Energetic, exergetic, environmental and economic assessment of a novel control system for indirect heaters in natural gas city gate stations

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Abstract

The energy consumption and greenhouse gases emissions in natural gas city gate stations are important issues in the natural gas industry. In order to improve efficiency, have a cleaner environment and achieve economic benefits, the present study aims to propose an optimal system for the indirect water bath heaters in natural gas city gate stations. The optimization procedure is carried out by designing a control system to gain an eligible discharge temperature for the heater based on the gas entry conditions to the city gate station. The controller calculates the temperature of hydrate formation in terms of passing gas pressure and gives this information to the torch of the heater for regulating fuel consumption. A comprehensive study is accomplished based on energy, exergy, environment and economic analysis for different pressure reduction stations. The results indicate that employing the proposed system decreases the amount of fuel consumption and greenhouse gases emissions along with increasing system efficiency. Analyzing the results reveals that using the proposed system leads to a maximum of 28.54% relative increment in the heater efficiency compared to the conventional system (at this condition, the heater efficiency of the conventional and proposed system is $\eta = 36.12\%$ to $\eta = 46.43\%$, respectively). Furthermore, with choosing a heater with a capacity of 100,000 SCMH, it is possible to reduce the pollutants emissions and total costs down to 142.6 tons per year and 3,671,000 \$ per year, respectively.
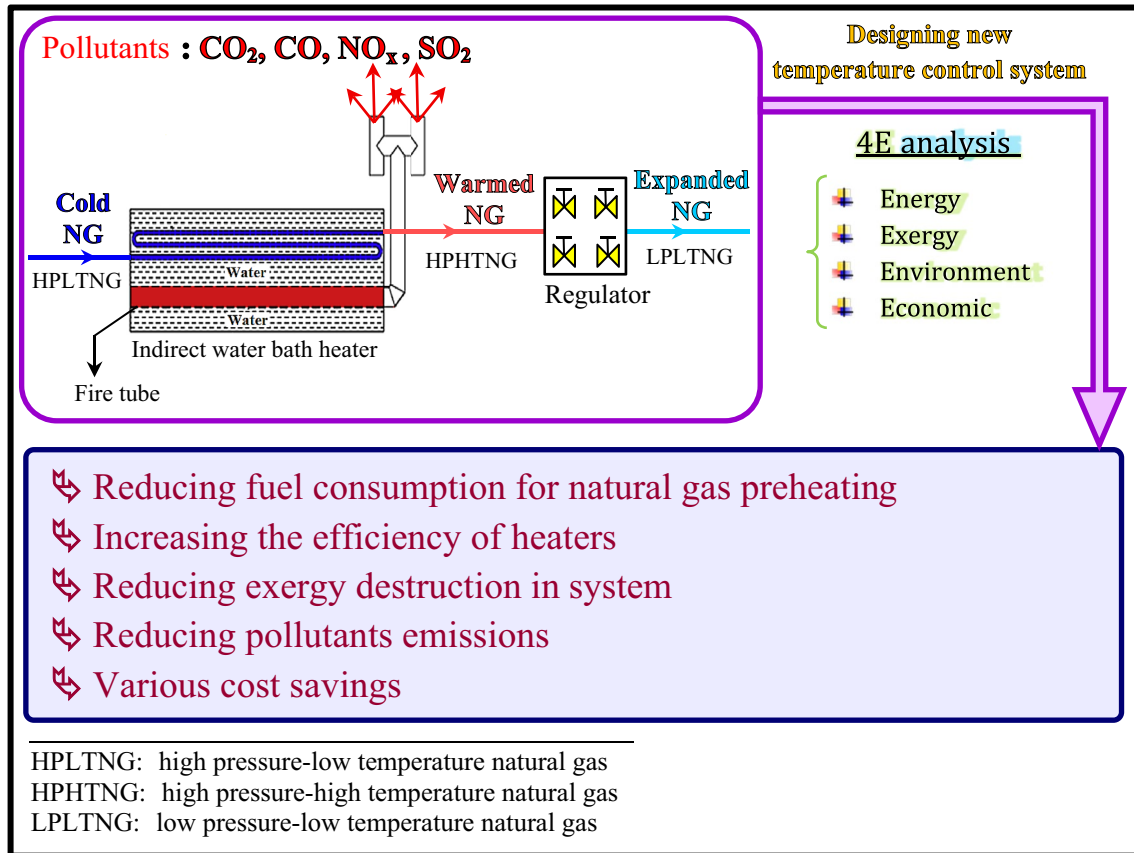
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Graphic abstract

Pollutants : CO_2, CO, NO_x, SO_2

Designing new temperature control system

Cold NG

HPLTNG

Indirect water bath heater

Water

Water

Fire tube

Warmed NG

HPHTNG

Expanded NG

LPLTNG

Regulator

4E analysis
- Energy
- Exergy
- Environment
- Economic

↬ Reducing fuel consumption for natural gas preheating
↬ Increasing the efficiency of heaters
↬ Reducing exergy destruction in system
↬ Reducing pollutants emissions
↬ Various cost savings

HPLTNG: high pressure-low temperature natural gas
HPHTNG: high pressure-high temperature natural gas
LPLTNG: low pressure-low temperature natural gas

Keywords City gate station · Water bath heater · Fuel consumption · Greenhouse gases emission · Techno-economic analysis

List of symbols

E	Exergy (J)
$\dot{E}$	Exergy rate (W)
$\bar{e}$	Specific exergy (kJ kmol^{-1})
g	Gravitational acceleration (m s^{-2})
h	Specific enthalpy (J kg^{-1})
$\dot{m}$	Mass flow rate (kg s^{-1})
P	Pressure (MPa)
$\dot{Q}$	Heat rate (W)
$\bar{R}$	Universal gas constant (J K^{-1} mol^{-1})
s	Specific entropy (J kg^{-1} K^{-1})
T	Temperature (°C)
t	Time (s)
$\dot{\forall}$	Volume flow rate (m^3 s^{-1})
v	Velocity (m s^{-1})
$\dot{W}$	Power (W)
y	Molar mass (–)
z	Height (m)

Greek symbol

η	Efficiency (%)

Subscripts

a	Ambient
des	Destruction
em	Pollutants emission
exh	Chimney exhaust
f	Fuel
g	Natural gas
gas1	Heater's inlet gas
gas2	Heater's outlet gas
in	Inlet
out	Outlet
w	Water
wbh	Water bath heater

Abbreviations

CGS	City gate station
CS	Cost saving

GHG　　Greenhouse gas
LHV　　Lower heating value
psig　　Gauge psi
SCMH　Standard cubic meter per hour

Introduction

Nowadays, natural gas is one of the most essential sources of energy in the world and this is the reason why remarkable advances are developed in wide knowledge fields associated with natural gas industry such as exploitation systems and transmission technologies [1–5]. On the other side, large amounts of greenhouse and pollutant gases are annually released from the natural gas industry into the atmosphere. Accordingly, optimizing the performance of different systems in the natural gas industry has attracted much attention due to the increasing demand for fossil fuels and also increasing the pollutants emission into the environment [6–9].

Investigating and optimizing the natural gas city gate stations (CGSs) from different points of view (such as energy, exergy, environmental and economic) are the most important concerns in the thermal and energy engineering fields [10–12]. Based on the thermodynamic principles, the exergy is the available energy which can be used while some part of the energy is lost due to the irreversibilities. Hence, lower exergy destruction leads to better system performance [13, 14]. In this regard, Olfati et al. [15] presented an energy- and exergy-based analysis for a CGS with a nominal capacity of 20,000 SCMH (standard cubic meter per hour) considering four seasonal strategies. Neseli et al. [16] investigated electricity generation from natural gas pressure reduction station. They considered a case study in Izmir (Turkey) and reported the energy and exergy analysis for their investigations. Mehdizadeh-Fard and Pourfayaz [17] provided an advanced exergy model for analyzing the heat exchangers of South Pars gas field in Iran. There are also some other published works around the importance of the exergetic analysis in different natural gas industries [18–20].

