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Structural improvement of a control valve to prevent corrosion in acid gas treating plant pipeline: An experimental and computational analysis

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ABSTRACT

A severe rupture of the carbon steel pipe next to a control butterfly valve caused a terrible explosion in real CO_2 removal plant of a petrochemical company. Using data from on-site acid gas treating plant, the valve shortcomings was investigated via experimental analysis and computational fluid dynamics (CFD) methodology. Six various valve degree openings from $\theta = 5^{\circ}$ to 60° was selected as the computational domains to clarify the link between localized corrosion thinning and the working fluid hydrodynamics. The high turbulence and rotational downstream flow can intensify the inhomogeneous deterioration of the surface in butterfly valve, due to its peculiar internal geometry. On this basis, an attempt was numerically made to improve the internal geometry of butterfly valve to avoid the high shear stress. Depending on the opening disk angle, the newly proposed model can reduce the wall shear stress by 20–90 times, that it is in favor of failure mitigation.

1. Introduction

CO_2 corrosion in gas sweetening process is one of the serious operational problems in CO_2 capture plants; it eventuates environmental damage and human hazards [1]. In this regards, carbon steels are the most commonly used pipeline materials in industrial areas; unpleasantly they are very prone to corrosion in environments containing CO_2 [2–5]. One of the reasons of corrosion damage in carbon steel pipes is high velocity and shear of fluid flow, which leads to abrasion of the protective surface layer [6]. In particular, flow-accelerated corrosion (FAC) referred to as erosion-corrosion (E-C), is defined as the processing of the accelerated degradation mechanism of metal because of the relative movement of a corrosive fluid over a metal surface [7–9]. The gradual loss of metal surface results in the wall thinning of piping. In this case, the wall surface of carbon steel piping gets involved the chemical oxidation and dissolves the oxide layer. As well as chemical oxidation, the mechanical erosion that includes the disruption of protective layers or droplet impingement on the oxidized pipe wall, causes the metal material loss [10]. The damage results of erosion-corrosion can cause early replacement of the line, resulting in great economic loss and accidents. The combined damage of E-C and interaction between them are very complex and are higher than whole influences of the processes acting separately [11–13]. Accordingly, it is difficult to determine the rate of material loss accurately and predict the lifetime of the equipment reliably. These effects cannot be modeled using any conventional electrochemical or mechanical approaches alone [14,15]. Many experimental variables can affect the synergistic damage mechanism of E-C such as flow rate, the composition of the structural material, chemistry of the flowing system, temperature, pressure, and pipeline design [16–18].

Even though in the past few years, extensive works have been performed on this issue, still, there has been limited works that have focused on the understanding of E-C interactions under realistic flow conditions. The portion of computational fluid dynamics (CFD) in simulating flow patterns in realistic industrial equipment and data reduction is proving fruitful [19,20]. In studies about the modeling of E-C, CFD techniques have shown great ability to improve the performance or prolong the service life of equipment which operates in the harsh working conditions [21–25].

Author's previous work [26] focused on assessing the corrosion behavior of activated MDEA (Methyl diethanolamine) solution in the background of CO_2 bulk removal in an ammonia plant, Kermanshah, Iran. Afterward, the hydrodynamic effect and velocity distributions on the corrosion characteristics were evaluated in an amine air-cooled heat exchanger (ACHE) via experimental investigations and CFD modeling by the current authors [27]. In the latter work, the developed numerical model provides the reasons for the erosion-corrosion damage at the tubes' inlet of ACHE. Continue with these studies; our research team was encouraged to start a new work to predict the corrosion reasons of a carbon steel pipe at downstream of a control butterfly valve in CO_2

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removal plant of a petrochemical company. As the control valve was exposed to the corrosion, the rupture of the pipe adjacent to the valve, lead to an unintended transfer of high pressure (30 bar) amine solvent and syngas to the environment. Unfortunately, the explosion of flammable gas caused economic damages and killed several staff members. Thereupon, studying this issue is of great importance to find an afterthought to avoid further risks. Recently, a solid particle erosion analysis of an actual butterfly valve has been reported based on the erosion theory by Bo Liu et al. [28]. Different parameters of butterfly valve including inlet velocity, particle mass fraction and solid particle diameter were separately investigated to simulate the main location of erosion and find the peak erosion rate.

This research attempts to investigate the effects of erosion-corrosion and fluid hydrodynamics to assess the E-C interactions inside the butterfly valve and its fitting including two pairs of reducer-elbow on both sides of it. To illustrate the observations, the chemical analysis of amine solvent and weight loss measurements were carried out to evaluate the material loss results of E-C processes and to determine the major mechanism influencing the synergism. CFD technique was also utilized to explore the link between the site of the corroded part in the reducer located in the downstream of the valve and the working fluid hydrodynamics. The geometrical modifications that would alter the flow pattern and alleviate the E-C problem were analyzed by CFD. Further, a novel distinct design was numerically studied for the internal geometry of butterfly valve to achieve uniform distribution of fluid flow in its downstream. Visual observations obtained from the photograph of the carbon steel damaged regions were applied to verify CFD results.

