SIMULATION OF BOILERS FOR HEATING AND HOT WATER SERVICES

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ABSTRACT

The combination of boilers of high efficiency is presented which contribute to energy saving in domestic heating plants and solve the problems of delivery of hot water in the favourable terms. They present the following features: conventional or condensing instantaneous boiler, flame modulating, and with electric ignition.

A natural gas-fired high efficiency conventional boiler is considered: maximum output 35kW; combined instantaneous boiler to produce heating and hot water; with a hermetically sealed gas combustion chamber, fan assisted, ready to be connected to flue-gas and external air ducts.

Experimental efficiencies and cyclic values, calculated by simulation at partial load, are compared with those of other three different high efficiency boilers, for heating and tap water services:

- ON-OFF, conventional boiler with tank;
- ON-OFF, conventional instantaneous boiler;
- flame modulating, conventional instantaneous boiler;

Keywords: combination boilers, plant efficiency, hot water supply

1. INTRODUCTION

Cyclical efficiency of a gas boiler can be defined by its experimental efficiency at full load, for a given return water temperature and by its experimental stand-by losses, considering its actual regulation system (Tosato R. 2008).

A relationship of the cyclic efficiency of the boiler to the regulation system can be calculated using two experimental curves: the efficiency at full load and the stand-by losses. This relationship can be used for condensing boilers, other kinds of boilers, and also for the usual regulation systems provided the appropriate values of the constants have been experimentally defined. The evaluation of the seasonal efficiency of boiler requires the knowledge of the estimated efficiency at the defined loads (Tosato R. 2009, Defu C., Yanhua L., Chunyang G., 2004).

Sinusoidal loads from zero to maximum load depending on season variations seems to be suitable in the apartment with heating plants. The relationship between energy consumption end energy demand in cyclical operation can be used with a sufficient degree of precision to calculate the seasonal consumption as a function of the sinusoidal load.

The efficiency of a condensing boiler is very high and it can exceed by 25% the efficiency of traditional boilers.

The energy problem of boilers lies in the unfavourable decrease in cyclic efficiency when boilers deliver hot water.

One way to maximize efficiency is to integrate space and water heating in a single appliance.

While improvements in the building envelope reduce the space of heating load it is somehow difficult to justify the expenses of a condensing boiler solely to provide the heating load. To take the advantage of the efficiency potential of condensing gas-fired systems, it makes sense to combine space heating with other functions, in particular, domestic water heating. Domestic hot water loads have remained fairly constant during season variations making it logical to put more effort into improving the efficiency of the hot water generator.

An integrated, high-efficiency space and water condensing gas-fired heating system, using water from municipal mains as the driving mechanism to condense the flue gas, maximizes efficient operation and it can achieve efficiencies of over 90 percent for both, space and water heating. This combination also eliminates the need for multiple exhaust systems.

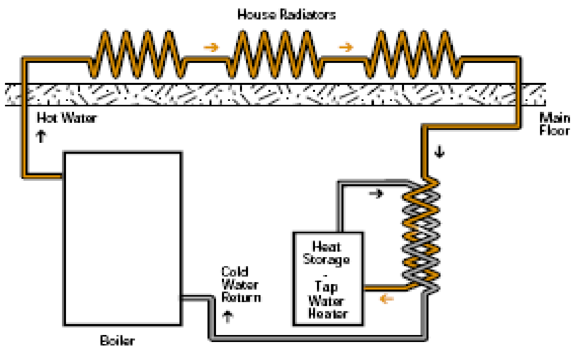

Figure 1: Scheme of high-efficiency combined space and water heating system (Heating With Gas *ISBN 0-662-34205-4, Cat N. M91-3/3-2003E*)

The gas-fired boilers can have problems in condensing when the return water temperature is above the dew point of the fluid gases. By installing a water-to-water heat exchanger and storage tank for tap hot water upstream of the boiler, the return water temperature can be brought below the dew point, fluid gases will condense and the efficiencies will be improved. Such a high-efficiency combined system is shown in Figure 1.

Standard-efficiency gas-fired combined systems also exist, but their efficiency is lower than those of condensing units. A standard-efficiency boiler coupled with an external storage tank is another efficient solution.

Combi boilers are highly popular in Europe, where in some countries market share is 70%.