There are various technical stations in natural gas transmission systems (such as pressure intensifier or attenuator stations) at different points along the path, which in each of them a specific mission and procedure must be conducted on the natural gas stream [21]. In fact, after being exploited, in order to overcome high friction losses of long pipelines from refinery to consumption points, natural gas is injected into transmission pipelines and it is likely that there are pressure intensifier stations for achieving high pressure. Normal pressure in intercity distribution networks is around 6.9 MPa (1000 psi) in Iran; however, depending on the pipeline distance, this value may rise up to 9.3 MPa (1350 psi) [22]. Additionally, near utilization locations, this pressure must be regulated to lower values depending on its

application, e.g., domestic applications, in which the required gauge pressure of natural gas is about 1.7 MPa (0.25 psig), while in large-scale factories or power plants with combustion procedures the higher pressure levels are needed [23]. In both domestic and industrial usage applications, pressure attenuation mission is carried in a few steps as the first step, which is common in both parts, is performed through city gate stations (CGSs). In these stations, natural gas is expanded to pressure in the range of 1.4–1.7 MPa (200–250 psi) [24].

There are some auxiliary facilities in a CGS, like a separator (which filters natural gas from possible solid particles in the stream), a vain (in which unfavorable fluids along with natural gas stream are cleaned up), etc., which are located before the indirect water bath heater [25]. However, in its main part, high-pressure low-temperature natural gas enters an indirect water bath heater to be warmed up and then the high-pressure high-temperature stream enters the pressure reduction unit. The station outlet is now a low-pressure low-temperature one. It should be noted that no cooling procedure is carried out in pressure attenuation unit, and the natural gas temperature falls considerably as its pressure decreases because of its positive Joule–Thomson coefficient [26]. This is actually the main reason why the gas is heated up through a heater before the expansion procedure. In fact, depending on the conditions, there is a specific dead point in terms of minimum allowable gas temperature [27]. This dead point temperature is called hydrate-forming temperature where water droplets suspended in natural gas start to change in state from liquid to solid. These micro-scale solid particles are called hydrate crystals, and they may obstruct the gas stream to flow fluently through the pipeline [28].

Numerous studies could be found in the literature focused on doing various kinds of optimizations in CGSs. These optimizations are conducted based on different terms such as modifying conventional configuration of the CGS, decreasing its water bath heater heating duty and employing renewable energy sources to supply the required heat of natural gas before expansion procedure. The following part presents a summary of the most important previous studies in the field. In one of the first efforts, Najafimoud et al. [29] developed a correlation for calculating the inlet natural gas temperature of CGS as a function of ambient temperature as the pipeline comes out from a depth of 1.5 m to the ground. Akhlaghi et al. [30] used renewable resources to improve the fuel consumption of the heaters and to prevent the high loss of temperature. They offered solar heaters that prevent relative gas hydration and also predicted a payback period of 6 years for their proposed system according to the investment costs. Khalili and Heybatian [31] measured the data such as gas flow rate, fuel consumption of the heater and temperature of the natural gas, and using the measured data, they found that the heater efficiency of Shahrekord station (in Iran) is near 47%. Riahi et al. [32] optimized the combustion efficiency

of indirect water bath heaters (case study: Ardabil CGS). The results of their work showed that by using barometric damper and regulation of burner, a reduction in heat losses as well as an increase in efficiency can be occurred. In one of the recently published works, Ghaebi et al. [33] proposed a system for power and hydrogen production by recovering the waste heat of CGS. They utilized 4E analysis for their proposed system. Saadat-Targhi and Khanmohammadi [34] proposed a new system for producing electricity in CGS. They also utilized genetic algorithm optimization method for presenting the optimal conditions of their proposal. Li et al. [35] proposed a new system for generating electricity in CGSs based on the low-grade heat sources. They developed a comprehensive thermo-economic model of their system and applied multi-objective optimization.

Employing various renewable energy resources for this goal has also been another debate over the recent years. In this respect, Farzaneh-Gord et al. [36] employed the flat-plate collectors in a series array to provide a portion of the required heat in a typical CGS. In the second step, they promoted their previous suggested configuration by adding a solar storage tank in order to enhance the solar module efficiency [37]. This solar-based system was later revised by Farzaneh-Gord et al. [38] with modifying the method of solar heat injection into the system. In another work, Arab-koohsar et al. [39] changed totally the conventional configuration of CGSs by replacing the throttling valve by a turbo-generator set to produce power and equipping the water bath heater with a solar thermal system consisting of flat-plate solar collectors and a shell and tube heat exchanger.

Although all of the aforementioned studies lead to important achievements, benefits and outcomes, there are still some shortcomings. The main common drawbacks of the proposed systems are that they are only applicable for CGSs supposed to be constructed in the future, and they are also so costly in terms of initial investment required. Based on the previous studies, the natural gas pressure passing into pipeline has a significant impact on determining hydration temperature. Ashouri et al. [40] proposed an equation for determining the minimum temperature required for heating gas in the indirect heater with using Peng–Robinson (PR), Soave–Redlich–Kwong (SRK) and AGA8 equations of state based on natural gas pressure.

Annually, a large amount of GHGs and pollutants have been emitted from CGSs into the environment. Besides, in conventional systems, which are used for heaters in CGSs, the temperature of the outlet gas from heaters (to prevent freezing gas) is set to a certain amount without considering the effect of seasonal variations (i.e., a mechanical system is used to control temperature). However, in the actual situation, this temperature depends on the condition of the gas entering the heater. Consequently, it is necessary to propose

a novel, efficient and cost-friendly system for controlling the gas temperature in CGSs during the pressure reduction process. To overcome this deficiency, a novel electronic control system has been proposed in the present investigation which by using it, the inlet gas to the CGS heater is pre-heated in accordance with the requirement (based on the conditions of the gas entering the heater). The proposed control system in CGSs causes a significant reduction in fuel consumption and pollutants emissions. Furthermore, this novel approach can be used in all CGSs (because it works according to the conditions of the gas entering the CGS). As the first study in the field, the results of this study are analyzed based on four points of view: (1) energy analysis, (2) exergy analysis, (3) environment analysis and (4) economic analysis. Comparison of fuel consumption, efficiency and different pollutants released into the atmosphere (CO_2, CO, NO_x and SO_2) and cost saving between conventional and proposed systems is made. One of the significant merits of this scheme is that it can be applied in existence CGSs and ones which are going to be built.

The proposed system

Pressure drop station of natural gas

The natural gas is consumed at a 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 process is carried out by throttling valves in CGSs. At CGSs, during the reduction in gas pressure, a severe drop in temperature is also occurred, which leads to the freezing of the throttling valves and the interruption of the gas flow. Hence, indirect water bath gas heaters, which are known as line heaters, have been used in CGSs for pre-heating the natural gas to prevent the freezing of gas. Figure 1a illustrates a schematic diagram of a typical CGS, and Fig. 1b depicts the internal image of an indirect water bath heater used commonly in CGSs. As shown in Fig. 1b, the heaters are comprised of various components including the heater shell, the fire-tube, the gas coil, the water expansion tank and chimney. According to the figure, the heater consists of a fire-tube coil ending to the exhaust and a multi-pass natural gas coil that both of them are plunged into hot water provided by super-hot combustion productions flowing through the fire-tube coil. In fact, at first, the heat is transferred to the water from the fire-tube and then from the hot water to the natural gas stream.

