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Are Intensified Processes Safer and More Reliable than Traditional Processes? An emblematic Case Study

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One of the best ways of preventing accidents is to avoid hazards by inherently safer design. As many processes, particularly those in the chemicals, nuclear and oil industries, involve the production, handling and use of hazardous substances, process intensification (PI) apparently offers to the plant managers many benefits such as safer, cleaner, smaller, and cheaper equipments.
Process Intensification could lead to a higher process flexibility, increased inherent safety and energy efficiency, distributed manufacturing capability, and ability to use reactants at higher concentrations. These goals are achieved by multifunctional reactors, e.g. reactive distillation or membrane reactors, and miniaturization that can be done by employing micro reactors and/or improving heat and mass transfer.
Within the benefits of process intensification with reference to process safety the following can be considered:
The use of process intensification can reduce the number of process operations, which leads to fewer transfer operations and less pipework, preventing source of leakages;
It can be easier to design a smaller vessel to contain the maximum pressure of any probable explosion;
For exothermic reactions, the enhanced specific surface area of intensified plants makes heat transfer, and thus heat removal, easier, minimising the triggering potential of a runaway reaction.
Process intensification has thus the potential to be a significant factor in the implementation of inherent safety practices Although safety can benefit from process intensification, it should be ensured that new hazards are not created.
This can be obtained applying at a early design stage the reliability and safety analysis that are traditionally used in process risk assessment.
In this paper in particular the above techniques are applied to a VOC (Volatile organic compound) treatment plant, comparing the traditional plant (a fixed bed reactor) to the intensified reverse flow reactor.
From the results of the application of a recursive operability analysis and the successive fault trees fully quantified, some conclusions are drawn from the point of view of the reliability of intensified processes and from the adequateness of risk assessment methodologies.

1. Introduction

Recently, a new philosophy for the equipment design is spreading among the chemical industry: the so-called "Process Intensification". This new approach has as main objectives the energy saving (Jachuck, 1997), the reduction of raw material employed, the space saving, the increase of the reliability and safety of the operators and the environment.
In order to reach these objectives, the equipment design developed new technologies and solutions, depending on the type of process: for instance, in the chemical industry were introduced new devices such as rotating disk reactors, or reactor heat exchangers. This kind of equipment allows to employ a reduced quantity of hazardous substances, and it is characterized by a restrained volume; as a consequence of the above-mentioned factors, the "PI" equipment can guarantee an higher level of safety than the tradition processes (Etchells, 2005).

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Thus, the equipment design based on “PI” also entails an increase of the complexity: a device developed with this methodology probably will have more moving elements, it will use new typologies of energy sources with an higher energy potential (such as microwave), and will be made of more fragile materials (for example a rotating disk realized in catalytic material).
The aim of this paper is analyzing the effect of the “Process Intensification” on the reliability of a VOC - Volatile Organic Compound - treatment plant, where the VOC is removed with a catalytic combustion. In order to evaluate the actual effect of “PI” on the reliability, a traditional equipment (a fixed bed reactor) is compared to an intensified equipments equipped with a reverse flow reactor. A Recursive Operability Analysis and a Fault Tree analysis fully quantified are applied to the processes analysed.

2. Process

The VOC contained in an inert stream is removed by a catalytic combustion. The process treats 5000Nm^3/hr and 0,001% of VOC.

