Optimization of Combustion Efficiency in Indirect Water Bath Heaters of Ardabil City Gate Stations

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Abstract

Energy consumption in heaters of city gate stations is considerable and high quality refined gas is used for combustion in these heaters. Due to the ascendant rate of fuel cost and also environmental laws; analysis, redesign, renovation and maintenance of indirect water bath heaters is of paramount importance. Because of high amount of oxygen or fuel entered into combustion chamber of the heaters as well as high temperature of stack, these heaters usually work in a low efficiently. This could be due to a low performance of burner, an inappropriate control of combustion air and an incorrect size of the heaters. Finding a proper way to control the combustion and to improve the efficiency in heaters of city gate stations located at Arjestan (a city of Iran in Ardabil province) is the main purpose of this study. By adjusting the length of flame proportional to the combustion chamber, control of air/fuel ratio and installation of a barometric damper, 10% increase in combustion efficiency and 30% increase in overall efficiency of heaters are obtained.

Introduction

Gas stations for pressure reduction are the major part of gas distribution which are designed and installed with different types of equipments. Manufacturing of these equipments are improved with development of technology. In order to adapt the gas specification of the pipe lines with required gas of the consumers, two different gas stations (i.e. city gas station (CTS) and town border station (TBS)) are designed. The CTS are installed as a belt around the cities and reduced the gas pressure from 1000 psig to 60 psig with capacities ≥ 10×10^3, 20×10^3 and 30×10^3 m^3 per hour. The stations with 2.5×10^3, 5×10^3 and 10×10^3 m^3 per hour can reduce the pressure up to 60 psig. They can also control the gas impurities and the input and output of gas flow. The gas transmission route from the gas station is demonstrated in Fig. 1.

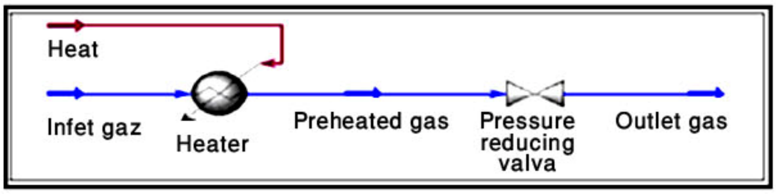


Figure 2. Schematic of gas transition from the gas station (reduction of gas pressure).

In 2007, considerable energy saving opportunities in the gas stations was predicted according to a survey performed by the IFCO (Iranian Fuel Conservation Organization) specialists. In this research, the performance of the gas stations according to the energy consumption was investigated [1].

In other project, the gas company of Zanjan province reduced the hourly gas consumption from 65-70 m^3 to 45-50 m^3 by modifying the combustion chamber and installing the electric valve [2]. After investigation of the heater and yellow burning effects, the structure of combustion chamber and gas transmission system were modified and resulted in improvement of flames' color and energy consumption. An incomplete gas burning due to the lack of oxygen, the serrated long yellow flames with fume shape, the small air chamber with poor oxygen content were reported. After modification of the combustion chamber, a solenoid valve was installed in the route of input gas to the chamber. The temperature of the chamber were adjusted between 37-43^{o}C such that the valve was opened at 37^{o}C and it was closed at 43^{o}C (no gas purging). By installation of this valve, the working state at low pressure was canceled and working hours of heaters was reduced by as much as 12 hrs [2].

Indirect water bath heaters generate the heat in a separate container (usually heater pipe) and transfer it to the process flow through an exothermic environment such as water, mixture of water and glycol, steam, salt and combustion gases. In these systems, the heat is transferred uniformly by an exothermic environment. The immersed heaters in water are the most common heaters in the gas stations. In these heaters, the water temperature is preserved by as much as 70^{o}C. These types of heaters had been used in the mentioned gas stations of this research. Fig. 2 demonstrates the schematic of an immersed heater in water. These heaters usually were designed according to the API 12K standard [3]. The main application of these heaters is heating of the high-pressure gases which their pressure has been decreased in the gas stations with pressure reduction. Decrease of gas pressure results in a reduction in temperature.. In these heaters, the exothermic environment is water or mixture of water and glycol and the pipes carrying the fluid are immersed in this media. The heater pipe transfers the liberated heat by the burners to the exothermic environment, and then the fluid pipes and fluids are heated accordingly.

