DEVELOP A DYNAMIC MODEL OF GAS AND OIL BURNED BOILERS FOR OPTIMISATION OF BOILER CONTROL IN CENTRAL HEATING SYSTEMS

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ABSTRACT

An innovative boiler controller was developed using the simulator described in this paper. A dynamic model of commercial hot water boilers has been developed and integrated with other heating system component models to create a simulator of central heating systems. Detailed experimental data was obtained to validate the boiler model. The validation results indicate that the model can accurately simulate both transient and steady state performance of such boilers as installed in central heating systems. The model development was carried out under a European Commission project with the aim to improve the overall efficiency of water heating systems. The simulator was subsequently used to develop an innovative boiler controller that has been tested in simulation, emulation, a test building and field trials in real buildings with successful results. Applying the controller to most boilers will result in significant energy savings. This paper presents the mathematical boiler model and its validation. The new boiler controller is also discussed.

INTRODUCTION

The capacity of boilers used in heating systems is often significantly oversized [Gardner, 1984]. As a result most boilers can deliver the required hot water to the building but in most cases do so in an undetected inefficient manner when controlled by most commonly used control devices [Liao and Parand, 2001]. This is because boilers in heating systems are normally controlled to maintain the temperature of supply hot water at a certain setpoint, which may be fixed or compensated with the external temperature [Levermore, 1992]. The variation of the building heating load is not normally considered in most existing boiler controllers. The overall energy performance is therefore much below the level that could be obtained if the boiler output was to match the demand [Liao and Parand, 2001].

A European Union project, funded under the CRAFT programme, in which BRE, University of Oxford and ICITE of Italy worked as the Research and Development arm of a number of industrial companies, investigated this problem and developed an innovative control technology for the optimal control of boilers in heating systems. The boilers investigated in this project were commercial gas or oil burned boilers with a normal heating capacity ranging from 40 kW to 300 kW, which are commonly used in heating systems in Europe. The investigation was carried out in both simulation and field trials. A simulation platform of central heating systems has been developed for this purpose, in which a dynamic model of gas and/or oil burn boilers played an important role.

Over the last 40 years a number of boiler models have been developed [Lu, 1993; Lang, 1992]. Some of these models have been integrated with some well established thermal simulation software packages. However, no model was found suitable for the purpose of this project because:

- They do not cover the type of boilers investigated.
- Rigorous validation was not reported for them.

A fundamental for the project was the reliability of the simulation platform for which the boiler model was the most significant part. A dynamic model of the targeted boilers was developed and validate using experimental data from a test rig, a realistic test building and field trials.

METHODOLOGY

The methodology adapted for developing and validating the boiler model is briefly described below:

- Literature study of gas or oil burned boilers used in heating systems in Europe. The objective was to collect technical information for the target boilers and to understand how they are installed and operated in practice. Through this study a number of typical boiler types were identified.
- Develop the mathematical model. The typical boilers selected were then analysed to identify essential heat transfer processes.

- Implement the model in Simulink™ for validation and utilisation.
- Validate the model using experimental data obtained from different sources.
- Integrate the validated boiler model into a simulator for central heating systems and use the latter to develop an innovative boiler controller that can save energy and improve the thermal comfort.

A hardware prototype controller has been developed for testing it in real installations through a number of field trials. The testing result was compared with the simulation study.

MATHEMATICAL MODEL

A simplified structure of a typical boiler representing the selected range is illustrated in Figure 1 showing major components of such boilers:

- Burner where fuel (gas or oil) is burnt to release heat.
- Flame tunnel along which the flame loses heat and cools down to as low as 150ºC at the exhaust.
- Inner shell that separates the flame and the water content.
- Water channels where water is heated.
- Outer shell that isolates the water from the ambient.
- Insulation material and casting shell.

The heat transfer among these major components is illustrated in Figure 2.

