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ENERGY RECOVERY IN AN ITALIAN OIL REFINERY BY MEANS OF A HYDRAULIC POWER RECOVERY TURBINE (HPRT) INSTALLED IN A H_2S REMOVAL PROCESS

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ABSTRACT

Industrial and chemical plants, especially oil refineries, are highly energy-consuming plants. Several energy efficiency interventions are being currently performed: besides gas recovery solutions, also energy recovery in liquid flows can be applied. In this paper, a case study of an Italian oil refinery regarding the use of a Hydraulic Power Recovery Turbine (HPRT), which is installed in a Hydrogen Sulphide (H_2S) removal process from the Syngas produced by an Integrated Gasification Combined Cycle (IGCC), is analysed and presented. The real performance data of the process are discussed: on average, 353.4 t/h of liquid SELEXOL can be elaborated by the HPRT with 445.4 m of head. Finally, the recovered electrical energy on a yearly basis is equal to 2966 MWh, or 531 tons of carbon dioxide equivalent. The pay-back period of the intervention ranges indicatively between 6 and 9 years, depending on the discount rate.

Keywords: High Power Recovery Turbine; Oil Refinery; H_2S Removal; Energy Efficiency; Emission Trading System.

1. INTRODUCTION

The increase of the industrialized countries is leading to higher gas emissions that are harmful not only for the living beings, but also for the environment. Developed countries are currently pushing to decrease this emissions trend by signing different agreements, starting from the Kyoto protocol to the Paris one [1]. The use of new renewable sources and intensive energy efficiency programs in industrial sectors [2] are crucial to achieve this goal. This work focuses the attention on the energy recovery potential in chemical industries. Among them, oil refineries, where the crude oil is treated to obtain fuels and other derivatives, are the most energy consuming. Wu et al. [3] performed a study related to the optimization of both pumps stations and pipelines located between the storage tanks and the charging ones that feed the main chemical processes related to the production of crude oil derivatives. Comodi et al. [4] carried out a feasibility study on a flare gas recovery system inspecting its chemical analysis. Zhou et al. [5] developed a model able to optimize the use of the fuel gas system considering the behaviour of both pipelines and flow inside them. Up to now, most of the energy recovery applications were applied moreover on gases rather than liquids. In oil refineries, there are some chemical processes where liquids are involved and they can be used for energy recovery purposes.

Pumps-as-Turbines (PaTs) are pumps that operates in reverse mode with the aim of recovering part of the liquid energy content and converting it in mechanical power. PaTs are known to be a suitable alternative to conventional hydraulic turbines, mainly due to their lower cost and market availability. However, there is still a challenge on the prediction of both Best Efficiency Point (BEP) and performance curves when they operate in reverse mode [6]. Gopalakrishnan [7] and Wildner et al. [8] analysed the so-called Hydraulic Power Recovery Turbine (HPRT) technology: it partially supplies the pump of the same process with the recovered energy to lower its electricity consumption. Among the chemical processes, the Hydrogen Sulphide (H_2S) removal is fundamental to clean the Syngas produced by an Integrated Gasification Combined Cycle (IGCC). Moioli et al. [9] described the H_2S removal process and the use of the Methyl diethanolamine (MDEA) in CO_2 capture, leading to both higher performance of the IGCC plant and lower CO_2 emissions. At present, to the author's knowledge, there are no works in literature presenting real experimental data and economic analyses of HPRTs installed as energy recovery systems in H_2S removal processes- The real operating data of the flow of physical solvent, which is known with the commercial name

SELEXOL®, are presented together with the recoverable pressure and HPRT performance and a technical and economic study of this application is carried out.
Section 2 describes the HPRT technology and the H_2S-removal process using the SELEXOL® solvent. Section 3 presents the operating data of the process, in terms of mass flow rates and pressure drops, as well as the HPRT performance. Section 4 shows the energy saving potential deriving from the installation of this system. Also an economic analysis is carried out, considering capital, maintenance costs and the economic saving: the PayBack Period (PBP) of the investment is presented for three different discount rates. Finally, Section 5 reports the conclusions of the work.

