CFD aided Design imperilment and the utilization, modification of exhaust gas treatment plant

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ABSTRACT

This research focused on a refit project for an Al2O3 calcination exhaust gas treatment line that included the installation of a fabric filter downstream of an existing electrostatic precipitator (ESP). In this scenario, replacing the old exhaust fan with a higher-performing one could have exposed the existing precipitator to suction circumstances outside of the process parameters contemplated when the ESP was developed. In other words, by conducting a detailed safety analysis focused on the interface between new and existing plants, it was discovered that there was a potential risk of implosion that would not have been discovered by using traditional methods such as historical analysis or a HAZOP limited to new equipments. Due to the difficulty (both technically and economically) of modifying such existing equipment, this threat could not have been simply mitigated by installing reinforcements. The selected solution was to handle the problem in the same way that a vessel is protected against overpressure: create a direct action PSV (counterweight triggered) that opens when a given differential pressure (with the opposite sign as the typical PSV design) is reached. The risk was then transformed into a worst-case scenario, on the basis of which safeguards were designed. This situation was chosen because all of the pressure drops are focused upstream of the equipment to be protected, exposing the filter to maximum suction levels. The worst case scenario included the presence of a fabric filter bypass duct that allowed direct communication between the fan and the ESP, the complete blocking of a duct upstream of it, and the fan running at full rotational speed. A computational fluid-dynamics analysis was used to verify and validate design choices, demonstrating that CFD can be a powerful and useful tool for addressing safety design issues, allowing for numerical testing of safeguards and, as a result, evaluating the impact that design choices would have for the purposes of risk reduction and mitigation.

Keywords: *Exhaust gas, plant, CFD, Risk reduction*

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1. INTRODUCTION

In many industrial operations, dust removal from a gas stream is a typical issue (e.g. power, cement, steel plants). Plant managers have increasingly been faced with the need to improve dedusting systems in order to meet more stringent legal requirements in recent decades, driven by the principle of "maximum safety technologically feasible" achievement, but also by the increased public awareness of environmental issues and their implications for company image.

Budgets for these upgrades are part of a broader asset management strategy: because they are typically dedusting an operation that has little – or no – impact on production performance, they are viewed as a "necessary cost" rather than a profit creator. Companies are increasingly opting to reuse existing dedusting units, thereby increasing their efficiencies, rather than installing new plants, which would include costs for decommissioning obsolete equipment (Skodras et al., 2006).

Retrofits' evident economic benefits are counterbalanced by technological drawbacks. A thorough assessment of safety issues is necessary in particular, not only for the safety-oriented design of new machines, but also for the evaluation of the influence that changes in process conditions (caused by new equipments) can have on existing ones.

A safety system was built for the refit of an alumina calcination flue gas dedusting plant, which included the installation of a new bag filter downstream of the existing electrostatic precipitator (ESP). A Computational Fluid-Dynamics (CFD) evaluation of the worst-case scenarios that could occur for the installed plant was used to verify the sizing of safeguards and auxiliary equipments (Etchells and Wilday, 1998) installed to minimise probable hazards.

2. SAFETY ANALYSIS

A new bag filter was installed downstream of the existing electrostatic precipitator to improve the dust collection efficiency of an alumina calcination exhaust gas dedusting line, as shown in Figure 1; this increased pressure drops, so it was decided to replace the existing tail fan with a more powerful one. A by-pass system, capable of excluding the fabric filter and placing in connection directly fan and ESP, was also added to facilitate plant operations in the event of bag filter unavailability. Only the ESP removes the dust in this instance. Two independent and complimentary methodologies were used to describe the safety issues generally involving electrostatic precipitators and bag filters: a historical analysis and a HAZOP investigation. The HAZOP study's dangers were found to be consistent with many accidents identified in historical databases (Lees, 2005). Because these precipitators are widely utilized in numerous process industries, it is simple to gather significant historical data from a variety of sources (Abbasi and Abbasi, 2007; FM Global, 2009). Over a ten-year period (2000-2010), the Occupational Safety and Health Administration (OSHA) archives reported 24 accidents involving dust collectors. The most prevalent occurrence is explosions (Khan and Abbasi, 1999; Eckhoff, 2009), followed by human errors and fires (Mastropietro, 2005; Nifuku et al., 2007). About half of these incidents resulted in fatalities, demonstrating the importance of risk assessment throughout plant design (Zio, 2007). 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 exhaust gas), and an ignition source (sparks due to electrostatic field) can easily lead to a high explosion risk, according to a HAZOP analysis aimed at identifying typical risks of dust collector plants.