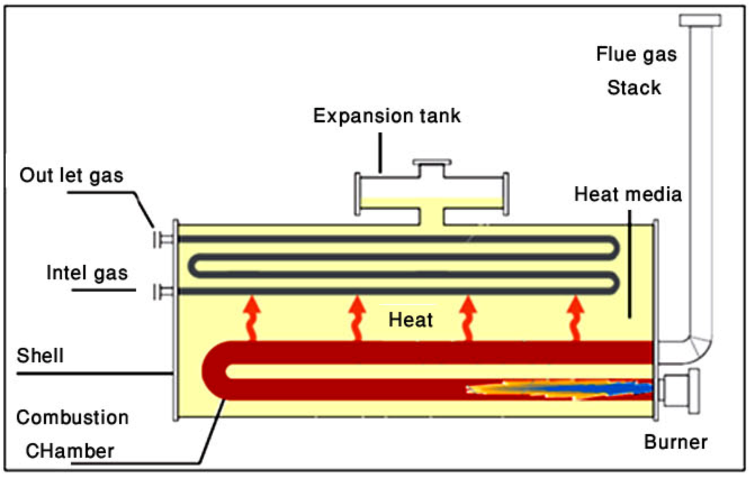


Figure 2. Components of immersed heater in water **[4]**

In this study, the gas station of Arjestan (The city in Ardabil province) was selected to determine the maximum amount of increase in system efficiency due to the optimization process of combustion.

Measurement method to evaluate the system efficiency in Arjestan station

The effect of various parameters on system and combustion efficiency was investigated by installation of the monitoring facilities and analysis of combustion products in heater number 1 of Arjestan city gate station. Therefore four temperature sensors were installed at the gas input entrance, gas output opening, inside the boiler water and in the surrounding environment, to allow continuous monitoring of the changes in heaters' temperature with respect to the surrounding. All these sensors were connected to a monitor for display purposes. Also a counter was installed at the opening of gas input valve to evaluate the amount of gas usage. To derive the most efficient performance condition for the heater, different capacities were investigated and calibrated; and finally the products of combustion were analyzed and recorded. In each capacity, to reduce the excess air and stack loss and also increase of combustion efficiency, the input air of the burner was adjusted. After finding the efficient capacity if the furnace, the changes in furnace temperature were measured in various ranges and by taking into account the environmental temperature change, the capacity was calculated. Therefore with the aid of a counter, the furnace efficiency and reduction in fuel consumption was calculated. In order to sustain the combustion products in the chamber for a longer period of time, a barometric damper was attached to the burner Number 1.

Calculation of the system efficiency of Arjestan station before and after optimization calculation of boilers

The boiler is a thermodynamic machine which its efficiency calculates based on the following methods [5]:

1- The output energy is compared with the input energy of boiler’s furnace and the heat transfer capability of the machine is evaluated. This calculation is named brief analysis, where equation (1) is used :

$$\text{Boiler efficiency} = (\text{output energy} / \text{input energy}) \times 100 \tag{1}$$

2- In other method, the energy wasted during the steam production is determined, where the possibilities to increase efficiency through potential saving solutions is also considered. This method is named elaborated analysis. As we know, lots of input and output have been attached to the steam boiler. Therefore, to involve each of them for an analysis with lower error, the boiler should be considered as a volume control. In the elaborated analysis, all the input and output energies of the system borders are determined and the thermal efficiency is obtained using equation (2) :

$$\text{Boiler efficiency} = [(\text{Input energy} - \text{wasted energy}) / \text{input energy}] \times 100 \tag{2}$$

In indirect water bath heaters, the heat generated from burning of the fuel in heater chamber by burner, results in heating of heat transfer environment (a bath of hot water) and transferring of the heat to the gas flow inside the pipe. Therefore, by considering the bath of hot water as a volume control, the conservation energy law can be written as follow:

$$\dot{E}_{Fuel} = \underline{(\dot{E}_{stack} + \dot{E}_{surf})} + (\dot{E}_{out} - \dot{E}_{in})_{NG} + \dot{E}_{stored} \tag{3}$$