2. ENERGY RECOVERY FROM LIQUIDS IN REFINERIES

2.1 HPRT technology

PaTs are taking the field mainly due to their cheapest cost and their large availability in the market compared with the traditional hydraulic turbines. In chemical plants, PaTs are named HPRTs because the machine operating in turbine mode, supplies mechanical power to another pump that is involved in the same process to reduce the electrical consumption of the overall system. Generally, the used HPRTs are multistage centrifugal machines because of the high liquid pressure that they have to exploit. HPRTs design is usually performed to grant the best performance in both pump and turbine modes. Some researchers studied different methods to increase their efficiency. Kim et al. [10] used an existing counter-rotating pump-turbine design to improve its efficiency using the Design of Experiment (DoE) methodology that was subsequently validated with Computational Fluid Dynamic (CFD) simulations. Wang et al. [11] designed a special PaT impeller with forward-curve blades to increase its efficiency in turbine mode.

2.2 H_2S removal process

The H_2S removal can be performed through i) physical or ii) physical-chemical absorption. In this case study, the first option is used, which is proportional to the partial pressure of the captured compound. Furthermore, the amount of the solution is proportional to the treated Syngas when a determined partial pressure is considered. The solvent can be regenerated by the means of three different processes: flashing, which is used to reduce the partial pressure of the captured compound inside the solvent, stripping and re-boiling to increase the temperature. In the physical absorption, the temperature is increased to reduce the solubility of the captured compound, while in the chemical one it allows to breakdown chemical bonds. In both cases, the captured compound is released at the same phase as it was absorbed, while the regenerated solvent is recirculated into the absorber. In the analysed oil refinery, the H_2S removal process is performed by a fluid called SELEXOL®, which is a physical solvent that has a high capability of capturing H_2S. Table 1 lists the properties of the SELEXOL® solvent.

Table 1: Properties of the SELEXOL® solvent [12]

PROPERTY	VALUE
Viscosity at 25 °C (cP)	5.8
Density at 25 °C (kg/m^3)	1030
Molecular weight (g/mol)	280
Vapour pressure at 25 °C (Pa)	0.097
Freezing point (°C)	-28
Boiling point at 101,325 Pa (°C)	275
Maximum operating temperature (°C)	175

2.3 H_2S removal efficiency

Another important aspect is the efficiency of the H_2S removal with SELEXOL®. In Italy, both industrial and chemical plants refer to a law [13] that limits the emissions of the most pollutant compounds in both air and marine environments; thus, the limit of the H_2S released by the analysed oil refinery must be lower than 5 mg/Nm^3 (3.33 ppm). The values of [13] refer to an amount of O_2 equal to 15% without considering water vapour; in addition, they are also evaluated as a weight ratio between the sum of the overall polluting masses released in the atmosphere and the sum of the gaseous volumes produced by the overall IGCC system. The limits of pollutant compounds refer to daily operating hours of the overall IGCC plant excluding start-up and the maintenance. In the analysed oil refinery, the daily averaged H_2S is equal to 4.91 mg/Nm^3 (3.27 ppm) with an H_2S efficiency removal of 99.97%, thus showing that emissions are below the imposed limit.

3. CASE STUDY

In this paper, a HPRT that is installed in an H_2S removal process of an Italian oil refinery is presented. The analysed process regards the H_2S removal from the raw Syngas produced by an IGCC plant. The H_2S removal unit consists on one absorber, a regenerator, a storage and drainage system. Figure 1 shows the H_2S removal unit scheme described in this chapter and used in the analysed oil refinery.

