approx 7$ g/dN m³), two different recirculation ratios (RR = 0 and 10), and with ($W = 5\%$) and without water added to the pugmill. Besides these, several additional tests were done using seawater for product humidification and high-BET-area lime.

Tables 2–4 contain the entire set of experimental results. The values of the operating variables included in these tables are the current ones, which were slightly different from the nominal values established in the experimental design. Both the efficiency figures and the operating data represent average measured values during periods of stable operation.

The effect of the main operating parameters, AST and the Ca/S ratio, is well known and will not be extensively analysed in this paper. Fig. 4 shows clearly the positive effects of

Table 2
First group of tests (without recirculation)

Ash pre-collection	Gas FR (N m³/h)	SO₂ (ppm)	Ca/S (mol/mol)	AST (°C)	Efficiency (duct) (%)	Efficiency (duct + ESP) (%)
No	9992	400	1.905	10.8	17.61	25.21
No	9080	400	1.85	13.7	9.74	16.45
No	9465	400	2.3	9.7	28.00	35.05
No	10628	400	1.88	13.4	10.22	18.88
No	6120	400	1.58	9.4	15.88	21.68
Yes	6060	400	1.64	9.3	29.80	35.36
No	6132	400	1.51	12.9	8.00	13.52
Yes	6147	400	1.91	13.7	13.75	29.90
No	5999	400	2.00	10.0	19.98	33.75
Yes	6102	400	2.26	10.0	38.09	44.18
No	6333	400	2.00	12.8	11.58	17.36
Yes	6122	400	2.25	13.7	21.54	32.10
Yes	8394	400	2.14	13.7	19.14	–
Yes	8394	400	2.14	8.3	–	29.19
Yes	8176	400	2.23	8.3	21.47	34.72
Yes	8044	400	1.48	8.3	22.83	31.06
Yes	8202	400	1.26	13.7	13.20	17.88
No	10151	1000	1.10	8.3	10.16	20.08
No	10092	1000	1.49	13.7	9.63	16.83
No	10079	1000	1.72	8.3	11.11	22.22
No	9306	1000	0.80	12.8	9.50	17.80
No	6114	1000	1.47	8.4	11.23	19.21
Yes	5873	1000	2.40	9.0	26.16	27.79
No	6102	1000	1.09	13.7	7.30	12.89
Yes	6176	1000	1.44	13.7	9.86	19.72
No	6057	1000	2.14	10.5	13.34	23.22
Yes	6010	1000	2.04	10.0	25.70	28.50
No	5761	1000	2.16	13.7	8.42	15.99
Yes	6132	1000	2.52	12.7	18.86	26.33

increasing the Ca/S ratio and of operating close to the adiabatic saturation temperature. Without product recirculation, increasing the Ca/S ratio from 1.5 to 2 enhances the yield less than five points, while decreasing the approach temperature from 15 to 10°C produces an efficiency gain of almost 10% points. However, the quantitative effects of these operating variables are doubled when the product is recycled to the duct entry.

4.1. Effect of product recirculation

Fig. 4 also shows quantitatively the benefit of recirculating a fraction of the partially converted sorbent at 1000 ppm of SO₂ concentration. With respect to the least efficient but simplest operating mode, i.e. without fly ash pre-collection, product recirculation, and sorbent reactivation, a recirculation ratio of 10 improves global desulphurisation efficiency up to 30 yield points at AST = 10°C and 10 at AST = 15°C.

Table 3
Second group of tests (with recirculation and 400 ppm SO_2)

Ash pre-collection	Pugmill	BET	Gas FR (N m³/h)	Ca/S (mol/mol)	AST (°C)	Efficiency (duct) (%)	Efficiency (duct + ESP) (%)
No	No	Medium	9660	1.37	9.7	33.88	49.82
Yes	No	Medium	8914	2.20	9.7	43.63	58.16
No	No	Medium	10187	1.34	12.3	21.7	30
Yes	No	Medium	9196	2.04	12.3	28.28	45.44
No	No	Medium	9703	1.89	8.3	–	58.61
Yes	No	Medium	9203	2.64	9.7	42.95	68.11
No	No	Medium	10030	2.57	13.7	24.5	33.1
No	No	Medium	6000	1.71	10.0	27.63	37.5
No	No	Medium	6000	1.44	15.0	15.62	27.19
No	No	Medium	6000	2.34	10.0	34.41	44.81
No	No	Medium	6000	2.22	15.0	21	33.54
Yes	Yes	Medium	10079	1.88	10.0	52.59	63.47
Yes	Yes	Medium	10111	1.77	13.7	24.51	47.38
Yes	Yes	Medium	10215	2.31	8.1	55.59	75.77
Yes	Yes	Medium	9690	2.58	12.3	42.02	59.15
Yes	Yes, sea	Medium	9873	2.58	8.0	78.33	89.19
No	No	High	10015	2.40	8.3	43.1	63.44
No	No	High	10010	2.00	8.3	29.81	47.08

Table 4
Third group of tests (with recirculation and 1000 ppm SO_2)

Ash pre-collection	Pugmill	BET	Gas FR (N m³/h)	Ca/S (mol/mol)	AST (°C)	Efficiency (duct) (%)	Efficiency (duct + ESP) (%)
Yes	Yes	Medium	9693	1.67	7.0	32.99	54.02
Yes	Yes	Medium	9452	1.68	12.3	25.06	46.87
Yes	Yes	Medium	9531	2.35	7.0	36.98	61.56
Yes	Yes	Medium	9636	2.32	11.5	29.73	47.10
Yes	Yes, sea	Medium	9963	1.43	8.3	33.4	–
Yes	Yes, sea	Medium	9963	1.43	7.0	–	59.34
No	No	Medium	10318	1.74	9.7	26.35	39.02
No	No	Medium	10142	1.50	15.0	22.88	26.87
No	No	Medium	10000	2.00	10.0	38.00	51.36
No	No	Medium	10133	2.24	13.7	18.57	33.12
No	No	High	10166	2.00	8.3	32.89	45.41
No	No	High	9690	0.96	13.7	15.89	29.68
No	No	High	10411	1.68	8.3	26.42	41.90