At the right side of equation (3), the underlined expression is the wasting energy, including the stack and wall wasting energies. The $(\dot{E}_{out} - \dot{E}_{in})_{NG}$ is the required energy to heat the natural gas flow and $\dot{E}_{stored}$ is the heat to increase the temperature of heat transfer environment from the minimum to maximum working temperature during a cycle which can be measured using equation (4) :

$$\dot{E}_{stored} = \int_{0}^{t_{ON}} m_{WF} C\left(\frac{dT}{dt}\right) dt \tag{4}$$

Where m_{WF} and C are the mass and specific heat capacity of heat transfer environment respectively. $\frac{dT}{dt}$ is indicative of water temperature variation versus time and t_{ON} is the time interval for transferring the heat to the water of boiler (where the burner is on). When the burner is off, $\dot{E}_{Fuel}$ and $\dot{E}_{stack}$ (i.e. fuel energy and wasting of stack) are removed. As shown in fig. 3, $\dot{E}_{stack}$ is approximately 25-40% and $\dot{E}_{surf}$ is around 0.5-1% of the product heat of the system.

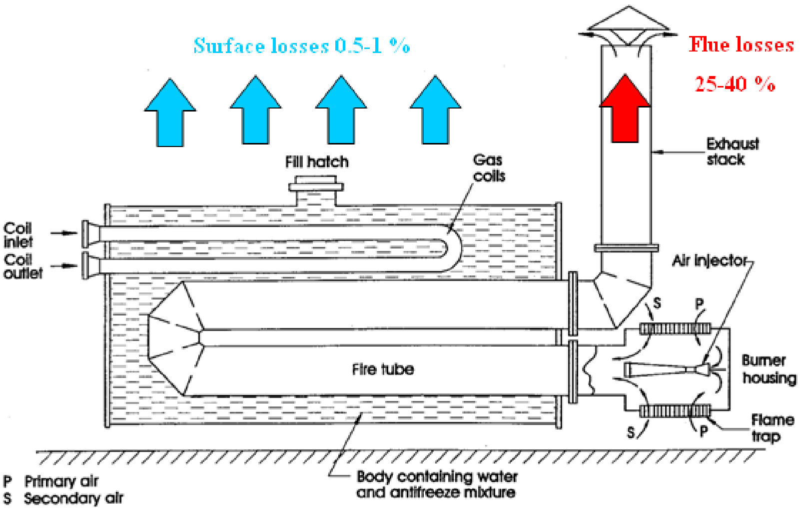


Figure 3. Schematic model of the heater in this research.

Wasting of Stack

The latent heat of evaporation and loss of energy due to formation of gaseous combustion products, are two major contributors to stack waste energy. To calculate the loss of energy due to latent heat of evaporation, the equivalent natural gas compound was calculated with the aid of the data presented in Table 1;

$$C_xH_y:$$

$$x=\frac{88.332\times 1+4.672\times 2+1.137\times 3+0.484\times 4+0.181\times 5+0.694\times 1}{100}=1.05$$

$$y=\frac{88.332\times 4+4.672\times 6+1.137\times 8+0.484\times 10+0.181\times 12}{100}=4$$

$$\rightarrow C_{1.05}H_4 \qquad (4)$$

Then, the net and gross heating values are calculated. The amounts of them are 8247 Kcal/m^3 and 9142 Kcal/m^3 respectively.

The loss percentage due to the latent heat of evaporation is determined using equation (5).

$$\frac{(C_g-C_n)\times 100}{C_g}=\frac{(9142-8247)\times 100}{9142}=9.8\% \qquad (5)$$

The wasting due to the warm gases can be obtained by analysis of the output gases from the stack. The volume of combustion products can be determined from the results obtained from the analysis of the products (Table 2). In order to measure the wasting due to the warm gases at a given temperature of the stack input, the enthalpy of each gases produced during the combustion is calculated [6]. The wasting related to the exhausting of combustion products can be obtained by adding the product of volume of each gas and its enthalpy at a temperature near the input of stack. However, to simplify the calculations, the average enthalpy for all the gases is considered and the wasting due to exhausting of the gases is determined according to equation (6).

$$\dot{E}_{stack} = \dot{m}_{stack}\left[\bar{h}_{stack\,@\,T_{in,stack}} - \bar{h}_{stack\,@\,T_{amb}}\,)\right] \tag{6}$$

Table 1. Volume percentage of the chemical compounds for the input natural gas.