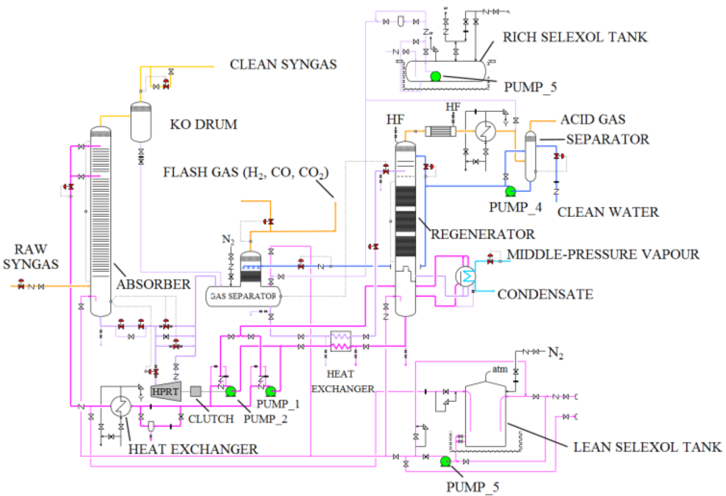


Figure 1: H_2S removal process

The absorber operates at high pressure (52 bar) and low temperature (40°C) because the solubility of the gases in liquids increases with the increase of pressure and the decrease of temperature, while the regenerator operates at low pressure (1 bar) and high temperature (100°C) to obtain the opposite phenomenon. The Syngas is sent to the bottom of the absorber and washed through the lean SELEXOL® that enter into the absorber from the top. The clean gas exits on the top of the absorber and reaches a KO drum where the dragging solvent is separated from the gas, which is subsequently sent to an expander of another unit. The amount of Sulphur (S_2) contained in the treated Syngas before reaching the expander is less than 50 ppm and it is continually monitored. Afterwards, the rich SELEXOL® exits on the bottom of the absorber and passes through a HPRT to lower its pressure from 52 bar to 7 bar. The HPRT replaces the PRV to decrease the pressure level of the SELEXOL® and to supply part of the mechanical energy to the feed pump (see Figure 1, PUMP_2), thus reducing its energy consumption. When the HPRT is not operating due to failure or maintenance, the pressure of the SELEXOL® is lowered by a PRV that bypasses the HPRT, reducing the risk of operational discontinuity. The rich SELEXOL® is heated up by a counterflow heat exchanger (it exchanges heat with the lean SELEXOL®) and subsequently sent to the regenerator. The enriched SELEXOL® enters the regenerator from the top and bumps into the vapours of the lean SELEXOL®, coming from the bottom of the regenerator, determining a countercurrent washing process. Due to the decrease of pressure and the increase of temperature, the solubility of H_2S decreases and it turns from liquid to vapour phase. The acid gas exits from the top of the regenerator and is condensed by a cooler, then they are routed to a gas-liquid separator. The liquid phase is sent to another IGCC process, while the gaseous one is directed to a Claus process for Sulphur recovery. The lean SELEXOL® coming from the regenerator goes through a heat exchanger where it decreases its temperature exchanging heat with the rich SELEXOL® and, by means of a pump (see Figure 1, PUMP_1 or PUMP_2), it is sent again to the absorber.

A tank of 300 m^3 is used as buffer for storing the lean SELEXOL®, whereas the drainages are collected in an underground tank.

3.1 SELEXOL® mass flow rate and pressure drop

The H_2S removal process is performed during the whole year, except when the unit is under maintenance. The unit operates for 340 days, which correspond to 93% of the entire year. During its operation, the mass flow rate between the absorber and the regenerator is monitored as Figure 2 shows, obtaining an average value of 353.3 t/h.

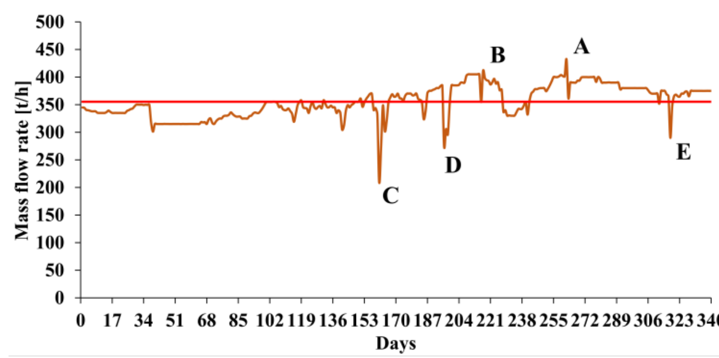


Figure 2: Available SELEXOL® mass flow rate

Figure 2 shows that the mass flow rate is quite constant and close to its average value, even though two high peaks of 432 t/h (+22.2% - A) and 411.1 t/h (+16% - B) together with three low peaks of 209.3 t/h (-40.8% - C), 274 t/h (-22.4% - D) and 296 t/h (-16.2% - E) were recorded. These outliers refer to unsteady or part load conditions and they correspond to the 1.8% of the occurrences, meaning that the influence on the average mass flow rate of SELEXOL® is minor. It is also important to study the trend of the pressure drop performed by the HPRT in order to evaluate the recovered hydraulic power. The trend of the pressure drop, corresponding to 445.4 m of average exploited head, is reported in Figure 3. Figure 3 shows that high- and low-pressure peaks of were detected in correspondence of the same peaks of mass flow rates depicted in Figure 2. The highest one is 456.1 m (+2.4% - G), while the lowest peak is equal to

325.4 m (-27% - A). Also in this case, these irregular operating conditions occur only in 12 days, corresponding to the 3.5% of the occurrences; thus, these peaks do not affect the evaluation of the average pressure drop considerably.