4.2. Effect of fly ash pre-collection

The favourable effect of reducing the fly ash load in the flue gas entering the desulphurisation duct by means of a pre-collector is also significant, as can be seen in Fig. 5. The global removal-efficiency gain at 400 ppm of SO_2 concentration is around 10 yield points with respect to cases with recirculation and 7 g/N m³ of fly ash load. This efficiency improvement seems to depend on the Ca/S ratio and the AST.
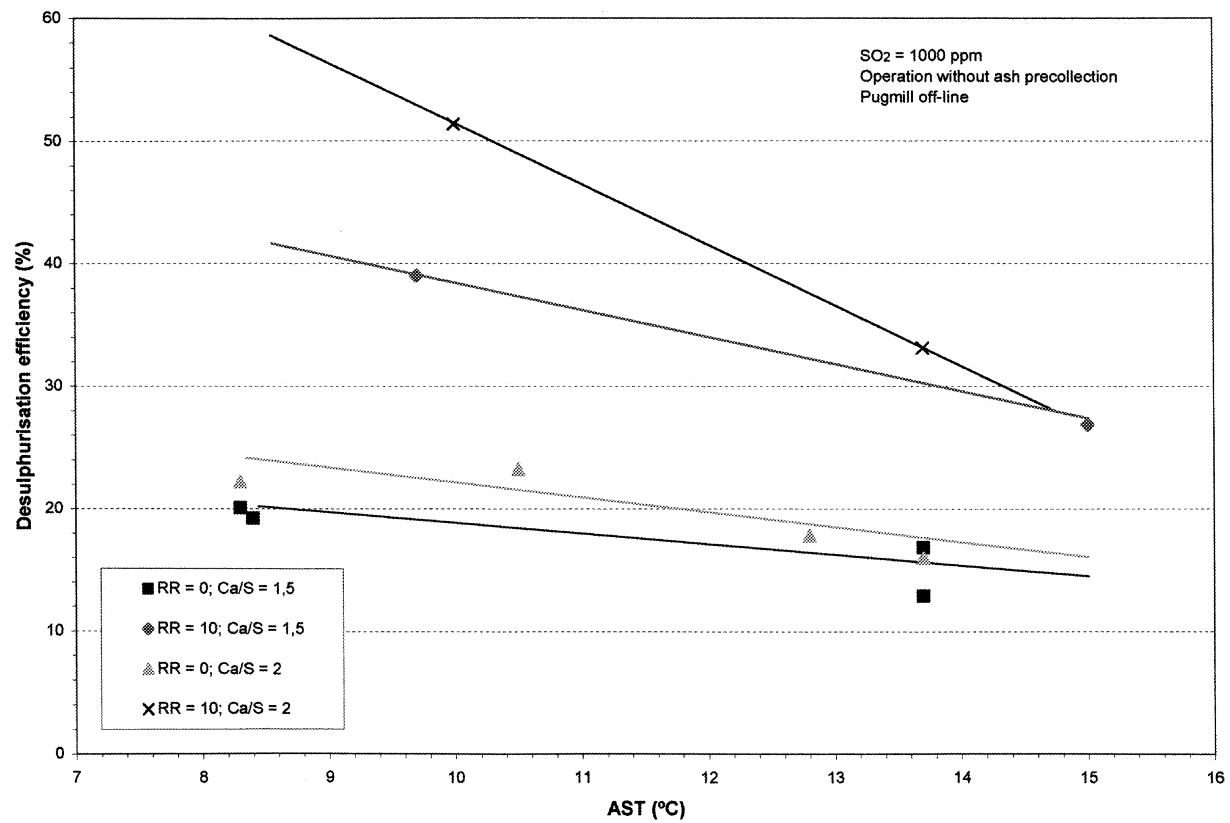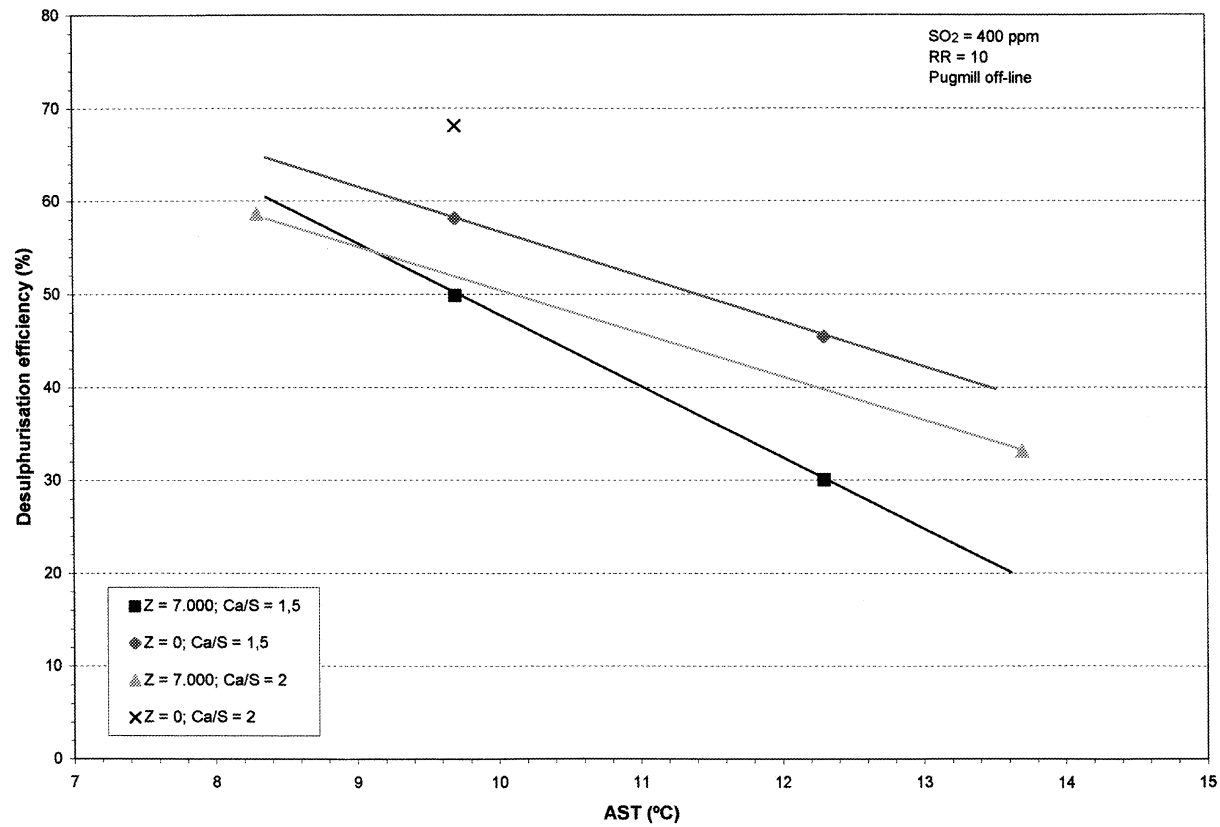
Fig. 4. Effect of the product recirculation.

