Study on the in situ performance of a 60 kW condensing gas boilers thermal installation and economic assessment

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Abstract. Condensing gas boilers currently represent the most advanced solution for heating based on combustion of fossil fuels from both efficiency and pollution points of view. Besides, compared with the district heating, condensing gas boilers make possible the entire management of the heat supply function by the real heating needs. Subsequently, minimization of the heating cost is possible. In this view, one of the buildings of the “Gheorghe Asachi” Technical University of Iasi was disconnected from the district heating and two condensing gas boilers – one of 25 kW and the other of 35 kW nominal output – were connected to the heating network to ensure the heat supply. A performance and economic analysis of the thermal installation with the two boilers, based on in situ experiments, was performed. The analysis was performed for nine operating regimes described by boilers flow water temperatures from 80 °C to 40 °C. Efficiency (in terms of higher heating value of the fuel) had varied from 86.7 % to 97.5 % and the price of thermal energy produced with the two boilers proved to be 21…30 % lower than the price of thermal energy coming from the district heating system. The annual heating savings are estimated to be 642…907 Euro/year, which induce a payback period of 1.6…2.3 years with strict reference to the investment represented by the two boilers.

1. Introduction
Since September 2015, when the Energy Related Products directive was implemented in EU countries, condensing boilers are the only hot water boilers available on the European market, because traditional (non-condensing) boilers are not compliant with the requirements of this directive.

The benefit of the condensing technology comes from the recovery of the latent heat of the water vapors from flue gas. Consequently, the higher the condensation fraction, the higher the latent heat recovery and boiler performance. A method currently studied for the improvement of the latent heat harnessed from flue gas is the rising of the dew point temperature of the flue gas by humidifying the combustion air. The experimental study in [1] shows that the dew point temperature increases with 6.4 °C when the combustion air humidity increases from zero to 49.0 g/kg of dry air, while the experiments presented in [2] indicated that boiler efficiency increases with 3.7 % – for an air excess ratio of 1.3 – when the combustion air temperature and relative humidity increase from 20 °C and 20 % to 40 °C and 90 %. If the combustion air is not only humidified but also preheated, the decreasing of the NOx concentration in flue gas is obtained additionally to the rise of the dew point temperature; according to [3], NOx decreases from 33 ppm to 24.6 ppm if combustion air is preheated over 50 °C. Experimental determination of the dew point temperature implies the accurate measurement of the flue
gas temperature. According to the experimental study presented in [4], the condensate droplets contained in flue gas induce measurement errors and the real temperature of flue gas is higher than temperature measured by direct contact with about 3 °C.

Beside the improvement of the latent heat harnessed from flue gas, reduction of the pollutant emissions also represents a current concern for research in condensing boilers field and most studies are focused on combustion process. A numerical and experimental analysis of the ignition process of premix combustion in condensing boilers was performed in [5] and shown that ignition time has a significant influence on the stabilization of the flame. An experimental study on two premix burner types, namely a metal fiber burner and a multi-hole stainless steel burner (the most common type used in condensing boilers, according to [6]), was performed in [7] and indicate that metal fiber burner is more convenient in terms of both thermal efficiency and emission.

Taking into account the benefits of the condensing technology, a new solution for heating, with condensing gas boilers, was assumed for the annex building of the Thermal Machines Laboratory – “Gheorghe Asachi” Technical University of Iasi. The annex building, with offices and seminar rooms, was disconnected from the district heating system and two condensing gas boilers, previously installed in the laboratory for experimental purposes, where connected to ensure the heat supply of this building. The paper presents the results of an experimental study on performance of the new heating system. The study was performed in situ, in real operating conditions. Based on the experimental result, the economic analysis of the thermal system was also performed. In the case of the analyzed heating system, the maximum condensation fraction in real operating conditions is 0.52, as indicated by the study presented in [8].