There are certain advantages to tankless water heaters :

- a tankless water heater may result in both energy and cost savings in the long term. As water is heated only when it is needed, there is no storage of hot water kept warm all day even if it never get used and heat loss through the tank walls will result in a continual energy drain.

- As water is heated while passing through the tankless water heater - an unlimited supply of hot water is available constantly.

- less physical space has to be dedicated to heating water.

Tankless heaters also have some disadvantages:

- there is a longer wait to obtain hot water, since heater starts only upon demand, which is one of its chief advantages, so all idle water in the piping starts at room temperature.

- for intermittent use applications (for example when a hot water faucet is turned on and off repeatedly at a sink) this can result in periods of hot water, followed by some small amount of cold water.

The word combi is a short term for combination. Combi boilers are the most energy efficient boilers in the actual market since they are above 90% energy efficient. As term suggests, combi boiler is both high-efficient water heater and a central heating boiler combined within a single unit presented in Figure 2. These type of boilers don't require any hot water cylinder, hence saving a lot of space in the storage area of a house. Combination boilers produce hot water immediately whenever it is required. It has a built-in water heater which boils the water instantly and produces hot water. They have internal heat exchanger which enables the boiler to heat and cool the water rapidly.

A combi-instantaneous boiler is the most widely used combi boiler type and directly heats incoming mains cold water to supply the taps of the house, showers and other hot water demanding appliances.

A combi-instantaneous-condensing boiler operates as an 'instantaneous' boiler but at somewhat higher efficiencies than the standard combi boiler.

A combi-storage boiler is a variant of the instantaneous combi boiler type and is designed to give better performance through the internal storage of heated water. The stored water also can give better initial water supply from cold water mains at the first tap turning. Once the stored heat has been used, this boiler will tend to operate as an 'instantaneous' type. In the various manufactures and models, the improvement in heated water delivery will depend upon the size of water store, and this can vary widely.

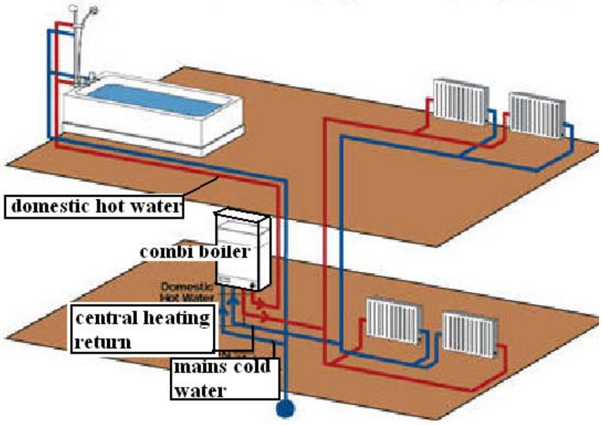

Figure 2 - Combination boiler

High costs often prevent the market diffusion of novel and efficient boilers. Monitoring cost and price decline for these technologies is thus important in order to establish effective energy policy. Experience curves and cost-benefit analyses for condensing gas **boilers** produced and sold in the Netherlands between 1981 and 2006 are important (Weiss M., Dittmar L., 2009). For the most dominant boiler type on the Dutch market, i.e., condensing gas combi boilers, the authors identify learning rates of 14±1% for the average price and 16±8% for the additional price relative to non-condensing devices. The net present value of condensing gas combi boilers shows an overall increasing trend. Purchasing in 2006 a gas boiler of this type instead of a non-condensing device generates a net present value of 970 EUR (Euro) and realizes CO_2 (carbon dioxide) emission savings at negative costs of −120 EUR per tonne CO_2. Tfey attribute two-thirds of the improvements in the cost-benefit performance of condensing gas combi boilers to technological learning and one-third to a combination of external effects and governmental policies.

2. DESCRIPTION OF THE BOILER

The main features of the boiler prototype are summarized in the abstract. Other particular functional and energy characteristics, tested with a laboratory test rig, are:

a) it is relatively cheap because it doesn't require the expensive exchanger of condensing boilers. The flue-gas temperatures are higher than 80°C and so they are very far from the dew point, throughout the entire range of operation conditions;

b) it is provided by a modulating combustion device, able to cover a wide range of loads. It attains an output of 35 kW to produce tap water and a very low level of output (lower than 6 kW) for heating and hot water services;

c) it is also provided with an ON-OFF combustion device, to control the output at partial loads (less than 6 kW during the heating operation);

Figure 3: The prototype of high efficiency domestic combined boiler.

d) the boiler is fan assisted, with an automatic variation in the 2-speed revolution, to provide the control of dew point of flue gases and the air excess, when the output decreases below 15 kW:

e) it has been designed to be connected to the plant without any mixing valve in the most efficient way (direct-connection), and is provided with an electronic power regulation depending on the external air temperature.

