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Dynamic Simulation of Disturbances Triggering Loss of Operability in a Biogas Production Plant

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In the recent years, the biogas industry is rapidly growing, but the sector has been affected by several major accidents related to its supply chain, which pointed out the need to perform a detailed process safety analysis. Hazards and operability analysis (HazOp) is one of the most used and efficient technique for the identification of potential accidents, but its main limitation is the qualitative nature of the results. This study aims to override this limitation by supporting HazOp study using a dynamic simulator, which is able to reproduce deviations and operational failures in a typical biogas production plant, in order to help in the quantification of HazOp results and to improve safety and reliability of the process.
The main result of the study is the maximum biogas production rate that can be safely handled by the system under normal conditions and then the maximum rate that can be allowed if some safety barrier (though correctly designed) should fail has been evaluated too. The most critical failure identified is a malfunctioning in the pressure relief system of the digester, because under this condition, the maximum biogas production rate that can be reached is about 2/3 of the corresponding value for a properly working system.

1. Introduction

Over the last 15 years, producing biogas from anaerobic digestion as a form of energy from renewable sources has become more and more common in Europe and worldwide (EurObserv'ER, 2014; REN21, 2015). For this reason, biogas sector experienced a fast growth, in terms of number of related facilities and installed capacity: in 2014, in the sole Europe, nearly 8 GW of energy have been produced from biogas (REN21, 2015). Unfortunately, this increasing trend has been accompanied by an even faster increase in the trend of major accidents related to biogas supply chain (Casson Moreno et al., 2016; Casson Moreno and Cozzani, 2015). The analysis of the accidents revealed several risk and operability issues with biogas production. From the process safety stand point, the majority of biogas production plants are medium to small scale, therefore not regulated by the Seveso III Directive (2012/18/EU); ATEX (2014/34/UE) and D.lgs 81/2008 are requirements only. On the other side, anaerobic digestion for biogas production entails some complex biological reactions (Findeisen, 2015), causing hazards and operability problems in facilities that usually are not managed by personnel familiar with biotechnological processes and generally are poorly trained in process safety aspects (Saracino et al., 2016). The overall outcome was the need for ad hoc hazard identification and operability studies specific for biogas facilities.
There are several consolidated hazard identification techniques, such as checklists, Failure Mode and Effect Analysis (FMEA), What-if analysis etc. Among them, Hazard and Operability study (HazOp) (Center for Chemical Process Safety - CCPS, 2008). HazOp study is recognized as one of the most used and frequently modified methodology for process safety analysis, but its main disadvantages are its time-consuming nature (mainly due to different expertise required for its correct application) and the qualitative nature of the results (Pasman and Rogers, 2016).
The progress in computer technology has created possibilities to eliminate or reduce the disadvantages of conventional techniques for process hazard analysis (Dunjó et al. 2010, Janošovský et al. 2016). Process simulation is hardly a new concept, but has been adopted in process engineering for decades. Traditionally,

simulation could be classified into two types, steady state simulation and dynamic simulation, with the latter deemed as the more powerful and versatile engineering tool in process engineering and also for safety examination, several examples for its use for study of operational failure of chemical process has been documented (Pannocchia and Landucci, 2014, Ramzan and Witt, 2007).
The goal of the presented paper is to support HazOp analysis that has been performed on a typical biogas production plant from anaerobic digestion, using dynamic simulation environment, including use of Aspen HYSYS v8.6 process modelling to determine the effects of operational disturbances on the entire system and its safe operating limits.

2. Methodology

Hazard and operability (HazOp) studies have become a significant part of the design of new process plants and of the revision of existing plants in the process industry (Center for Chemical Process Safety - CCPS, 2008). The HazOp analysis systematically identifies all the possible causes and consequences within the system for each hypothesized deviation of one of the variables of the process: the research is carried out applying a set of qualitative guidewords (such as 'No', 'less', higher, 'instead') to the process variables of the plant and determining all process variable deviations.
On the other hand, the design and optimization of a chemical process involves the study of both its steady state and dynamic behaviour. While in steady state energy and material balances are solved to evaluate different plant scenarios, with dynamic simulation, we can confirm that the plant can produce the desired product in a manner that is safe and easy to operate. By defining detailed equipment specifications in the dynamic simulation, we can verify that the equipment will function as expected in an actual plant situation. With dynamic analysis, we can design and test a variety of control strategies before choosing the one that may be suitable for implementation, and examine the dynamic response to system disturbances and optimize the tuning of controllers.
The idea is to represent the plant and part of its control and safety system within a dynamic process simulator (Aspen HYSYS), which should be able to simulate dynamically deviations previously identified in a HazOp analysis, taking also into account the possibility of failure in single equipment or protection system. Thus possible effects of these deviations can be rigorously quantified and operational safety limits identified.

