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Process Safety and Environmental Protection
Available online 29 August 2023
In Press, Journal Pre-proof What's this?

Techno-economic assessment of a proposed novel hybrid system for natural gas pressure reduction stations

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Received 4 March 2023, Revised 27 July 2023, Accepted 28 August 2023, Available online 29 August 2023.

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https://doi.org/10.1016/j.psep.2023.08.082
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ABSTRACT

To prevent Natural Gas (NG) frozen during pressure reduction process, a heater is contrived for preheating NG. In this study, a novel system is suggested to supply part of heat demand of a NG City Gate Station (CGS). The system consists of a heat pump in which the compressor input work is supplied by the turbo-expanders. In the proposed system, pressure reduction is carried out by turbo-expanders instead of Regulator Valve (RV) to recover the energy of high pressure NG. The recovered energy by turbo-expanders meets the heat pump cycle work demand. A CGS is selected as a case study, and the suggested system is assessed in terms of energy, exergy, and economics. The amount of the annual fuel savings is calculated 2.42×10^6kg (70.08%). Exergy analysis shows that the most exergy destruction occurs in the RV and heater. The exergy factor of the proposed system in the days that the system works, is about 2.2 to 5.1%. Based on the economic analysis, the value of simple payback period and discounted payback period are calculated 2.63 and 3.08 years, respectively. The annual revenue that comes from saving fuel is 310,000 $/year based on the current price of NG.

Introduction

In recent years, increasing energy consumption and the limited energy resources of fossil fuels have prompted researchers to study the efficiency of energy consuming systems and strive to optimize these systems. With the development of human societies, the need for available energy is increasing day by day (Alirahmi et al., 2021). The number and variety of required goods and services are growing, as a result, the trend of energy consumption has also increased. Consumption of fossil fuels leads to the release of pollutants and raises environmental concerns. Global warming due to the increase of energy demand is a major challenge for the world today. World energy consumption is projected to increase by 50% between 2020 and 2050 (International-Energy-Agency, 2021).

The importance of sustainable development and addressing climate change hinges on the reduction of fossil fuel energy usage. Earlier research has indicated that technological advancements offer significant potential in minimizing the consumption of fossil fuels for heating and power generation. An illustrative instance is the work of Dai et al. (Dai et al., 2019), which revealed that implementing a transcritical CO_2 heat pump system with dedicated mechanical subcooling for space heating in China could lead to a reduction of primary energy consumption from coal by 18-33% when compared to traditional coal-fired boilers. Additional studies have also emphasized the prospects of utilizing heat recovery, integrating renewable energy, and employing storage technologies to replace fossil fuels in both the building and industrial sectors.

Delivering natural gas (NG) to consumption areas is an energy consuming process as well as cost consuming. NG is transported from production to consumption points in various ways such as Liquefied Natural Gas (LNG), Compressed Natural Gas (CNG), and pipeline. In Iran, almost all produced NG is transported and distributed through the pipeline in three pressure classes of 1000, 250, and 60 psi from the gas refinery to consumption points. The main transmission lines with a pressure of 1000 psi are implemented outside urban areas, and at the entrances of cities. Due to safety considerations, the pressure of these lines is reduced to 250 psi. Finally, the NG pressure is reduced to around 60 psi to make it usable for domestic and some industrial applicants. This final pressure reduction is traditionally done using regulator valves (RVs), and comes with a severe temperature reduction. The process is carried out in a place called City Gate Station (CGS). The dramatic temperature drop due to the passage of NG flow through the regulator valve in most cases leads to gas freezing, which is also called the phenomenon of NG hydration. To overcome this phenomenon, the NG flow is firstly preheated before passing through RV (more details are presented in Section 2).

Lots of studies have been done to improve these systems. It is possible to categorize these studies into two general categories. The first category examines the possibility of improving the existing pressure reduction system in the CGS, such as improving the heater performance or using the waste energy of the heater (Ghaebi et al., 2018, Rahmati and Reiszadeh, 2019, Razavi et al., 2020). The second category proposes the idea of replacing the existing RV or heater by other equipment, such as using turbo-expanders and vortex tubes instead of the RV or using renewable energy sources (Arabkoohsar et al., 2015, Farzaneh-Gord et al., 2016) instead of the heater, or combining them with another system like Combined Heat and Power (CHP) systems to improve the overall performance. Many studies have used vortex tube instead of RV in CGSs (Ghezelbash et al., 2016, Guo and Zhang, 2019, Kargaran et al., 2013, nejad et al., 2022). Some studies have examined the possibility of using NG pressure energy for the NG liquefaction process (Pają착czek et al., 2020, Tan et al., 2016), hydrogen production (Ghaebi et al., 2018, Kowsari et al., 2020), and producing fresh water (Deymi-Dashtebayaz et al., 2021).

