Application of Waste Heat Recovery Unit for CGS Heater

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Abstract

A waste heat recovery unit is a heat exchanger that transfers the high temperature waste heat of a process to another part of that usually increases efficiency. In this paper, the effect of using waste heat recovery unit for preheating of water/glycol mixture of city gate station bath heater is thermodynamically investigated. Water bath heaters are common heating systems used in city gate stations which heats high pressure gas before passing regulators. Governing equations (mass and energy conservation equations) on the heater performance is solved using EES software and the results are compared with/without using waste heat recovery unit. As a case study, a city gate station located in cold climate of Iran (Shahrekord) with nominal capacity of 120000 SCMH has been considered. Comparison of the results show that the energy consumption of heaters is decreased by about 50% using heat recovery unit during a year which results in approximately 82200$ cost saving. The heater efficiency is also increased by about 20%.

Keywords: Gas City gate station (CGS), Water Bath Heater, Heat Recovery, Cold Climate.

1. Introduction

Natural gas has become an essential part of national energy policies in many countries, since it accounts for 22% of global total primary energy supply (IEA,2005). According to a report conducted at the end of 2008, the global gas reservoir is estimated 185 trillion cubic meters out of which Iran holds 29.61 trillion cubic meters with the proportion of 16%, containing the second largest gas reserves in the world (OECD/IEA, 2005). Natural gas travels from the wellhead to end consumers through a series of pipelines. High pressure in pipeline (700-1000 psi), which has produced in compressor stations, should be reduced at pressure reduction stations (City gate station (CGS) and Town Border stations (TBS) in order to meet the low pressure gas distributing network requirements. Gas pressure is reduced from 600-900 psi to 250 psi in CGS, passing through a regulator or pressure reducing valve. This pressure reduction is based on Joule-Thomson effect and cause also temperature reduction. The amount of temperature reduction depend on inlet pressure, pressure change and fluid (gas) composition and is determined by adiabatic flash calculation. Temperature drop across regulator may be so high that gas begins to condensate or hydrate formation. Therefore, a CGS needs heating systems to maintain gas temperature in desired range.

Water bath heaters are common heating systems used in CGSs which heats high pressure gas before passing regulators. In an indirect-fired linear heater, a fire tube transfers the heat released by a gas-fired burner to a heating medium in the heater shell (such as water or water/glycol mixture). One of the main advantages of these heaters is uniformly transferring heat to the medium. To prevent overflow of distilled water during warming, a smaller reservoir is installed above it. Gas pipes are entered in multiple passes to the heater from one side and leave it from another side after heating. The pressure and temperature gauges are installed on the pipes. The controller of exit gas temperature is also installed on the outlet pipe. This type of heaters keeps the water/glycol temperature above 70°F. The image of CGS heater is indicated in Figure 1.

Fig 1. The image of indirect bath heater of CGS

Extensive researches have been done about the performance of CGS heaters. Riahi et al. (2011) investigated the effect of burner adjustment on the performance of CGS heater of Ardabil. The results show that the heater and total efficiencies are increased 10% and 30% respectively. Khalili et al. (2012) studied the efficiency and heat losses of indirect water bath heater of Shahrekord CGS. They reported that heat losses from heater surface and stack is annually 4667 GJ and causes the heater efficiency less than 47%. The effect of equivalence ratio on heat flux and combustion efficiency of the burners of CGS heaters was investigated by Hashemi et al. (2012). They concluded that combustion efficiency of burner is firstly increased by increase of the equivalence ratio and then reduced. The maximum thermal efficiency of burner has been occurred at initial and final equivalence ratios of 1.67 and 1, respectively. Kianifar et al. (2014) modeled the heat loss from the heater stack and reported that the daily heat loss from the heater surface is 3.46 kWh and this value from the stack is 55.2 kWh. Considering the heater operation time in year and the high number of heaters in the whole country, an energy source can be achieved by recovering this energy. Ashouri et al. (2014) considered the minimum gas temperature at the inlet of regulators in natural gas pressure reduction stations (CGS) for energy saving in water bath heaters. The results show that heating the gas up to calculated minimum temperatures can save energy consumption of heaters by 43%. Also, it is indicated that by applying a control system, based on the result of this study, the payback period would be less than a year. Taherian et al. (2015) presented the solutions including preheating inlet air to the heater and power production by recovering heat loss form the stack. Bayat et al. (2016) analyzed the CGS heater of Zanjan thermodynamically. They resulted that the amount of energy needed to heat natural gas to prevent the hydration of natural gas for a CGS with a capacity of 80,000 m^3/hr per year varies between 45.3 GJ in July and 146.5 GJ in January.