Fig. 5. Effect of the fly ash pre-collection.

4.3. Effect of sorbent humidification

The reactivation of the sorbent in a pugmill by adding liquid water also has a favourable effect, as can be seen in Fig. 6. With respect to cases with solid recirculation and fly ash pre-collection, the efficiency improvement at 400 ppm is around five yield points. As can be seen in Fig. 7, the use of seawater to wet the solid sorbent prior to its injection into the duct has a significant beneficial effect. We achieved 90% sulphur dioxide removal in the global system (duct + ESP) operating with a Ca/S ratio of 2 and a recirculation ratio of 10. This efficiency is 12 points higher than what can be achieved with running water. The figure also shows that the sulphur removal in the electrostatic precipitator is quite remarkable due to the comparatively long residence time in this unit.

Summarising, if one compares the best but most complex operating mode with the least efficient but simplest ones at the same Ca/S ratio and AST, the average improvement is more than 50 yield points (Fig. 8).

4.4. Effect of lime-BET-area

Unfortunately, only five tests with high-BET-area lime were included in the experimental programme. These tests were inconclusive with respect to the advantage of using this specially slaked lime. Although the number of tests is too small to make a categorical assertion, it seems that high-BET-area lime does not contribute significantly to achieving high removal yields.

4.5. Effect of the gas flow rate

In order to simulate the effect of power plant load changes, the experimental programme included tests at different gas flow rates. Fig. 9 shows the results of tests without product recirculation. It can be seen that, when operating with ash pre-collection, the behaviour of the process was as expected; i.e. increasing the gas flow rate leads to lower global removal yields. However, the opposite effect was obtained when operating without fly ash pre-collection. A statistical analysis taking into account the whole set of experimental data has shown that this parameter is not statistically significant. This agrees with the tests carried out for the Advanced Coolside process (Withum et al. [5]) where the effect of the in-duct residence time was found significant below 1.7 s, verifying a little effect of additional residence time on in-duct SO_2 removal. In our tests, the minimum residence time in the duct was 2.2 s.