Several studies have proposed the combination of CGSs with the CHP systems (Arabkoohsar et al., 2017, Ebrahimi-Moghadam et al., 2020a, Shokouhi Tabrizi et al., 2021). In these systems, the waste heat of CHP system is used to preheat the NG in CGS. Li et al. (Li et al., 2019) investigated a power generation system using the energy released during the NG pressure reduction process and low-grade heat. An expander was used to recover the pressure energy of NG, and an organic Rankine cycle was utilized to retrieve the cold energy of NG and low-grade heat. Farzaneh-Kord et al. (Farzaneh-Kord et al., 2016) presented a CHP system combined with CGS. In their study, the effects of flow rate and pressure of NG flow on the system's operation were investigated thermodynamically and economically. They concluded that using the CHP system is more effective when it operates at greater power levels.

Utilizing turbo-expanders instead of conventional RVs is another way of energy recovery in CGSs. Replacing the RV by a turbo-expander causes a much more significant temperature reduction in the pressure reduction process due to the conversion of the pressure energy of gas into mechanical work. Various studies have been carried out on this topic. Kolasi´nski et al. (Kolasiński et al., 2017) investigated using rolling piston expanders to recoup the pressure energy of the NG during expansion in CGS. Among volume expander and turbine options for using instead of RV, they chose volume expander, because of its simplicity and cost effectiveness compared to the turbine. Farzaneh-Gord et al. (Mahmood Farzaneh-Gord et al., 2015) investigated using the reciprocating expansion engine in Town Border pressure reduction Station (TBS). They chose expansion engines over expansion turbines due to their ability to operate with wet NG flow. In another study, Farzaneh-Gord et al. (M. Farzaneh-Gord et al., 2015) optimized using this reciprocating expansion engine. Their findings indicated that employing expansion engines in TBSs, results in about 91% efficiency of pressure energy recovery. Badami et al. (Badami et al., 2017) presented a turbo-expansion system for a NG pressure reduction plant, that was paired with a CHP system fueled by rapeseed oil. Two turbo-expanders and a CHP system based on an internal combustion engine were used in this system. According to their results, although the proposed system was efficient from an energy perspective, it was not economically viable. Kostowski and Usón (Kostowski and Usón, 2013) suggested a combination of two-stage turbo-expander installation with a CHP unit and assessed its feasibility to apply for a case study in Switzerland. Both of these systems generate electricity, and the recovered waste heat from the CHP system was utilized to preheat the NG before pressure reduction in turbo-expanders. Neseli et al. (Neseli et al., 2015) considered the possibility of using turbo-expanders instead of the conventional RVs at a CGS in Izmir, Turkey. In their work, maximum energy efficiency for the system was determined to be 94.96%, while maximum exergy efficiency was determined to be 70.61%. Borelli et al. (Borelli et al., 2018) studied the integration of pressure reduction station equipped with turbo-expanders with low temperature heat sources. Two arrangement were proposed in their study: high and low temperature arrangement. The results illustrated that low temperature arrangement could attain greater energy efficiency than high temperature one, reaching additional energy savings of roughly 14%. Zabihi and Taghizadeh (Zabihi and Taghizadeh, 2016) proposed two different scenarios to use turbo-expander instead of regulators. In the first scenario, one turbo-expander was installed instead of two RVs, and in the second scenario, one turbo-expander was installed in place of one of the two RVs. According to the economic analysis, the second scenario has a shorter payback period than the first. The total annual electricity production and the payback period for the proposed system were calculated to be 3.2 GWh and 12.9 years, respectively. Cascio et al. (Lo Cascio et al., 2018) investigated using turbo-expanders instead of RVs in CGSs to generate electricity. Taheri-Seresht et al. (Seresht et al., 2010) proposed four scenarios for using the turbo-expander in Tehran CGS. In the best scenario, the exergy recovery and payback period were calculated as 96% and 2 years, respectively. Yaxuan et al. (Xiong et al., 2018) investigated using a single screw expander to recover the pressure energy of NG pressure reduction in a station with inlet and outlet pressure of 6 to 1 bar. An air-source heat pump unit that works with electricity is used to preheat the NG before expansion. Golchoobian et al. (Golchoobian et al., 2021) investigated use of turbo-expanders to recover the energy from NG pressure reduction in CGS. The proposed system uses this energy in a trigeneration system that produces power, refrigeration and freshwater.