Name	Chemical formula	volume percentage		
		Gas analysis	Lower limit	Higher limit
Methane	CH_4	88.332	85	95
Ethan	C_2H_6	4.672	2	9
Propane	C_3H_8	4.137	0.5	3
Isobutane	C_4H_{10}	0.484	0.2	0.3
Normal Butane			0.25	0.5
Isopentane	C_5H_{12}	0.181	0.1	0.15
Normal pentane			0.06	0.1
Carbon dioxide	CO_2	0.694	0.1	0.4
Nitrogen	N_2	4.5	2	5.7
Solfide	H_2S	0.849 ppm	1.25	6.25
Heavy compound	-	0	0.02	0.2

Table 2. Combustion Products Analysis

Fuel Flow Rate (m^3/hr)	Carbon Monoxide (ppm)	Carbon Dioxide (%)	Nitrogen Oxides (ppm)	Oxygen (%)	Stack Temperature at input gate (°C)	Ambient Temperature (°C)	Combustion Efficiency (%)
102	81	4.14	22	13.69	274	8.4	73.35
111	284	5.63	25	11.60	314	9.7	76.55
180	202	7.92	39	7.20	412	9.7	76.54
186	301	8.14	37	6.64	407	9.7	77.33
192	159	7.52	33	7.73	427	9.5	74.56
204	111	8.41	42	6.16	437	1.1	76.31
228	44	8.36	47	6.25	455	0.8	75.11
252	32	8.89	57	5.31	488	9.8	74.61
In presence of barometric damper							
182	722	9.59	31	8.10	349	11.8	78.90
186	676	10.07	39	6.00	392	12.7	78.97

Considering the total wasting measured from equations (5) and (6), the combustion efficiency has been calculated in the last column (Table 2). The wasting of the stack was minimum, when the burner was working with a flow rate of 186 m^3/hr (capacity 1, 530000 Kcal/ hr, nominal capacity of the burner). Therefore, this point has been considered as a optimization state of the system. After installation of the barometric damper, the burner has been adjusted at the same capacity.

By comparing the 1^{st} row (the status before optimization) of, the 4^{th} row (the status after optimization) and the last row (the statues after optimization and installation of the barometric damper), we found that the adjustment of burner and installation of barometric damper, resulted in 5.1 and 7.1 % reduction in stack wasting respectively, and consequently the increase of system efficiency was obtained (Table 2).

Wasting of energy from the walls

To calculate $\dot{E}_{surf}$, the temperature of inner wall is considered as the water temperature. The steel wall, glass wool insulator, aluminum shell and the flowing air around the burner with velocity of 6 m/s were considered as series resistances. By using equation 13 and having the value of convection coefficient from appendix 1, the wasting from the surfaces is calculated [7].

$$\dot{E}_{surf} = \frac{T_w - T_{amb}}{\frac{x_{steel}}{K_{steel} \times A_{steel}} + \frac{x_{wool}}{K_{wool} \times A_{wool}} + \frac{x_{Al}}{K_{Al} \times A_{Al}} + \frac{1}{h_{air} \times A_{heater}}} \tag{7}$$

Where T_w and T_{amb} are the water temperature inside the boiler and the temperature of environment (Kelvin) respectively; x is thickness of each layer (meter); K is heat transfer coefficient ($W/m{\circ}K$); h is heat transfer coefficient of air ($W/m^2{\circ}K$) and A is the heat transfer surface (m^2). We can obtain T_w and T_{amb} values for the conditions before and after optimization and after installation of barometric damper using Figs 4, 5 and 6.

Required Energy for heating of natural gas flow

Considering the natural gas flow as a volume control and neglecting the variation in kinetic and potential energy of natural gas flow from the entry to emergence, the heat transferring to natural gas flow is obtained according to equation 8:

$$(\dot{E}_{out} - \dot{E}_{in})_{NG} = \int_0^t m_{NG}(h_{out} - h_{in})dt \tag{8}$$

Where m_{NG} is the mass flow rate; h_{out} and h_{in} are the enthalpy of output and input natural gas versus time respectively. H is calculated as a function of temperature using equation 9 [6].

$$\frac{(h - h_{ref})}{R} = A(T - T_{ref}) + \frac{B}{2}(T^2 - T_{ref}^2) + \frac{C}{3}(T^3 - T_{ref}^3) \tag{9}$$

Where R is gas universal constant (8.314 KJ/Kmol K) and T_{ref} (is 298 K. The constants for gas fuels have been listed in Table 3.