Problem statement and system description

This work focuses on modifying the fuel consumption pattern of CGSs as the primary objective; afterward,

Fig. 1 a CGS schematic; **b** the internal image of a typical indirect water bath heater
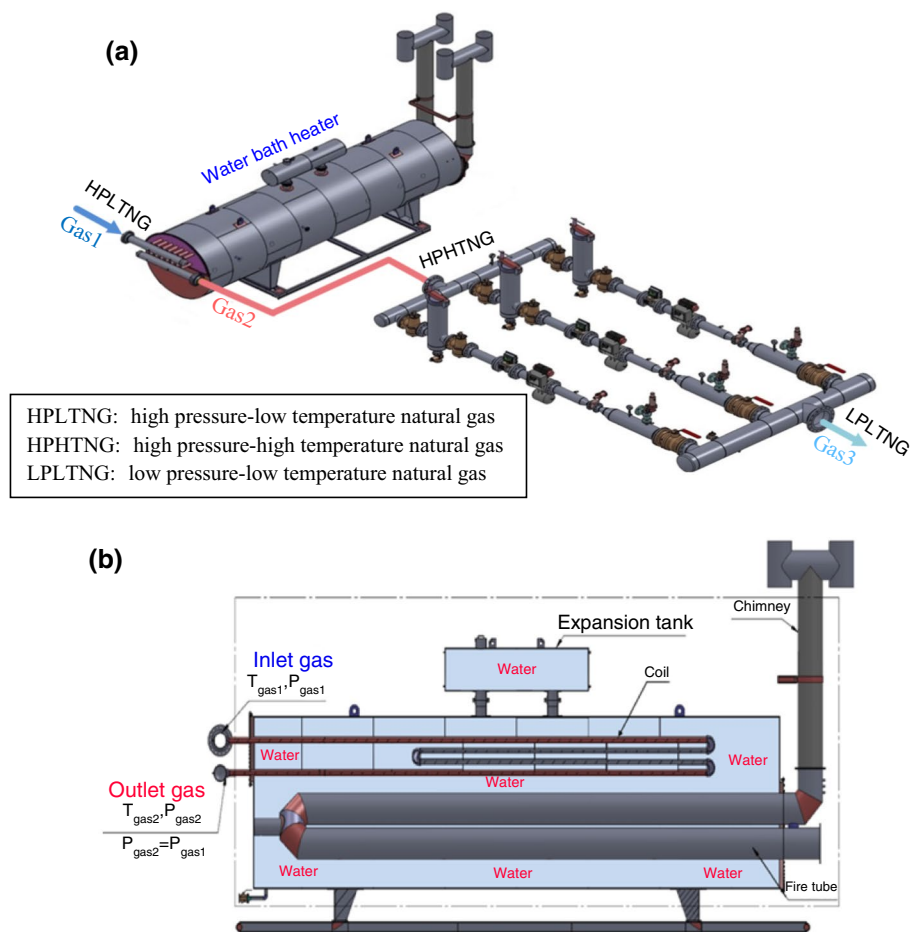
improvements in system efficiency, environmental issues and costs are investigated. The target control volume to analyze this system is the indirect water bath heater.

In conventional systems that are used in CGSs, a mechanical system detects the gas temperature in order to avoid the freezing of gas. Therefore, it has been designed for the worst condition and only when the temperature of the gas reaches a special point, the fuel flow is cut off (e.g., temperature of the thermostat in coil output is regulated on 38 °C in Iran). It means that the heater works and consumes fuel until the entering gas into it does not reach this predefined temperature, while there are many different climates and extreme changes in ambient temperature in Iran (and anywhere else).

In the present study, a novel electronic control system is proposed to overcome this deficiency. As it was said in the previous section, due to the existence of the mechanical detection systems on fuel line and the problems mentioned, an electronic system for detecting temperature and pressure is recommended instead of the conventional mechanical systems. ETI (electrical temperature indicator) and EPI (electrical pressure indicator) sensors, which recognize temperature and pressure, respectively, are considered for this purpose.

With installing electronic sensors on input and output of the heater and connecting it to fuel line control box, the electronic and mechanical systems are applied as a parallel system. In the mechanical system, the thermostat (which detects gas temperature) cuts off passing gas flow with reaching its temperature to 38 °C, and then input flow into the valve related to end of the line is closed. Given that this valve is usually a closed type, it causes the main fuel line cutoff.

Several studies have been conducted to determine the exact hydration temperature of natural gas. As noted before, Ashouri et al. [40] proposed an equation for determining the minimum required temperature for heating gas into indirect heaters based on natural gas pressure to avoid gas freezing. This correlation was developed based on a wide dataset with high accuracy ($R^2=0.997$) which is presented as [40]:

$$T_{gas2} = 9.83 + 3.24P_{gas1} \tag{1}$$

where P_{gas1} is the pressure of the inlet gas into the heater and T_{gas2} is temperature of gas heated in proportion to the pressure required for it not to be frozen in the regulator. As mentioned previously, in conventional mechanical control systems, which are used for the heaters in CGSs, the amount

of T_{gas2} is assumed to be constant based on the worst condition. But, in the novel electronic control system proposed in present work, T_{gas2} is considered as a function of the inlet gas conditions. (The condition of the gas entering the heater is also dependent on the weather and environmental conditions.)

Pressure electronic sensors installed on the input and output parts of the heater recognize any changes in pressure, and the required temperature is calculated according to Eq. (1). Following that, command of cutting off is given to the solenoid, which is installed on the second valve in the mainline, so fuel flow to the torch is stopped.

In comparison with the conventional systems, using the proposed system has many benefits such as reducing the energy consumption, reducing the GHG/pollutant emissions into the atmosphere and cost saving. Figure 2a presents a schematic diagram of the proposed controller for the fuel line of heater, and Fig. 2b shows the process flowchart of proposed and conventional systems.

In this study, the effect of the heater capacity and pressure is investigated on the various energetic, exergetic, environmental and economic parameters. For achieving this goal, the structural details of such a heater should be known. Depending on the CGS capacity, the heater capacity may vary from 10,000 to 100,000 SCMH. Dimensions of the heaters are shown in Fig. 3. Besides this, the specifications of heaters including dimension, heat capacity and minimum required heat transfer area (coil surface area) are presented in Table 1 [41]. The pressure in any CGS varies between 4.8 MPa (700 psi) and 6.9 MPa (1000 psi) [40, 42, 43]. Finally, it should be noted that the heaters in CGSs work in 7 months of the year (from October to April) [40, 42, 43].

4E modeling of the proposed system

Computing required fuel for heat production to prevent hydration

In this section, a comprehensive mathematical modeling for the energy and exergy performance of the control volume is presented.

For energy analysis of the heater, as the first step, the inlet natural gas temperature through the heater (T_{gas1}) should be calculated. It is a function of ambient temperature (T_a) and is given as [43]:

$$T_{gas1} = 0.0084T_a^2 + 0.318T_a + 11.403 \tag{2}$$

According to the standard API-12K, the required heat ($\dot{Q}_g$) for the natural gas stream in high pressures is calculated as [44]:

$$\dot{Q}_g = 109.8 \times \dot{m}_g \times \left(h_{gas2} - h_{gas1}\right) \tag{3}$$

in which $\dot{m}_g$ is the natural gas mass flow rate, and h_{gas2} and h_{gas1} are the specific enthalpy values of natural gas at the outlet and inlet of the heater, respectively.

Evidently, taking the heater thermal efficiency and the fuel lower heating value (assuming LHV of the natural gas equal to 38,500 MJ m^{-3} [45]) into account, the amount of instantaneous required fuel ($\dot{\forall}_f$) to provide the required heating demand is calculated by Kargaran et al. [46]:

$$\dot{\forall}_f = \frac{\dot{Q}_g}{\eta \times LHV} \tag{4}$$

Energy and exergy analysis

Energy balance is the most important equation for any thermodynamic analysis, and exergy is an important definition of the second law of thermodynamics which can determine the maximum obtainable work in a material or energy stream. The energy balance and exergy equilibrium for each system are described as Eqs. (5) and (6), respectively [47].

$$\dot{E}_{in} - \dot{E}_{out} - \dot{E}_{des} = \frac{dE_{system}}{dt} \tag{5}$$

$$\sum_k \dot{Q}_k - \dot{W} + \dot{m}_{in}\left(h + \frac{v^2}{2} + gz\right)_{in} - \dot{m}_{out}\left(h + \frac{v^2}{2} + gz\right)_{out}$$
$$= \frac{dE_{system}}{dt} \tag{6}$$

where $\dot{E}_{in}$ and $\dot{E}_{out}$ are the rate of input and output exergies, $\dot{E}_{des}$ is the rate of exergy destruction, and $\frac{dE_{system}}{dt}$ describes the rate of changing exergy over time in the system.