The literature review reveals that various methods have been explored to recover wasted energy from regulator valves and reduce energy consumption during the preheating of natural gas flow in gas pressure reduction stations. One such method involves the use of a turbo-expander as a replacement for the regulator valve, enabling the recovery of the wasted energy. While most studies proposing the use of turbo-expanders have focused on electricity generation from the recovered energy, this approach comes with considerable costs related to equipment and electricity transmission to the grid. Moreover, electricity generation can be subject to instability due to fluctuations in inlet flow rate and pressure to CGS across different seasons.

The novel contribution of this research lies in the utilization of two turbo-expanders in combination with a heat pump cycle, replacing the conventional regulator valve and indirect heater. The work produced by the turbo-expanders directly drives the heat pump cycle, and the heat generated from this cycle is utilized to preheat the natural gas flow. Consequently, this innovative system significantly reduces the reliance on indirect heaters present in conventional stations, leading to substantial fuel consumption savings and, in turn, a notable reduction in greenhouse gas emissions.

To summarize, the primary innovations and objectives of this research are as follows:

- Propose an efficient, cost-effective, and environmentally friendly technique to utilize wasted energy from regulator valves and natural gas preheaters in gas pressure reduction stations. To achieve this, a novel configuration of a hybrid energy system is introduced, replacing conventional regulator valve and indirect heaters in gas pressure reduction stations.
- Develop a robust and accurate model to evaluate the feasibility of the proposed system. This model encompasses energy, exergy, and economic analyses. The application of thermodynamic principles, coupled with suitable assumptions, ensures a technical evaluation that aligns closely with real-world conditions.
- Demonstrate the practical viability of the proposed system by selecting a real case study, the CGS west of Mashhad in Iran, and employing actual data to illustrate the system's usability and benefits.

Section snippets

Description of the proposed system and conventional system

As mentioned, NG pressure reduction occurs in CGS, where a RV is typically used to reduce the pressure, which imposes a great deal of irreversibility to the system (Olfati et al., 2018). The flow's temperature drops along with the reduction in pressure because of the positive Joule-Thomson coefficient of NG (Farzaneh-Gord et al., 2020). At the low temperatures, due to the pressure and composition of NG, there is a possibility of undesirable gas hydrates formation in RVs and pipelines. Gas…

System modeling

In this section, a detailed modeling of the conventional CGS system and the proposed system is presented. The modeling of the presented systems includes energy, exergy, and economic analysis. The following assumptions are made in this work:

- Changes in kinetic and potential energies are neglected (because of negligible variations of the velocity and height between the inlet/outlet sections of the components) (Kowsari et al., 2020).…
- Pressure drops along heat exchangers and connecting pipes are…

…

Case study

The Mashhad west CGS is selected to examine the proposed system. The main information required to perform the necessary calculations and simulations in this study are the mass flow rate, NG inlet temperature, and inlet pressure in Mashhad west CGS over a whole year. These data have been recorded on daily basis (Farzaneh-Gord et al., 2012).

Fig. 4 shows the average daily inlet volumetric flow rate, pressure, and temperature in Mashhad west CGS. The inlet gas flow rate is increased through the CGS …

Validation

The modeling of HPC used in this study is validated with Kabul et al. (Kabul et al., 2008). The parameters used for this modeling are shown in Table 6. The results for the thermodynamic analysis are compared and are presented in Table 7. As it can be seen, the minimum and maximum values of relative deviation between the results are 0.3% and 3.34%. Also, the average of relative deviation from all of the evaluated parameters is 1.82%. These findings demonstrate that the modeling outputs have…

Results and discussion

The purpose of this section is to present the outcomes of the proposed CGS system's simulation. The fuel consumption in the heater of a conventional CGS can be decreased by the proposed CGS system, as was indicated in earlier sections. This reduction is accomplished by using turbo-expanders instead of RV and using the produced mechanical work to run a HPC that preheats the NG before the pressure reduction process.…

Conclusion

In this study, a system was proposed to reduce the fuel consumption in NG CGSs. The main idea of this study is to utilize the exergy lost in the RV of a CGS, in order to provide the required heating in the station. For this purpose, the use of turbo-expanders instead of RVs was proposed to generate some power. The generated power was then utilized to run a HPC. Part of the required heating in the station to preheat the NG stream was provided by the HPC. The proposed system comprises two…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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