It was discovered that an extreme pressure reduction into the ESP might cause the equipment to implode at the investigated plant. The addition of a new fan capable of producing higher static head values to compensate for bag filter pressure losses, as well as a by-pass duct capable of connecting directly the ESP to the fan inlet, could produce static heads as high as 1000 mmH2O at full speed; on the other hand, structural verification revealed that the ESP was designed to withstand a maximum suction level of - 715 mmH2O: This indicates that, even though each piece of equipment was properly constructed, the new dedusting plant was not protected against high negative pressure events due to the process conditions that existed in the plant prior to the refit operation.

Due to the difficulty (both technically and economically) of modifying such existing equipment, this threat could not have been simply mitigated by installing reinforcements. The preferred solution was to handle the problem in the same way as a vessel is protected from overpressure, which includes sizing a vacuum-breaker damper (counterweight actuated) that opens when a given differential pressure (with the opposite sign as 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

The worst-case scenario was evaluated when it came to the risk of the ESP implosion, with the fan spinning at full power. To complete the scenario, it is required to state that pressure decreases on the duct line are distributed according to "resistance jumps," just as they are in an electrical circuit. Then, in order to get the largest negative pressure at the ESP, the case with the highest resistance upstream the precipitator and the lowest resistance downstream the equipment must be considered. According to this idea, the worst-case scenario must include the bypass duct open (which works as a shortcut, allowing direct contact between the ESP and the fan, excluding the bag filter) and a full obstruction upstream the dust collector (such as a damper closed or a duct clogged).

The gas flow rate in the circuit would theoretically be zero in the worst-case situation. Opening the vacuum breaker damper at the ESP output would allow ambient air into the line, changing the centrifugal fan's work point as a result. The gas flow rate through the vacuum breaker damper is determined by its cross section as well as the negative pressure imposed at the damper input. When air passes through the circuit and reaches the tail fan, it causes a pressure drop that is proportional to the gas flow rate. The pressures of the vacuum breaker and the fan, Pv and Pf, can be connected as follows:

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

The mass flow rate is denoted by F. The actual gas flow-rate can be computed as the intersection of the damper aspiration function and the fan characteristic curve once a characteristic aspiration curve F (Pv) for the vacuum breaker device has been defined. Dampers of a square section and various sizes were evaluated in this investigation, as shown in Table 1. The 0.9 m damper, in particular, was found to be incapable of lowering the negative pressure below the objective of 715 mmH2O even when the valve was fully open, and so failed to meet the safety criteria.

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

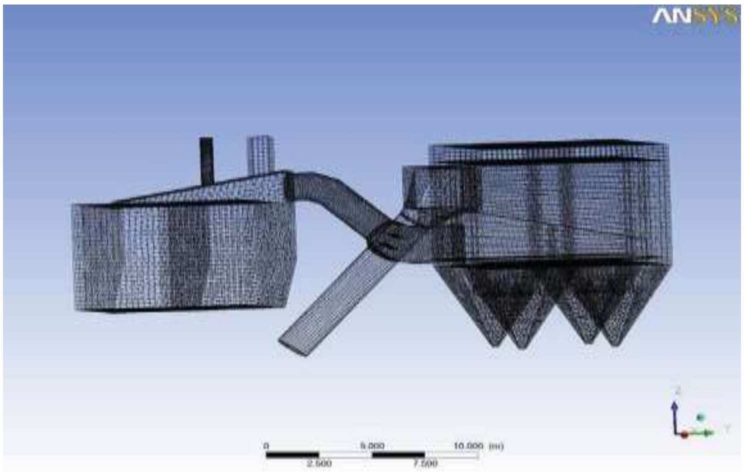

Figure 2: Computational domain and mesh realized to study the effects of a high negative pressure into the installed dedusting system.