4.6. Effect of the SO_2 concentration

Two SO_2 concentration levels were considered in the experimental programme to assess the DSI process with respect to this important input variable. Fig. 10 compares the results obtained in two different cases: with ash pre-collection and humidification in the pugmill and without these two options. In both cases, it can be clearly seen that at 400 ppm of SO_2 concentration the global removal yields are greater than at 1000 ppm concentration.
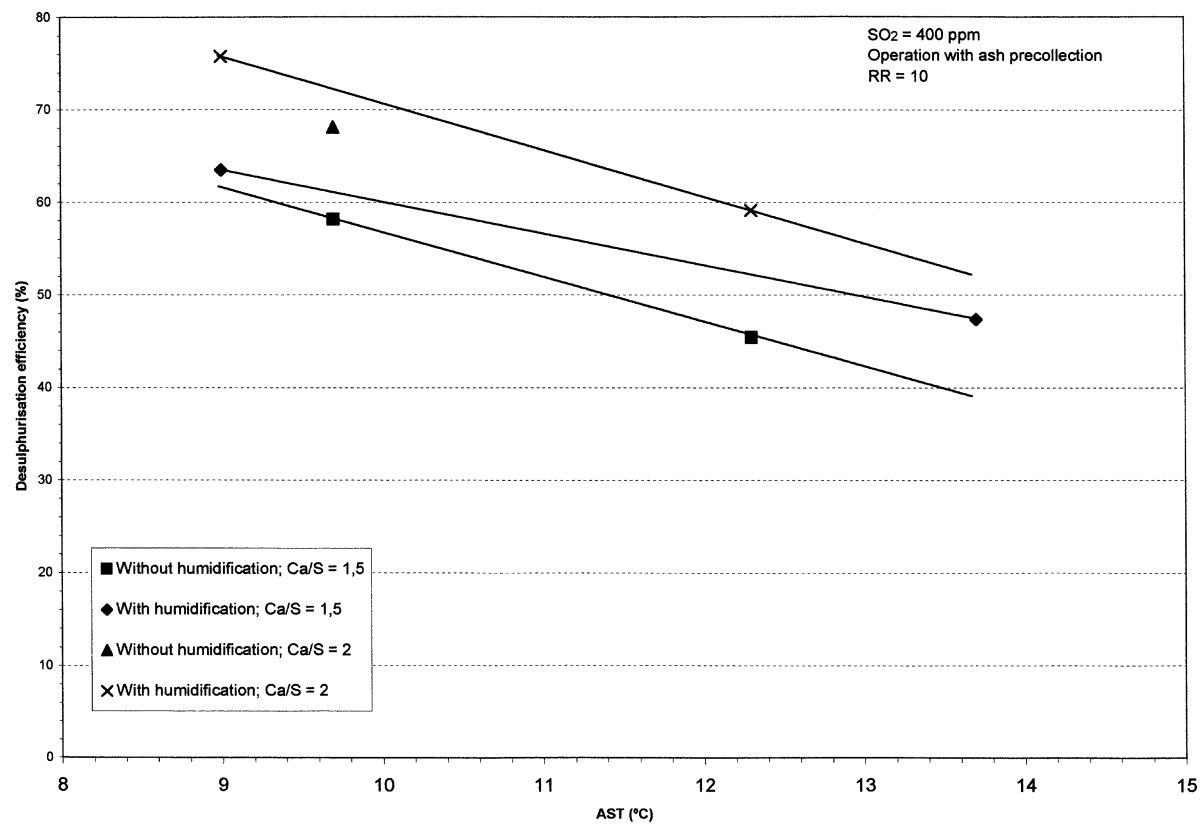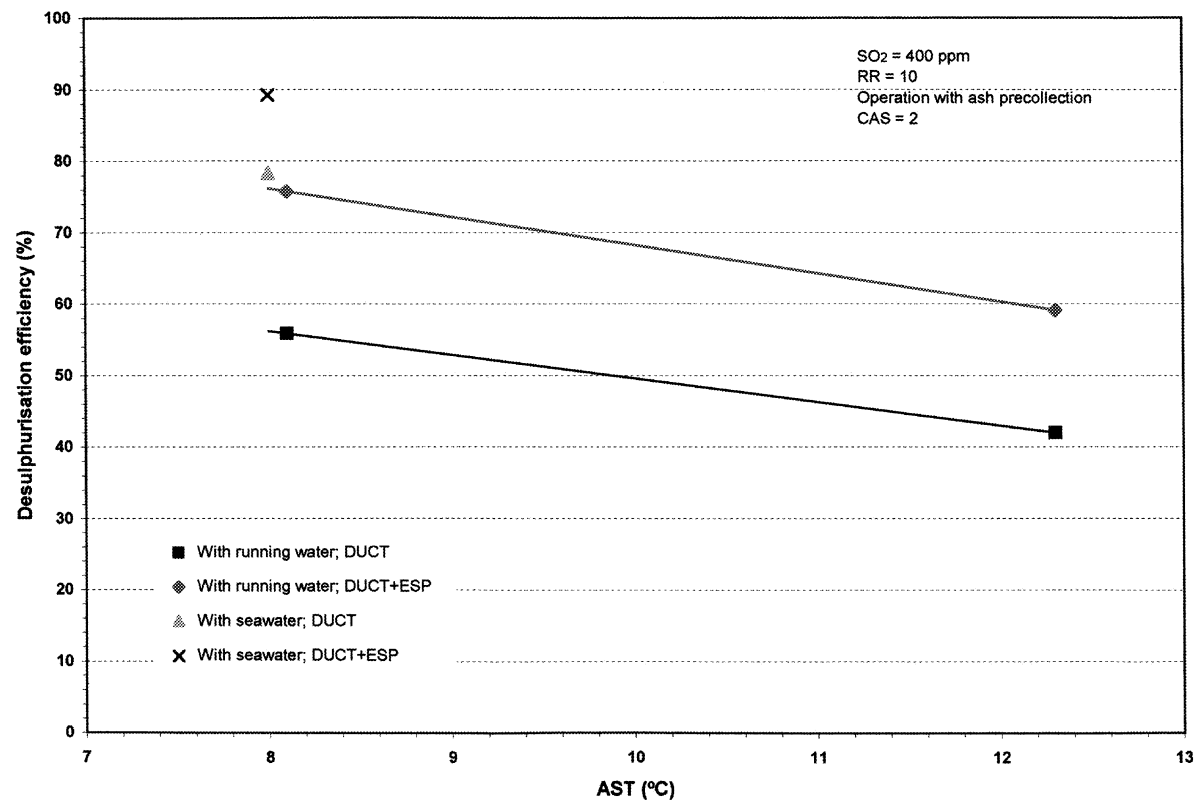
Fig. 6. Effect of the sorbent humidification.