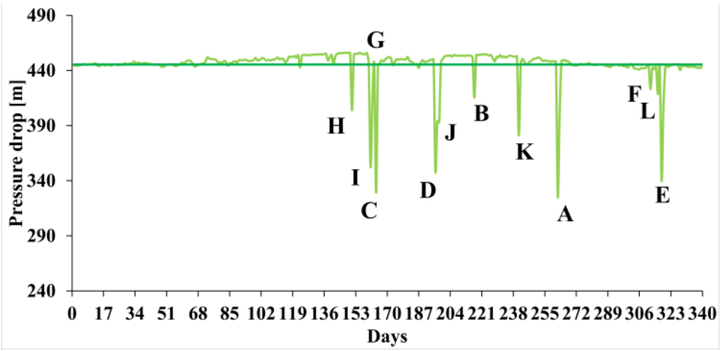
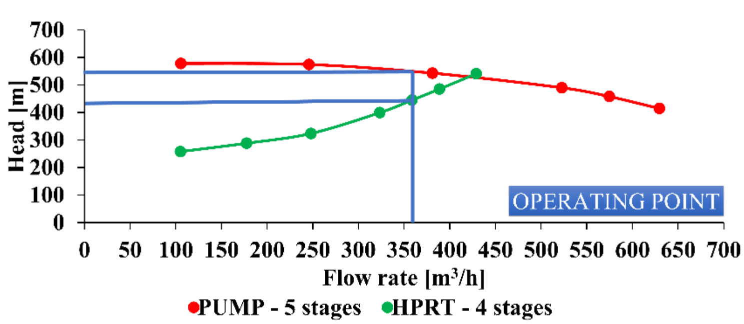


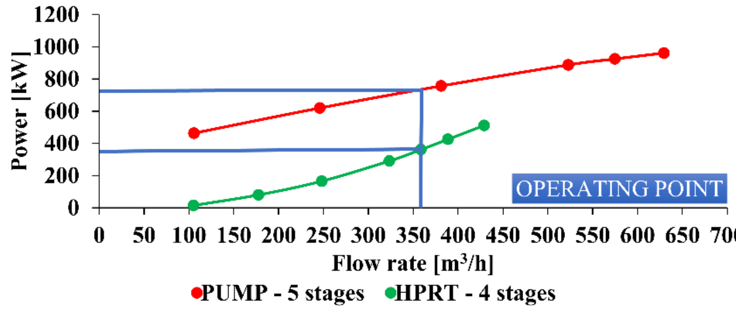
Figure 3: Available pressure drop

3.2 Pump and HPRT performance

Both process pump and HPRT were selected considering the average SELEXOL® mass flow rate and pressure drop as design values. Due to their high values, a pump and a HPRT with four and five stages, respectively, have been chosen. The HPRT has been selected using the results of the measurement campaign in terms of flow rate and pressure during the operating conditions. Figure 4 shows characteristic, power and efficiency curves of the feed pump (red) and the HPRT (green), respectively, with a highlight on the design operating points. Figure 4a shows the characteristic curve of the two machines. The vertical blue line refers to the rated operating conditions, corresponding to a flow rate of 345 m^3/h and a head of 445 m. Figure 4b shows the power required for feeding the pump and the power generated by the HPRT, which are equal to 756.7 kW and 361.4 kW, respectively. The HPRT supplies to the feed pump about 48% of its mechanical power requirement. Finally, Figure 4c shows the nominal efficiencies that are equal to 0.77 (pump) and 0.81 (HPRT-BEP), respectively.



a)