Based on the above explanations, the effect of preheating the heat transfer medium (water/glycol mixture) has not been investigated using exhaust gases from the heater stack. Due to the high heat losses from the stack that was mentioned in previous studies, the aim of this study is to determine the effect of using a waste heat recovery unit (WHRU) on the performance of the heater and its energy consumption by using the thermodynamic analysis. Because of the large need for the use of heaters at CGS located in cold climates (Khalili et al., 2015), which results in more heat losses, the CGS station in Shahrekord has been selected as a case study.

2. Materials and methods

Figure 2 show the schematic of water bath heater with and without WHRU. A waste heat recovery unit is an energy recovery heat exchanger that recovers heat from hot streams with potential high energy content, such as hot flue gases from the stack. Considering the water bath heater as a control volume, the steady state energy conservation law is (Cengel and Boles, 2015):

$$\dot{Q}_f + \dot{Q}_R = \dot{Q}_{NG} + \dot{Q}_{stack} + \dot{Q}_{surf} \quad (1)$$

where $\dot{Q}_f$ is the amount of heat produced by burning fuel in heater burner, $\dot{Q}_{NG}$ is the amount of heat absorbed by the natural gas to increase its temperature, $\dot{Q}_{stack}$ and $\dot{Q}_{surf}$ are the stack and surface heat losses and $\dot{Q}_R$ is the heat recovered from stack flue gases.

Based on API 12K (2008), gas entering to CGS should be 15°C and at the exit of heater should be 30°C. Using thermodynamic first low and ignoring kinetic and potential energies, $\dot{Q}_{NG}$ is calculated using the following relation:

$$\dot{Q}_{NG} = \dot{m}_{NG}\,(h_{out} - h_{in}) = \dot{m}_{NG} c_{p,NG}(T_{in} - T_{out}) \quad (2)$$

where c_p is the constant-pressure specific heat of natural gas (kJ/kgK), $\dot{m}_{NG}$ is inlet gas mass flowrate (kg/s), h_{in} and h_{out} are the enthalpies of gas inlet and outlet to the heater and T_{in} and T_out are the temperatures of gas inlet and outlet to the heater. Average specific heat as a function of temperature is calculated as:

$$C_{p,NG} = \sum mf_i \; c_{p,i} \quad (3)$$

where mf_i is mass fraction of constituent and $c_{p,i}$ is its specific heat. For simplification, the methane was supposed as combustion fuel. The general equation of combustion reaction of this hydrocarbon fuel and air is written as:

$$\begin{aligned} &C_a H_b + A(a+b/4)(O_2 + 3.76N_2 + 4.76\times 1.61\omega H_2 o) \\ &\rightarrow aCO_2 + [b/2 + 4.76\times 1.61A(a+b/4)\omega]\ H_2 o + \\ &(A-1)\times(a+b/4)\ O_2 + 3.76A(a+b/4)N_2 \end{aligned} \quad (4)$$

where A represents equivalence ratio shows the percentage of excess air with respect to the theoretical air. The parameter ω is the amount of humidity ratio of the ambient air (combustion air). Excess air wastes energy by carrying heat up the stack. Regarding the 50% excess air and the humidity ratio of 0.005 (based on site condition), the equation of combustion will be:

$$CH_4 + 3O_2 + 11.28N_2 + 0.1149H_2o \rightarrow CO_2 + 2.1149H_2o + O_2 + 11.28N_2 \quad (5)$$

The stack losses are calculated as (Incropera et al., 2002):

$$\dot{Q}_{stack} = \dot{m}_s c_{p,s} \Delta T = UA_s \Delta T_{lm} \quad (6)$$

where U is the overall heat transfer coefficient:

$$\frac{1}{UA} = \frac{1}{(hA)_c} + R_w + \frac{R''_f}{A_h} + \frac{1}{(hA)_h} \quad (7)$$

where the indices c and h are related to outside air and combustion products and R_w is conductive thermal resistance because of stack thickness against heat transfer. R''_f is the fouling factor and its value for combustion products is between 0.0005-0.003 $m^2.K/W$ (Incropera et al., 2002).