Tests have been performed at full and partial loads, by directly connecting the boiler to an experimental rig, and they show the actual possibilities of comfort and energy saving of this system:

a) constant tap water temperature (between 30 and 60°C) and a flow of up to 1200 kg/h to ensure a high degree of comfort for the whole family;

b) high efficiencies (H.E. 0.73-0.81 on High Heat Value) at an output higher than 6 kW, on heating or tap water production in cyclic operation modes. The same acceptable mean seasonal efficiency may be reached in comparison with other H.E. boilers providing only heating services.

3. SIMULATION OF TAP WATER AND HEATING SYSTEM

By means of a control system, two pumps transfer hot water from the boiler to the central heating system or to the tap water heater. A three-way valve permits the use of only one pump.

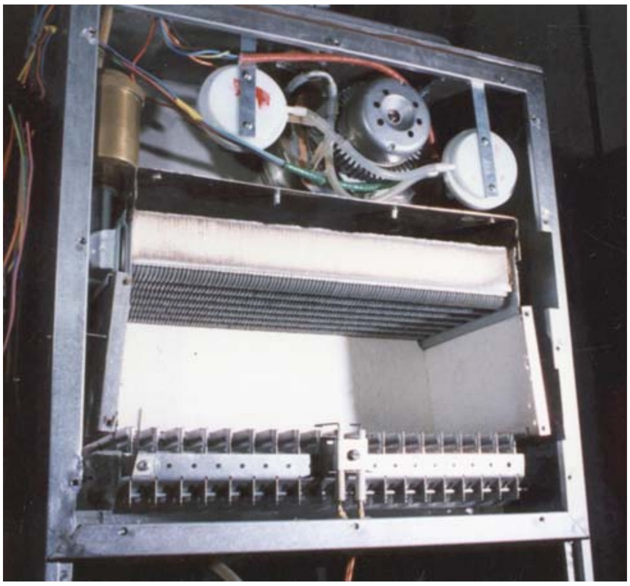

Figure 4: Dry combustion chamber: atmospheric burner, igniter, flame sensor and compact heat exchanger mounted at the ceiling.

Generally, the outputs required for heating systems in small apartments (0-15 kW) are always lower than the output for hot water (10-35 kW).

Usually this problem is solved by an ON-OFF boiler with low nominal output and a storage tank for hot water. But this device decreases the thermal seasonal efficiency of the system in comparison with the seasonal efficiency of the boiler, even if the boiler is a condensing one. Only the instantaneous production of hot water can ensure a high level of seasonal efficiency.

A domestic heating system, which has the same kind of boiler as the prototype, can be reduced as in Fig. 3. Even though there is one fluid-gas water heat exchanger and one natural gas burner inside the boiler, the energy flow has been separated in order to better specify the heat input QSR for heating service and QST for tap water with QUR and QUT corresponding to the outputs. In every combined boiler and in the prototype as well, there is an automatic device which stops any heat being transferred to the heating plant at the moment when hot water is required.

During the summer and winter seasons these operational loads vary greatly and energy flow is transferred with different efficiencies to the tap water and central heating device. Especially, the energy amounts are not constant throughout the days and months.

Slow variations in heating loads permit the transient effects on thermal balance in every heating system to be neglected. In the case of tap water device each ignition causes an additional loss of PA energy .

