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Energy and exergy analysis of natural gas pressure reduction points equipped with solar heat and controllable heaters

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ABSTRACT

In order to prevent gas hydrate forming, Natural gas has to be warmed up at natural gas pressure reduction point (usually called City Gate Station (CGS)) before pressure reduction takes place. The gas is warmed up using the bath type heater which burns the natural gas as fuel. Employing solar heat in CGSs had been previously proposed by the authors; however, there were two shortcomings in the previous articles. Firstly, the employed heater was not equipped with an automatic control system (instantaneous control could not be achieved) and secondly, the exergy destruction rate of the proposed system had not been compared with the conventional configuration of a CGS. This article presents the feasibility of employing solar heat storage system at CGSs equipped with controllable heaters. The proposed system is thoroughly evaluated in terms of fuel providence and exergy destruction rate and the results are compared with the conventional and the previous proposed configurations.

1. Introduction

Fossil fuels are the main sources of energy in Iran and their usage increases sharply. Burning fossil fuels has negative impact on the environment which makes the use of alternative energies an attractive option. Among the renewable energy sources, the sun is the most plentiful and available one. The radiated energy from the sun is about 3.8×10^{23} kW, of which, approximately 1.8×10^{14} kW is received by the earth [1]. This amount of energy is almost more than 7500 times the world's total annual energy demand [2].

Thirugnanasambandam et al. [1] presented various types of solar thermal technologies such as solar water heaters, solar cookers, solar driers, solar ponds, solar architecture, solar air-conditioning, solar chimneys and solar power plants. Solar collector is the most important part of solar thermal systems. The device receives the solar heat and transfers it to a working fluid (usually water or the mixture of water and glycerine) [3]. Kalogirou [4] introduced various kinds of solar thermal collectors and their respective applications.

As there is usually enough low temperature heat source in industrial places, the application of solar heating systems is not common in such places. However, some exceptions could be found in where there is not any waste heat (Baldini et al. [5]). Norton [6] presented the most common applications of industrial process heat such as the solar industrials and agricultural applications background and samples. Sharma et al. [7] reviewed solar energy drying systems consisting of passive and active solar dryers. Bal et al. [8] presented a review of solar dryers with thermal energy storage facilities employed in agricultural industry. Muthusivagami et al. [9] thoroughly reviewed solar cookers with and without thermal storage equipment. Muneer et al. [10] have studied the prospects of solar water heating for textile industry in Pakistan. Benz et al. [11] presented the planning of two solar thermal systems generating process heat for a brewery and a dairy in Germany. In the both systems, the solar systems yields were found to be comparable to the yields of solar systems for domestic applications or space heating. Through another research, Benz et al. [12] presented a study for utilizing non-concentrating collectors for food industry in Germany. Li et al. [13] quoted that simpler concentrating collectors with much less cost and facility can also be applied for those applications that lower temperatures and pressures are required relative to those essential for producing electricity.

Natural gas consumption in Iran is between 450×10^6 m^3/day for summer and 550×10^6 m^3/day for winter [14]. The natural gas is transported from refineries to consuming points by

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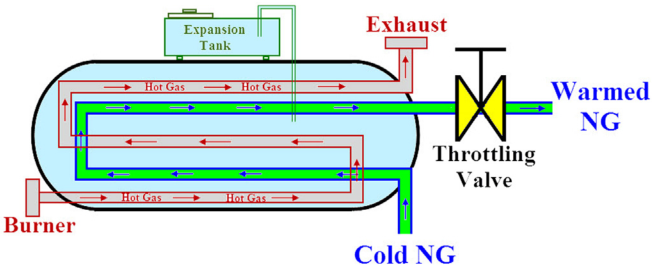

Fig. 1. A schematic diagram of a CGS.

transmission pipelines in Iran (and probably similar to other countries). The natural gas pressure in transmission pipelines is nearly 5–7 MPa. At consumption points such as power plants, big industries and the entrance of cities, the natural gas pressure has to be reduced. This pressure reduction is carried out in the CGSs, decreasing from 5–7 MPa to 1.5–2 MPa (1.7 MPa for the case study) [15]. There are about 2500 CGSs in Iran [14]. At present, the pressure drop is carried out by throttle-valves in all Iran's CGSs, where the constant-enthalpy expansion is accomplished and a significant value of energy is lost (Farzaneh-Gord et al. [16], Farzaneh-Gord and Magrebi [17]). The natural gas has to be warmed up before the pressure drop procedure to ensure that its temperature stays over the hydrate-formation zone and dew point, therefore, no liquid or solid phase condenses at the CGS outlet [18]. Indirect Water Bath Gas Heaters (line heaters) are employed in the CGSs to warm up the natural gas stream. The heaters consume a remarkable value of natural gas as fuel to provide the required heat.