In Eq.6, A_s is the stack lateral area and ΔT_{lm} is the log mean temperature difference:

$$\Delta T_{lm} = \frac{\Delta T_o - \Delta T_i}{\ln(\Delta T_o / \Delta T_i)} \quad (8)$$

where $\Delta T_o = T_\infty - T_{m,o}$ and $\Delta T_i = T_\infty - T_{m,i}$.

To obtain internal and external heat transfer coefficient of stack pipe, the following relations are used (Incropera et al., 2002):

$$\overline{Nu_D} = 3.66 \quad (9)$$

$$\overline{Nu_D} = 0.3 + \frac{0.62 Re_D^{1/2} Pr^{1/3}}{[1 + (0.4/Pr^{2/3})]^{1/4}} \left[1 + \left(\frac{Re_D}{282000}\right)^{5/8}\right]^{4/5} \quad (10)$$

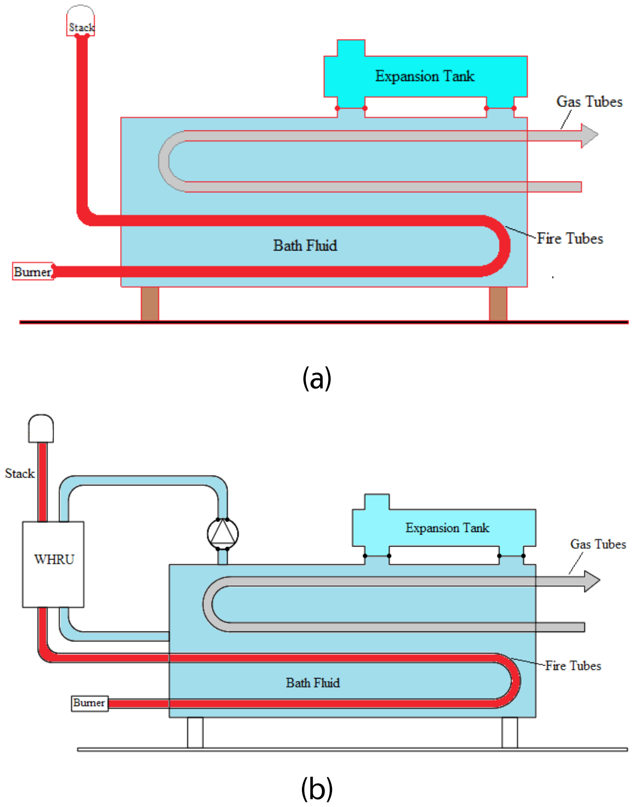

Fig. 2. Schematic of indirect bath heater of CGS (a) without WHR (b) with WHR

To obtain the heat losses from heater walls, the internal heater wall temperature was supposed to be equal to the water bath temperature (Hashemi et al., 2012) so the equation will be:

$$\dot{Q}_{surf} = \frac{T_w - T_{amb}}{\sum R_t} \quad (11)$$

where R_t is the overall thermal resistance.

In this study, heat losses from heater stack is recovered using a heat exchanger for preheating of water/glycol mixture. Details of heat recovery unit are listed in Table I. This results in reduction of heat losses and enhancement of heater efficiency. In Figure 3, the schematic of CGS heater equipped with WHRU is shown. The amount of recovered heat is calculated using governing equation on the performance of heat exchangers:

$$q = \varepsilon C_{min} T_{h,i} - T_{c,i} \quad (12)$$

where $T_{h,i}$ is inlet exhausted gas temperature and $T_{c,i}$ inlet water/glycol temperature. ε is the heat exchanger efficiency (Incropera et al., 2002):

$$\varepsilon = \frac{1 - exp[-NTU(1 - C_r)]}{1 - C_r exp[-NTU(1 - C_r)]} \quad (13)$$

$C_r = C_{min}/C_{max}$ is the ratio of thermal capacities and NTU is the number of transfer units:

$$NTU \equiv \frac{UA}{C_{min}} \quad (14)$$

Finally, the heater efficiency is calculated using the following relations:

$$\eta_{heater} = \frac{\dot{Q}_{NG}}{\dot{Q}_{in}} = \frac{\dot{Q}_f + \dot{Q}_R - \dot{Q}_{stack} - \dot{Q}_{surf}}{\dot{Q}_f + \dot{Q}_R} = 1 - \frac{\dot{Q}_{stack} + \dot{Q}_{surf}}{\dot{Q}_f + \dot{Q}_R} \quad (15)$$

The amount of $\dot{Q}_R$ will be positive if heat recovery unit is used which cause increase of heater efficiency. In heaters without heat recovery unit, the amount of $\dot{Q}_R$ is zero.