As shown in Fig. 1a, the CGSs consist of two main parts: indirect water bath heater (for pre-heating the natural gas) and regulator (for pressure reduction process).

The heater is considered as a steady flow system, and exergy equilibrium for it is defined as Eq. (7) [48]:

$$\dot{E}_{des-wbh} = \sum_k \left(1 - \frac{T_a}{T_k}\right)\dot{Q}_k - \dot{W} + \sum_{in} \dot{m}E_{wbh} + \sum_{out} \dot{m}E_{wbh} \tag{7}$$

where T_a, $\dot{E}_{des-wbh}$, $\dot{Q}_k$, $\dot{W}$, $\sum_{in} \dot{m}E_{wbh}$ and $\sum_{out} \dot{m}E_{wbh}$ are ambient temperature, exergy destruction of the water bath heater, exergy transfer by heat transfer work and eventually exergy transfer by mass in input and output ports, respectively. In Eq. (7), the amount of exergy transfer accompanying work is assumed to be zero. With considering these assumptions, E (exergy flow) is described as [49]:

Fig. 2 **a** A schematic of the proposed controller system for fuel line of heater; **b** process flowchart of current and proposed control systems
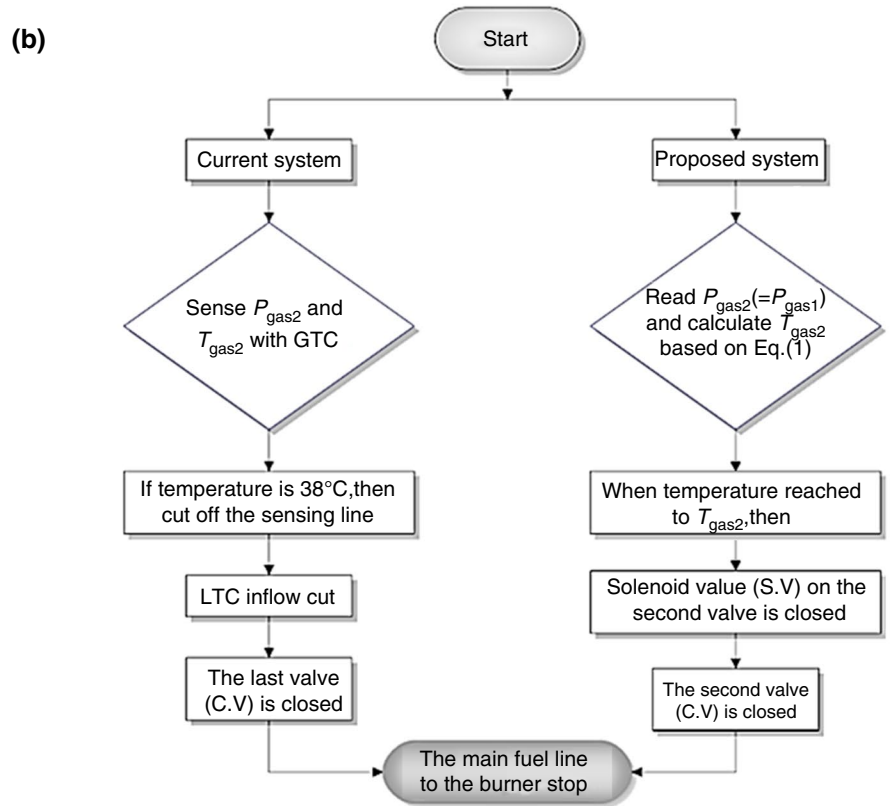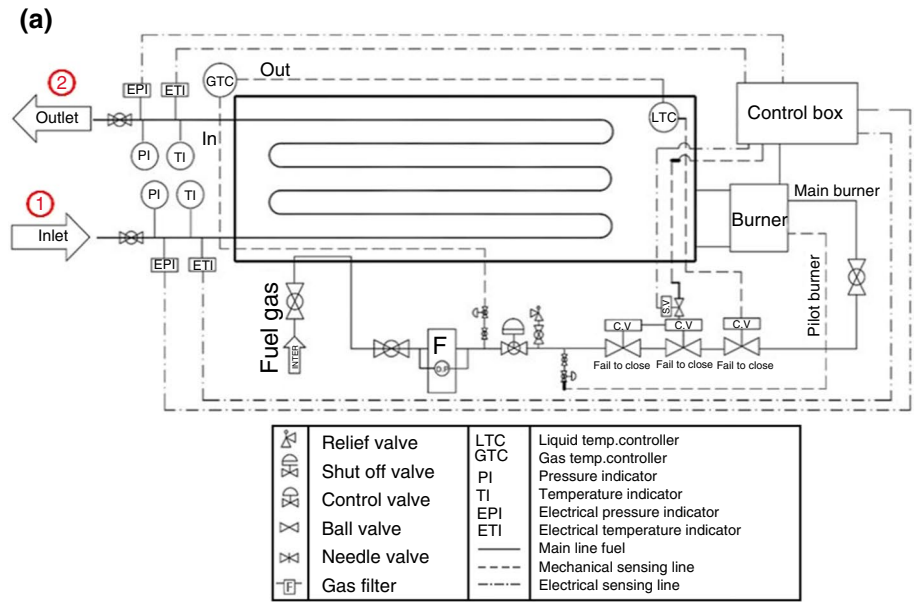
$$E = (h - h_a) - T_a(s - s_a) + \frac{V^2}{2} + gz \qquad (8)$$

In the above equation, h and s are enthalpy and entropy in the target stream in turn, and h_a and s_a refer to enthalpy and entropy of the stream at the ambient condition, respectively. Also, in Eq. (8), the potential and kinetic exergy are

negligible and can be ignored. As shown in Fig. 1b, the heater is considered as the control volume, so the exergy equilibrium for this system is given as Eq. (9) [50]:

$$\dot{E}_{des-wbh} = \Delta\dot{E}_{fire-tube} - \Delta\dot{E}_g - \Delta\dot{E}_{tank} \qquad (9)$$
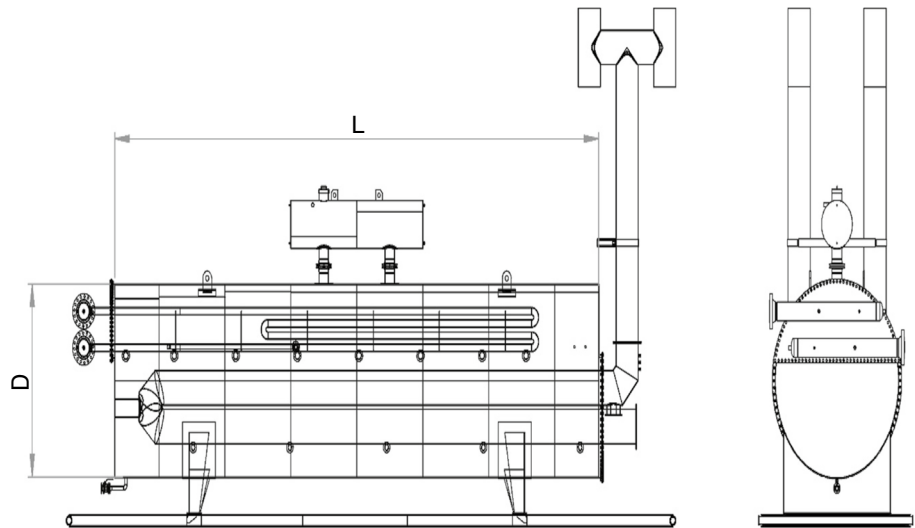
Table 1 Various capacities of indirect heaters [41]

Heater capacity/ SCMH	Minimum required net absorbed heat duty/kW	Minimum required heat transfer area: coil surface area/m²	Dimension/mm	
			D	L
10,000	196	10.5	1220	3900
30,000	589	22	1900	5500
50,000	982	45	2382	6000
100,000	1964	92	2800	12,000

where $\Delta \dot{E}_{\text{fire-tube}}$, $\Delta \dot{E}_g$ and $\Delta \dot{E}_{\tan k}$ are fire-tube exergy, passing gas exergy and water storage tank exergy, respectively.