The variation in temperature of input and output natural gas, air and water bath versus time can be determined using Figs 4, 5 and 6, and therefore the heat transferring to the gas flow is calculated using equation (8). For the considering system, the efficiency can be defined using equation (10).

$$\eta_{sys} = \frac{output}{input} = \frac{\dot{E}_{stored}}{\dot{E}_{fuel}} = \frac{\dot{E}_{input} - (\dot{E}_{NG} + \dot{E}_{surf} + \dot{E}_{stack})}{\dot{E}_{fuel}} \times 100 \tag{10}$$

Table 3. Required constant for calculation of enthalpy as a function of temperature for some fuel gases.

Fuel Gas Type	Chemical Formula	T_{max}	A	10^3B	10^6C
Methane	CH_4	1500	1.702	9.081	-2.164
Ethane	C_2H_6	1500	1.131	19.225	-5.561
Propane	C_3H_8	1500	1.213	28.785	-8.824
Normal Bothane	C_4H_{10}	1500	1.935	36.915	-11.402
Isobutane	C_4H_{10}	1500	1.677	37.853	-11.945

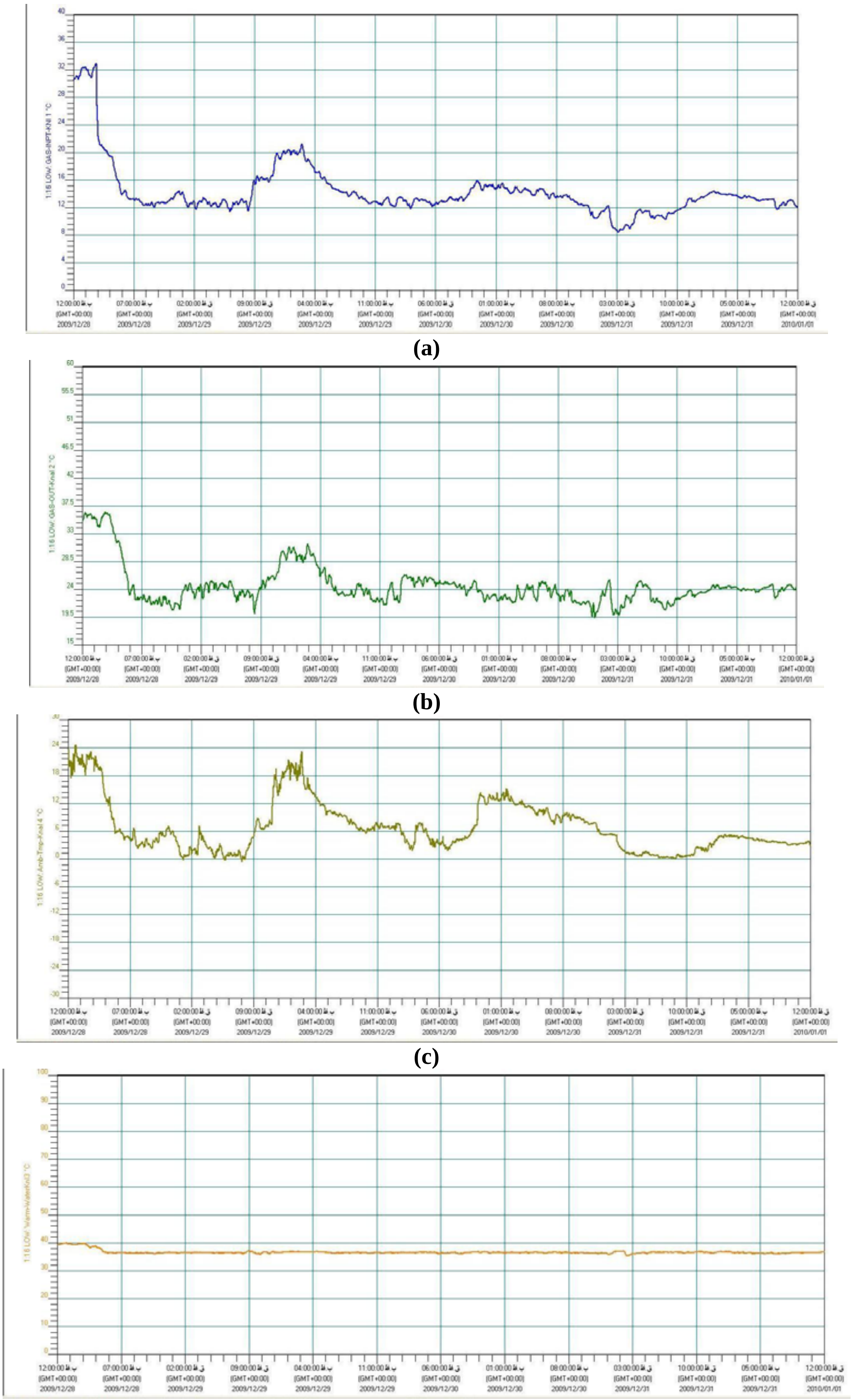
The efficiency of the system before optimization, after optimization and after installation of the barometric damper has been measured (Table 4). All the calculations have been made for a week working conditions.