3. Description of the reference scheme and simulation

The most typical configuration of a biogas production plant, which consists of a single digester with internal desulfurization unit where the biogas is produced, has been selected as a reference case study (Figure 1). The size of the plant and its operating conditions, reported in Table 1, are those typical of a 1 MW production plant (Scarponi et al., 2016, 2015).

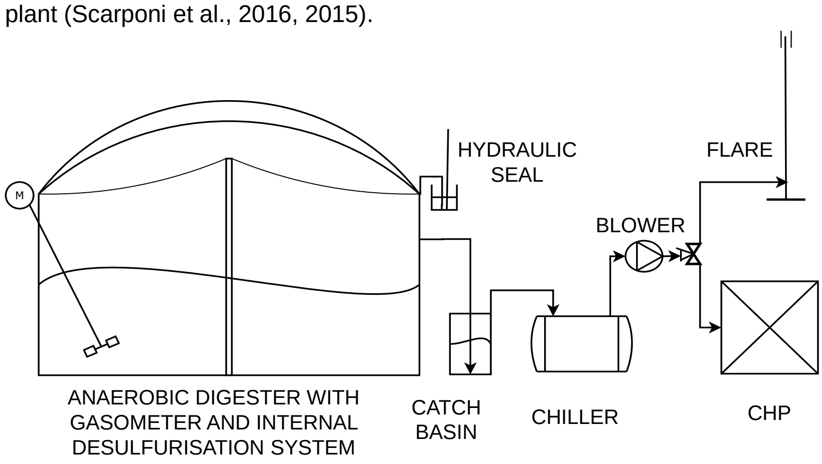

Figure 1. Block diagram of the biogas production plant used in the dynamic simulation.

HazOp analysis performed on this configuration, showed that the most important deviations in process variables may lead, to an abnormal increase in the biogas production rate, which in turn causes an increase in the pressure inside the digester (and in the downstream units), if equipment and/or protection systems should fail, as schematically shown in Figure 2.

Table 1: Operating conditions for the biogas production plant used in the dynamic simulation.

Process variable	Digester	Blower	Dryer
Flow rate [Nm^3/h]	300	300	300
Biogas inventory [m^3]	900	N.R.	N.R.
Temperature [°C]	47	47	15
Pressure [kPag]	1	2	2
Composition [CH_4/CO_2]	60/40	60/40	60/40
H_2S [ppm vol]	200	200	<100
Piping max. diameter [m]	0.150	0.150	0.150

Pressure increase should be limited through three different systems:
1. the basic pressure control acting on the valve before the Combined Heat and Power unit (CHP valve), which should be automatically switched from 60 % to 100 % opening when the digester pressure is greater than 1 kPag;
2. the flare, whose valve is completely opened when the pressure reaches 2 kPag;
3. the hydraulic seal directly installed on the vapour space of the digester, which starts relieving the gas at 4 kPag (maximum head of 6 kPag) in order to keep the pressure below the safety threshold of 8 kPag.

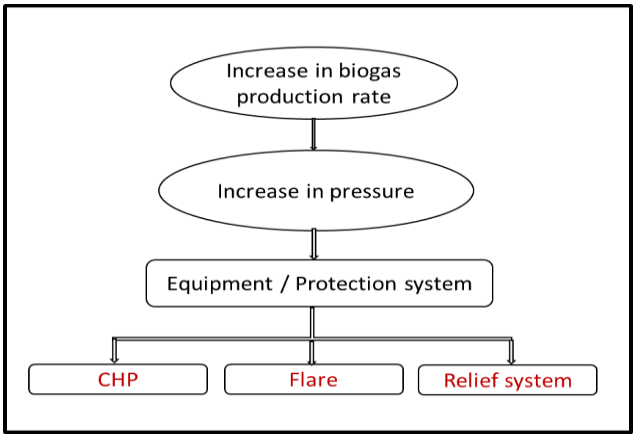

Figure 2: Schematic description of the analysis.