2. Presentation of the thermal installation

The two gas condensing boilers of the analyzed heat generation system have 25 kW nominal output and 35 kW nominal output, respectively (see figure 1). Both boilers have premix combustion systems with cylindrical perforated burner. The primary heat exchangers are made of AISI 316L stainless steel and are spiral shaped. A low loss header connects the condensing boilers system and the heating network – the two components of the heating installation. Pump P ensures water circulation in the heating installation. Protection against excessive pressure of water is ensured by the expansion vessel EV and the safety relief valves of the boilers.

Figure 1. Schematic of the thermal installation.
Once put into operation, the heat generation system ensures not only the heat independence of the building but also the entire management of the heat supply (time intervals for heat delivery as well as temperature and flowrate of the thermal agent), which can be optimized function by the real heating needs. Control of the heat supply time intervals and temperature levels in the building is ensured by a chronothermostat. Thus, the heating cost can be minimized by minimizing the fuel (natural gas) consumption. Besides, the unnecessary cycling (on-off cycles) – which causes unjustified wear and tear of the boilers as well as efficiency losses [9] – are significantly reduced.

Flow water temperatures of the two boilers were measured by using the temperature probes $T_{wf1}$ and $T_{wf2}$, which are NTC Brahma ST07 type. The flow and return temperatures of the heating network were measured with the temperature probes $T_{f}$ and $T_{r}$. These two temperature probes as well as the ultrasonic water flowmeter WM are all parts of the heat meter HM, Itron CF Echo II model. The natural gas consumption was measured by using an Aerotech BK-G6 MT gas consumption meter (GCM).

3. Method of analysis

The analysis was performed for nine operating regimes of the thermal installation. A certain boiler flow water temperature, $t_{wf}$ (the same for both boilers), was set in the range 40 - 80 °C in each analyzed regime; the set values of this temperature are indicated in table 1. The measurements were performed after temperatures stabilization, which was assumed as confirmed in each regime by a maximum variation of the flow and return temperatures of the heating network ($t_{f}$ and $t_{r}$) of 0.5 K. Besides water temperatures, natural gas consumption and water flow in the heating network ($V_{g}$, and $V_{w}$, respectively), both expressed in m$^3$, were measured. Their values are also indicated in table 1.

The gross heat input of the condensing boilers system, in kW, was expressed as

$$\dot{Q}_{\text{has}} = 10^3 \cdot V_{g} \cdot \tau_{g}^{-1} \cdot H_{hg}, \quad (1)$$

while the net heat output of the thermal installation, in kW, was calculated as

$$\dot{Q}_{w} = \rho \cdot V_{w} \cdot \tau_{w}^{-1} \cdot c_{pw} \cdot (t_{f} - t_{r}), \quad (2)$$

The following notations were used in equations (1) and (2):

- $\tau_{g}$ - time interval for gas consumption, in s;
- $H_{hg}$ - higher heating value of the natural gas, expressed in MJ/m$^3$; there were assumed the official values daily recorded by Delgaz Grid S.A. (the fuel gas supplier of “Gheorghe Asachi” Technical University of Iasi), as presented on its website (see table 1);
- $\tau_{w}$ - time interval for water consumption, in s;
- $\rho_{w}$ - density of water; $\rho_{w} = 1000$ kg/m$^3$;
- $c_{pw}$ - specific heat capacity of water at constant pressure; $c_{pw} = 4.186$ kJ/(kg K).

Efficiency of the thermal installation (in terms of higher heating value of the natural gas), in %, was defined as

$$\eta = 100 \cdot \dot{Q}_{w} \cdot \dot{Q}_{\text{has}}^{-1}, \quad (3)$$

If the higher heating value of the natural gas ($H_{hg}$) is replaced with the lower heating value ($H_{lg}$) in equation (1) than the net heat input of the condensing boilers system ($\dot{Q}_{\text{has}}$) is defined. Replacement of $\dot{Q}_{\text{has}}$ with $\dot{Q}_{\text{hii}}$ in equation (3) leads to

$$\text{RPI} = 100 \cdot \dot{Q}_{w} \cdot \dot{Q}_{\text{hii}}^{-1}, \quad (4)$$

which defines the relative performance indicator, in %, as was previously defined by the authors in [10]. The lower heating value of the natural was assumed to be $H_{lg} = 1.11 \cdot H_{hg}$, also according to [10].