The dynamics of the inner shell (T_{is}) is governed by:

$$C_{is} \cdot \frac{dT_{is}}{dt} = Q_{burner} - K_2 \cdot (T_{is} - T_w) \qquad (1)$$

where: Q_{burner} is the heat transfer from the flame to the inner shell. Q_{burner} can be treated as a constant determined by the normal heating capacity and efficiency of the boiler. In this paper, Q_{burner} is treated as a constant but of different values for different boiler operations. In general the cycle of boiler operation can be distinguished into three steps, as below:

- Idle: the burner is not firing and the ventilation fan is not running. During this period, the inner shell may lose heat to the air naturally ventilated through the combustion chamber and flame tunnel.
- Purge: the burner is not firing but the ventilation fan is running. During this period, the inner shell may lose heat to the air forcibly ventilated through the combustion channel and flame tunnel.
- Firing: the burner is firing and the ventilation fan is running. During this period, heat is transferred to the inner shell from the flame.

It is given by:

$$Q_{burner} = \begin{cases} Q_{idle} & Idle \\ Q_{purge} & Purge \\ Q_{fire} & Firing \end{cases} \qquad (2)$$

The dynamics of the water node (T_w) is governed by:

$$C_w \cdot \frac{dT_w}{dt} = K_2 \cdot (T_{is} - T_w) - K_4 \cdot (T_w - T_{os}) - \dot{m} \cdot (c\rho)_w \cdot (T_{ws} - T_{wr}) \qquad (3)$$

The lumped water temperature (T_w) is related to the water temperature at the inlet (T_{wr}) and outlet (T_{ws}) of the boiler through the following equation [Niu, 1994]:

$$T_w = \alpha \cdot T_{wr} + (1-\alpha) \cdot T_{ws} \qquad (4)$$

The dynamics of the outer shell (T_{os}) is governed by the following equation:

$$C_{os} \cdot \frac{dT_{os}}{dt} = K_4 \cdot (T_w - T_{os}) - K_5 \cdot (T_{os} - T_i) \qquad (5)$$

Finally the dynamics of the insulation layer and the casting shell (T_i) is governed by:

$$C_i \cdot \frac{dT_i}{dt} = K_5 \cdot (T_{os} - T_i) - K_6 \cdot (T_i - T_o) \qquad (6)$$

VALIDATION

Figure 3 presents how the experimental data is used to validate the boiler model. It shows that the recorded data of the water parameters at the inlet of boiler (flow rate and temperature) and the boiler control signal are fed into the boiler model that in turn simulates the water parameters at the boiler outlet (Outlet_sim). The simulated outlet parameters are compared with the experimental data of the outlet water (Outlet_test). The comparison shows how accurate the model can simulate the dynamic performance of the boiler.

Different sources of experimental data have been used to validate the boiler model. These sources include:

- Measurement carried out in real installations acquired from the literature study mentioned above.
- Experiments carried out in a boiler test-rig that was specially built for the project. The rig consists of three major components, including two boilers with a total heating capacity of 100 kW, a heat rejection system emulating the heating load and a software simulating the building. The validation results are presented in Figure 4 (a and b).
- Medium-term testing in a test facility in the Italian research partner (ICITE). A commercial boiler with 40 kW of heating capacity was installed in the fully instrumented test building to test the medium-term performance of boiler. The validation result is presented in Figure 5.

Figure 4 and 5 show that a good agreement exists between the simulated and tested boiler performance and that the boiler model can sufficiently accurately simulate the dynamic performance of targeted boilers.

INNOVATIVE BOILER CONTROL

The boiler model was integrated with other component models, including radiator model, the BRE's own 3TC building model [Tindale, 1993], a sensor model, a room temperature controller, the distribution system, including boiler room headers, etc., to build a simulator of the complete central heating system. The simulator was in turn validated using experimental data. The validated simulator has been used to carry out the following tasks:

- Analyse the boiler control schemes applied in the practice to identify the potential for improvement.
- Develop an innovative boiler control scheme that can significantly improve the long-term performance of boiler control. This scheme is called as OWT (Optimal Water Temperature). It is designed to determine the optimal water temperature that enables both the boiler and the distribution system work at the highest efficiency while desired room temperature can be maintained.
- Assess this scheme under different scenarios.