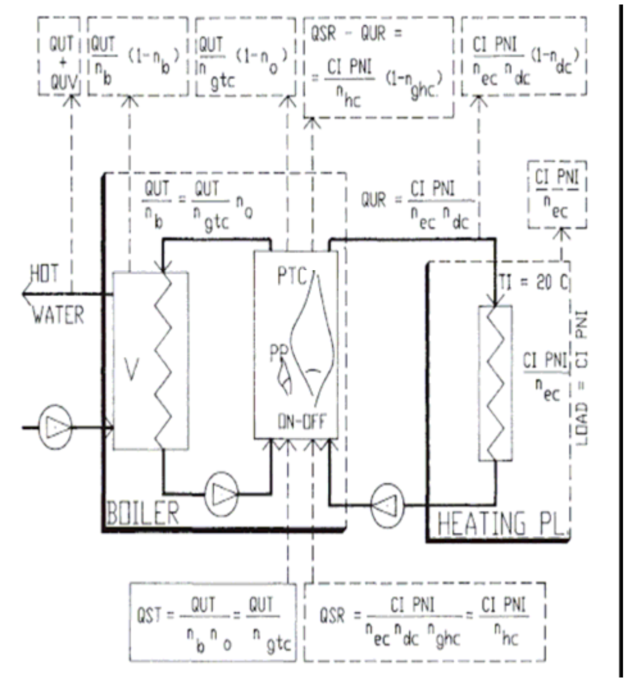

Figure 5: Thermal balance of the plant for the time step

The well known cyclic efficiencies, usually considered to forecast mean efficiency, have to be thought as being constant over each time interval of the entire season *:*

ηghc = cyclic efficiency of heating device at partial load;

ηtc = cyclic efficiency of tap water at partial load.

3.1. Energy Balance of Tap Water Service

The heating system in a closed circuit is composed of three elements:

a) the heat generator, characterized by a nominal thermal input PTCMAX and the output PP of the possible pilot burner. The nominal efficiency η* is defined by means of PNC=η**PTCMAX. PTC is the nominal input PTCMAX if the regulation system is ON-OFF, otherwise PTC is the thermal input as fixed by the flame modulation device. Cyclic efficiencies, at partial loads C=QUR/PNC, are ηghc=QUR/QSR;

b) the hot water circuit, without any loss (ηdc=l).

c) the utilization, composed of heating bodies and an internal distribution circuit, is taken as ideal (ηec=l).

By applying the conservation law of mean energy transferred in a time interval **t**, to maintain the rooms at a comfortable temperature **TI**, the following formula may be used:

$$CI \cdot PNI \cdot t = \eta ghc \cdot QSR \cdot t = \eta hc \cdot QSR \cdot t \qquad (1)$$

A curve of cyclic efficiency of the boiler only can be expressed very simply, as function of the load C, by:

$$\eta ghc = \eta o / \left[1 + (1/I1 - 1) \cdot PR1/PTC\right] \qquad (2)$$

The boiler load is:

$$C = I1 \cdot \eta o \cdot PTC / (\eta * \cdot PTCMAX \qquad (3)$$

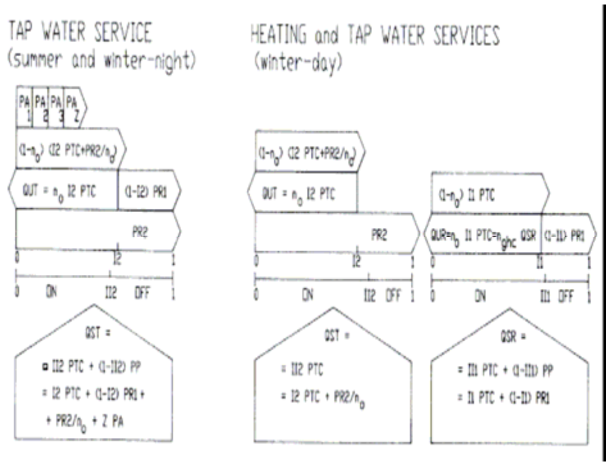

Figure 6: Simulation of boilers at partial loads.

This mathematical equation results from an operational model of boilers at partial loads based on the following assumptions (Fig. 6):

- if the boiler is ON-OFF**,** PTC=PTCMAX and ηoMAX is the efficiency of the boiler at full load, PR1 is the power lost at null load to maintain the boiler at a mean temperature (PRl* to maintain the water at 70°C inside the heat exchanger). During the time I1 the efficiency is the same ηo **=** ηoMAX as during the full load operation. In the model, the energy consumption QSR in the time unit is composed of [Il*PTC + (1-Il)*PRl] which is the same as that used in the actual boiler, composed of (III*PTCMAX), burnt during the ON time II1, and (l-III)*PP, burnt during the OFF time. The energy losses during the OFF period are (l-Il)*PRl and the load is C=I1*ηo/η*

- if the boiler is flame modulating, IIl=Il=l and the input QSR=PTC, stand-by losses are nil and the boiler load is C=(ηo*PTC)/(η**PTCMAX).