2.1 Traditional equipment

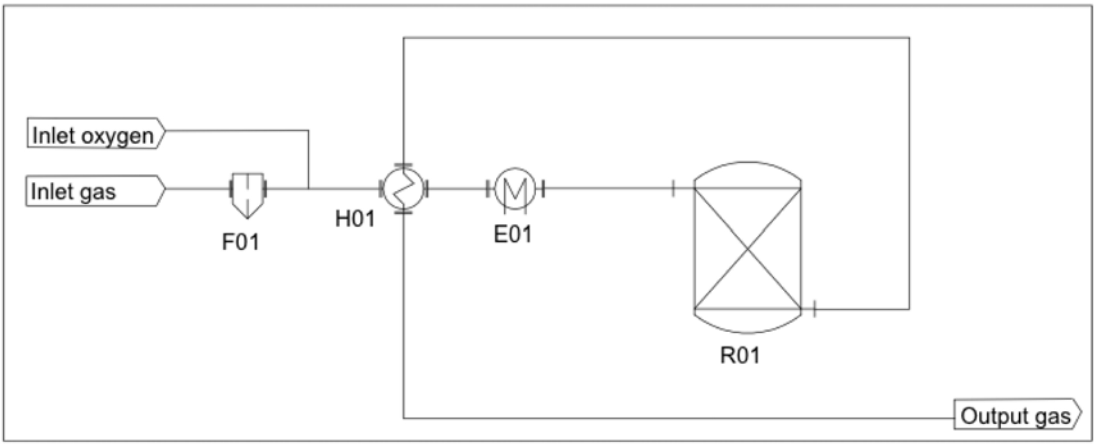

Figure 1: Flow scheme of the traditional plant

The traditional equipment (figure 1) employs a fixed bed reactor. The gas is filtered in (F01), in order to remove the solid particles that could be present in it; after the filtering, there is an addiction of oxygen, necessary to activate the catalytic combustion. Then the gas passes through an heat recover (H01), where it is preheated by the already treated re-circulated gas, and later it arrives at the electrical heater (E01), where its temperature is again increased in order to reach the reaction temperature. Finally the gas enters the reactor (R01), which contains the catalyst: here the VOC is removed with catalytic combustion. Before the exit, the treated gas is re-circulated through the heather (H01), in order to transfer its heat to the untreated gas.
This equipment is certainly simpler than the “PI” equipment, and it uses only ten alarms and one automatic protective system.

2.2 PI equipment

The same process developed with “PI” (Barresi, 2005) employs a reverse flow reactor (figure 2), which permits to save more energy compared to the traditional plant.
The gas enters the blower (B-01), where its pressure is increased; then it passes through the filter (F-01), which removes the solid particles contained in it. After the addition of the oxygen, the gas enters the reactor (R-01). In figure 2 it is also illustrated the heater (E-01), located on the gas line before the reactor, but in normal operational conditions this device is turned off, because the reactor does not need an higher gas temperature. The heater (E-01) is used only in the start-up phase, in order to lead the gas temperature to the adequate value for the reaction.