The OWT control scheme is described briefly as below:

- There is a functional unit that can determines whether the terminals are well controlled, e.g. when TRV's are fitted and working properly, or no control is applied to the terminals or if they exist are not performing correctly. This is done through studying the daily profile of energy intensity (energy consumption during a certain period). A pattern matching algorithm was produced to recognise whether the system has uncontrolled terminals or they are well controlled.
- A daily commissioning algorithm was also developed which re-commissions the staring parameters using the information collected from the two sensors and the duty of the boiler during the previous days and the set-back period.
- The algorithms for a system with controlled terminals is different from that for uncontrolled or badly controlled terminals. The details of these algorithms are subject of an international patent and cannot be revealed here.

To assess the performance of the OWT controller, Two types of traditional boiler controllers were selected as the reference:

- Type I: ON/OFF controller. It controls boilers to maintain the supply (or return) water temperature at a certain setpoint. The setpoint is normally fixed for a long period until it is adjusted by the operator.
- Type II: external temperature compensated boiler controller. The setpoint of water temperature is compensated with the external temperature on daily basis.

Figure 6 presents an example of simulation study comparing the performance between the OWT and Type I boiler controllers in systems with terminals well controlled. It shows that more energy is consumed when Type I controller is operated with high temperature setpoint (Type I @80C). Note that the room temperature is mostly maintained at higher temperatures than the set point. Much less energy is consumed when the boiler is operated with low temperature setpoint (Type I @60C) but the room temperature falls too low in many instances. The OWT controller, however, uses more energy during the periods of high heating demand and less energy during the periods of lower heating loads. Compared with Type I @80C, the OWT can save energy without compromising the thermal comfort. Compared with Type I @60C, the OWT can significantly improve the thermal comfort though slightly more energy would be consumed.

Figure 7 presents the comparison in systems with uncontrolled terminals. It shows that Type I can not maintain the room temperature close to the desired range for the period when the setpoint of water temperature is fixed. The room temperature may be too high during periods of low heating load and too low during periods of high heating load. The OWT controller adjusts the setpoint such that the energy delivered from the boiler matches the heating load of the buildings. As a result, the room temperature can be maintained within a narrow range.

More systematic study indicates that the performance improvement obtainable by the OWT compared with Type I is sensitive to the following factors:

- Type of boiler. The energy efficiency of a boiler declines when the water temperature increases. The potential for energy saving is bigger if this variation is larger.
- The ratio of the capacity of boilers to the heating load. The bigger this ratio the higher the potential for energy saving.
- The heating capacity of terminals. This is especially important in systems with uncontrolled terminals.

Considering boilers commonly used in heating systems in Europe and the industrial standards for system sizing, a series of typical systems were configured in the simulator. The simulation study shows that the OWT controller can achieve:

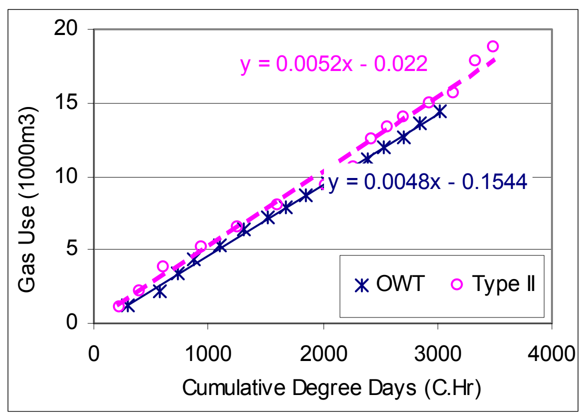
- 5% to 10% of energy saving in systems with controlled terminals compared with Type I controllers whilst the thermal comfort is not compromised.
- Up to 30% of energy saving in systems with uncontrolled terminals compared with Type I controllers whilst the thermal comfort can be significantly improved.
- 3% to 7% of energy saving in systems with controlled terminals compared with Type II controllers whilst the thermal comfort is not compromised.
- Up to 20% of energy saving in systems with uncontrolled terminals compared with Type II controllers whilst the thermal comfort can be significantly improved.