The exergy equation of natural gas, passing within the coil and to be warmed, is defined by Eq. (10) [10]:

$$\Delta \dot{E}_g = \dot{m}_g \left[\left(h_{\text{gas2}} - h_{\text{gas1}} \right) - T_{\text{air}} \left(s_{\text{gas2}} - s_{\text{gas1}} \right) \right] \tag{10}$$

where $\dot{m}_g$, h_{gas1}, h_{gas2}, s_{gas1} and s_{gas2} are mass flow rate, input and output enthalpies and entropies of the gas, which passes within the heater, in turn.

The exergy equilibrium for the water storage tank is obtained as Eq. (11) [51]:

$$\Delta \dot{E}_{\tan k} = \left(1 - \frac{T_a}{T_w} \right) \dot{Q}_{\tan k} \tag{11}$$

In the above equation, T_w and $\dot{Q}_{\tan k}$ are temperature of the water stored into the tank and waste heat, respectively. For the fire-tube, the equilibrium equation is calculated as Eq. (12) [50]:

$$\Delta \dot{E}_{\text{fire-tube}} = \dot{E}_f - \dot{E}_{\text{exh}} \tag{12}$$

where $\dot{E}_f$ is exergy of the fuel and $\dot{E}_{\text{exh}}$ is exergy of the exhaust from the chimney of the heater. For acquiring fuel exergy, Eq. (11) is applied as [51]:

$$\dot{E}_f = \dot{m}_f \left[\left(\bar{h} - \bar{h}_a \right) - T_a \left(\bar{s} - \bar{s}_a \right) + \bar{e}^{\text{ch}} \right] \tag{13}$$

where $\bar{e}^{\text{ch}}$ is chemical exergy, $\left(\bar{s} - \bar{s}_a \right)$ and $\left(\bar{h} - \bar{h}_a \right)$ are entropy difference and enthalpy difference with respect to the base state, respectively.

In order to calculate the exhaust fluid exergy, which exited from the chimney, Eq. (13) is used. In this study, since the majority of natural gas is composed of methane, pure methane is considered as the working gas. Equation (13) can be written as [52]:

$$\dot{E}_{\text{exh}} = \sum_i \dot{m}_{\text{exh}} \left[\left(\bar{h}_i - \bar{h}_a \right) - T_a \left(\bar{s}_i - \bar{s}_a \right) + \bar{e}_p^{\text{ch}} \right] \tag{14}$$

where $\dot{m}_{\text{exh}}$ is output mass flow rate of the combustion products, $\left(\bar{h}_i - \bar{h}_a \right)$ and $\left(\bar{s}_i - \bar{s}_a \right)$ are enthalpy and entropy of them with respect to the base state, respectively. Moreover, $\bar{e}_p^{\text{ch}}$ is chemical exergy of them, which is acquired by Eq. (14) [51]:
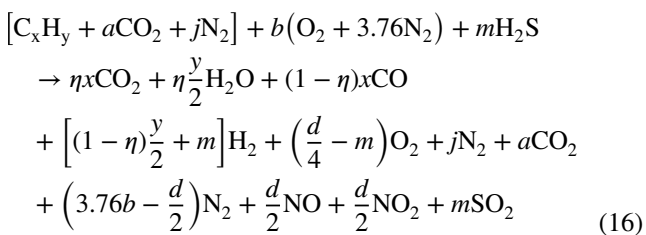
$$\bar{e}_p^{\text{ch}} = \bar{R} T_a \sum_i y_i \ln \left(\frac{y_i}{y_i^e} \right) \tag{15}$$

where y_i is the molar mass of each component of the combustion products.

Table 2 The amount of the air pollutants produced per billion kJ of energy in natural gas [53–56]

Component	Air pollutants/kg
Carbon dioxide (CO_2)	50,666.788
Carbon monoxide (CO)	18.143
Nitric oxide (NO_x)	41.731
Sulfur (SO_2)	0.272
particulates	3.175
Formaldehyde (H-CHO)	0.340

In order to compute the above-mentioned parameters, the combustion equation should be solved. Some of the fuels (hydrocarbon) may not completely burn during combustion, and therefore pollutants are released into the atmosphere along with the products. The most important pollutants are carbon dioxide (CO_2), carbon monoxide (CO), oxides of nitrogen (NO_x: NO (nitric oxide) + NO_2 (nitrogen dioxide)) and sulfur (SO_2). Accordingly, the combustion reaction can be expressed as follows [53, 54]:

$$\begin{aligned}
&\left[C_xH_y + aCO_2 + jN_2\right] + b\left(O_2 + 3.76N_2\right) + mH_2S \\
&\quad \rightarrow \eta xCO_2 + \eta\frac{y}{2}H_2O + (1-\eta)xCO \\
&\quad + \left[(1-\eta)\frac{y}{2} + m\right]H_2 + \left(\frac{d}{4} - m\right)O_2 + jN_2 + aCO_2 \\
&\quad + \left(3.76b - \frac{d}{2}\right)N_2 + \frac{d}{2}NO + \frac{d}{2}NO_2 + mSO_2
\end{aligned} \tag{16}$$

where η is combustion efficiency or heater thermal efficiency.

Environmental analysis

CGS produces various kinds of environmental pollutants such as sound, natural gas leaks and contamination from products of combustion heater. Controlling the minimum temperature can decrease pollution and particle values in the atmosphere. The permissible mass emission of natural gas, according to the standards of energy oil and America gas associations, is presented in Table 2 [53–56]. In this study, a comparison of the gas emission amount between conventional and proposed systems is conducted.

Economic analysis

In this section, the effort has been paid to present the details of economic analysis. The economic analysis consists of the cost savings due to the reduction in fuel consumption and GHG/pollutant emissions. As a result, the total cost saving is defined as the sum of these two terms as Eq. (17). In order to investigate the economic effects, some cost-factors should be considered. The costs of fuel consumption and the costs

Table 3 Damage cost-factor for different GHG/pollutant emissions [40, 57–59]

Component	Pollutant emission factor/\$ kg^{-1}
Carbon dioxide (CO_2)	0.024
Carbon monoxide (CO)	0.0208
Nitric oxide (NO_x)	6.853
Sulfur (SO_2)	7.521

Table 4 Cost of natural gas fuel in different months of a year [60]

Month of year	Cost of fuel/\$ m^{-3}
January and February	0.1440
March–November	0.0894
December	0.1447

of damage caused by GHG/pollutant emissions are listed in Tables 3 and 4, respectively.

$$CS_{total} = CS_f + CS_{em} \tag{17}$$

in which CS is the amount of cost saving. Also, the indices of 'total,' 'f' and 'em' represent total cost saving, cost saving due to fuel consumption and cost saving due to GHG/pollutant emissions, respectively.

As noted, choosing the optimal heating gas temperature into indirect water bath heater leads to reduce natural gas consumption as fuel in heaters based on stream pressure. In the present study, a thermo-economic-environmental analysis is performed and the optimal performance conditions could be chosen for each desirable working conditions. The key parameter in determining the optimum temperature of gas heating is the pressure of the inlet natural gas flow to the CGS station. Based on this, the important parameter of 4E analysis including fuel consumption, energy and exergy efficiencies of water bath heater and the amount of GHG/pollutant emissions (including CO_2, CO, NO_x, and SO_2) released into the atmosphere is studied. In the results section, a comparison between the 4E analysis parameters of the conventional system and the proposed system is presented.