TABLE 1. Characteristics of heat recovery unit

Type	Shell and tube counter flow, Hot fluid in the tube and cold fluid in the shell
Shell inside diameter	1 m
Tube inside diameter	70 cm
Length of the heat exchanger	2 m
Material (Thickness)	Steel (1 cm)
Thermal conductivity	43 W/m.K
Overall heat transfer coefficient	100 W/m^{2}K
Combustion product inlet pressure	1 Bar

3. RESULTS AND DISCUSSION

In this research, thermodynamic equations governing on the performance of water bath heater equipped with WHRU were modeled using EES software. For validation of calculations, a case study in Iran (CGS of Shahrekord) with nominal capacity of 120,000 SCMH has been considered. The analysis of natural gas from the test case location is shown in Table II (Khalili er al., 2012). Considering the compositions, the density of 0.717 kg/m^3 and the heat value of 8400 kcal/m^3 for natural gas in the station are obtained.

Stack losses and required energy to heat the gas during a year in Shahrekord's CGS are shown in Figure 3 (Khalili er al., 2012). If WHRU is used for preheating water/glycol mixture, heat loss will be reduced which cause reduction of energy consumption by heater. Based on the results of Figure 4, the reduction of stack losses with WHRU is about 50% during a year.

TABLE 2 .Volumetric analysis of Natural Gas (Shahrekord Station-Iran)

Constituent	Percent by volume	Specific heat (kJ/kg.K)
Methane (CH_4)	89%	2.22
Ethane (C_2H_6)	4.1%	1.75
Propane (C_3H_8)	1.2%	1.67
Nitrogen (N_2)	5%	1.04
Carbon dioxide (CO_2)	0.7%	0.844

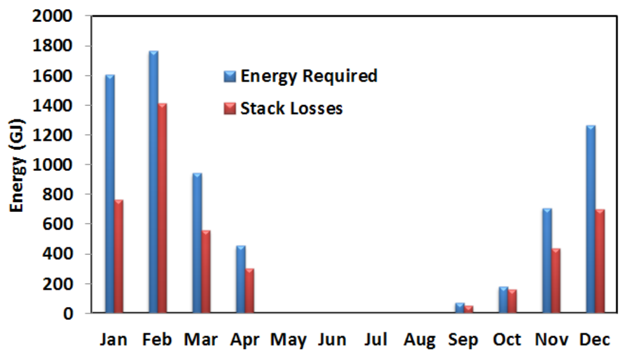

Fig 3. Stack losses and required energy to gas preheating of Shahrekord CGS (Khalili et al., 2012)