The OWT control scheme, which shows significant potential for energy saving and comfort improvement in simulation, was implemented in a hardware prototype for testing in real installations. The prototype has been tested in three different installations, including:

- Test I: in the boiler test-rig that was also used to obtain experimental data for the validation of the boiler model (see above).
- Test II: in a fully instrumented test facility at ICITE, Italy.
- Test III: in real buildings through a number of field trials. This was carried out by the industrial partners respectively in Italy, Germany and the UK.

Figure 8 presents the result of Test II. In this test, a well commissioned Type II controller was used as the reference. The daily energy use and average room temperature are plotted against the daily heating degree hours with reference temperature of 18 ºC. It shows that OWT controller can save energy by about 10% while the room temperature is only 0.2 ºC lower than that obtained by the Type II controller. This is consistent with the simulation study.

Test III (field trials) also shows similar results consistent with the simulation study and Test II. The figure below presents an example of the field trials. The cumulative energy saving is plotted against the cumulative heating-degree-days respectively for the periods when OWT and a Type II controller was operated. About 11% of energy saving is observed.



CONCLUSIONS

The overall conclusions are:

(1) A simplified model has been developed to simulate the dynamic performance of commercial gas or oil burned boilers that are commonly used in heating systems in Europe. The model has been rigorously validated using experimental data obtained from different sources. The validation results show that the model can accurately simulate the dynamic performance of the targeted boilers.

(2) This model had been integrated into a simulation platform for central heating systems, which was in

turn used for the development of an innovative boiler controller (OWT) that can significantly improve the long-term performance of central heating systems.

(3) Simulation studies show that compared with traditional boiler controllers (ON/OFF controller, or external temperature compensated controller) the OWT controller can achieve up to 30% of energy saving when applied in systems with uncontrolled terminals. At the same time the thermal comfort in the building can also be significantly improved.

(4) Simulation studies show that compared with traditional boiler controllers the OWT controller can achieve 5% to 10% of energy saving when terminals are tightly controlled, without compromising the thermal comfort in the building.

(5) Testing in the ICITE test facility shows that the prototype OWT controller can save 5% to 11% of energy while the room temperature is only 0.2 ºC lower, still well within the desired comfort range. The terminals of the heating system in this testing system were well controlled by room thermostat and motorised valves. The testing result is consistent with the simulation study.

(6) The field trials shows that the prototype OWT controller can save up to 11% of energy in the system with well controlled terminals. Up 30% of energy saving can be observed in the system with uncontrolled terminals. This is consistent with the simulation study.

The energy saving is achievable due to the following factors:

- The energy efficiency of boiler varies with the return water temperature. Generally the lower the return water temperature, the higher the energy efficiency. The OWT controller always intends to keep the water temperature as low as possible and as high as required.
- The standing loss of the distribution system varies with the water temperature. In many old systems, this represents up to 5% energy savings.
- Overshooting or undershooting of room temperature. In systems with uncontrolled terminals, the room temperature is very sensitive to the temperature of the water. If the supply water temperature is too high, energy will be wasted in heating up the building unnecessarily. If it is too low, the desired room temperature can not be maintained.

The OWT controller can maintain the water temperature at an optimal point because it is capable of detecting the heating load of the building. As a result, both the energy efficiency and the thermal comfort can be obtained.