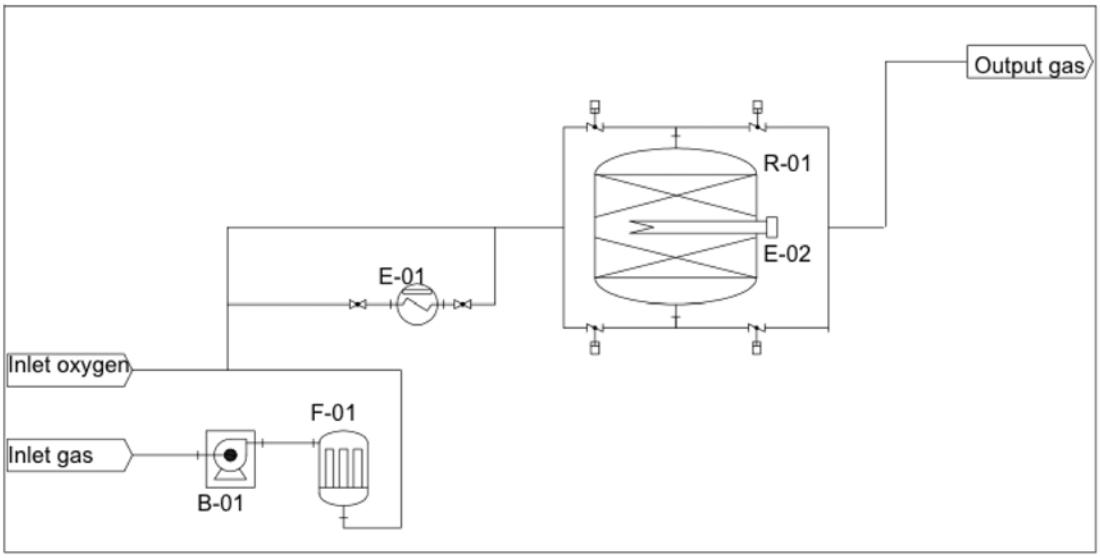

Figure 2: Flow scheme of PI plant

In the reactor (R-01), the gas, while passing through solid material, accepts heat from the hotter solid material. Thus, gas temperature rises while the solid material is cooled. Once the gas flow is sufficiently heated, catalytic reaction begins and, in the case of exothermic reaction like the VOC combustion, heat is released. After leaving the reaction zone, hot gas flow passes through outlet portion of the bed. Heat is transferred from the gas to colder catalyst. Cooled gas flow then leaves the reactor through a valve.
After the inlet portion has been sufficiently cooled, the flow is reversed and Phase 2 begins. The gas flow now enters catalyst bed from the side preheated during the previous phase. After reaction zone, it gives up heat energy to previously cooled portion of the bed and leaves the reactor through another valve. Periodical reversals of the gas flow help maintain the catalyst temperature at design conditions as long as enough heat is released by the reaction. Anyway, in the reactor (R-01) is located a small electrical heater, which can be used to heat and maintain in temperature the catalyst, if necessary.
In conclusion, the reactor is not characterized by a stationary level of temperature, but this is precisely the condition that permits the employment of a minor quantity of energy to heat the gas. Therefore, the adoption of the “PI” equipment means an higher energetic efficiency.
Obviously, this equipment requires an emergency system more complex than the traditional one: indeed it has about thirty alarms and ten automatic protective systems.

3. Method of Analysis

3.1 Recursive Operability Analysis

The operability analysis was carried on through the Recursive Operability Analysis - ROA (Piccinini, 1997), because of its clear logic processes and simplicity in obtaining the fault trees, compared to the traditional methods. In ROA it is possible to focus the attention on the process variables of higher concern; obviously the development of the analysis requires to consider also the deviations that can affect the process. The ROA methodology is described in Figure 3.
In ROA it is hypothesized a deviation of a process variable at a significant point of the plant, called “node” (Demichela, 2002)(Lees, 2001); the analysis considers what happen: are actuated protective devices? Can the deviation amplify? Is the deviation spreading to other nodes? Could the deviation cause a deviation of another variable? Answering to these questions, the ROA allows to identify the possible TOP EVENTS and all their possible causes, at any protective level.

3.2 Fault tree analysis

The following step is developing a Fault tree (FT) for any TOP EVENT identified by the ROA. The FT is a graphical representation of the sequence of events that conducts to the TOP EVENT. In this field, ROA is better than other operability analysis because is simpler to produce a FT starting from it (Piccinini, 1997).
On a FT is possible to carry out both qualitative analysis and quantitative analysis. The qualitative analysis consist in finding the quantity and dimensions of minimal cut sets; a minimal cut set is the minimal set of events occurring to obtain a TOP EVENT. The quantitative analysis permits to specify the probability of occurrence of a TOP EVENT (Demichela, 2003): this scope is achieved using the Boolean algebra and a probabilistic approach on reliability.

Nowadays are available software for the analysis of FT: in this case “ASTRA” was used, a software