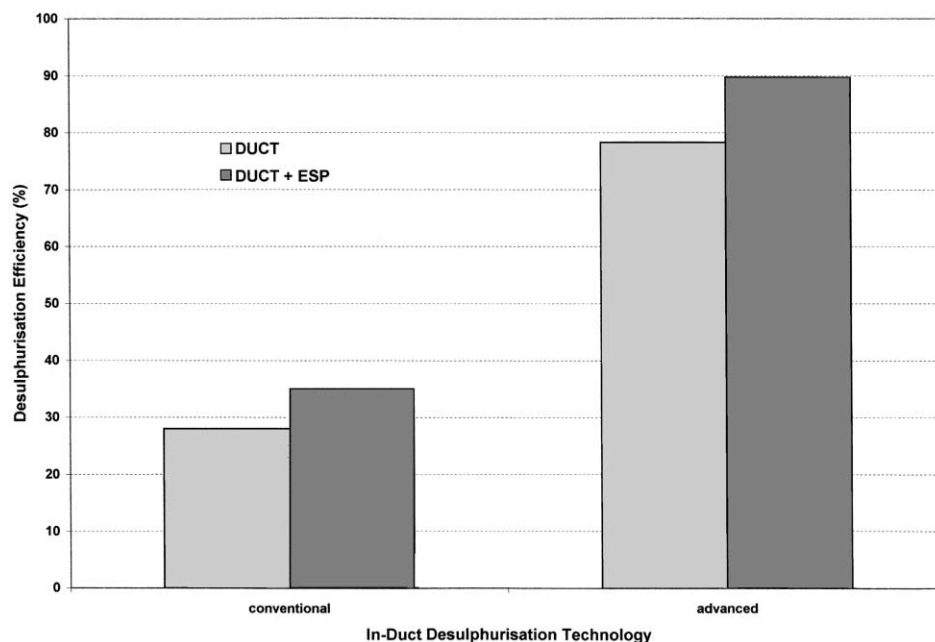Fig. 7. Effect of the seawater versus the running water.

Fig. 8. Comparison the conventional with the advanced in-duct sorbent injection.

4.7. Impact of in-duct desulphurisation on ESPs

The installation of a DSI desulphurisation process upstream from an ESP raises the particulate loading to the collector by a factor ranging from 1.5 to 12.5 depending on the SO_2 of the inlet gas, the Ca/S ratio and the recirculation ratio. Thus, if the collection efficiency of the ESP remains at the original level, the particulate emissions will increase by the same factor, creating a serious dust emission problem. However, the desulphurisation process also produces positive effects that should enhance the ESP collection efficiency. The decrease of gas temperature in the desulphurisation unit increases the specific collection area (reduces gas flow rate) in the ESP, reduces non-ideal effects such as sneakage and scouring (lower gas velocity), increases migration velocity (lower gas viscosity) and increases spark-over voltages (higher gas density). On the other hand, the dust resistivity drops under $10^7 \, \Omega \, cm$, which could produce electrical reentrainment, and the particulate space charge could limit the corona current. Thus, the particulate emissions will remain at an acceptable level only if the ESP performs with higher efficiency, i.e. only if the global or net effect is sufficiently positive.

