Experimental study regarding the implications of "Eco-Design" Directive over conception and performances of small boilers

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Abstract. The paper makes an analyse regarding the implications of "Eco-Design" Directive over conception and performances of small boilers. The study is based over a large number of tested boilers under certified conditions. There are mainly two families of condensing boilers: those projected from the beginning as condensing boilers and those who initially were non-condensing boilers and then were shifted to condensing functioning. The study compares the technical performances reached by the boilers of each family considering also the economical and engineering constraints implied.

1. General considerations
An important segment of the energetic consumption at household level is generated by the boilers with thermal output up to 70 kW (usually under 40 kW) and using as combustible the natural gas delivered by the national distribution network. They are used in uni-familial or multi-familial households for heating purposes or for double service (heating and hot water production).

Because the many advantages for household use of "atmospheric" burners (with self-absorbed by ejection primary air and with secondary air absorbed by the burning’s chamber draught), by the years 2000 – 2010, those were widely spread in the field of small boiler producers. Those burners (simple, reliable, quiet, but with medium burning performances due to the big air excess and the bad response to thermal load lowering) were usually coupled with "quasy-adiabatic" burning chambers followed by (mainly convective) aqua-tubular heat exchangers with finned external surfaces (on the side of the flue gases). In order to overcome the problem generated for the secondary air absorption by the variable chimney draught, there were implemented two regulatory measures: either the "chimney base zero pressure" solution, either the "sealed chamber" with exhausting fan solution. The final product was a reliable and most important cheap boiler with medium performances [1], [2].

In the same time, there were boiler producers developing condensing boilers with all the necessary elements for this heat exchange technique: pre-mixed modular burners with modulating thermal power and radiant surface stabilised burning, flue gases vertical flow high speed heat transfer over condensing surfaces, “near to perfect” counter-current flow, high range thermal power modulation with constant air excess etc. Those boilers were by all means superior to those presented previously, both from thermal efficiency as from ecological point of view, but they were also significantly more costly.

The result was the presence of two different constructive solution in the same time, the “classical ones” and the “condensing” ones. Although the second family was clearly superior to the first one by means of performances, the first one remained the preferred one by most of the buyers because of their significantly lower purchase price and their handling and maintenance simplicity.

In the last decade the awareness about thermal efficiency and ecological functioning of household boilers become more and more present in the legislation field linked to those appliances [3], [4], [5]. The European Parliament Directive 2009/125/CE was a milestone for thermal and ecological performances regulation by stating the necessity for small boilers to meet some minimal conditions.
regarding both thermal efficiency and ecological performances. It was the producer’s responsibility to comply with the legal demands. Later, the Delegated Regulation of the Comity (European n.a.) No.811/2013 defined the main efficiency classes for the small boilers. Those classes went from G (worst) to A+++ (best) and referred to seasonal boiler’s efficiency, expressed as a weighted average between nominal thermal output efficiency and partial thermal output (30%) efficiency. The Comity (European n.a.) Regulation No.813/2013 defined the weighting factors for the two efficiencies in the yearly functioning of the boiler and gave the calculus methodology for the “seasonal boiler’s efficiency” (needed for the boiler energetical classification). Also, it was stated by the European Comity that starting with 26 of September 2015, the seasonal boiler efficiency for thermal powers of less than 70 kW and using gaseous combustible, must be superior to 86% when referred (reported) to high caloric power of the combustible (PCS).

This regulation indirectly eliminated the non-condensing small boilers (previously presented from the constructive point of view) from the market, simply because their usual values (percentage expressed) of thermal efficiencies were about 92% for nominal output and 88% for partial charge (about 30%) referred to PCI, that meaning approximately 82% for nominal output and approximately 78% for partial charge (about 30%) referred to PCS, thus an overall “seasonal boiler’s efficiency” undeniably under the minimum required value of 86%.

Under those circumstances, the producers oriented to “classical boilers” production faced the choice to either completely change their production lines, or to upgrade their products. Of course, many of them chose the second alternative and started to switch the “classical” functioning of their small boilers to “semi-condensing” or “hybrid” functioning.