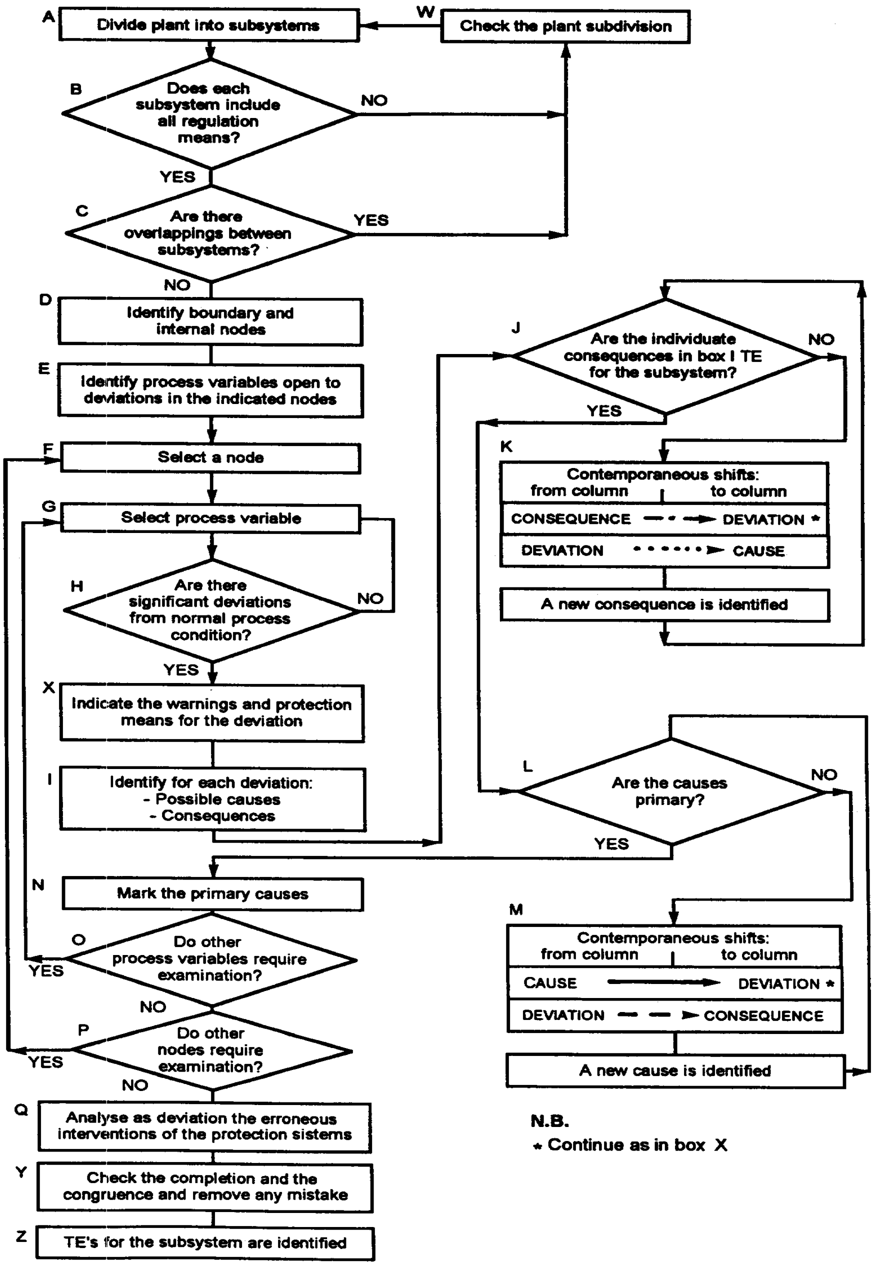

Figure 3: Scheme of recursive operability analysis

developed by the Joint Research Centre (Contini, 1997). "ASTRA" procures results both in qualitative analysis (number and maximal order of minimal cut set) and in quantitative analysis (probability to occurrence of a TOP EVENT).

4. Application of ROA and FT analysis

First of all, a ROA was developed both for the traditional equipment and the "PI" one, presuming variations on the temperature, the pressure, the concentration of VOC and the quantity of oxygen.
In both cases these possible TOP EVENTS were found:

- Failure of the reactor;
- Excessive VOC concentration in output;
- Sintering catalyst;

Only for the PI process, we identified another possible TOP EVENT:

- Release from the safety valve.

