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CFD - Assisted Safety Design in a Flue Gas Treatment Plant Retrofit

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A retrofit project related to an Al_2O_3 calcination flue gas treatment line, consisting in the installation of a fabric filter downstream an existing electrostatic precipitator (ESP) was the object of this study. In this case, the replacement of the existing exhaust fan with a more performing one would have been potentially exposed the existing precipitator to suction conditions that did not fall within the process conditions considered when the ESP was designed. In other words, performing a detailed safety analysis focused on the interface between new and existing plants it was highlighted a possible risk of implosion that would not be easily found by following the most common classical approaches as the historical analysis or an HAZOP limited to the new equipments.
This hazard would not have been easily reduced by installing reinforcements due to the difficulty (both technical and economical) to modify such existing equipment. The chosen approach was to face the problem analogously to the protection of a vessel from overpressure, that means to size a direct action PSV (counterweight actuated), which opens when a given differential pressure (with opposite sign with respect to the traditional PSV design) is reached.
The risk thus determined was translated in terms of a worst case scenario, on the basis of which the design of safeguards has been carried out. In particular, this scenario was identified considering that all the pressure drops are concentrated upstream the equipment to protect, exposing the filter to maximum suction levels. The presence of a fabric filter bypass duct, allowing direct communication between fan and ESP, the complete obstruction of a duct upstream of it and the fan running at full rotational speed were the main hypotheses constituting the worst case scenario. Design choices were verified and validated through a computational fluid-dynamics analysis, evidencing that CFD can be a powerful and useful tool to address safety design issues, allowing to numerically test safeguards actions and consequently evaluating the impact that design choices would have for the purposes of risk reduction and mitigation.

1. Introduction

Dust removal from a gas stream is a common problem in many industrial processes (e.g. power, cement, steel plants). In the last decades, plant managers faced more and more often the necessity to improve dedusting systems in order to meet more stringent law requirements, inspired by the principle of the "maximum safety technologically feasible" achievement, but also pushed by the increased penetration of environmental issues into public opinion, and its meaning in terms of company image.
Budgets for these improvements play a role in a general asset management strategy: being often dedusting an operation having low – or even none – influence on production performances, it is more seen as a "necessary cost" than a profit generator. Companies' trend, especially in the actual economical scenario, is to reuse existing dedusting plants, enhancing their efficiencies rather than install new plants that would involve costs for the decommissioning of obsolete equipments (Skodras et al., 2006).
The obvious economic benefits of retrofits are counterbalanced by technical disadvantages. In particular, a systematic assessment of safety issues is required, not limited to the safety-oriented design of new

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machines, but extended in the evaluation of the impact that changes in process conditions (induced by the new equipments) can have on the existing ones.
A safety system was designed for the retrofit of an alumina calcination flue gas dedusting plant where, downstream to the existing electrostatic precipitator (ESP), a new bag filter was installed. In particular, the sizing of safeguards and auxiliary equipments (Etchells and Wilday, 1998) installed to reduce possible risks has been verified by means of a Computational Fluid-Dynamics (CFD) study of the worst case scenarios that could occur for the installed plant.