ACKNOWLEDGEMENTS

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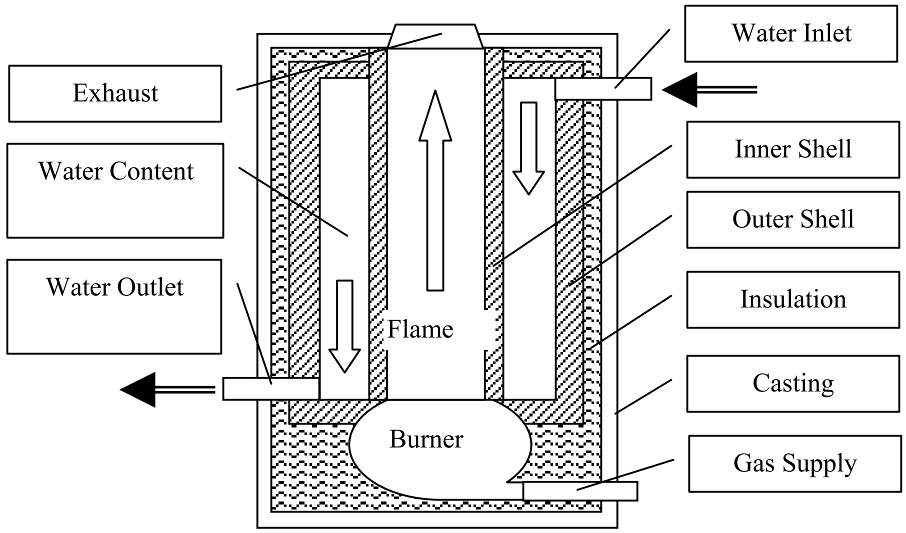