The cyclic efficiency is ηghc=ηo. The following equation accounts for the PREA losses due to flame modulation:

ηo = ηoMAX/(l+(l-PTC/PTCMAX)*PREA/PTC) (4)

PREA losses can be attributed to the increases in excess air at partial loads.

3.2. Energy Balance of Tap Water Service

The energy balance of the rig used for the tap water production can be written imagining the rig inside the boiler, even if this is true only for instantaneous boilers. This open circuit is composed of:

a) the heat generator, characterized by the same nominal parameters already considered.

b) a water to water compact heat exchanger, characterized by a low boiler water content and by little inertia;

c) the volume V of a possible tank is characterized by a continuous power loss PR2. The efficiency of the tank and exchanger is ηb.

Everybody knows that the tank is used only to ensure comfort, disregarding cost and size of boiler and its extra energy consumption. The loss PR2 increases the seasonal fuel consumption because stand-by periods are over 10 times longer than tap using periods. Comfort is ensured by the very high available flow (QUT+QW) of hot water, 2-10 times greater than those corresponding to the boiler output.

When the volume V is nil, the boiler is regarded "instantaneous" and the efficiency ηb=l. The available flow is limited to the nominal output of the boiler (QUT=PNC).

In comparison to the previous energy balance, some different aspects now have to be considered:

a) for instantaneous boilers, the tap water causes great load increments and corresponding transient losses have to be accounted for in energy terms PA, spent at every time the tap is turned on. In the time unit, z*PA is the amount of this energy loss. The value **z** changes with loads and depends on how tap water is drawn;

b) during the cyclic operation, the boiler is affected by PR2 losses, when a tank is installed.

Stand-by losses PR1 are again present, so the cyclic efficiency ηtc is generally lower than $\boldsymbol{\eta ghc}$.

c) during winter days, when heating service is also supplied, it is not realistic to consider PR1 and PA in the energy balance of tap water.

Mean seasonal load of boiler on heating service assumes that stand-by losses PR1 and transient losses PA are negligible. Therefore the cyclic efficiency $\boldsymbol{\eta gtc}$ of the boiler only is not too different from $\boldsymbol{\eta o}$.

Referring to Fig. 6 **,** during the summer season and the winter nights, to produce a useful power QUT the input has to be:

$$QST = II2 \cdot PTC + (1 - II2) \cdot PP = \\ = II2 \cdot PTC + (1 - I2) \cdot PR1 + PR2/\eta o + z \cdot PA \quad (5)$$

and the cyclic efficiency is:

$$\eta tc = QUT/QST = \eta o \cdot [1 + (1/I2 - 1) \cdot PR1/PTC + \\ + 1/I2 \cdot (PR2/\eta o/PTC + z \cdot PA/PTC)] \quad (6)$$

where all three kind of losses are considered.

On winter days PR1 and PA are supposed to be negligible in the tap water energy balance and the cyclic efficiency is reduced to the following equation:

$$\eta tc = \eta o \cdot [1 + (PR2/(\eta o \cdot I2 \cdot PTC)] = \\ = \eta o / [1 + \eta^* / [CA \cdot (1 - PR2 \cdot \eta^* / (PNC \cdot \eta o)] \cdot PR2/PNC] \quad (7)$$

where the load CA when tap water is being used

$$CA = QUT/(\eta o \cdot PTCMAX - PR2) \quad (8)$$

The comparison between Eqns. (5) and (7) shows very clearly that PR1 and PA losses affect efficiency only when, on summer and winter nights, tap water only is being used, especially if boilers are poorly insulated and heavily constructed. Seasonal efficiency is always very low when a tank is installed because the extra losses PR2 are continuously present and its mean load is very low.

4. RESULTS OF SIMULATION

To compare performances of the prototype, especially its cyclic efficiency measured on laboratory test rig, three other high efficiency boilers (tab. I) have been chosen and all of them have been simulated by the model already described. The boilers were:

(1) high efficiency, ON-OFF, conventional boiler with tank: permanent pilot;

(2) high efficiency, ON-OFF, conventional instantaneous boiler: permanent pilot;

(3) high efficiency, flame modulating, conventional instantaneous boiler: permanent pilot;

(4) prototype: high efficiency, flame modulating, conventional instantaneous boiler: electric ignition.