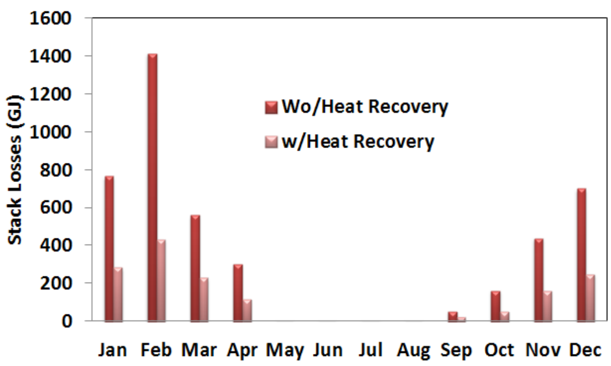

Fig 4. Effect of using WHRU on stack losses of Shahrekord CGS

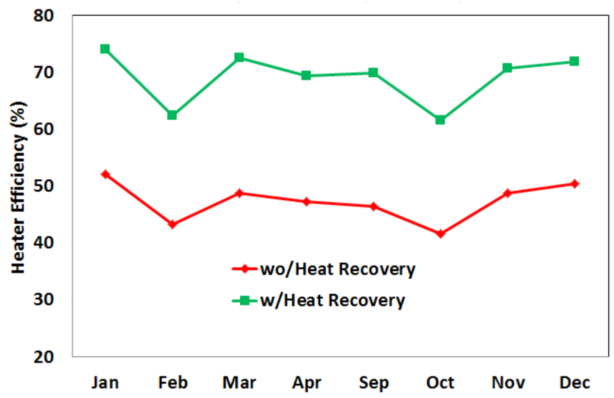

Fig 6. Heater efficiency with and without heat recovery unit

The effect of water/glycol mixture flowrate on reduction of fuel consumption is shown in Figure 5. It can be said that the increase in flowrate of mixture leads to an increase in the Reynolds number which results in the increase of the heat transfer coefficient and hence the increase of heat transfer, based on the Eq.10. While increasing the flowrate means more energy consumed by the pump, the amount of energy saved is such that the pump energy consumption is negligible. Another point of this diagram is the asymmetric behavior of reducing gas consumption with increasing flowrate. This indicates that there is a limit to increase flowrate and a higher flowrate will not have effect on reducing of gas consumption.

Figure 7 show the effect of ambient temperature on the gas burner flow. As expected, the gas burner consumption is decreased by increasing ambient temperature. In other words, the burner consumes less fuel to heat the gas flow in warm seasons than that in cold seasons. The experimental and model results are in the good agreement (Khalili et al., 2012). The variation of burner gas consumption by gas flow and inlet temperature is depicted in Figure 8. The results show that the gas inlet temperature has as insignificant effect on burner gas consumption, while the increase of gas flow leads to a linear increase of burner gas consumption.

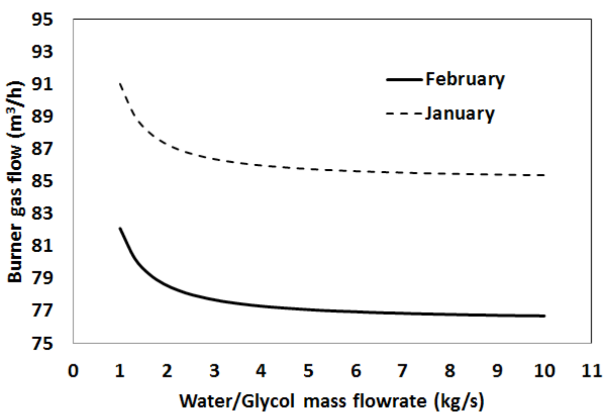

Fig 5. Effect of water/glycol flowrate on energy consumption of heater using WHRU

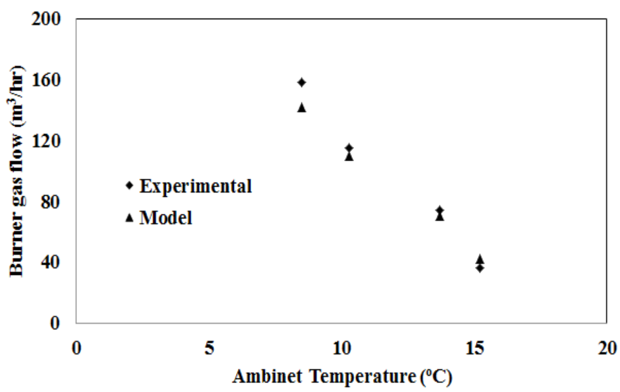

Fig 7. Effect of ambient temperature on burner gas consumption

In Figure 6, the variation of the efficiency of heater using heat recovery unit is shown. It can be seen that the recovery of stack losses increase the efficiency about 20%. This amount

The reduction of fuel consumption by the burner is given in Table III. The results show that the annual gas consumption of burner is decreased from about 411,000 m^3 to 246,000 m^3; In other words, heat recovery, on average, reduced about 45% of fuel consumption by the burner. Total energy saving per year from the recovery of stack heat losses for preheating of water/glycol mixture is 6000 GJ (equivalent to 165000 m^3 gas savings). In other words, half of the energy needed to increase the temperature of the mixture, resulting in the preheating of natural gas, is derived from stack losses. With considering $0.5 per each m^3 of natural gas, there will be an annual savings of $ 82,200.