Figure 1 A simplified structure of gas or oil burned boilers

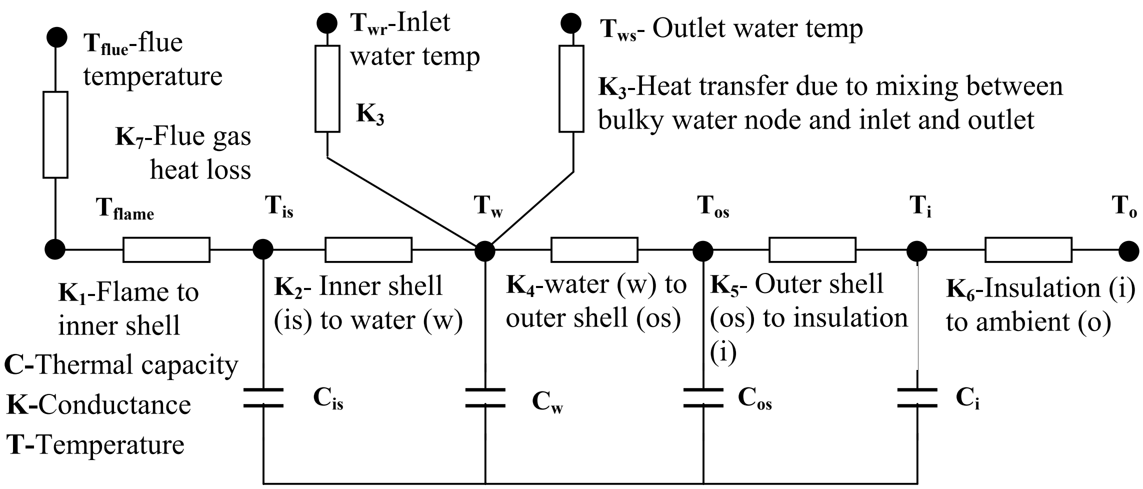

Figure 2 Electrical circuit model of a gas or oil burned boiler

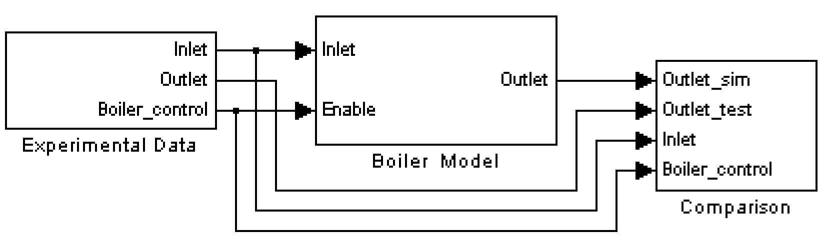

Figure 3 Validating the boiler model using experimental data

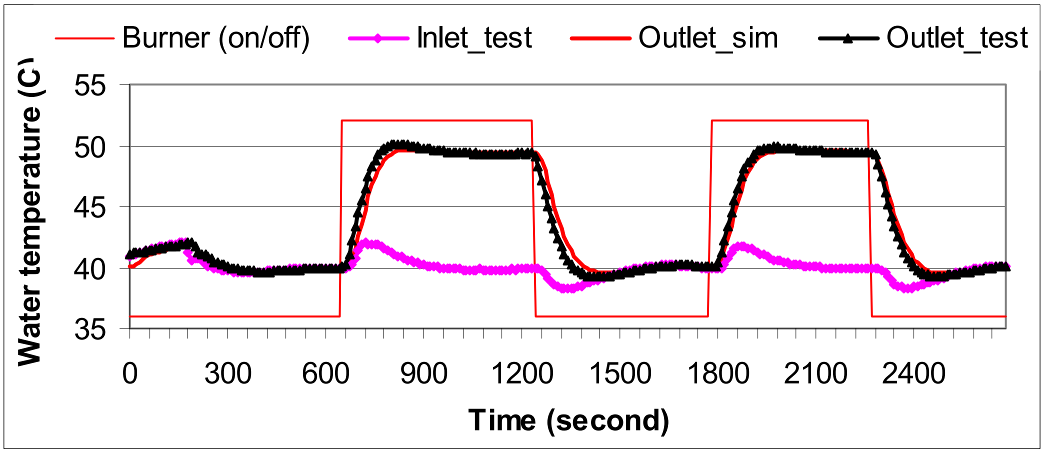

Figure 4 (a) Validation by test-rig data (constant Inlet temperature)

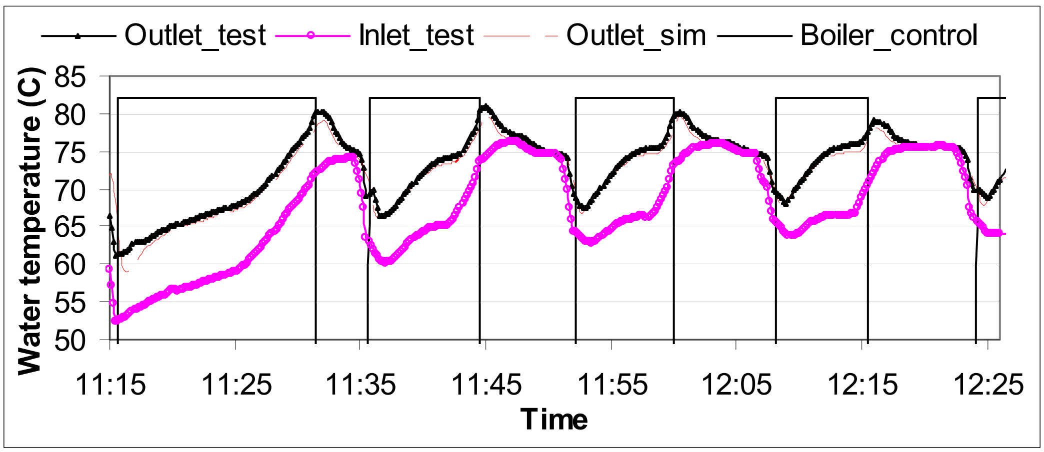

Figure 4 (b) Validation by test-rig data (floating Inlet temperature)