In order to assess the impact of the DSI unit on the ESP, the electrical operating points (secondary voltage and current) of the three electrical fields of the pilot ESP were carefully monitored during the experimental tests. Fig. 11 shows the *V–I* points at baseline conditions, i.e. bypassing the desulphurisation unit, and during the desulphurisation tests carried out without product recirculation (dust load to the ESP between 3 and 15 g/N m^3). At baseline conditions and with standard continuous energisation, the precipitator operates with spark-
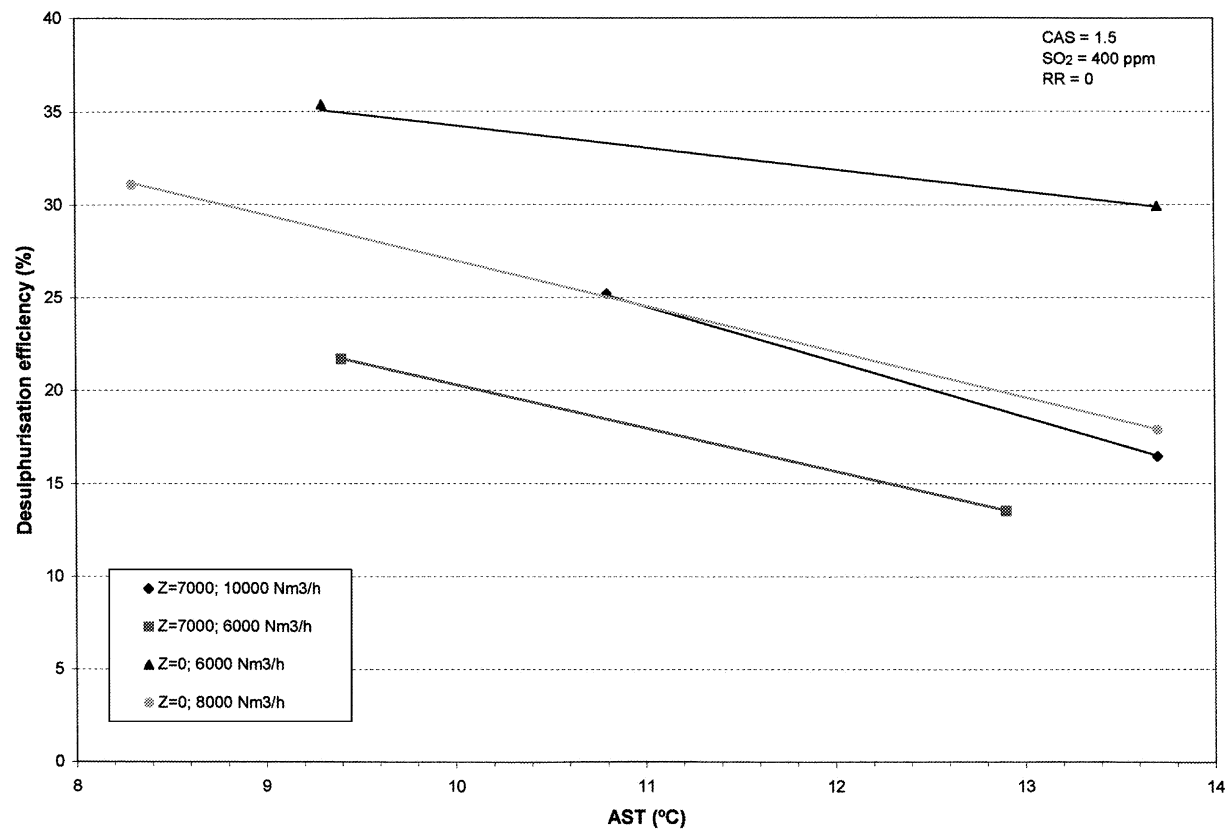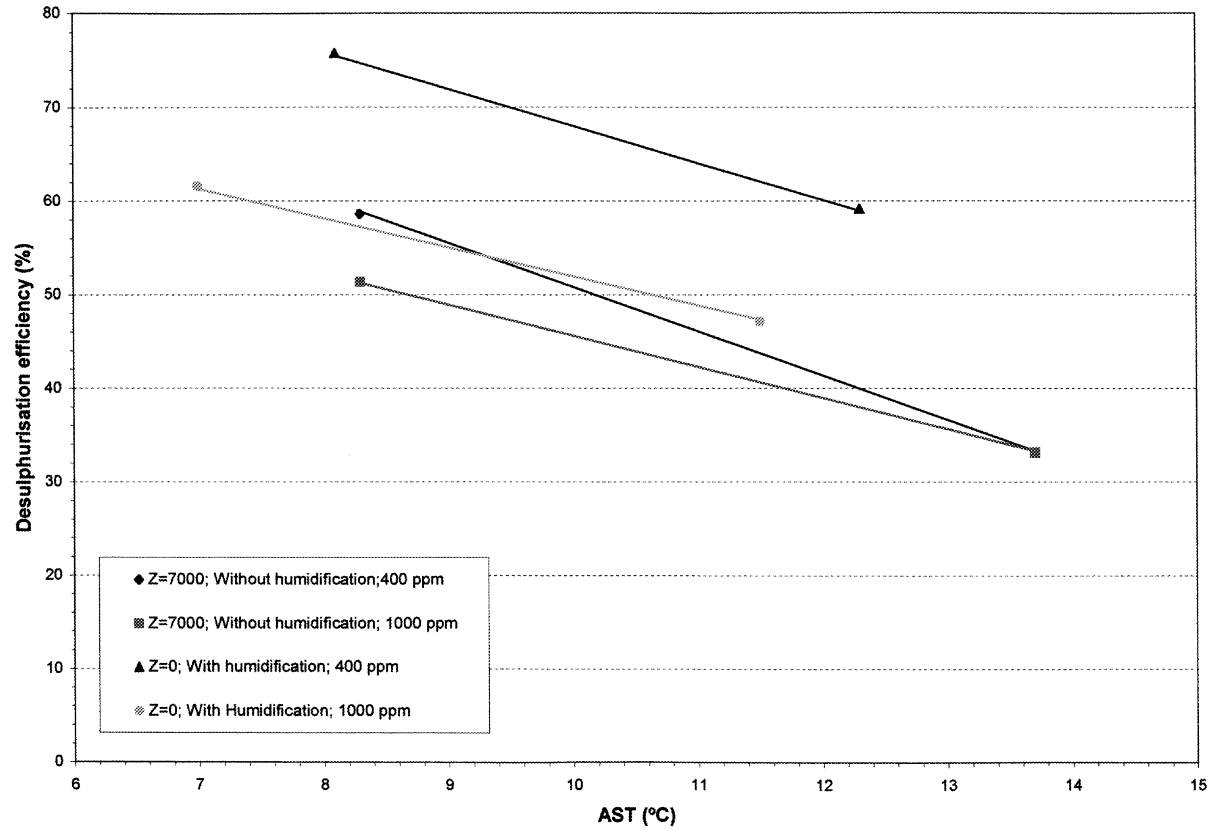
Fig. 9. Effect of the gas flow rate.