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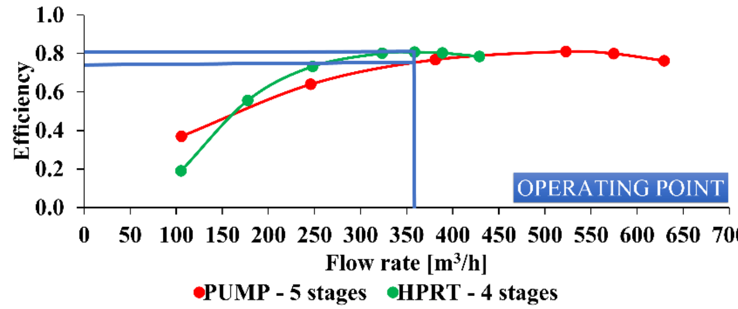

c)

Figure 4: Performance curves of pump (red) and HPRT (green)

4. RESULTS AND COMMENTS

In the previous section, the main data for evaluating the recovered mechanical power were reported. Considering an average SELEXOL® mass flow rate of 355.3 t/h, a pressure drop of 445.4 m and an operating period of the H_2S removal unit equal to 8208 h/year, the energy retrieved by the system was evaluated. A yearly primary energy saving of 10.3 TJ (205 Tons Of Natural Gas Equivalent) that can also be expressed as 233 TOE (Tons of Oil Equivalent) or 531 tons of CDE (Carbon Dioxide Equivalent) was recovered. In addition, the environmental benefit, in terms of emission trading system grant, was analysed. An amount of 495,000 tons of CDE was awarded to the refinery in one year and the allowances will be reduced to 446,000 tons of CDE in the following 2 years, according to the Italian legislation [13]. The energy efficiency improvements in oil refineries reported in this work represent a good practice to achieve this goal. Finally, energetic advantages were evaluated in 2966 MWh of recovered electric energy, considering the BEP operating conditions. In this study, also the overall economic saving was presented. In this evaluation, the considered costs are: i) the purchase of the HPRT and ii) the installation works considering piping, interconnections, civil, electric and engineering works; iii) an expense of 10,000 €/year for both utilities and maintenance. A contingency equal to the 5% of the total cost was considered. The costs were provided by the purchasing department of the refinery itself. Considering an electricity cost of 0.083 €/kWh, which is the electricity price payed by the oil refinery, the energy recovered by the system allows the company to save 246,178 €/year. Furthermore, CDE allowances were also considered in the cash flow analysis: with an average fee of 4.77 €/ton of CO_2 in the period 2012-2017 [14], an additional saving of 2532 €/year was reached. Finally, an overall economic saving of 248,710 €/year was obtained. The cash flow and the PBP of the investment, considering an expense of 10,000 €/year for both utilities and maintenance, which were parametrized using three different discount rates (7.5%, 10% and 12.5%), are shown in Figure 5. The PBP ranges between 6 years and 11 months and 9 years and 2 months.

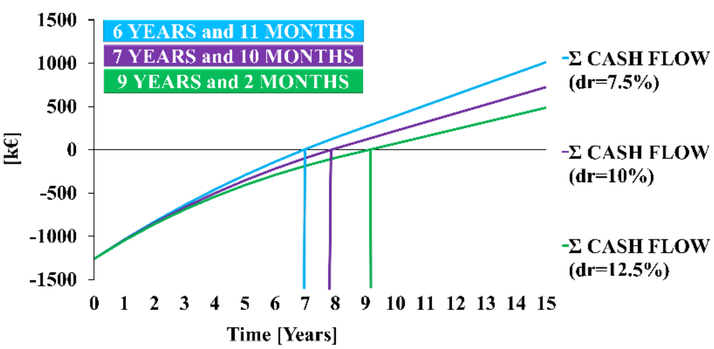

Figure 5: Cash flow trend and its PBP

5. CONCLUSIONS

In this paper, an energy recovery intervention in an Italian oil refinery related to the installation of a HPRT in a H_2S removal process is discussed. This solution regulates the liquid pressure and recovers a significant amount of energy. A HPRT is installed between the absorber and the regenerator and recovers part of the SELEXOL® energy content to lower the electric consumption of the feed pump used in the same process. Real operating data of the process are presented and the energy recovery performance is discussed. The HPRT exploits an average mass flow rate of 355.3 t/h and a head of 445.4 m, resulting in a power output of 349.3 kW and in an energy recovery of 2966 MWh. An economic saving equal to 248,710 €/year was obtained. Results show that the PBP ranges between 6 years and 11 months and 9 years and 2 months depending on the selected discount rates (7.5%, 10% or 12.5%).

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