An Experimental Study on the Energy Efficiency of Gas-Burned Boilers in Heating Systems

Engineering

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ABSTRACT

A gas-burned boiler was tested in a boiler test rig in order to understand how the energy performance is affected by relevant operating condition. This paper presents the testing method and results.

1. Background

In common with many other types of building services equipment, boilers in heating systems are often considerably oversized in order to provide a substantial margin of capacity [1, 2]. As a result, most boilers can generate sufficient heating capacity but often do so inefficiently, especially when they are operated under part-load [3] and controlled by conventional boiler controllers, such as thermostats and weather compensators [4]. There are a broad range of boiler controllers used in current practice to maintain a satisfactory performance of heating systems. A conventional weather compensator changes the set-point of water temperature according to the external temperature such that the system can be operated at lower water temperature when the heating load is low [4]. Liao and Parand developed a boiler controller that can measure the heating load and accordingly determine the optimal water temperature at which the boiler efficiency can be maximized whilst sufficient heat can be delivered to the building [3]. Liao and Dexter developed a novel boiler controller, referred to as Inferential Control Scheme (ICS), that varies the water temperature according to an estimate of the average air temperature in the building [5, 6, 7, 8, 9]. One of energy saving strategies employed by these boiler controllers is to maximize the energy efficiency of the boilers through varying water temperature according to load or optimising the mixture of oxygen and fuel, in additional to minimizing the heat loss throughout the heat distribution system and avoiding the overheating in the controlled spaces. The scientific credibility of these control techniques relies on a good understanding on how the energy efficiency of boilers is influenced and can be optimized in both short-term and long-term.

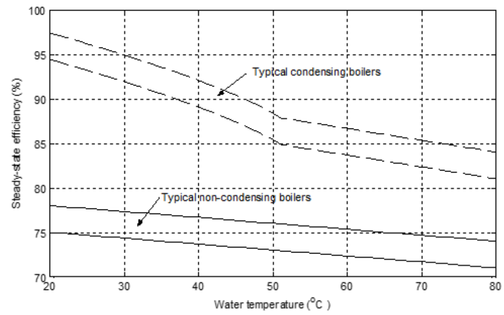
2. Boiler energy efficiency

It is well understood that there are at least three interrelated definitions of boiler efficiency:

- Combustion efficiency: how efficiently the combustion takes place in the burner. Higher combustion efficiency means that more heating capacity can be generated by consuming the same amount of fuel.
- Steady-state efficiency: how efficiently the heat is transferred from the combustion gases to the water when the boiler is running under full load.
- Seasonal efficiency: how efficiently the fuel is used by the boiler over the entire season.

The seasonal efficiency depends on the steady-state efficiency, the combustion efficiency and the downtime losses that occur when the boiler is not operating. The downtime losses are affected by the boiler structure, type of application and design of the system.

The steady-state efficiency declines when the water temperature increases. This is because the temperature difference between the combustion chamber and water is higher when the water temperature is lower. Figure 1 shows how the steady-state efficiency of non-condensing and condensing boiler is affected by the water temperature. It shows that the steady-state efficiency of condensing boilers increases significantly when the water temperature is below about 50 °C due to condensation of the flue gases. In order to maximise the efficiency, it is always desirable to operate the boiler at as low a water temperature as possible, e.g. when the system is operating under part load.



<Figure 1 Variation of the steady-state efficiency with water temperature [BRESCU, 1996]>

When a boiler is turned off, it continues to lose heat due to:

- Radiation through the boiler shell or jacket.
- Convection between the boiler and the air that is drawn by the chimney draft and continues to flow through the boiler.

The more often the boiler cycles, the greater the downtime losses and the lower the seasonal efficiency are.

Katrakis and Zawachi studied the relationship between the seasonal efficiency and the load of a steam boiler through a field experiment [10]. They concluded that the seasonal efficiency of the boiler was highly sensitive to the control of boiler and the characteristic of the heating load. Higher seasonal efficiency can be achieved if the system is designed such that the off-cycling of the boiler is minimised.

Anglesio gives a relationship between the seasonal efficiency (η) and the load factor [11]. The load factor (L_f) is defined as the ratio of produced power (Q) to the maximum power (Q_{max}) of the boiler.

$$\eta = 0.9/(1 + 0.02/L_f) \qquad (1)$$

where: $L_f = Q/Q_{max}$

Based on Equation 1, Cardinale and Stefanizzi investigated the seasonal efficiency of boilers when different control schemes were used to determine the water temperature [12]. They concluded that the annual distribution of the load factor was sensitive to how the water temperature was determined.

3. Experimental study of boiler efficiency

An experiment was carried out in a boiler test rig (see Appendix) in order to:

- Examine the relationship between the boiler efficiency and the load;
- Examine the relationship between the boiler efficiency and the water temperature.
- Collect data for validation of the boiler model that is needed for the simulation study on boiler efficiency.