2. Safety analysis

To increase the dust collection efficiency of an alumina calcination flue gas dedusting line, a new bag filter was installed downstream the existing electrostatic precipitator, as shown in Figure 1; this increased the pressure drops, so it was decided to replace the existing tail fan with a more powerful one. To allow plant operations in case of bag filter unavailability, a by-pass system, able to exclude the fabric filter putting in communication directly fan and ESP was also installed. In this case, the dust is removed only by the ESP.
To define in a clear way the safety issues generally concerning electrostatic precipitators and bag filters, two different and complementary approaches were applied: an historical analysis and a HAZOP study. It was found that the hazards evidenced by the HAZOP study are coherent with many accidents found in historical datasets (Lees, 2005). Being these precipitators widely used in many process industries, it is easy to collect significant historical information by means of many sources (Abbasi and Abbasi, 2007; FM Global, 2009). Occupational Safety and Health Administration (OSHA, 2011) archives reported, over a 10 years period (2000-2010), 24 accidents regarding dust collectors. Explosions represent the most common event (Khan and Abbasi, 1999; Eckhoff, 2009), followed by human errors, and fires (Mastropietro, 2005; Nifuku et al., 2007). About half of these events produced fatalities: these data clearly confirms how critical is the role of risk assessment during plant design (Zio, 2007). The HAZOP analysis aimed at identifying typical risks of dust collector plants evidenced that inside electrostatic precipitators, coexistence in the same environment of a flammable fuel (dust to be collected or products of incomplete combustion such as CO), oxygen (always present in flue gas) and an ignition source (sparks due to electrostatic field) can easily lead to high explosion risk.
For the investigated plant, it was found that an excessive pressure reduction into the ESP could lead to the equipment implosion. The presence of a new fan, able to provide higher values of static head, in order to counterbalance the bag filter pressure losses, and of a by-pass duct able to connect directly the ESP to the fan inlet, could produce, at full speed, static heads even higher than 1000 mmH_2O; on the other hand, a structural verification has shown that the ESP was designed to withstand a maximum suction level of -715 mmH_2O: this means that even if each equipment was properly designed, considering the process condition existing in the plant until the retrofit operation, the new dedusting plant was not protected against high negative pressure events.
This hazard would not have been easily reduced by installing reinforcements due to the difficulty (both technical and economical) to modify such an existing equipment. The chosen approach was to face the problem analogously to the protection of a vessel from overpressure, that means to size, in this case, a vacuum-breaker damper (counterweight actuated), which opens when a given differential pressure (with opposite sign with respect to the traditional PSV design) is reached.

Figure 1: Example of a hybrid dedusting system constituted by an ESP coupled with a bag filter.

3. Worst case scenario: definition and results

Regarding the risk of the ESP implosion, the worst case situation was considered, with the fan running at full speed. To set the remaining conditions necessary to define the scenario, it must be said that, as in an electrical circuit, pressure drops on the duct line are distributed according to “resistance jumps”. Then, in order to reach the highest negative pressure at the ESP, it is necessary to consider the case with the highest resistance upstream the precipitator, and the lowest downstream the equipment. According to this hypothesis, the worst case scenario must consider the bypass duct open (that actually acts as a shortcut, allowing a direct communication between ESP and fan, excluding the bag filter), and a full restriction (like a damper closed or a duct clogged) upstream the dust collector.
When the worst case scenario occurs, the gas flow rate in the circuit would be theoretically zero. Opening the vacuum breaker damper, located at the ESP outlet, would allow atmospheric air flow into the line, modifying consequently the work point of the centrifugal fan. The gas flow-rate that goes through the vacuum breaker damper is a function of its cross section and of the negative pressure imposed at damper inlet. Air flowing through the circuit reaches the tail fan, generating a pressure drop along the circuit that is a function of the gas flow-rate. The vacuum breaker and the fan pressures, P_v and P_f, respectively can be correlated as follows:

$$P_v = P_f - \Delta P\ (F\ (P_f)) = P_v\ (P_f) \qquad (1)$$

where F is the mass flow-rate. Once a characteristic aspiration curve F (P_v) for the vacuum breaker device is defined, the actual gas flow-rate can be calculated as the intersection between the damper aspiration function and the fan characteristic curve. As summarized in Table 1, dampers with a square section and different sizes were considered in this study. In particular, it was found that the 0.9 m damper was not able to reduce the negative pressure below the target of 715 mmH_2O even if the valve was fully opened; for this reason, it did not meet the safety requirements.

Table 1: Main characteristics of the investigated vacuum damper alternatives.