The price of the thermal energy produced in the analyzed installation, expressed in Euro/MJ, was calculated based on the price of the natural gas $P_{NG} = 39.9$ Euro/MWh = 0.01108 Euro/MJ, as
\[ PTE = P_{NG} \cdot \dot{Q}_{bs} \cdot \dot{Q}_w^{-1}. \] (5)

Taking into account the price of thermal energy coming from the district heating system, namely \( PCTE = 67.739 \) Euro/Gcal = 0.01618 Euro/MJ, thermal energy cost savings, in Euro/MJ, were calculated as

\[ CS = PCTE - PTE. \] (6)

It should be mentioned that both prices \( P_{NG} \) and \( PCTE \) were quoted in February 2020, in Iasi, Romania, and VAT is included.

4. Results and interpretation
The set values of \( t_{wf} \), the assumed values of \( H_{hg} \) as well as all the measured values (of \( V_g \), \( \tau_g \), \( t_f \), \( t_r \), \( V_w \) and \( \tau_w \)) are presented in table 1. Based on these values, there were calculated \( \dot{Q}_{bs} \), \( \dot{Q}_w \), \( \eta \), RPI, PTE and CS with equations indicated above, from (1) to (6). Variations of the performance indicators \( \dot{Q}_w \), \( \eta \) and RPI

| Date             | \( H_{hg} \) [kWh/m³] [MJ/m³] | \( t_{wf} \) [°C] | \( V_g \) [m³] | \( \tau_g \) [s] | \( t_f \) [°C] | \( t_r \) [°C] | \( V_w \) [m³] | \( \tau_w \) [s] |
|------------------|-------------------------------|-----------------|---------------|----------------|----------------|----------------|---------------|----------------|
| February 13, 2020| 10.647/ 38.329                | 80              | 3.830         | 3757           | 77.6           | 67.0           | 2.8           | 3666           |
| February 14, 2020| 10.636/ 38.290                | 75              | 3.635         | 3832           | 71.7           | 63.1           | 3.3           | 3741           |
| February 14, 2020| 10.636/ 38.290                | 70              | 5.283         | 6442           | 67.2           | 59.7           | 5.8           | 6480           |
| February 15, 2020| 10.693/ 38.495                | 65              | 6.023         | 8867           | 62.8           | 56.3           | 6.4           | 7382           |
| February 17, 2020| 10.689/ 38.480                | 60              | 2.680         | 4165           | 57.9           | 51.9           | 3.0           | 3360           |
| February 18, 2020| 10.689/ 38.480                | 55              | 2.887         | 5506           | 53.5           | 48.3           | 4.9           | 5621           |
| February 19, 2020| 10.693/ 38.495                | 50              | 3.247         | 7950           | 49.0           | 44.9           | 6.9           | 7942           |
| February 21, 2020| 10.679/ 38.444                | 45              | 2.422         | 6832           | 44.2           | 40.5           | 5.7           | 6760           |
| February 25, 2020| 10.691/ 38.488                | 40              | 1.285         | 5717           | 36.7           | 34.3           | 4.8           | 5719           |

**Table 1. Assumed parameters and measured data.**

\( Q_w \) [kW] vs. \( t_{wf} \) [°C]

**Figure 2.** Variation of net heat output of the thermal installation with boiler flow water temperature.
Figure 3. Variation of the efficiency and relative performance indicator of the thermal installation with boiler flow water temperature.

Figure 4. Thermal energy price produced in the analyzed installation and thermal energy cost savings function by the boiler flow water temperature.

with $t_{wf}$ are presented in figure 2 and figure 3 while variations of the parameters with economic relevance, namely PTE and CS, are presented in figure 4.