2. Experience from industrial plant

2.1. Process flowsheet

Unfortunately, many industrial failures in acid gas treating plants were reported; thus, purifying the fluids, separation of various components and eliminating undesirable species is very essential. The removal of H_2S/CO_2 (known as acid gases) using alkanolamine solvents as an absorbent is one of the oldest approaches to capture acid gases for purification and separation.

The CO_2 removal process with alkanolamine solvent of an ammonia plant in Asaluyeh, Iran is described in Fig. 1. Based on this figure, the amine-based gas sweetening unit was configured with absorber, T-2001, and stripper, T-2002. As shown, the raw synthesis gas, containing 17.7% by volume CO_2, is sent to the bottom of the absorber tower. A part of the CO_2 is removed by absorption process with MDEA and then the gas flow goes upward through the packed bed in this column. The rich solution is introduced to the flash vessel, T-2003, afterwards, it is regenerated in the stripper column. Two streams of lean solution arrive the absorber; one of them (38.4 bar, 48 °C) is pumped by P-2001 A, B, C to the top of the absorber and flows downward through the column. The CO_2 gas flowing upward through the packed bed column is selectively absorbed by this stream. The second stream of the lean solution (36.3 bar, 77 °C) arrives the middle of the absorber and moves downward flowing through this column for absorbing CO_2 from the gas. In fact, the gas treating unit has two loops of lean solution for a high quality of CO_2 absorption. This process results in a selective absorption of the CO_2 from the gas, since the ability of amine solution for absorption of CO_2 is very high. The rich amine solution (6.6 bar, 84 °C) enters the top of the stripper and flows downward through the beds. The stripper column operates at a pressure of 1.8 bar and temperature of 43 °C. Heating is supported by a reboiler (E-2002) with design heat duty of about 30.48 MW. The semi-lean solution that arrives from the stripper is pumped by P-2003 A, B to exchanger E-2004 and returns to the middle of the stripping section at the pressure of 7.2 bar and temperature of 114 °C (boiling point). The fully regenerated solution exiting from the stripper column at a temperature of 123 °C, arrives at lean/semi-lean exchanger E-2004 and is cooled to 65 °C by lean solution cooler, AE-2001. Then, it returns to the top of absorber column, where it is further cooled to about 48 °C. The CO_2 released from the stripping steam and rich solution exits from the top of the stripping column and pumped by P-2004 A, B to a quench cooler, E-2006.

To sum up, absorption and desorption are the common process in such unit occurring continuously during the circulation of amine solvent. However, corrosion has always been thought out as one of the significant operational problems associated with this process. Generally, amines are not intrinsically corrosive because of having high pH and low conductivity. However, they may become corrosive when they absorb CO_2 or H_2S [7,9,29]. This evaluation study focused on the reasons of corrosion at downstream of a butterfly valve (FV-2004 in Fig. 1), placed in the way of the lean solution that arrives at the absorber column.

2.2. Failure case description

The failure case is include a pair of reducer-elbow was joined to both inlet and outlet sides of a butterfly valve, FV-2004. The reducers and elbows were manufactured from carbon steel. The two utilized eccentric reducers have normal pipe size of 32 × 24 based on ASME/ANSI B16.9 (ECC model). Moreover, the elbow pipes have the same nominal inner diameter of reducers. The flange of the butterfly valve is fabricated from cast iron with a magnitude of 24 in 2000 Butterfly Valve-Bare Stem, Drawing number: VMC-2024/BS. During the unit operation, the amine solution flows through the upstream of the elbow-reducer, the butterfly valve and the other pair of reducer-elbow, respectively.

According to the amine plant report, a zone by the scale of 30 × 14 cm, at downstream of the mentioned valve, close to the junction of the reducer and the elbow, was ruptured. One sample of the damaged site in the elbow was removed from corroded pipeline during a unit turnaround, as shown in Fig. 2. Table 1 presents the operating condition and properties of the material flowing into the studied control valve.

3. Corrosion experiments

To accomplish the research objectives, this part of the study is focused on the experimental evaluation of the corrosion behavior of carbon steel in an aqueous MDEA solution.

3.1. Materials

The chemical composition of carbon steel, A-179, which was used as specimens in weight-loss measurements, is given in Table 2.

3.2. Weight-loss measurements

The weight-loss method was used to measure the corrosion rate (CR, mm $year^{-1}$) of carbon steel coupons at the end of 30-day exposure. The details of this method were introduced in author's previous works [26,27]. Moreover, the corrosion rate, CR (mm $year^{-1}$), is given by the following relation [26,27]:

$$CR = \frac{(m_1 - m_2) \times 365 \times 100}{\rho \times t \times A} \tag{1}$$

Where m_1 (g) is the mass of the specimen before corrosion, m_2 (g) is the mass of the specimen after corrosion, $\rho (g/cm^3)$ is the density, A (cm^2) is the total area of the specimen and t (h) is the corrosion time. To convert CR (mm $year^{-1}$) to milli-inch per year (mpy), the following equation was given [27]:

$$\text{Corrosion rate in mils per year (mpy)} = \text{CR(mm year}^{-1}) \times 40 \tag{2}$$