Damper size [m]	Gas flow rate [kg/s]	Negative pressure P_v [mmH_2O]	Negative pressure P_f [mmH_2O]	Vacuum breaker opening [%]
0.9	90.0	791	950	100
1	92.9	696	862	71
1.1	93.2	686	853	56

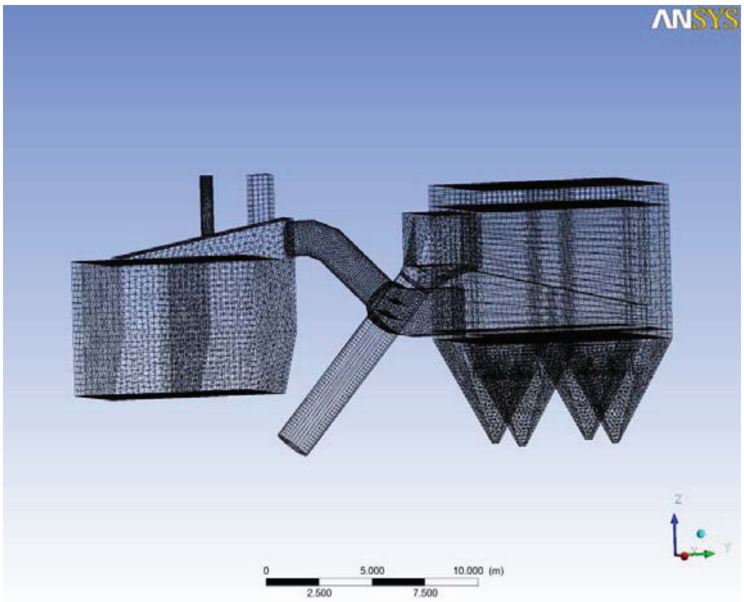

Figure 2: Computational domain and mesh realized to study the effects of a high negative pressure into the installed dedusting system.

On the other hand, both the remaining dampers were able to keep the negative pressure below the safety thresholds; among them, the 1 m device was chosen, not only for economical reasons, but also for technical ones: smaller dampers usually ensure a better pressure control and limit chattering phenomena.
CFD can be used to simulate worst case scenarios and the correspondent action of safeguards, showing the changes induced in process variables. This can help to understand the influence and the impact of the devices on the process, allowing optimization (e.g. change in sizing, position adjustment). CFD codes solve the Navier-Stokes equations, together with specific model equations, such as mass and energy balances, species diffusion, turbulence, etc. In particular, the commercial ANSYS Fluent 13.0 suite was used in this study. A detailed 3D model of the system (from the ESP inlet to the tail fan) was realized to analyze the previously defined worst case scenario, as shown in Figure 2. In order to minimize errors due to discretization operation, a grid independence analysis was also performed. Table 2 summarizes the main settings used for the analysis of the high negative pressure scenario: all the gas flow is introduced through the vacuum breaker damper, according to what was actually foreseen in the scenario definition.

Table 2: Settings of the CFD simulation.

Parameter	
ESP inlet gas flow rate	0 kg/s
Vacuum breaker damper inlet gas flow rate	92.9 kg/s
Gas composition	Air (21% O_2, 79% N_2)
Temperature	20 °C
Static pressure at fan inlet	-8455 Pa (-862 mmH_2O)
Number of elements	438,600
Discretization method	2^{nd} order upwind
Turbulence model	RANS k-ε realizable

Figures 3 and 4 show a side and a 3D view, respectively, of the predicted pressure field obtained after the vacuum breaker damper action. As foreseen, the choice to install the damper at ESP outlet allows limiting the negative pressure raise in all the zones upstream the valve. Highest pressure drops are concentrated on the air intake, as better evidenced by the pressure contours of Figure 5, which illustrates a detail of the ESP outlet zone.