2. The studied boilers

The producers had in mind to preserve the constructive solutions already existent and upgrade them with additional parts in order to switch the boiler’s functioning to condensing. The general line was to fit an additional condensing heat exchanger after the “classical” one. The new heat exchanger had to comply (as much as possible) with the basic demands of a condensing unit, i.e. condensate elimination (by vertical down-flow of the flue gases) and counter-current flow (flue gases vs. secondary agent). Of course, by maintaining the “atmospherical” burner, the air excess remained high (contrarily to the recommendation for condensing boilers). Finally, a “hybrid” small boiler type emerged, based on the “classical” one but with enhanced thermal capabilities (i.e. functioning in condensing regime).

In Figures 1 to 4 is presented such an evolution from classical solutions (Figure 1 and Figure 2) to condensing solutions (Figure 3 and Figure 4). Figure 1 presents the schematics of a small boiler with natural draught and Figure 2 presents a constructive solution for the same type of small boiler but with an exhausting fan used to generate and regulate the draught.

In Figure 3 and Figure 4 we can observe the supplementary condensing heat exchanger in two constructive solutions (although very similar because the technological and functional constraints were the same).

An interesting solution for enhancing the burning performances of the atmospheric burner by regard to NOx emissions was to cool the burner with the secondary agent. Of course, it is well known that the NOx emissions are exponentially dependent on real burning temperature (theoretical temperature diminished due to heat losses – cooling – at the burning process level). Due to the fact that the burner cooling process is realised by the means of a thermally useful agent (so representing a supplementary useful heat exchange surface), the boiler efficiency will slightly increase.

In order to have a consistent comparison, all the studied boilers were of approximately same thermal output (24 kW), with the same number of individual burner blades, same overall blade geometry and same constructive solution for the burner.

Of course, the burning chamber dimensions, as well as the principal heat exchanger, were maintained, in order to outline mainly the influence over the boiler’s thermal performances of the supplementary condensing unit and of the burner’s cooling system (when existing).
The interest of this paper is to create a comparison picture between the “classical” small boilers and the “hybrid” ones that derived from them. Of course, this picture is interesting because the “hybrid” solutions are closely related from construction point of view to the “classical” ones and so the production
and final costs of those boilers ranges the small prices characteristic for the “classical” solutions, far more inexpensive than the “fully condensing” boilers. Just for exemplification, in Figure 5 are presented two classical condensing boiler solutions.

![Classical condensing boiler](image1)

**Figure 5.** Classical condensing boiler

Even if they are some of the simplest ones, still they are significantly more complicated and require more complex technologies for production than the “classical” small boilers. The fact is further supported by the technological complications required by the construction of the premixed, surface stabilized burners, which equip such boilers. A classical solution of such burner is presented (as an example) in Figure 6.

![Premixed, surface stabilized burner](image2)

**Figure 6.** Premixed, surface stabilized burner
3. The testing method

The testing method was the one generally accepted in the field of thermal performances boiler testing, the one required by the SR EN 15502-1(2-1): Central heating boilers using gaseous combustibles. Part 1: General demands and testing. The tests were performed for the four types of boilers previously presented and schematically pictured in Figures 1 to 4. All the tests were performed in the certified laboratory belonging to the Technical University for Constructions Bucharest and located at the site of the Installations Faculty – Thermodynamics and Thermal Appliances Chair.

Some definite testing regimes, further referred to as “setting points” (because this is the reference element due to the fact that the setting point is the regulated element and the real functioning regime is only the result of the setting point implemented to the boiler when functioning coupled with a thermal consumer, in this case a testing loop), were chosen to be representative from the testing standard point of view. So, the nominal (100%) setting point, along with the partial 30% setting point, were measured and outlined, because of their importance in determining the seasonal boiler’s efficiency.

Tests were performed with G20 test gas. The testing loop was designed to regulate the main parameters of the boiler’s functioning in order to meet all the conditions imposed by the measuring standard, such as inlet water temperature, outlet water temperature, continuous and constant (after regulation, of course) heat dissipation (to the environment, via a heat dissipation forced draught cooling tower) and steady-state functioning regime.

The inlet and outlet water temperatures were regulated by a double loop, both with step-by-step automated regulation valves, one loop for thermal agent recirculation (mainly determining the temperature difference on the boiler) and one loop for cooled water injection and extraction (mainly determining the thermal power dissipation of the testing ring). The water debit was measured by the means of a rotary flowmeter with immersed turbine and digital output, the temperatures were measured by two sets of double thermo-resistances with limit error alarm, the flue gases temperature and composition with electronic gas analyser and the combustible consumption by the means of a specially designed gas-meter with pressure and temperature corrections in real time and digital parameter transmission.