The plant and part of its control system has been reproduced within the simulator, by means of the scheme shown in Figure 3. Since the biogas produced (B-G out) is saturated with water it passes through an underground pipe, simulated as a cooler (E-102), to reduce the humidity. The condensate is separated in a separator (Sep1) and dumped out using a pump (P-100) actuated by an on-off level controller, while the biogas is further cooled in a chiller (E-100) with a temperature controller where the condensate is separated in a second separator (Sep2) and dumped out through a valve (VLV-103) actuated by another on-off level controller. The dry biogas is then sent to the CHP unit through a blower (K-100). The nominal operating conditions for the production plant are presented in the Table 1.
The content of the digester is simulated using two streams (Gas_feed and water_in). Gas_feed stream is also used to simulate the biogas production rate and can be freely manipulated thanks to the controller FIC-100. Cooler E-101 is used to simulate the coil that recirculates water for heating purposes. The plant has three level controllers to maintain the level inside the vessels (Digester, Sep1, and Sep2), and two temperature controllers to maintain the temperature of the Digester and of the second separator (Sep2).
The first system to protect the digester against overpressure is simulated through PIC-100 controller, which switches the CHP valve from 60 % to 100 %. The second measure is simulated by the on-off controller DIG-100, which activates the flare valve (VLV-102) that sends the biogas to torch. The third measure is the hydraulic seal, which is simulated as a relief valve (RV-100) with a set pressure of 4 kPag, a full open pressure of 6 kPag, and an orifice area of 800 mm^2, calculated in order to relief the nominal biogas production rate when all the remaining systems should fail.
The plant will be analysed at two operational levels. At the first level (Case 1), it will be analysed without failure in any equipment (CHP valve and protection systems), while at the second level (Case 2, Case 3, and Case 4), failure of single equipment or protection system is considered.

In all the cases, the increase in biogas production is simulated through a ramp (after 20 minutes of normal operation) in order to obtain more realistic results. The flow rate linearly increases from the nominal value to the maximum allowable flow rate that can be handled by the system without explosion of the digester, which is assumed to occur when the pressure inside the digester reaches the design value (8 kPag).

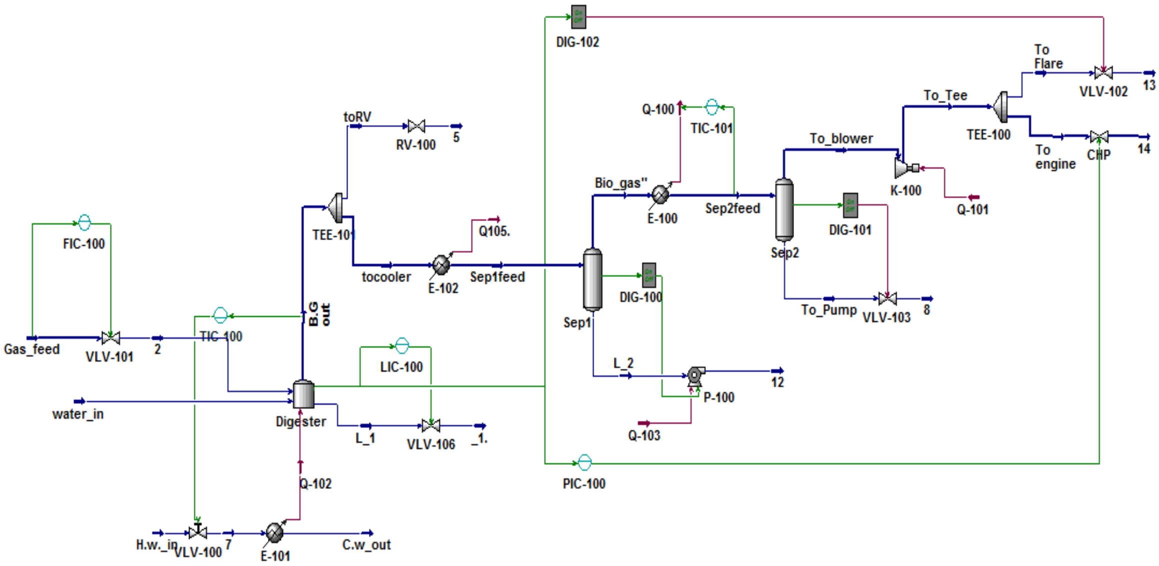

Figure 3: Process flow diagram of the plant representation within the simulator.