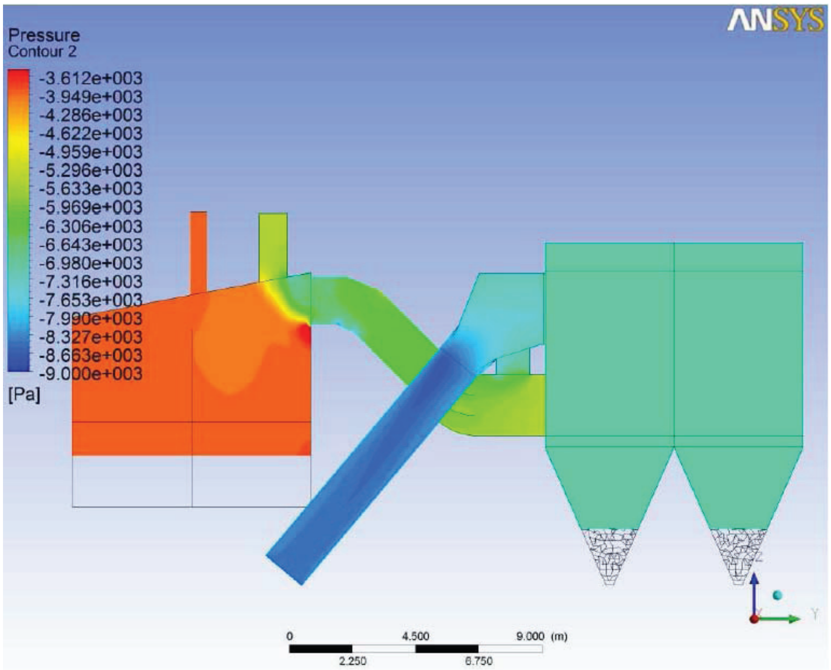

Figure 3: Pressure contours predicted by the CFD model for the investigated scenario (side-view of the installed dedusting plant and vacuum breaker damper).

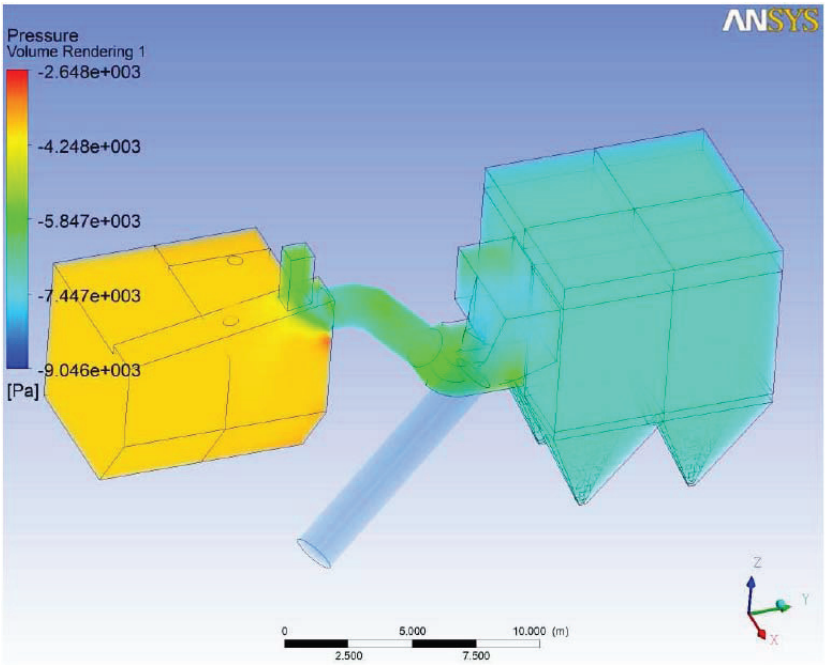

Figure 4: Pressure distribution predicted by the CFD model for the investigated scenario (full 3D view of the installed dedusting plant and vacuum breaker damper).