The losses PR1 become proportional to the boiler load following the simple equation:

PR1 = (PP + PRl*).C (9)

and PR2 is proportional to the mean temperature of the tank (PR2* at 50°C).

tab. I. Experimental parameters to forcast ηghc and ηtc of the four combined boilers.

boiler	1	2	3	4	
η^*	0.81	0.81	0.81	0.81	
PNC	14.0	23.0	23.0	35.0	kW
PTCMAX	17.3	28.4	28.4	43.2	kW
PR1*	0.7	1.15	1.15	1.75	kW
PP	0.25	0.25	0.25	0.	kW
I1	0÷1	0÷1	1	1	
PR2*	0.7	0.	0.	0.	kW
PA	0.	0.7	0.7	0.7	kW
I2	0÷1	0÷1	1	1	

The curves in Fig.7 represent the simulation results of the prototype and of three combined boilers as functions of outputs of heating and tap water.

Values obtained by tests on the prototype are also indicated. The main energy results can be analysed as follows:

a) the efficiency ηghc of the prototype is high when the heating service operates at a nominal output of 35 kW and at outputs usually required by a domestic heating plant, at partial load during the winter season. The seasonal efficiency is almost the same as high efficiency boilers having the 14 kW nominal output usually adopted:

b) for tap water, the cyclic efficiency ηgtc is at the same levels of ηghc values without any unacceptable decrease at partial outputs.

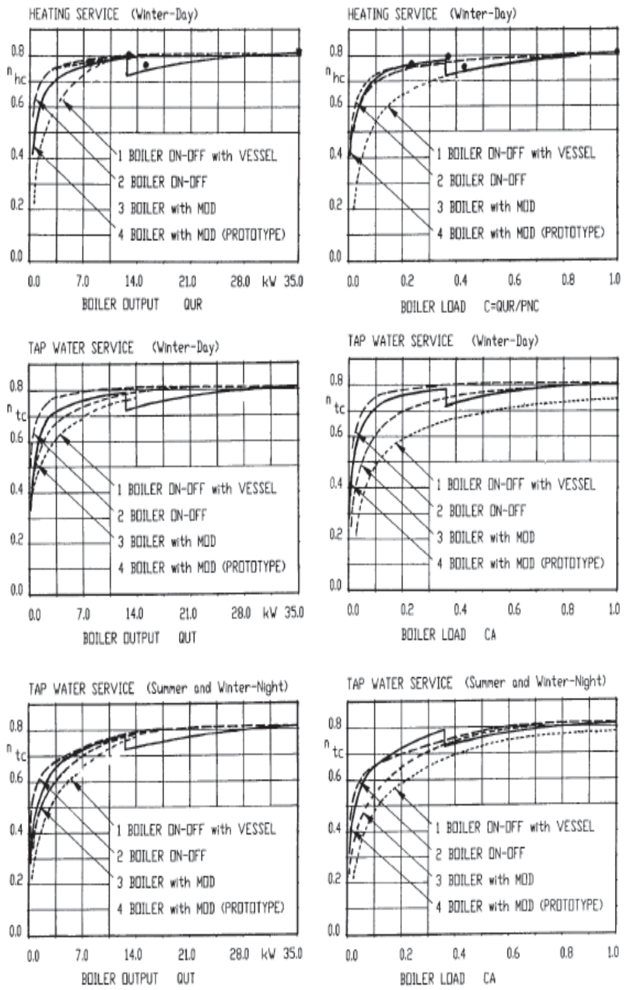

Figure 7: Cyclic efficiency of four combined boilers calculated from the operating model on heating service during the winter season and on tap water service, as functions of the output and the load.

5. CONCLUSION

A model of energy losses of gas-fired domestic boilers at partial loads providing heating and tap water enables to calculate using experimental parameters of boilers, of their cyclic efficiencies including the effects of tank losses.

These results are in agreement with experimental values obtained by testing a prototype combined boiler, characterized by a high nominal output (35 kW) and, capable of maintaining high efficiency when it operates at loads required by heating installation (below 14 kW). This system gives high efficiency values on both services because:

- permanent pilot and vessel volume are not used,
- inertia losses and stand-by losses are very low in comparison with the nominal output of the boiler,
- an automatic device with the varying revolution speed of the combustion air fan is used to reduce excess air losses and to control the dew point of flue-gases at low loads.

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