Table 4. Comparison of the system status in three time intervals. The results were obtained before and after optimization and also after using barometric damper.

Time interval	Status	Burner fuel flow rate (m^3/hr)	Fuel consumption for a week (m^3)	Input energy to the system (MJ)	Wall wasting (MJ) (%)	Transferred energy to heat the gas (MJ) (%)	Stack wasting (MJ) (%)	Efficiency (%)
28 Dec 2009 – 4 Jan 2010	Before optimization	102	15855.2	547287	1493 (0.27)	158485 (28.9)	145852 (26.65)	44.12
13 Jan 2010- 19 Jan 2010	After optimization	186	1031.75	35614	986 (2.77)	2047 (5.7)	8074 (22.67)	68.81
31 Jan 2010- 7 Feb 2010	After using barometric damper	186	17419.82	601294	2044 (0.34)	100096 (16.6)	126452 (21.03)	61.98

The results demonstrate that the adjustment of burner and installation of barometric damper result in a decrease in stack wasting and also reduction in working hours of burner (by adjusting the flame length in an optimized state, the heat transfer rate is increased and the reduction in working hours of the burner is expected), consequently, according to equation 11, a 29% reduction in fuel consumption of the system is observed (Table 4).

$$Energysaving = (1 - \frac{\eta_1}{\eta_2}) \times 100 \tag{11}$$



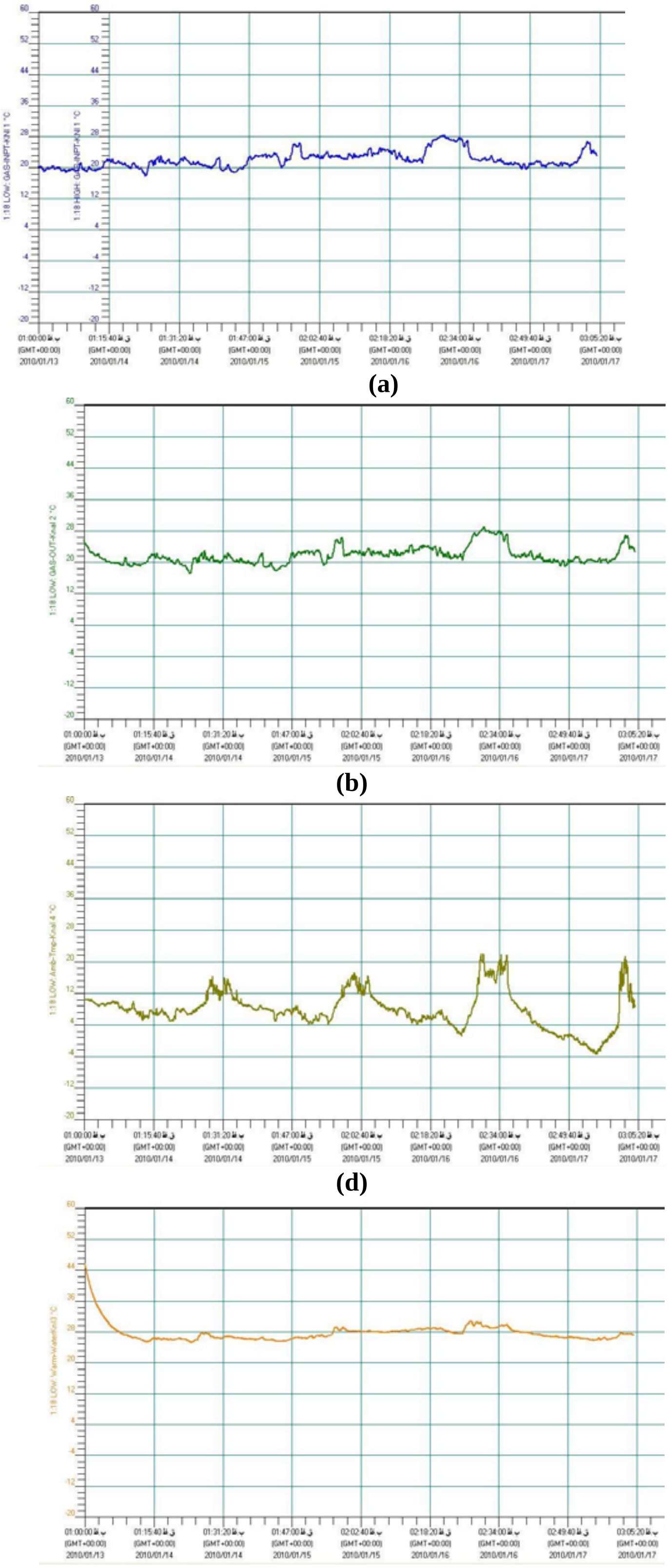
(a)

(b)

(c)

(d)

Figure 7. Temperature variation in (a) gas input entrance (b) gas output opening (c) environment (air) and (d) water bath, before optimization (28 Dec 2009 – 4 Jan 2010).



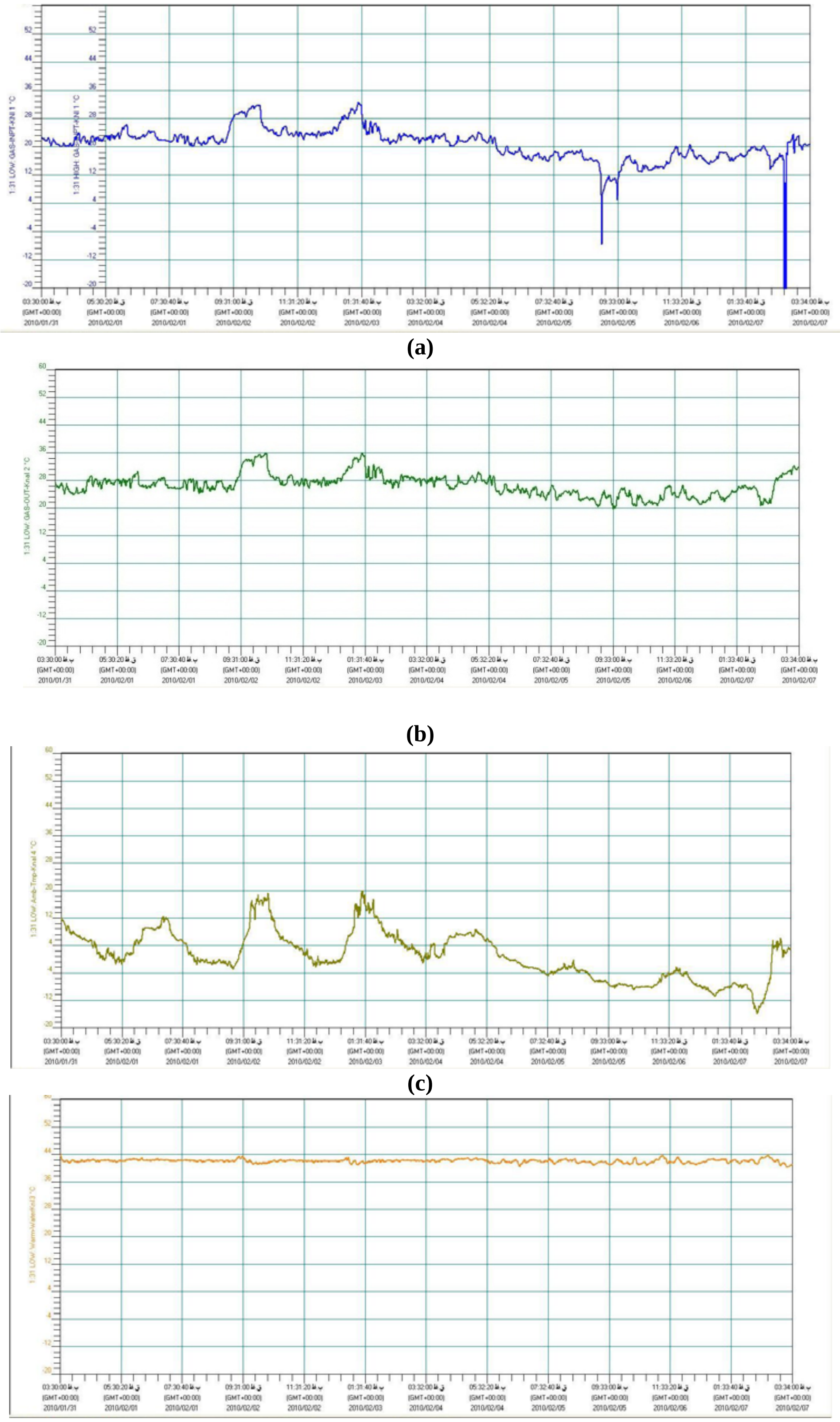
(a)