3.1 No failure in any equipment or protection system (Case 1)

The flow rate start increasing until it reaches 310 Nm^3/h (after 5 minutes from the ramp start), when the CHP is switched to 100 % opening. The flare (VLV-102) is activated after 11 minute, when the flow rate reaches 353 Nm^3/h and the relief valve (RV-100) starts opening after 19 minute, at flow rate of 437 Nm^3/h, until it becomes fully open at a flow rate of 779 Nm3/h, after 51 minute. The maximum allowable value for the biogas flow rate is found to be 886 Nm^3/h (see Figure 4a) because the digester pressure floats around 8 kPag but does not exceed this limit value (Figure 4b).

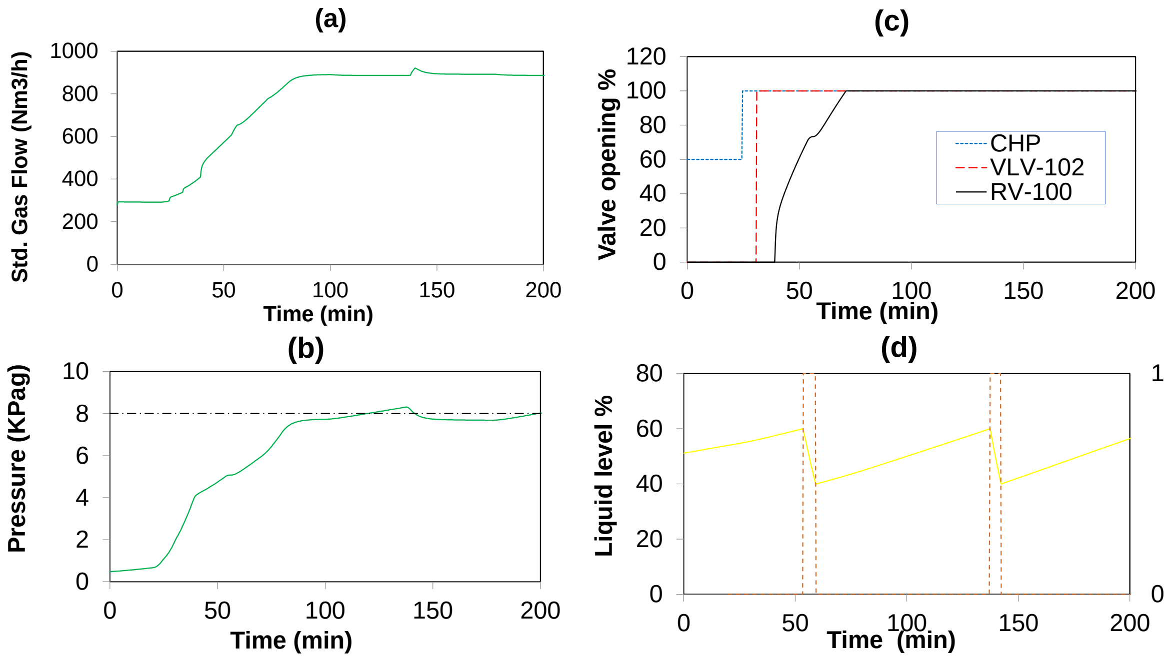

Figure 4: Results of Case 1: a) biogas production rate, b) digester pressure, c) valves opening, d) liquid level in Sep1.

3.2 Failure in one equipment or protection system (Cases 2 to 4)

The same disturbance (ramp increase in the biogas production rate) has been applied to other three situations (summarized in Table 2), in which one item has been considered has failed during the deviation.

Table 2: Summary of the main result of all cases studied.

Item	Case 1 Flow rate (Nm3/h)	Case 1 Time (min)	Case 2 Flow rate (Nm3/h)	Case 2 Time (min)	Case 3 Flow rate (Nm3/h)	Case 3 Time (min)	Case 4 Flow rate (Nm3/h)	Case 4 Time (min)
CHP	310	5	Failure		310	5	310	5
Flare	353	11	activated manually		Failure		353	11
RV-100 (start open)	437	39	364	14	418	18	Failure	
max. allowable flow rate	886	n.r.	660	45	850	60	602	35

From the analysis of the time at which 8 kPag is reached (Time To Failure of the digester) reported in the last row of Table 2, it is clear that the most critical situation is when the relieving system (hydraulic seal) is not available (Case 4), because the time required before digester failure is only 35 minutes.