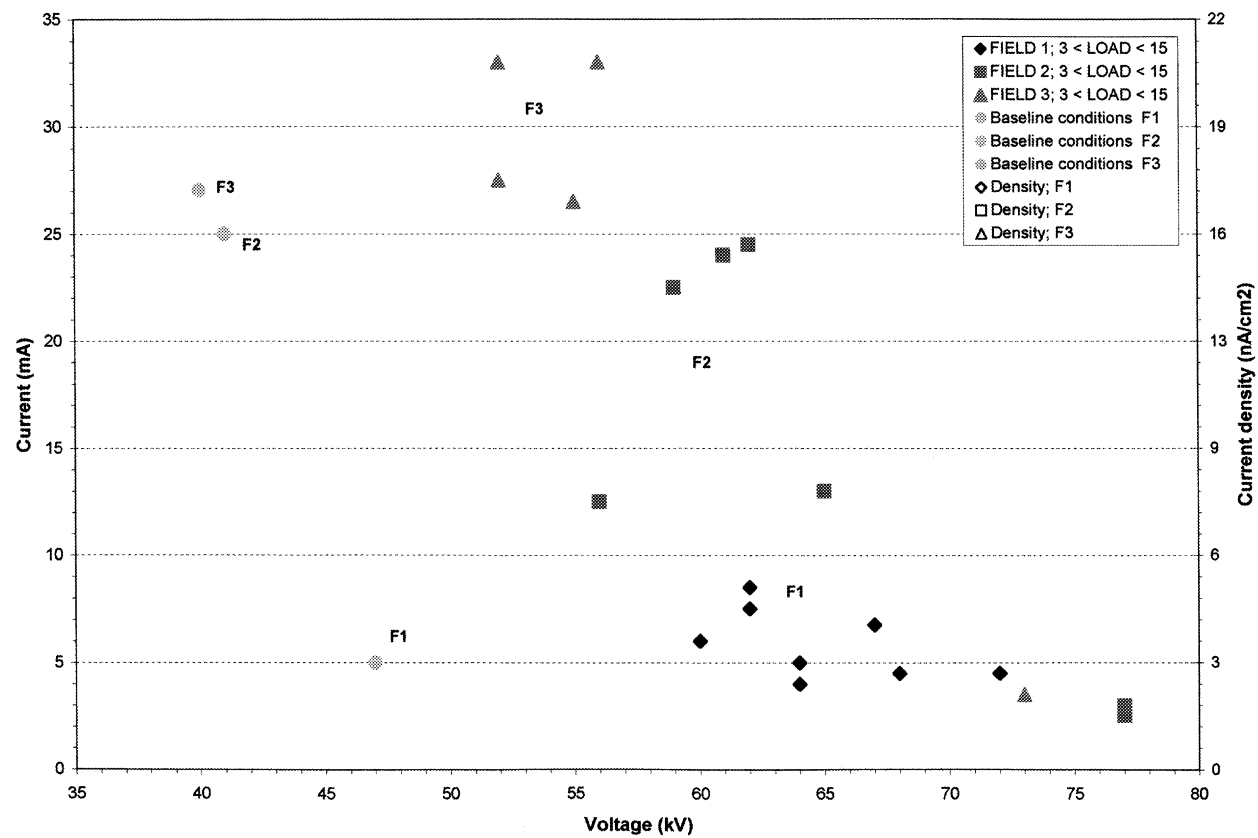Fig. 10. Effect of the SO_2 concentration.
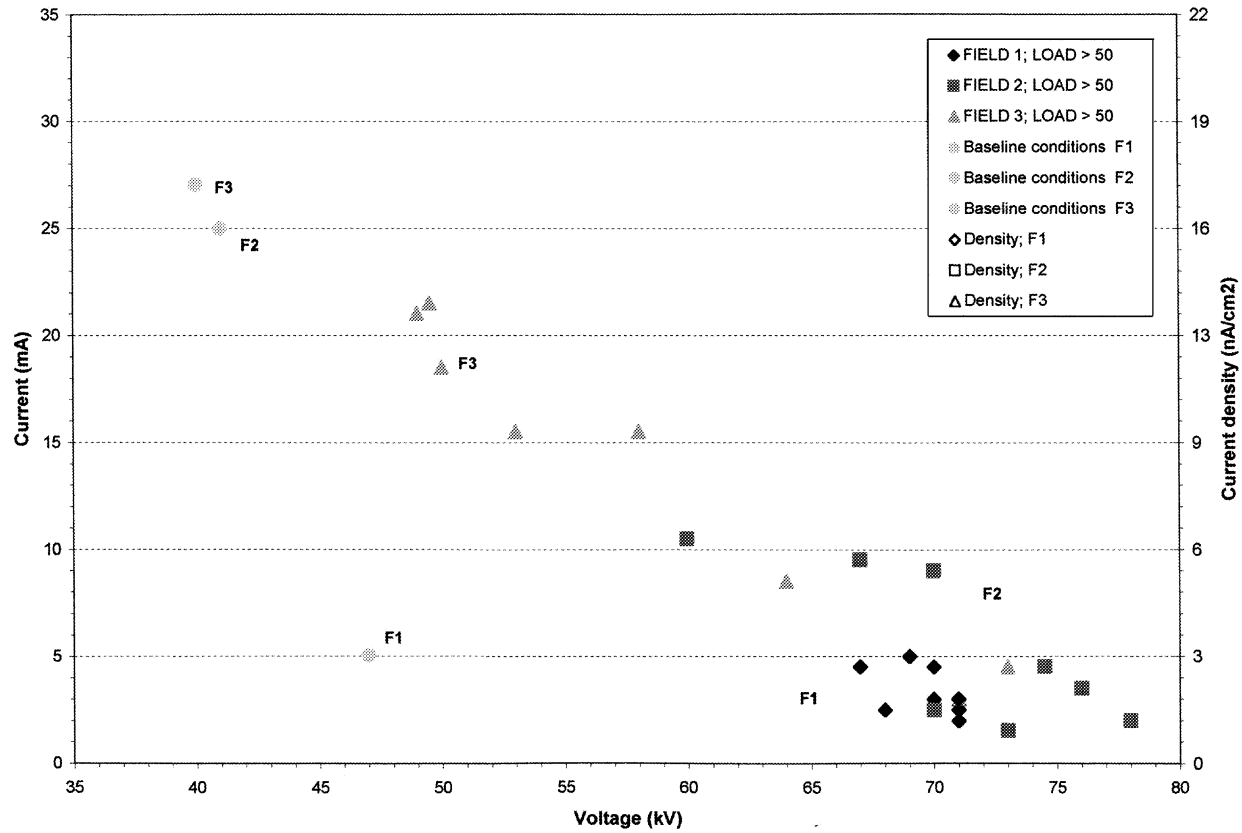
Fig. 11. ESP at low dust load.

Fig. 12. ESP at high dust load.

ing rates of 31–33 sparks per minute in all fields, and the dust collection efficiency of the pilot ESP, which has a small specific collection area (see Table 1), was 96%. Under DSI conditions the three fields are also limited by sparking but at significantly higher voltages, which results in higher field strengths. Lower gas temperature and resistivity, higher moisture and a moderate particulate space charge can explain this electrical improvement that clearly favours ESP efficiency. This electrical behaviour is very similar to that obtained when this ESP operated downstream from a desulphurisation spray dryer (Ollero et al. [9]) when the dust load also was between 3 and 15 g/N m^3. Thus, as on that occasion, it is expected that the efficiency increase will balance the dust load increment so as to maintain the same particulate emission level as without upstream desulphurisation.