(b)

(d)

(d)

Figure 8. Temperature variation in (a) gas input entrance (b) gas output opening (c) environment (air) and (d) water bath, after optimization (13 Jan 2010-19 Jan 2010).



(a)

(b)

(c)

(d)

Figure 9. Temperature variation in (a) gas input entrance (b) gas output opening (c) environment (air) and (d) water bath, after installation of the barometric damper (31 Jan 2010- 7 Feb 2010).

Conclusions

Considering the results obtained from the continuous monitoring of the heating system 1 of Arjestan station, the main problem of these heaters was nonconcurrence of heat capacity of burners with the required thermal loads of the heaters. Due to the highest capacity of the burners compared to the heaters, the possibility of optimization at superior efficiency was not feasible. This nonconcurrence also caused a sudden increase in the stack temperature. The produced heat exhausts from the stack without transferring the heat to the water inside the heater; this increases the stack wasting, and consequently reduces the total efficiency of the heating system. In the systems that the capacities of burner and boiler are selected proportionally; with increase of burner capacity to the required thermal load of boiler, a considerable increase in the stack temperature is not observed. However, in the systems such as current heaters, since the capacity of burner is significantly higher than the thermal load of hearer and also due to the massive amount of soot in the combustion chamber , with increase of burner capacity (to reduce the excess air and to increase the burner efficiency), in the capacities higher than the maximum thermal capacity of the boiler , a sudden and an intensive increase in the stack temperature was observed , and consequently resulted in an increase in stack wasting and reduction of system efficiency .

In the boilers with the efficiency of > 90 %, according to the temperature of natural gas flame (1200^{o}C), the temperature of the exhausting gas from the stack is approximately between 180 and 200^{o}C. However, in the boilers with lower efficiency that the heat transfer between the combustion gas and the fluid is not performed completely, the temperature of the exhausted gases is profoundly higher resulting in a great wasting of stack.

On the other hand, the burner designs are usually proportional to the highest nominal performance capacity and in the high or low capacity, an incomplete combustion or an increase in excess air are observed, and results in reduction of combustion efficiency.

To increase the boiler efficiency and reduction of their gas consumption, the burners should be adjusted in an optimum amount of temperature and excess air. For this purpose, first with increase of gas amount through regulators and pressure breakers (when the gas valve is open all the way), the burner capacity is increased to reduce the amount of excess air (the CO gas should not exceed from 300 ppm) and the increasing is proceeded before a sudden jump in a temperature of the output gas from the stack. Finally, the amount of excess air is decreased by reducing the input air to the burner. The input air of burner is reduced till the point that the flame is still stable and the amount of CO gas < 300 ppm.

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