Results and discussion

In this section, the results of energy, exergy, environmental and economic (4E) analysis on the natural gas CGS heaters is presented to illustrate the advantages of using the optimal proposed control system in comparison with the conventional systems. In this study, the effects of variation of pressure between 4.8 MPa (700 psi) and 6.9 MPa (1000 psi) on
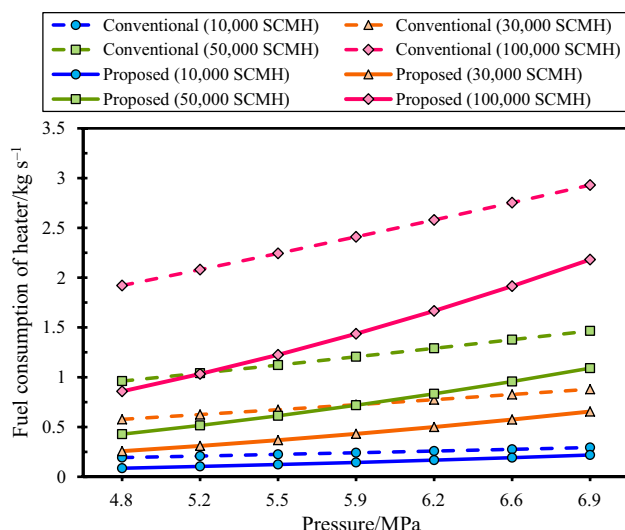
Fig. 4 Fuel consumption of the heater in conventional and proposed systems for different pressures and heater capacities

the performance of gas at the ambient temperature of 10 °C are scrutinized. Furthermore, the effect of the heater capacity is examined in the range of 10,000–100,000 SCMH.

Energy analysis

Figure 4 shows the information about how many kilograms of fuel per second is used with respect to the two considered systems. It is clear that at low pressures, heater consumes a lower amount of fuel in all capacities. Furthermore, analyzing this figure specifies that the proposed system has a greater impact on fuel consumption reduction at lower capacities. For example, the proposed system for 10,000 SCMH consumes 55% fuel lower than the conventional one, but this percent reduces down to 25% for 100,000 SCMH. Therefore, applying the proposed system can save a considerable amount of fuel during each year. For instance, for the heaters with capacities of 10,000 SCMH and 100,000 SCMH, fuel saving will be 2360 tons and 23,605 tons in a year, respectively.

Variations of the heater efficiency in terms of the pressure for different heater capacities are depicted in Fig. 5a. It is observed that the impact of inlet pressure on efficiency difference between the two conventional and proposed systems is very low at lower capacities, while it increases at higher capacities considerably. For instance, this efficiency difference between pressure of 4.8 MPa (700 psi) and 6.9 MPa (1000 psi) for a heater with a capacity of 10000 SCMH is 1.7%, while this amount is 11.09% for the 100,000 SCMH one. Another substantial point is that increasing the pressure causes efficiency reduction in both systems.

Figure 5b illustrates clearly the percentage of the increment in efficiency for the proposed system compared to the

conventional system.[1] Based on this figure, the maximum efficiency improvement occurred for a CGS with capacity of 100,000 SCMH and pressure of 5.5 MPa. At these conditions, the heater efficiency is increased from $\eta = 36.12\%$ (for the conventional system) to $\eta = 46.43\%$ (for the proposed system) which leads to 28.54% relative increment of the efficiency.

Exergy analysis

In this part of study, the results of exergy analysis are presented. Based on the thermodynamic principles, the exergy is the energy that is available to be used and some energy is getting lost due to the irreversibilities. Accordingly, lower exergy destruction, better system performance. Figure 6 demonstrates the variations of the heater exergy destruction versus pressure for different employed capacities in CGSs. This figure indicates that the heater exergy destruction in the proposed system is less than that of the conventional system at all the investigated pressures. The trends of the exergy destruction curves have a good agreement with heater efficiency curves (Fig. 5a). Besides this, the difference between the heater exergy destruction values of the two mentioned systems decreases with increasing the inlet pressure. For example, this difference for a heater with 10,000 SCMH is 18,216 W when inlet pressure is 4.8 MPa (700 psi), but it is 3649 W at $P = 6.9$ MPa (1000 psi).

Figure 7 shows the exergy destruction rate of the chimney in terms of the inlet pressure for different capacities of the heaters. As it can be seen in this figure, the highest difference between the conventional and proposed systems refers to the heater with a capacity of 10,000 SCMH and this difference decreases with reducing the heater capacity. Another key point is that the exergy destruction values of chimney are much more than the values for exergy destruction of the heater. For example, in the proposed system, the values of heater exergy destruction and chimney exergy destruction at $P = 6.9$ MPa (1000 psi) are 44,700 W and 75,929 W, respectively. This means that, at the mentioned conditions, the chimney destroys the exergy 69.86% more than the heater.

Environmental analysis

In this part of the work, the amount of GHG and pollutant emissions (including CO_2, CO, NO_x, and SO_2) released into the atmosphere is studied for the proposed and conventional systems. (Due to the large number of the figures obtained in this section, only the figures for the heater with capacity of 10,000 SCMH are presented.) As shown in Fig. 8, there are two common points in all of these figures: The first point

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1 $\left[\dfrac{\eta \text{Proposed system} - \eta \text{Conventional system}}{\eta \text{Conventional system}} \right] \times 100$.

Fig. 5 a Efficiency of the heater in conventional and proposed systems; **b** percentage of the heater efficiency increment by using the proposed system, for different pressures and heater capacities
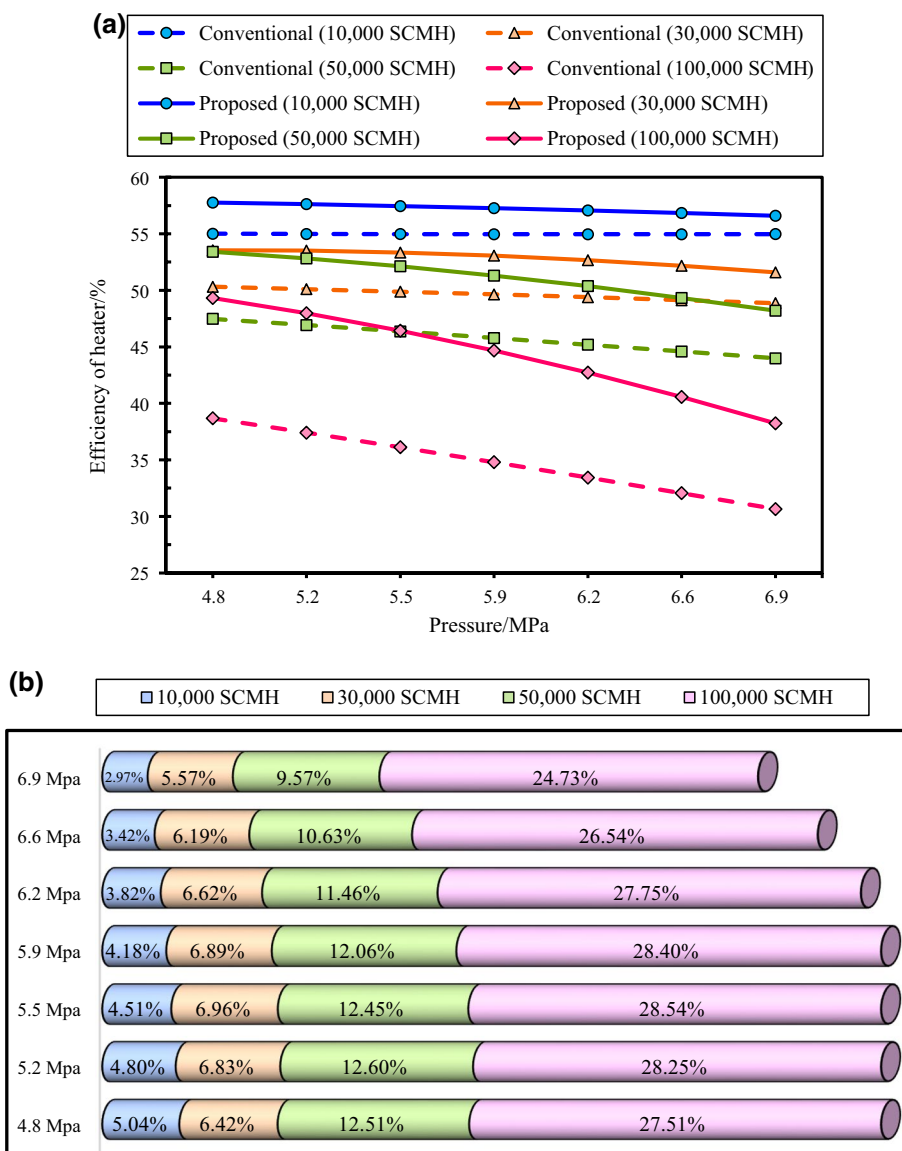
is that as the CGS's pressure level increases (at a certain heater capacity), the amount of GHG/pollutant emission is increased; and the second one is that using new proposed system leads to significant reduction in GHG/pollutant emission at all of the investigated conditions.