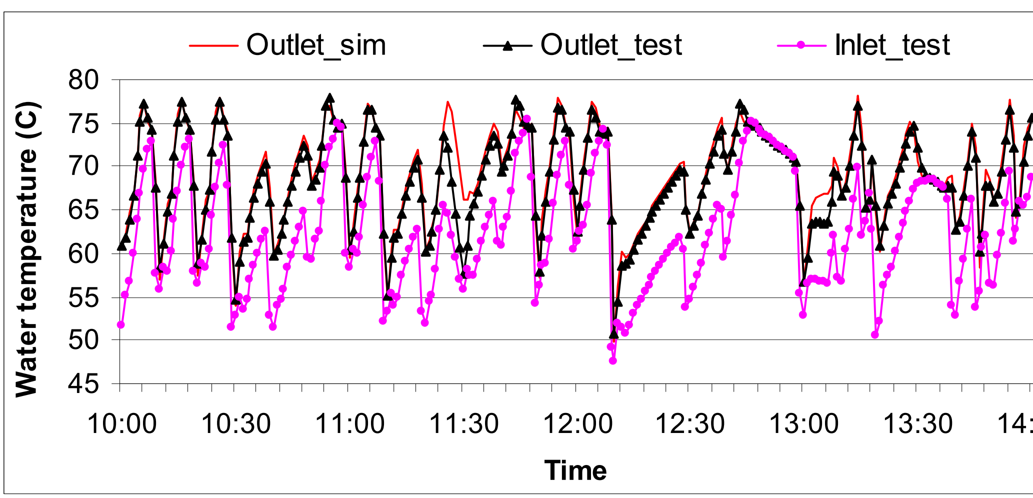

Figure 5 Validation by ICITE data (an example)

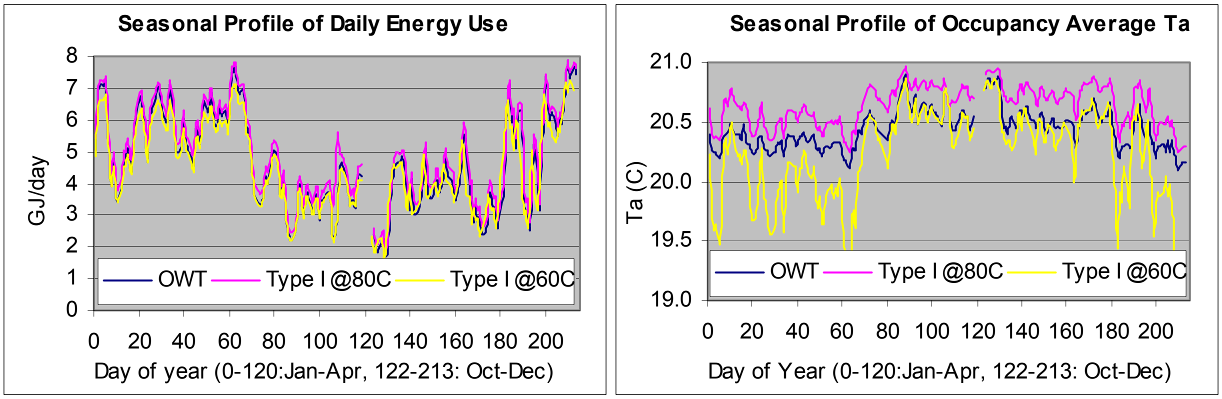

Figure 6 Comparison of annual performance between OWT and Type I boiler controller (Simulation in a system with well controlled terminals)