All the elements were integrated in the testing loop industrial software, that was conducting the regulation and measuring process.

| Case number / condensing | Type of boiler | * Thermal output percentage vs. real percentage | Thermal power output [kW] | Secondary agent temp. inlet / exit [°C] | Thermal efficiency according to standard [%] | Thermal efficiency as defined by thermodynamics [%] | CO [ppm] | NOx [ppm] | Air excess [-] | Flue gases temp. at chimney [°C] | NOx weighted with the thermal output [mg/kWh] |
|-------------------------|---------------|-----------------------------------------------|---------------------------|----------------------------------------|-----------------------------------------------|-----------------------------------------------|---------|----------|-------------|-------------------------------|-----------------------------------------------|
| 1 / No ND              | 100 / 100     | 23.4                                          | 60/80                     | 92.91                                   | 83.12                                         | 455                                           | 105     | 1.39     | 139                     | 183                                           |
| 2 / No ND              | 30 / 36       | 8.5                                           | 40/60                     | 91.48                                   | 81.84                                         | 5                                             | 18      | 2.08     | 90                      | 149                                           |
| 3 / No ND              | 30 / 31 **    | 7.2                                           | 40/60                     | 91.2                                    | 81.59                                         | 97                                            | 29      | 1.47     | 121                     | 99                                            |
| 4 / No FD              | 100 / 100     | 23.2                                          | 60/80                     | 92.83                                   | 83.05                                         | 51                                            | 58      | 1.7      | 156                     | 149                                           |
| 5 / No FD              | 30 / 37       | 8.7                                           | 40/60                     | 88.14                                   | 78.85                                         | 26                                            | 11      | 2.47     | 105                     | 99                                            |
| 6 / No FDC             | 100 / 92      | 23.3                                          | 60/80                     | 96.83                                   | 86.63                                         | 116                                           | 94      | 1.44     | 83                      | 149                                           |
| 7 / Yes FDC            | 100 / 100     | 25.2                                          | 30/50                     | 104.1                                   | 93.13                                         | 108                                           | 83      | 1.56     | 63                      | 149                                           |
| 8 / Yes FDC            | 30 / 29       | 7.4                                           | 30/50                     | 100.1                                   | 89.55                                         | 18                                            | 46      | 1.91     | 45                      | 45                                            |
| 9 / No FDCCB           | 100 / 96      | 24.2                                          | 60/80                     | 96.81                                   | 86.61                                         | 96                                            | 36      | 1.78     | 79                      | 55                                            |
| 10 / Yes FDCCB         | 100 / 100     | 25.2                                          | 30/50                     | 104.4                                   | 93.40                                         | 87                                            | 26      | 1.81     | 49                      | 55                                            |
| 11 / Yes FDCCB         | 30 / 29       | 7.2                                           | 30/50                     | 100.2                                   | 89.64                                         | 17                                            | 29      | 2.1      | 41                      | 41                                            |

* The thermal output percentage is the value that was desired to be reached for the respective functioning regime
** For this case the thermal power was realized by using an "all or nothing" functioning regime

The inlet and outlet water temperatures were regulated by a double loop, both with step-by-step automated regulation valves, one loop for thermal agent recirculation (mainly determining the temperature difference on the boiler) and one loop for cooled water injection and extraction (mainly determining the thermal power dissipation of the testing ring). The water debit was measured by the means of a rotary flowmeter with immersed turbine and digital output, the temperatures were measured by two sets of double thermo-resistances with limit error alarm, the flue gases temperature and composition with electronic gas analyser and the combustible consumption by the means of a specially designed gas-meter with pressure and temperature corrections in real time and digital parameter transmission.

All the elements were integrated in the testing loop industrial software, that was conducting the regulation and measuring process.
4. Testing results

In Table 1 are presented the most important measured parameters needed for the functioning characterisation of the four discussed solutions. As a general observation, the tested boilers are classified as non-condensing or condensing from the start in order to ease the comparisons.

The first column defines the order number of the test and states the presence (Yes) or the absence (No) of the condensing regime (for each testing situation).

The second column defines the exact type of boiler tested. So, ND mean natural draught, FD means forced draught, FDC refers to condensing boilers with forced draught (the constructive solution illustrated in figures 3 and 4 – i.e. separate condensing stage after the main heat exchanger) and FDCCB means condensing boilers with forced draught and cooled burner.