The boiler under test is a gas-fired condensing boiler. The full power of the boiler is 60 kW. The experiment has been carried out with the load set at ten different levels by changing the external temperature in the building simulator. The efficiency is calculated by:

$$\eta = \frac{\sum_{i=1}^{N} \dot{m}_w(i).\rho_w.C_p.(T_{w\_out}(i) - T_{w\_in}(i))}{\sum_{i=1}^{N} \dot{m}_g(i).\rho_g.CV(i)}$$

(2)

where:

$\dot{m}$ Flow rate (l/s).

ρ Density (kg/l).

T Temperature (°C).

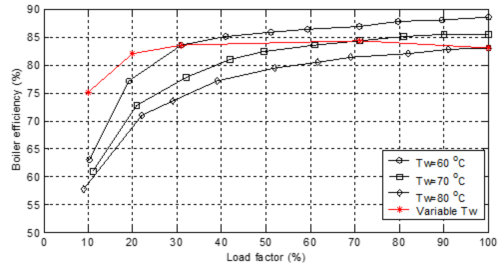
C_p Specific thermal capacity (J/kg/°C).

CV Net calorific value of gas (J/kg).

w and g refer to the water and gas respectively.

w_out and w_in refer to the outlet and inlet of the boiler respectively.

The experiment results are shown in Figure 2. T_w in Figure 2 refers to the temperature of the water at the boiler inlet (return water).



< **Figure 2 Experimental results of the boiler efficiency** >

The results show that:

- With a fixed water temperature, the boiler efficiency reduces as the load becomes lower. However, the efficiency remains within a fairly narrow range when the load ranges from 100% to 40%. When the load is below 40%, the boiler efficiency declines much more quickly.
- As shown by the starred line, it is possible to maintain high energy efficiency when the load is low by changing the inlet water temperature appropriately. However a high water temperature is needed when the heating load is high.
- The lower the load factor, the higher the potential for improving the boiler efficiency by reducing the water temperature.

The experimental results demonstrate that the boiler efficiency can be maintained at a high level over the entire heating season by changing the water temperature appropriately.

4. Conclusion and On-going work

The following conclusions can be drawn:

- The energy efficiency of boilers in heating systems is influenced by a number of factors, including the water temperature, the load factor and the boiler control strategy.
- The energy efficiency of boilers declines if the water temperature increases.
- If the heating system is operated with a fixed supply water temperature, the boiler efficiency reduces as the load becomes lower.
- It is possible to maintain high energy efficiency when the load is low by changing the inlet water temperature appropriately. However a high water temperature is needed when the heating load is high.
- The lower the load factor, the higher the potential for improving the boiler efficiency by reducing the water temperature.
- When the boiler is oversized, there is a bigger potential for improving the boiler efficiency by reducing the water temperature. This potential is much less when the boiler is undersized.

Currently we are developing an accurate boiler model for integration with thermal modelling technologies. This model will be validated using the experimental data obtained from this study. This model will enable us to investigate the performance of boilers in a broader range of heating systems and to develop optimal boiler control strategies.

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Appendix The Boiler Test Rig

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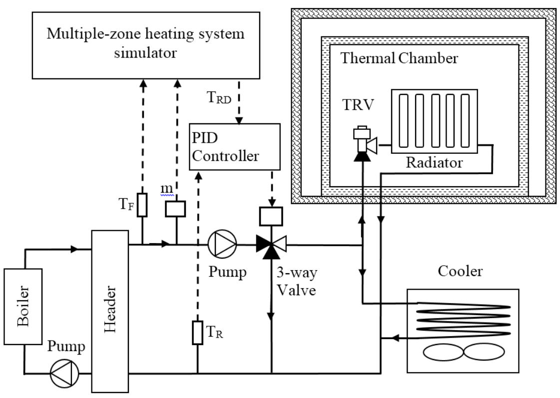
Figure 3 shows a diagram of the boiler test rig. It consists of four major components: the boiler, a hydraulic and heat releasing system, a thermal chamber, and a building simulator. The supply water temperature (T_F) and flow rate (m) are measured and sent to the multiple-zone heating system simulator. The simulator computes the value of the return water temperature that is sent to the PID controller (T_{RD}). The PID controller controls the three-way valve such that the temperature of water returning to the header equals to the value determined by the simulator (T_{RD}). This is done by changing the flow rate of water going through an air-to-water cooler that has a constant speed fan. A part of the hot water flows through a radiator installed inside a thermal chamber. Both the temperature and flow rate of water supplied to the radiator can be pre-defined according to the purpose of test. A simulated heating load is installed in the thermal chamber.

To test the efficiency of the boiler under different heating loads, the simulator is run with pertinent climatic conditions.



< **Figure 3 Diagram of the boiler test rig** >

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