Fig. 12 shows the same information but corresponding to tests carried out with product recirculation. Specifically, this figure includes tests at 1000 ppm of SO$_2$ concentration where the dust load was over 50 g/N m^3. Now, it can be seen that both the first and the second fields show intensity currents clearly under 5 mA, which means that the particle space charge had quenched the corona current. The third field also shows lower intensity currents than before, but still maintains satisfactory electrical behaviour. Under these electrical conditions, it is very doubtful that the pilot ESP could maintain the same emission level as at baseline conditions.

5. Conclusions

In order to assess several improvement options of the DSI desulphurisation process, an extensive experimental programme was carried out in a 3-MWe equivalent pilot plant, which processes real flue gas withdrawn from a 550 MWe coal power plant. The experimental work includes the study of several aspects in regard to the design and operation of the DSI process. Of the design modifications that could enhance the performance of the basic DSI process without sacrificing its inherent advantages, the ones assessed in this work were: ash pre-collection; sorbent recirculation and sorbent reactivation with both current water and seawater. The main conclusions related to these design options are:

- Fly ash pre-collection has proved to have a significant beneficial effect on the desulphurisation yield. Thus, using a medium-efficiency particulate collector, such as a small ESP, upstream from the sorbent injection makes possible the collection of saleable fly ash and reduces both the amount of final solid disposal and the recirculation flow.
- The recirculation of the partially converted sorbent enables the reduction of the required Ca/S ratio, increasing the sorbent utilisation and reducing the operating costs related to the expensive calcium hydroxide sorbent.
- The reactivation of the partially spent sorbent by means of humidification with current water or, preferably, with seawater in a pugmill, is very effective for achieving high desulphurisation yields and has been, perhaps, the most important finding of this study.

The operational aspects considered in this experimental study were the use of a high-BET-area lime, the impact of the DSI process on the ESP acting as the final collector and its effect on the desulphurisation efficiency of the Ca/S ratio, the recirculation ratio and the approach to the saturation temperature. The most significant findings concerning to these issues are as follows:

- The use of a high-BET-area lime did not show a significant beneficial effect on the desulphurisation efficiency. However, the number of tests conducted with this type of lime was limited and more experimental work is required in order to be able to make a conclusive assessment of the matter.
- The impact of the DSI process with product recirculation on the electrical behaviour of the pilot ESP was severe. The high dust load of the gas entering the ESP produces a high particulate space charge that suppress the corona current in the first fields and reduces the collection efficiency. Although the magnitude of the adverse effects depends on the specific operating conditions (ash pre-collection and recirculation ratio), a pre-collector or an upgrade of the existing ESP would be required in any case to reduce the dust load of the gas entering the final ESP, in order to meet the stringent emission levels.

This experimental study has demonstrated at a 3-MWe pilot plant scale that the DSI process, with its multiple enhancement options, is an effective and economical option for retrofitting old power plants with FGD. Taking the most simple DSI process as the base case, it has been shown that the global SO_2 removal increased from 35% (without ash pre-collection and product recirculation) to 90% (with ash pre-collection, product recirculation and seawater humidification in a pugmill). At the same time, the solid utilisation increased from 11 to 45%.

The use of any additional operating unit to enhance the removal efficiency as compared to the basic DSI process obviously leads to additional capital and operating costs. However, it seems that the resulting advanced DSI process may still retain some of its inherent economic advantages. This assessment arises from the fact that the equipment required to make the improvements is very simple and does not significantly increase energy consumption.

On the other hand, it must be noted that the applicability of the improvement options for DSI process is very site-specific as it depends on a number of factors, such as the following:

- enough space to humidify the flue gas upstream from the sorbent injection;
- availability of space to install a particulate pre-collector;
- feasibility of upgrading the existing ESP to deal with a greater dust load;
- solid disposal costs and associated regulations;
- availability of seawater.

Acknowledgements

References

[1] H.W. Pennline, J.H. Tice, JAPCA 38 (10) (1988).
[2] J.J. Battista, A.G. Rubin, J.Z. Abrams, A.L. Baldwin, in: Proceedings of the 1993 SO_2 Control Symposium, Boston, MA, USA, August 1993.

[3] M.R. Babu, C. Forsyte, C.F. Runyon, D.A. Kanary, H.W. Pennline, T. Sarkus, J.L. Thompson, in: Proceedings of the Third Annual Pittsburgh Coal Conference, Pittsburgh, PA, September 1986.

[4] M.R. Stouffer, H. Yoon, F.P. Burke, I&EC Research 35 (4) (1989).

[5] J.A. Withum, J.T. Maskew, W.A. Rosenhoover, M.R. Stouffer, M.M. Wu, in: Proceedings of the 1995 SO$_2$ Control Symposium, Miami, FL, March 1995.

[6] J. Khinast, C. Brunner, G. Aichinger. G. Staudinger, in: Proceedings of the 1995 SO$_2$ Control Symposium, Book 2, Miami, FL, March 1995.

[7] J. Khinast, Ph.D. Thesis, Technical University of Graz, Austria, 1995.

[8] H. Nalbandian Soud, Development in FGD, IEA Coal Research, London, 2000, pp. 47–51.

[9] P. Ollero., L. Cañadas, L. Salvador, in: Proceedings of the 1995 SO$_2$ Control Symposium, Miami, FL, March 1995.

[10] F.J. Gutiérrez, R. Ortiz, P. Ollero, A. Cabanillas, L. Sallvador, J. Otero, in: Proceedings of the 6th International Conference on Circulating Fluidised Beds, Würzburg, Germany, August 1999.