Figure 8a shows that how much CO_2 is released into the atmosphere at various inlet pressures for the two systems. As it can be inferred from this figure, difference between two systems at the lowest pressures [4.8 MPa (700 psi)] is

7.7 tons per year which causes 55.8% reduction in emission of this gas, which is the maximum amount between the investigated pressures in this study, whereas this difference at the maximum surveyed pressure of 6.9 MPa (1000 psi) is the minimum amount of 5.4 tons per year that means 25.7% reduction. Figure 8b compares the amount of CO emitted into the atmosphere by applying the two considered systems. As it can be seen in this diagram, the reduction percentage of the emitted CO gas is 55.56% at $P = 4.8$ MPa (700 psi),
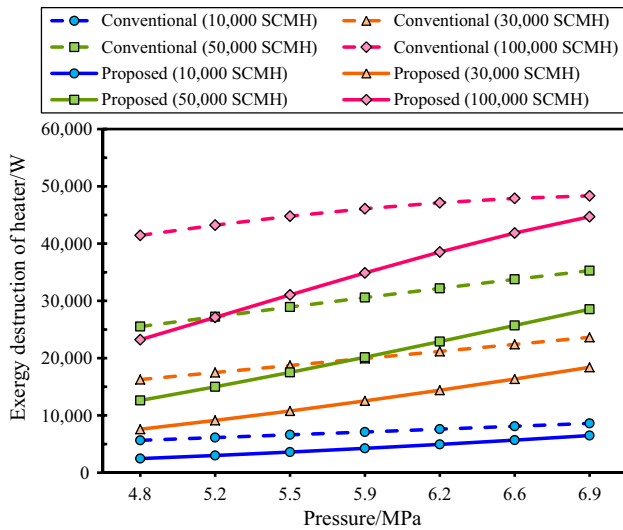
Fig. 6 Exergy destruction rate of the heater in conventional and proposed systems for different pressures and heater capacities
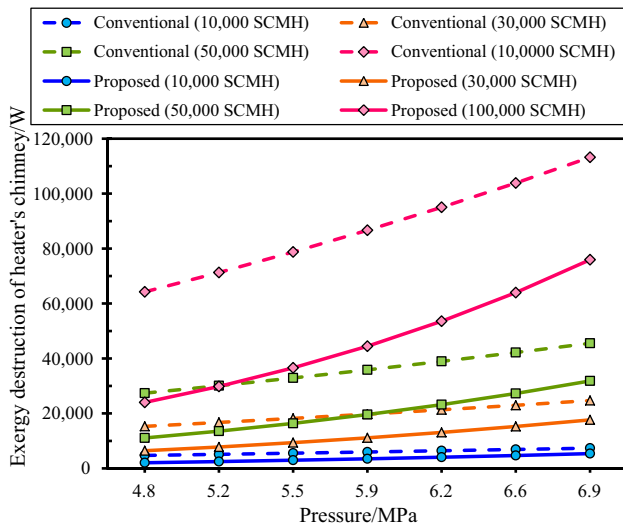

Fig. 7 Exergy destruction rate of the heater's chimney in conventional and proposed systems for different pressures and heater capacities

while it is 25.45% at $P = 6.9$ MPa (1000 psi). Thus, it is accessible to achieve 2 tons reduction in CO per year by applying this system. Figure 8c shows the amount of NO_x released into the atmosphere considering the conventional and proposed systems. The amounts of NO_x emission reduction (compared to the conventional system) with employing the proposed system are 4.6 ton year^{-1} and 3.3 ton year^{-1} at pressures of 4.8 MPa (700 psi) and 6.9 MPa (1000 psi), respectively. This means that using the proposed system leads to 55.42% and 25.98% reduction in NO_x emission at pressures of 4.8 MPa (700 psi) and 6.9 MPa (1000 psi), respectively. The amount of reduction for SO_2 emission is demonstrated in Fig. 8d. This gas is one of the most toxic ones in the world, and reduction in its emission into the atmosphere can help to have cleaner air. As it is shown, using the proposed system can have a significant effect on emission reduction in this gas. The amount of emission reduction in the proposed system is between 0.02 and 0.03 tons per year for the investigated pressures.

Considering Fig. 8a–d together, it can be concluded that a maximum of 14.23 ton year^{-1} CO_2, CO, NO_x and SO_2 emissions reduction will be achieved by applying this novel control system instead of the conventional systems for a capacity of 10,000 SCMH. Considering the results obtained for all capacities of the heaters, it showed that the maximum amount of GHG/pollutant emission reduction is 142.6 ton year^{-1}. This point is noteworthy that there are about 2500 CGSs in Iran, so this can prevent from emitting at least 356,500 tons of pollutants into the atmosphere.