Under these conditions, the CHP is switched to 100 % opening after 5 min, as for Case 1. The flare (VLV-102) is activated after 11 minute but, since the hydraulic seal fails to let the gas flow out, when the flow rate reaches the value of 602 Nm^3/h (after 35 minute), the pressure increases up to 8 kPag and over causing the failure of the digester (see Figure 5).

Similar conclusion with different Time to Failure can be obtained for Cases 2 and 3, being the latter, reproducing a failure of the flare, the less critical because the system can withstand up to 1 hour of biogas flow rate increase.

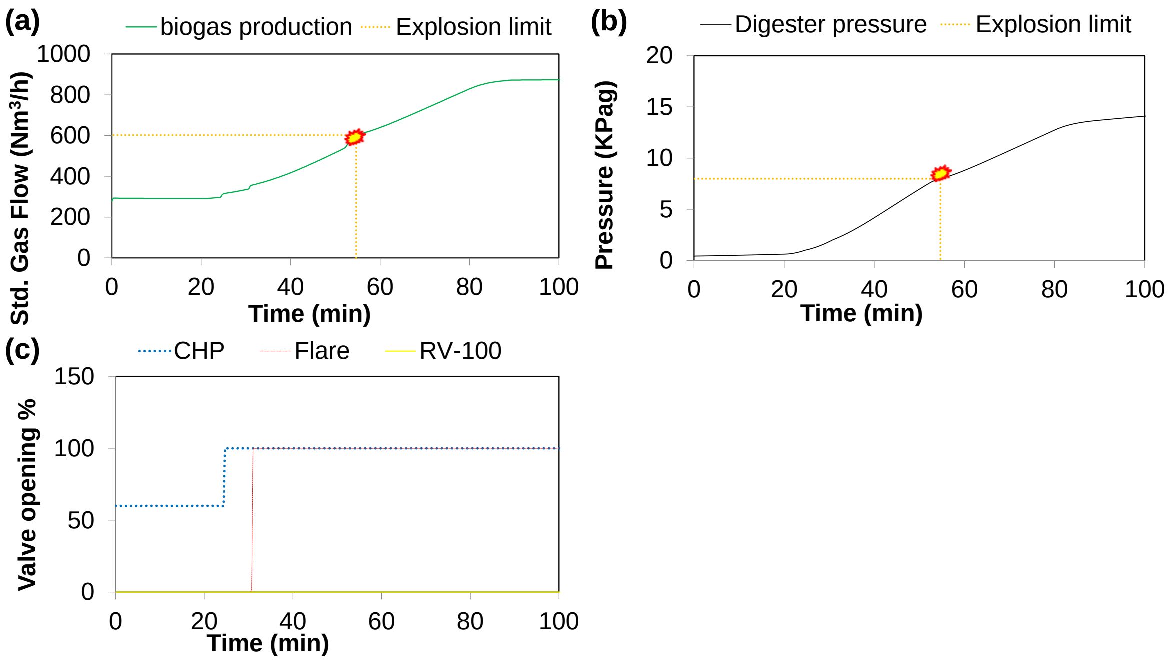

Figure 5: Results of the Case 4 "failure in relief system" (a-biogas production rate, b-digester pressure, c-valve opening).

4. Conclusions

The results of the plant analysis show that when all equipment and safety barriers are properly working, the system could handle about three times the nominal biogas production rate and the system reaches a sort of steady state within the safe operating limits, i.e. below the design pressure of the digester (explosion pressure). When a failure in a single equipment or safety barrier is considered, the most critical situation is when the hydraulic seal is out of service, because the system could handle only about two times the nominal biogas production rate before reaching the design pressure of the digester after approximately 35 minute.

When the CHP is stopped (or its valve failed closed) the flare should be manually opened (e.g. during maintenance) and the system can handle about 2.3 times the nominal biogas production rate before reaching the design pressure of the digester after approximately 45 minutes. A failure in the flare system seems to be safer, since the system is still able to handle about three times the nominal production rate, even if after 1 hour the digester failure pressure will be anyway reached.

As a general result, this study showed that dynamic simulation is a powerful tool to analyse disturbances and operational failures in a process plant, being in the quantification of deviations only qualitatively identified in a typical HazOp study.

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