The failure of the reactor can happen when there is an exceeding pressure and the reactor is subjected to a loss of containment.
The excessive VOC concentration in output occurs when in the reactor the VOC contained in the input gas is not completely removed.
Sintering catalyst is caused by an uncontrolled temperature in the reactor, which destroys the catalyst.
Finally, the release from safety valve is due to an excessive pressure, that opens the safety valve and spreads the gas contained in the equipment. This TOP EVENT was identified only in the "PI" equipment because in the traditional one is not foreseen a safety valve.

4.1 Results of the analysis

After the ROA a quantitative analysis of the FT for the two equipments was carried on. In order to quantify it, the reliability data found in literature sources (Lees, 2001) were used, despite they were not very recent. On the other hand, the purpose of the analysis was to compare two possible designs, thus the use of not very recent data can be acceptable.

Table 1: Results of FT analysis

TOP EVENT	Traditional Plant	PI Plant
Overpressure in the reactor	$1.12 \cdot 10^{-3}$	$6.752 \cdot 10^{-5}$
Excessive VOC concentration in output	$1.74 \cdot 10^{-2}$	$6{,}57 \cdot 10^{-1}$
Sintering catalyst	$5.702 \cdot 10^{-2}$	$5.641 \cdot 10^{-5}$
Release from the safety valve		$4.801 \cdot 10^{-3}$

As it is possible to see in Table 1, the failure of the reactor turns out to be the less probable event, and in this case "PI" equipment shows a better outcome than the traditional plant. This result depends on the higher quantity of safety systems placed on the "PI" equipment, that could intervene in case of exceeding pressure in the reactor.
An excessive VOC concentration in output is more probable than the previous TOP EVENT, and this condition affects especially the "PI" equipment because of its more complex control system of the composition in output gas.
The TOP EVENT sintering catalyst is more probable in the traditional equipment plant; indeed the reactor of "PI" equipment is equipped with a more sophisticated temperature control system.
The release from a safety valve in "PI" equipment is identified as a probable TOP EVENT, but notice that the presence of this valve reduces the probability of a failure of the reactor.
In conclusion, Table 1 shows that obtaining the results above-mentioned in a "PI" equipment requires more safety system and alarms than in the traditional plant.

5. Comparison between system with similar safety system

The FT analysis revealed that the two equipments presented similar results of reliability, but in order to obtain these outcomes, the "PI" equipment needed a greater number of safety systems (interlocks and alarms). The presence of all these systems in a certain way hides the actual effect of the "PI" on reliability.

Table 2: Results of FT analysis in equipments with a similar safety system

TOP EVENT	Traditional Plant	PI Plant with reduced safety system
Overpressure in the reactor	$1.12{\cdot}10^{-3}$	$5.00{\cdot}10^{-1}$
VOC concentration excessive in output	$1.74{\cdot}10^{-2}$	$6.57{\cdot}10^{-1}$
Sintering catalyst	$5.70{\cdot}10^{-2}$	$5.70{\cdot}10^{-5}$

The table 2 shows that, bringing the protection system to the same level, the highest change in the probability of occurrence occurs for the TE “Overpressure in the reactor” in the “PI” equipment, because of the removal of the protection systems for the high pressure.
The other TOP EVENTS are not interested by relevant modification, because they depend on the temperature control in the reactor, which was the part of the “PI” equipment not modified.

6. Conclusion

The paper aimed at investigating the effect of Process Intensification on the safety and reliability of a system, although a general assessment of this effect could not be defined because of the great differences between the typologies of equipment developed with “PI”.
The results of the specific case study show that the increased level of complexity associated to the PI requires the use of more level of protection with respect to traditional plants. So, apparently, as far as safety and reliably are concerned, the Process Intensification appears to be less reliable. On the other hand, this is an incomplete point of view, which does not consider the positive effects of “PI” on the consequences of unwanted events, in terms of productivity, reliability and safety. .
In conclusion, the reliability assessment performed with traditional methodologies and not integrated with a phenomenological modeling, is not sufficient to demonstrate the advantages of “PI”.. In order to improve the quality of the results, it is necessary to perform an integrated analysis, which should take into account also transient behavior.

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