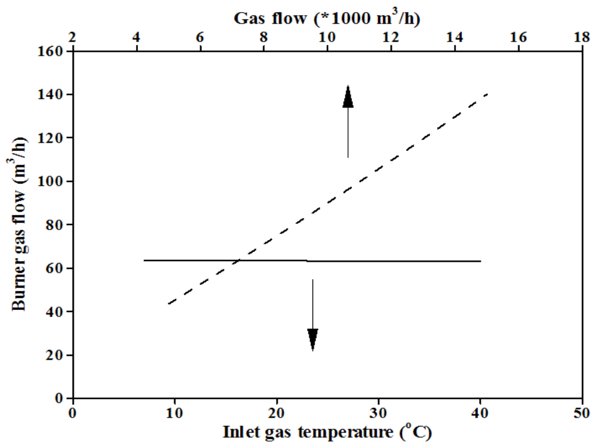

Fig 8. Effect of gas flow and inlet temperature on burner gas consumption

TABLE 3. Reduction of flowrate and cost of gas consumption by CGS heater using WHRU

Month	Station gas flow (m^3)	Burner gas flow (m^3/h) wo/HR	Burner gas flow (m^3/h) w/HR	Cost saving ($)
Jan	39720000	115	77.1	13644
Feb	37800000	158	85.9	25966.8
Mar	23142000	74	44.5	10612.8
Apr	14880000	36	21.3	5292
May	9393000	-	-	-
Jun	5889000	-	-	-
Jul	5068500	-	-	-
Aug	4929000	-	-	-
Sep	5053000	11	3.8	2597.76
Oct	7110000	20	8.6	4085.64
Nov	22560000	55	33.2	7855.2
Dec	32850000	94	60.2	12178.8

4. CONCLUSION

Using a WHRU to reduce heat losses from the stack of the water bath heater of city gas station (CGS) can play an effective role in reducing the consumption of fuel by the heater burners. To investigate this idea, the performance of the CGS of Shahrekord (as a case study) was analyzed thermodynamically in different months of the year and the effect of using the WHRU the on different parameters was investigated. The results showed that about half of the stack losses could be recovered, which would save 45% of the fuel consumption of heater burners. This gas savings will save $ 82,200 annually. In addition, the efficiency of the station heaters increases by about 20%. The above results confirm that due to the large number of CGSs in the country, it is economically and environmentally necessary to use a heat recovery unit in CGS heaters, especially in cold climates.

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کاربرد واحد بازیافت گرمای اتلافی در گرمکن ایستگاه تقلیل فشار گاز شهری

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چکیـــــده

واحد بازیافت گرمای اتلافی یک مبدل گرمایی است که گرمای اتلافی دما بالای ناشی از یک فرایند را به قسمتی از یک فرایند دیگر معمولا با هدف افزایش بازده منتقل می‌کنند. در این مقاله، تاثیر استفاده از واحد بازیافت گرمای اتلافی برای پیش گرمایش مخلوط آب/گلیکول گرمکن ایستگاه تقلیل فشار گاز شهری (CGS) به صورت ترمودینامیکی بررسی شده است. گرمکن‌های حمام آبی سیستم‌های گرمایی رایج بکاررفته در ایستگاه تقلیل فشار گاز شهری هستند که گاز فشار بالا را قبل عبور از رگلاتورها گرم می‌کنند. معادلات حاکم (معادلات بقای جرم و انرژی) بر عملکرد گرمکن با استفاده از نرم افزار EES حل شده و نتایج در حالت با/بدون استفاده از واحد بازیافت مقایسه شده است. به عنوان مطالعه موردی، ایستگاه تقلیل فشار گاز شهری واقع در منطقه سردسیر ایران (شهرکرد) با ظرفیت اسمی 120000 SCMH انتخاب شده است. مقاسه نتایج نشان داد که مصرف انرژی گرمکن‌ها در طول یک سال با استفاده از واحد بازیافت گرما حدود ۵۰٪ کاهش می‌یابد که منجر به صرفه‌جویی ۸۲۲۰۰ دلار شده است. بازده گرمکن نیز حدود ۲۰٪ افزایش می یابد.

واژگان کلیدی: ایستگاه تقلیل فشار گاز (SGC)، گرمکن حمام آبی، مبدل بازیاب گرما، اقلیم سرد