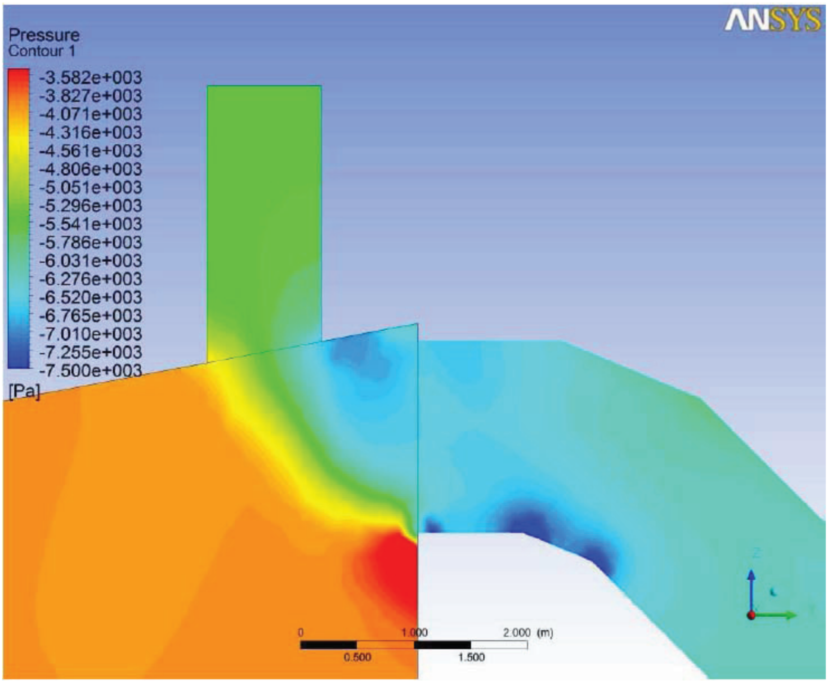

Figure 5: Pressure distribution predicted by the CFD model at the ESP outlet when the vacuum breaker damper is open. Negative pressures that exceed the threshold limit of -715 mmH_2O are concentrated just downstream the ESP exit.

The average value of the negative pressure at ESP outlet flange was found to be -682 mmH_2O that, compared to the calculated value of -696 mmH_2O means that these results are consistent both qualitatively and quantitatively (the difference between the two values is below 2%), and that CFD analysis was able to highlight when the safety requirements are met, thus validating the choices made during the vacuum damper sizing.

The present work puts in evidence the added value of computational fluid dynamics, that allows studying phenomena occurring in complex geometries with no need of further simplifications (e.g. concerning flow, geometry). Moreover, a well-done post-processing analysis allows catching non trivial aspects that can help to understand, or even to foresee, phenomena otherwise not evident a priori.

4. Conclusions

Retrofit of existing plants, where the designer is required to introduce changes on an existing line to improve its performance or useful life, poses a problem of interface between new and existing elements that must be addressed in a critical manner. In fact, if new plant can be directly designed to meet reliability and safety requirements, the same cannot be said, usually, for the existing: even assuming that existing machines were designed to meet appropriate safety requirements, the influence of new machines and moreover the variation of process parameters and conditions (e.g. increasing production rate), makes necessary to extend the safety analysis also to the interface between new and existing.

In the present case, a possible risk of implosion of the electrostatic precipitator was identified. This aspect puts in evidence the importance to perform a risk assessment with competence and extreme care: there is no technique (or combination of them) able a priori to ensure that all risks can be identified for a specific process plant.

A CFD study was performed on a alumina dedusting plant in order to simulate the worst case scenarios and the safeguards action. CFD analysis provided outcomes highly consistent with the safeguards sizing calculations. This aspect is very important, because the use of CFD can be easily extended to more complex systems, where direct calculations are difficult or they require too many simplifications, thus increasing the uncertainty related to the estimated parameters. CFD is suitable to be a very useful tool in assisting risk analysis, since it allows simulating different scenarios on the same geometry or, on the other hand, changing easily the geometrical configuration (e.g. insertion of guide vanes, modification of the position of a safeguard) and evaluating the direct impact of safeguards action on the risk reduction and consequences mitigations.

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