As the low temperature heat is needed, a CGS is a suitable place to employ solar energy. Farzaneh-Gord et al. [19] have proposed a solar collector array in order to decrease the heater heating duty and the fuel consumption. Then, Farzaneh-Gord et al. [20] improved their previous proposed system by adding a storage tank. The line heater is also assumed to be not controllable so the heater burns a constant value of fuel during each day. In this work, the prior proposed systems by Farzaneh-Gord et al. [19,20] have been improved by adding a storage tank and a controllable heater. The storage tank can store energy during low heating demands and provide stored energy during high energy demand. On the other hand, the controllable heater produces heat exactly as much as the natural gas stream needs to approach the desired temperature. These features help the system to be much more beneficial than the previous ones. In order to prove the adequacy of the proposed configuration, Akand station which has been located in the north of Iran has been selected as the case study. Comprehensive energy and exergy evaluations have also been accomplished on the new/previous proposed systems to demonstrate the priority of the current proposed system.

2. The proposed system

2.1. The natural gas pressure drop station and energy demand

The natural gas is consumed at much lower pressure than its pressure through the transmission pipelines. Consequently, its pressure has to be reduced to a much lower level. The pressure reduction is carried out by throttling valves in CGSs. Fig. 1 illustrates a schematic diagram of a typical CGS.

High pressure natural gas enters the CGS with pressure $P_{NG\text{-}1}$ and temperature $T_{NG\text{-}1}$. The natural gas stream temperature generally depends on the environment temperature (T_o). The gas has to be warmed up before it passes through the pressure drop facilities to ensure that no condensation and hydrate forming happens at the CGS outlet where its temperature reduces to $T_{NG\text{-}3}$. The standard warmed gas temperature ($T_{NG\text{-}2}$) is about 30–55 °C.

The heat exchangers employed in the CGSs are usually named line heaters. As it could be seen in Fig. 1, the heater consists of four main parts, namely the shell, the fire tube, the gas coil and the water expansion tank. The heater shell environs the fire tube, the gas coils and water. The heat produced by the combustion through the fire tubes is transferred to the water and subsequently to the natural gas. Once the water is warmed, it expands and flows into the expansion tank which is placed on the top of the heater.

The heater heating duty and water temperature could be calculated by knowing the inlet and outlet natural gas temperatures and pressures as discussed below. Thermodynamic relations could help to calculate hydrate forming temperature (T_{hyd}) based on the natural gas compositions and the target pressure. The outlet natural gas temperature ($T_{NG\text{-}3}$) must be chosen 5 °C above the hydrate temperature [21]. Knowing $T_{NG\text{-}3}$, one could calculate the heater outlet natural gas temperature as follow [19,20]:

$$T_{NG\text{-}2} = \overbrace{T_{hyd} + 5}^{T_{NG-3}} + \Delta T_{tv} \tag{1}$$

In the above equation, $\Delta T_{tv}(=T_{NG\text{-}2}-T_{NG\text{-}3})$ is the temperature decline due to the pressure drop through the throttling valves. The amount of temperature decline depends on the inlet and outlet natural gas pressure and its compositions. As the output natural gas temperature is found (the output and input pressures are known), the heater heating duty could be found as follow [19,20]:

$$\dot{Q}_{gh} = \dot{m}_{NG}\left(h_{NG\text{-}2} - h_{NG\text{-}1}\right) \tag{2}$$

Since the natural gas transmission pipelines are buried in depth of 1.2 m, the natural gas temperature presumed to be equivalent to the soil temperature in this depth (Edalata and Mansoori, [22]). The soil temperature changes with the ambient temperature. Najafimod et al. [23] offered an experimental correlation for a simple and logical relationship between the environment and soil temperatures in various depths. Based on this report, the soil temperature in depth 1.2 m (or natural gas inlet temperature) could be calculated as below:

$$T_{NG\text{-}1} = T_{soil} = 0.0084T_o^2 + 0.3182T_o + 11.403 \tag{3}$$

The heater heating duty is generated by burning a portion of the natural gas stream as its fuel. Regarding the thermal efficiency of the heater (η_h), fuel consumption ($\dot{m}_f$) could be computed as follow:

$$\dot{m}_f = \dot{Q}_{gh}/(\eta_h \mathrm{LHV}) \tag{4}$$

In the above relation, LHV is the natural gas lower heating value. It is worth mentioning that the heater thermal efficiency encompasses the heater heat lost through its surface which is about 0.35%–0.5% of $\dot{Q}_{gh}$ [21]. Here, the heater thermal efficiency is presumed 0.4.

The gas flow through the heater coils which are immersed in water bath could be considered as an isothermal environment pipe flow, for which Incropera and DeWitt [24] proposed a relation as follow:

$$\frac{T_w - T_{NG\text{-}2}}{T_w - T_{NG\text{-}1}} = e^{Y}, \quad Y = \frac{-\pi D_{oc} L_c U_c}{\dot{m}_{NG} c_{pNG}} \tag{5}$$