The remaining dampers, on the other hand, were both able to keep the negative pressure below the safety thresholds; among them, the 1 m device was chosen, not only for cost reasons, but also for technical reasons: smaller dampers typically provide better pressure control and limit chattering phenomena. CFD can be used to simulate worst-case scenarios and the resulting safeguard action, displaying the changes in process variables. This can aid in the understanding of the devices' influence and impact on the process, allowing for optimization (e.g. change in sizing, position adjustment). The Navier-Stokes equations, as well as specialized model equations such as mass and energy balances, species diffusion, turbulence, and so on, are solved using CFD codes. This study employed the commercial ANSYS Fluent 13.0 package in specific. To examine the previously established worst case scenario, a comprehensive 3D model of the system (from the ESP input to the tail fan) was created, as shown in Figure 2. A grid independence analysis was also undertaken to reduce mistakes caused by the discretization procedure. The major settings employed for the study of the high negative pressure scenario are summarized in Table 2: all gas flow is introduced through the vacuum breaker damper, as specified 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	2nd order upwind
Turbulence model	RANS k-ε realizable

Figures 3 and 4 show a side and 3D view of the expected pressure field after vacuum breaker damper action, respectively. As expected, installing the damper at the ESP output limits the negative pressure rise in all zones upstream of the valve. As shown by the pressure contours in Figure 5, which depicts a detail of the ESP exit zone, the highest pressure dips are focused on the air intake.

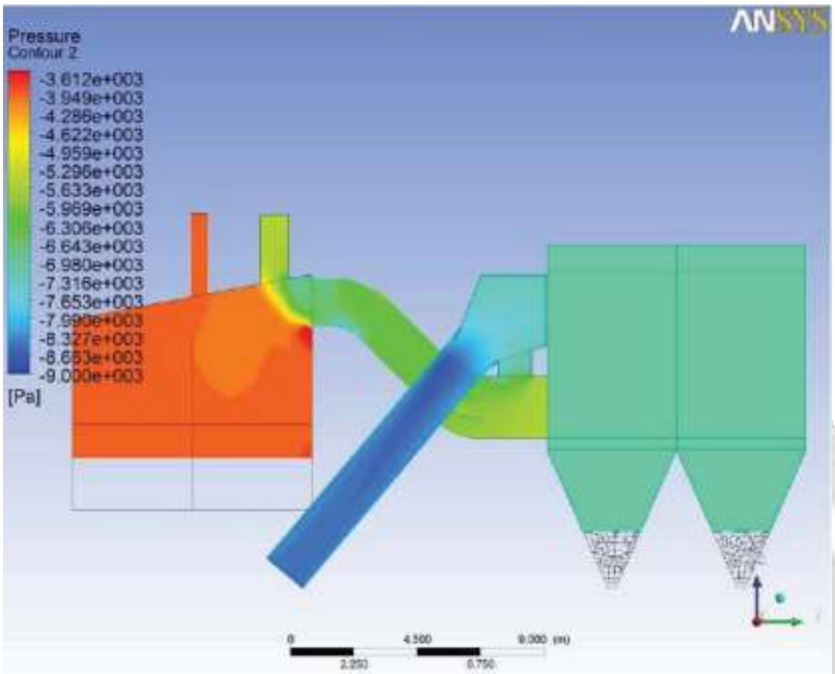

Figure 3: Pressure contours predicted by the CFD model for the investigated scenario (side-view of the installed dedusting plant and vacuum breaker damper)

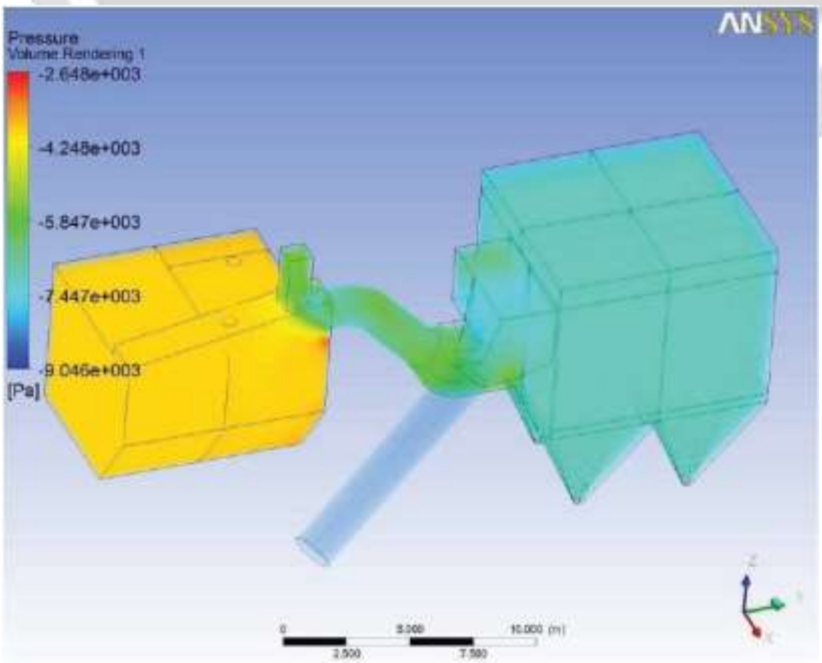

Figure 4: Pressure distribution predicted by the CFD model for the investigated scenario (full 3D view of the installed dedusting plant and vacuum breaker damper).