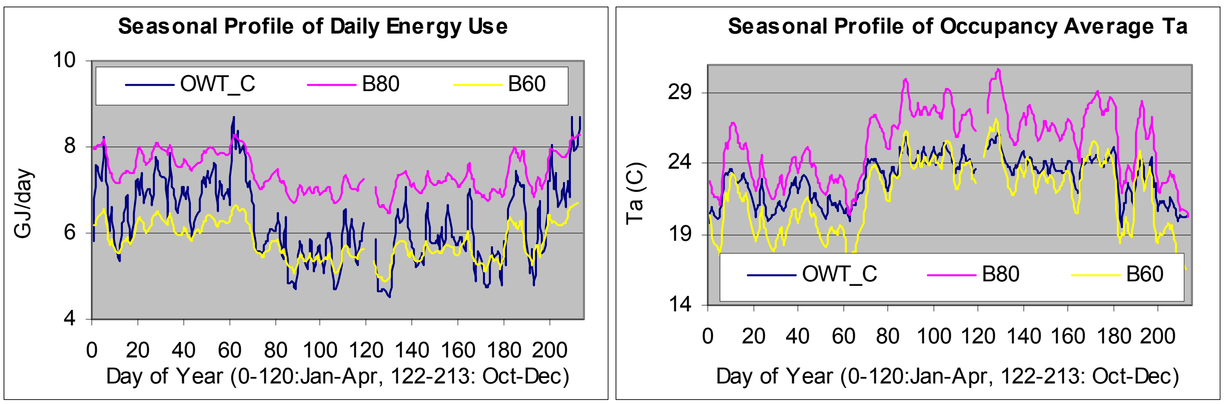

Figure 7 Comparison of annual performance between OWT and Type I boiler controller (Simulation in a system with uncontrolled terminals)

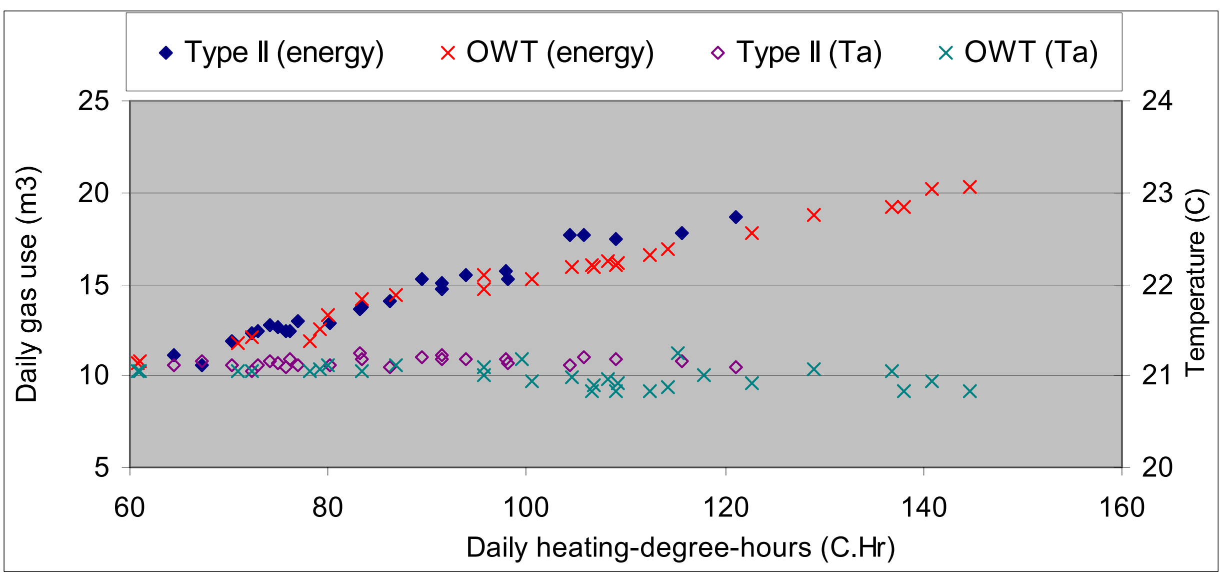

Figure 8 Comparison of performance between OWT and Type II boiler controller (Experiment in the ICITE testing facility)