As can be seen in figure 2, $\dot{Q}_w$ increases continuously with $t_{wf}$ (which is normal) and has an almost linear evolution; the minimum and maximum values of $\dot{Q}_w$ are 8.43 kW (when $t_{wf} = 40$ °C) and 33.89 kW (when $t_{wf} = 80$ °C), respectively.

Maximum efficiency and relative performance indicator – achieved at the minimum boiler flow water temperature, $t_{wf} = 40$ °C – are 97.5 % and 108.2 %, respectively (see figure 3). These two parameters decrease continuously with $t_{wf}$, so reach the minimum values of 86.7 % and 96.3 % at the maximum boiler flow water temperature $t_{wf} = 80$ °C. It means that $\eta$ and $RPI$ lose roughly 11 % and 12 %, respectively, when $t_{wf}$ increases from 40 °C to 80 °C. But even so, one can see that even in the most
inconvenient conditions (when $t_{wf} = 80 \, ^{\circ}\mathrm{C}$), the performance of the analyzed thermal installation is still significant. Due to this high performance, the economic benefits are important. As can be seen in figure 4, the thermal energy is produced in the analyzed installation with a price ($P_{TE}$) between 0.01137 Euro/MJ (when $t_{wf} = 40 \, ^{\circ}\mathrm{C}$) and 0.01277 Euro/MJ (when $t_{wf} = 80 \, ^{\circ}\mathrm{C}$), which is considerably lower (with 21...30 %) than the price of thermal energy coming from the district heating system – $P_{CTE} = 0.01618$ Euro/MJ. The difference of the two prices – of maximum 0.00482 Euro/MJ (or 30 % of $P_{CTE}$), when $t_{wf} = 40 \, ^{\circ}\mathrm{C}$, and minimum 0.00341 Euro/MJ (or 21 % of $P_{CTE}$), when $t_{wf} = 80 \, ^{\circ}\mathrm{C}$ – is marked with green color in figure 4 and represents the thermal energy cost savings ($CS$). Taking into account that average heat consumption of the annex building during an entire cold season is 45 Gcal/188361 MJ, it means that annual heating savings could be estimated from 642 Euro/year (for $t_{wf} = 80 \, ^{\circ}\mathrm{C}$) to 907 Euro/year ($t_{wf} = 40 \, ^{\circ}\mathrm{C}$). In terms of investment with strict reference to the boilers price, of 1460 Euro, it results a payback period of 1.6…2.3 years.

5. Conclusions
Implementation of the 60 kW condensing heating system, experimented in situ in “Gheorghe Asachi” Technical University of Iasi, ensured not only the heating independence but also the entire management of the heat supply, making thus possible minimization of the heating cost by minimizing the natural gas consumption.

The performance of the thermal installation was high in all nine analyzed operating regimes. Efficiency and relative performance indicator varied from 86.7 % and 96.3 % (when $t_{wf} = 80 \, ^{\circ}\mathrm{C}$) to 97.5 % and 108.2 % (when $t_{wf} = 40 \, ^{\circ}\mathrm{C}$).

The economic benefits proved to be significant as a direct consequence of the high performance of the thermal installation. The price of thermal energy produced in the analyzed installation is lower with 21...30 % than the price of thermal energy coming from the district heating system ($CE = 0.00341$ Euro/MJ for $t_{wf} = 80 \, ^{\circ}\mathrm{C}$ and $CE = 0.00482$ Euro/MJ for $t_{wf} = 40 \, ^{\circ}\mathrm{C}$). Since the average heat consumption of the building during an entire cold season is estimated to 45 Gcal/188361 MJ, the annual heating savings are estimated to be from 642 Euro/year (for $t_{wf} = 80 \, ^{\circ}\mathrm{C}$) to 907 Euro/year ($t_{wf} = 40 \, ^{\circ}\mathrm{C}$). Accordingly, the payback period for investment – with strict reference to the boilers – is 1.6…2.3 years.

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