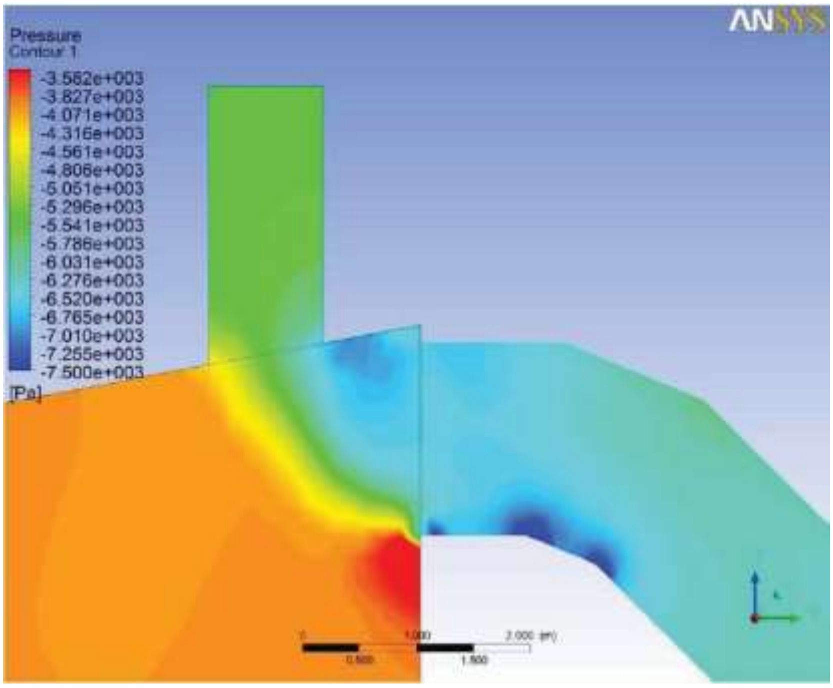

Figure 5: Pressure distribution predicted by the CFD model at the ESP outlet when the vacuum breaker damper is open. Negative pressures that exceed the threshold limit of -715 mmH_2O are concentrated just downstream the ESP exit.

The average negative pressure at the ESP outlet flange was found to be -682 mmH2O, which, when compared to the calculated value of -696 mmH2O, indicates that the results are qualitatively and quantitatively consistent (the difference between the two values is less than 2%), and that CFD analysis was able to highlight when the safety requirements are met, thus validating the vacuum damper sizing decisions. The current study demonstrates the added utility of computational fluid dynamics, which allows for the investigation of events in complex geometries without the need for additional simplifications (e.g. concerning flow, geometry). Furthermore, a well-done post-processing analysis allows for the detection of non-trivial elements that might aid in the understanding or even foreseeing of phenomena that would otherwise be invisible a priori.

4. CONCLUSIONS

Retrofitting existing plants, in which the designer is forced to make changes to an existing line in order to improve its performance or usable life, creates a key interface difficulty between new and old pieces. In fact, while new plants can be designed to meet reliability and safety requirements directly, the same cannot be said for existing plants: even if existing machines were designed to meet appropriate safety requirements, the influence of new machines, as well as changes in process parameters and conditions (e.g., increasing production rate), necessitates extending the safety analysis to the interface between new and existing machines.

The possibility of the electrostatic precipitator imploding has been detected in this scenario. This aspect demonstrates the need of performing a risk assessment with expertise and extreme caution: no technique (or combination of techniques) can guarantee that all risks for a specific process plant can be recognized a priori.

A CFD analysis on an alumina dedusting plant was carried out in order to explore worst-case situations and protections. The results of the CFD study were very similar to the safeguards sizing calculations. This is critical because CFD can readily be applied to increasingly complex systems where direct calculations are impossible or require too many simplifications, increasing the uncertainty associated with approximated parameters. CFD is a suitable tool for assisting risk analysis because it allows simulating different scenarios on the same geometry or, on the other hand, changing 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 risk reduction and mitigation.

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