Economic analysis

The aim of this section is to present the results of economic modeling. As it was mentioned in previous sections, the total cost saving is composed of two terms: cost saving due to the reduction in fuel consumption and cost saving due to GHG/pollutant emissions reduction. Figure 9 displays the amount of annual cost saving due to the use of the proposed system instead of the conventional systems for a heater with a capacity of 10,000 SCMH. As it can be seen in this figure,
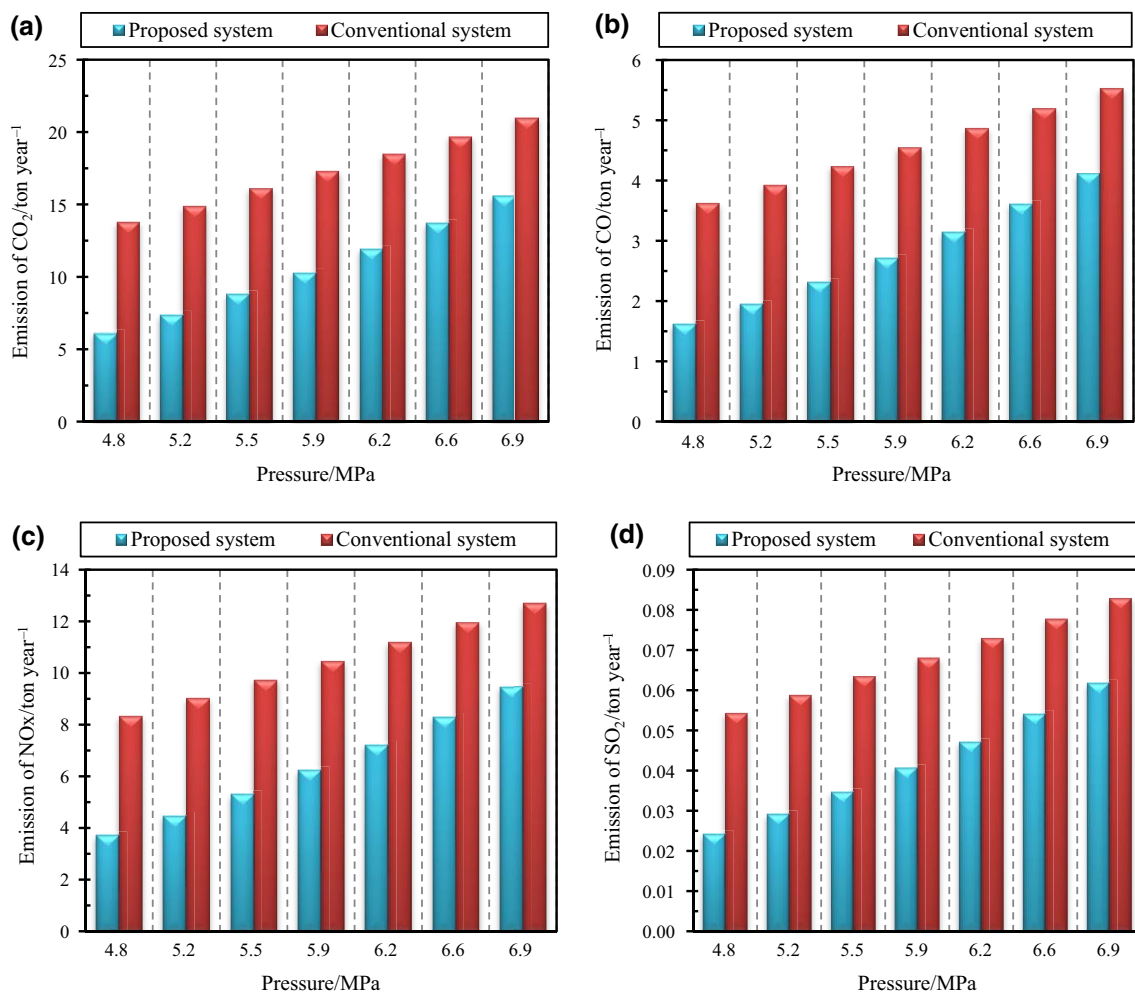
Fig. 8 Comparison between released, **a** CO_2, **b** CO, **c** NO_x, **d** SO_2, into the atmosphere for different pressures using the conventional and proposed systems (for a heater with a capacity of 10,000 SCMH)

both of the costs saving terms are decreased by increasing the pressure of CGS. The maximum amount of the total cost saving (CS_{total}) is 367,541 \$ year^{-1} for a heater with a capacity of 10,000 SCMH. (Of this amount, 335,468 \$ is for fuel consumption reduction and 32,073 \$ for GHG/pollutant emissions reduction.) This reveals that 91.27% of the total cost saving is related to fuel consumption reduction, and 8.73% is related to the reduction in GHG/pollutant emissions.

Analyzing the results of the environmental section indicates that the SO_2 and CO_2 have the lowest and highest amounts of emissions, respectively (see Fig. 8). But the cost saving of SO_2 is higher than that of CO_2 and CO (see Fig. 9). This is due to the fact that SO_2 is a toxic gas which causes the greatest damage to the environment. (It has the largest damage cost-factor.) Furthermore, the results show that NO_x

has the highest share in cost savings due to GHG/pollutant reduction. (Almost 98% of the GHG/pollutant emissions cost savings is related to the reduction in NO_x emissions.)

Summarizing and reviewing the obtained results in present work, it is proven that using the proposed system instead of the conventional systems in CGS leads to remarkable advantages in sustainable development/cleaner production. The proposed system can be applied by paying a very low implementation cost, and using the proposed system causes reduction in fossil fuel consumption in CGS, and consequently, it causes having a cleaner production compared to the conventional systems. Additionally, the reduction in fossil consumption fuel and increment of system efficiency result in a lot of cost savings (at the same conditions compared to the conventional systems).
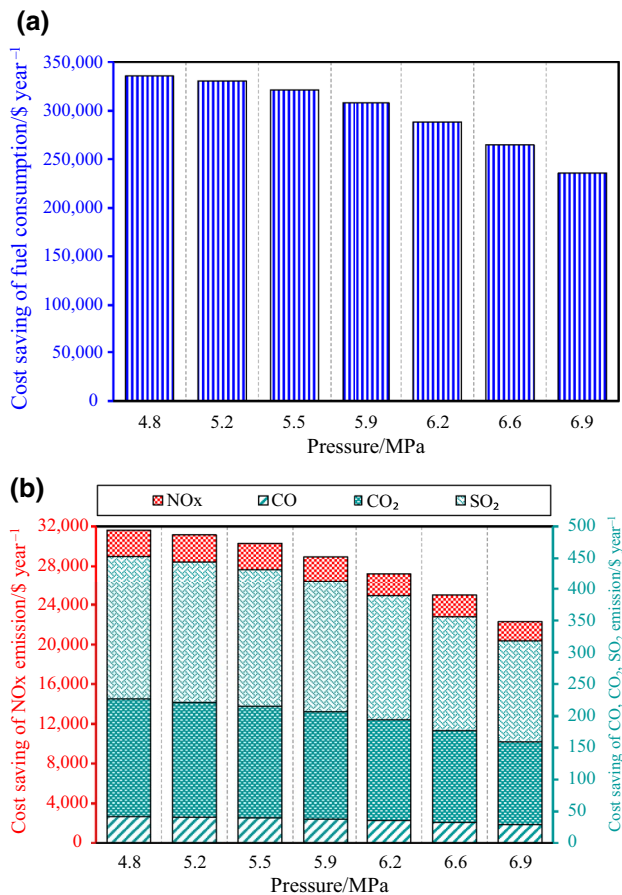
(a)

(b)

Fig. 9 Annual cost saving by using the proposed system instead of the conventional systems for different pressures, **a** fuel consumption cost saving; **b** GHG/pollutant emission cost saving (for a heater with a capacity of 10,000 SCMH)

- Using the proposed system leads to the system improvements from the perspective of energy and exergy viewpoints. Comparing the efficiency of the two considered systems showed that the maximum value of the percentage of relative difference is 28.54% (At this condition, the heater efficiency is increased from $\eta = 36.12\%$ to $\eta = 46.43\%$.)

  The increase in the efficiency of the heater (compared to the conventional systems) is more tangible for higher heater capacities and lower pressures.
- Applying this approach causes a significant reduction in various GHG/pollutant emissions into the atmosphere. As a result, using this novel control system for a heater with the capacity of 100,000 SCMH results in a maximum of 142.6 tons decrease in emissions of CO_2, CO, NO_x and SO_2 per year. Moreover, this amount is more significant for higher heater capacities.
- A significant cost saving is achieved by using the proposed system. The total cost saving is due to the reduction in fuel consumption and GHG/pollutant emissions taxes. For example, up to 3,671,000 \$ year^{-1} total cost savings will be achieved for a heater with a capacity of 100,000 SCMH.
- Low implementation cost and various benefits (energy savings, environmental impacts and economic benefits) of applying this system are advantages of this proposal for encouraging companies to apply such plans for having cleaner production.

Conclusions

In present work, an optimal novel control system was proposed to prevent natural gas freezing due to pressure reduction in CGSs. This process was done by installing a number of temperature and pressure detection sensors in the front and end of the heater fuel line and connecting them to a control system for heater and also using an empirical equation. The applied sensors recognize temperature and pressure and have a similar and parallel performance with mechanical system installed on the fuel line. The sensors send signals to the control box, and the control box gives a command over the solenoid, which is installed on the second main valve, and it causes the main fuel flow to torch to cut off. Using the new proposed control system leads to efficiency improvement, a cleaner environment and cost savings. In summary, the main conclusions can be drawn as follows:

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