In the third column are presented the specific setting points for each tested boiler. The first figure represents the desired (optimal) setting point and the second figure represents the real functioning regime acquired after steady-state functioning on the measuring loop (after no more regulating actions were taken and steady-state functioning was allowed to settle).

The real thermal powers obtained and measured (which also determine the real percentile load when reported to nominal thermal power considered reference value) are detailed in the fourth column. In the next column are defined the thermal conditions for each measured setting point, as imposed by the testing standard (column five).

The sixth column offers probably the most important functioning parameter for this study, the boiler’s thermal efficiency. The value is calculated as demanded by the standard, i.e. by reporting the useful heat flow of the boiler to the combustible debit chemical potential expressed as inferior calorific power. For non-condensing boilers there is no contradiction, but for condensing boilers the value may be over 100% due to the fact that in reality the inlet energetical flow is in fact the combustible debit chemical potential expressed as superior calorific power.

In the next column (number seven) it is calculated and presented the real thermodynamic efficiency of the boiler, as reported to the combustible debit chemical potential expressed as superior calorific power. It is interesting to mention that the measuring standard and the performance estimation standards are not consistent, the first one using for the combustible’s thermo-chemical potential the lower calorific power and the others using the superior calorific power of the gaseous combustible. Nevertheless, the efficiency values presented in column seven are to be considered references, both for pure thermomechanical characterisations or comparisons as for the boiler’s classification from the standardised point of view.

Columns eight and nine are presenting the two main emissions parameters, the CO and the NOx concentrations in the flue gases. Based on those values, the boiler admission from the point of view of incomplete combustion emissions is decided and the classification from NOx emission class is made. The air excess, presented in column ten, is an important indication for the burning process performance and stability. It is well known that a high value of the air excess determines high thermal losses with the eliminated flue gases (at chimney level) and diminishes the condensing potential of the condensing unit (due to the rise of the dew point of the flue gases). As a reference value, for “pure breed” condensing boilers with premixing burners, the level of the air excess normally ranges between 1.05 and 1.15, value maintained quasi-constant when the boiler (and implicitly the burner) is functioning at partial loads. The values for natural draught burners are significantly higher, averaging 1.5 for nominal functioning conditions, but going up to 2 when partial loads are required.

In the penultimate column is presented the flue gas temperature at chimney level, value of outmost importance, along with the air excess, in determining the boiler’s efficiency.

Finally, in the last column, the characteristic NOx emission is calculated for each boiler, as indicated by the specific standard, considering the NOx emissions in several functioning regimes (nominal and partial loads) weighted in an averaging formula.

5. Comments and conclusions

From the functioning comparison of the four related, but still very different boilers, some very important comment stand out. So, even if all the functioning parameters are correct for each boiler class, determining a good appreciation from a specialist’s point of view (and correct results for a beneficiary),
still the two first solutions do not comply with the minimal requirements of the energy efficiency standards, while the two condensing solutions do. The sezoanal boiler thermal efficiency averages 80% to 82% for the non-condensing boilers while for the condensing ones, the value for the sezoanal boiler thermal efficiency averages 89% to 90%. Considering the minimal level of the boiler’s sezoanal efficiency required by regulation standards as being 86%, the previous statement is clearly demonstrated.

As a conclusion, the necessity of complying with the “Eco-Design” Directive regulations, forced the small (wall-hung) boilers producers to develop performance enhancement solutions (supplementary condensing heat exchangers) for the existing boilers, in order to maintain the production chains and technologies for the “basic” boiler and to secure an entry level price for their commercial boilers while complying with the performance demands enforced by the specific legislation.

The enhancement (upgrade) solution with supplementary condensing unit is widely spread among the small (wall-hung) boiler producers and proved correct both from technological and commercial point of view, bringing an average efficiency rise (gain) of approximately 8%, but still maintaining a low price for the boiler production.

In future papers, we intend to closely and detailed study the comparison between “hybrid” boilers and “pure breed” condensing boilers, in order to analyse and compare their functioning parameters from both the thermodynamic (thermal and ecological performances) and economic (purchase and maintenance costs) point of view.

References

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[4] Delegated Regulation of the European Comity No.811/2013.
[5] European Comity Regulation No.813/2013.
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