ACCURATE BOILER MODELS FOR LARGE SCALE SIMULATION

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ABSTRACT

Today, the development of computer makes the accurate performance analysis of complex system by simulation available for most of the research community, and very soon for every concerned engineer. However, the simulationist approach requires a strong investment on the modelling of the system behaviour. This paper deals with a basic contribution on domestic hot water gas or fuel oil boiler models, usable for large scale simulation involving building and HVAC. This model is primarily issued from a task in International Energy Agency Annex 10 [4] and is now developed at the CSTB for a large scale analysis on the experimental building of Gaz de France, Paris [7].

I INTRODUCTION

Detailed boiler models were developed for power plant analysis. These models consider very accurately the combustion process and the complex heat transfer inside the combustion chamber. The detailed geometry and composition of the different boiler elements has to be input. The model is very heavy and obviously far overdetailed for the simulation of domestic hot water boilers.

At the opposite side, the simple model approach is based on limited operating curve, even sometimes a constant efficiency. A rather fair approximation is given by the Dietrich law which considers a linear operating curve between the useful heat and the time on ratio in cycling conditions.

But this last model cannot consider some significant effects occuring in the new strategies developed around the up-to-date hot water heating systems, for instance, the accurate performance sensitivity to the water temperature, to the air excess or burner tuning,...

The model proposed in this paper will overcome most of these drawbacks as it will be shown in the following.

2 BOILER MODEL PRINCIPLE

In fact, the interest and accuracy of the detailed models derive mainly from their physical relation with the concerned phenomena. Unfortunately the detailed models are too complex for most applications.

On the contrary, the simple models directly fit on experimental data, are too simple and almost no link with the physical aspect can be established. This latter point makes that these models cannot be improved, even if their main basis are in the right direction.

The conclusion of these observations is that a better formulation of the component models is required for the simulation [1]. This "reformulation" must include the simple and right basis of the direct fit models, but has to add a physical link, leaned on the basic phenomena. This very promising approach called "adapted model generation" is based on a model reduction by some rules of physical simplification [2][3].

The main model principles are based on the fourth following related aspects :

- combustion involving fuel and air excess,
- heat transfer from combustion chamber to the working fluid (hot water),
- surrounding losses by boiler envelope and ventilation rate during burner off time,
- dynamics of the boiler, especially involving the aquastat control by ON/OFF action.

Figure 1 gives a schematic diagram of the domestic hot water boiler.

2.1 Combustion

The combustion is assumed to be perfect with a fixed air excess and the fuel flow is set by the burner control. Conventionally, the burner power will be based on the fuel lower caloric power P_{ci} or combustion enthalpy with no water condensation.

$$\dot{Q}_b = \dot{m}_c P_{ci}$$

where $\dot{Q}_b$ is the theoretical burner power (W),

$\dot{m}_c$ is the fuel flow (gas m^3N/hr, fuel kg/hr).

Considering an air excess of 1, the combustion can be defined by a purely theoretical adiabatic temperature of combustion T_1.

This theoretical value can be established by an enthalpy balance between air and fuel input and combustion products :

$$H_{fg}[T_1] = Pci + H_a(T_a) + H_c(T_c)$$

T_1 is a pure theoretical value, able to characterize the combustion for the further heat transfer.

2.2 Heat transfer

If we consider the scheme of figure 1 and 2, we are now able to establish a simple relation for the heat transfer :

$$Q_{tran} = \dot{C}_g (T_1 - T_{ch}) = \dot{C}_w (T_{wex} - T_{wsu})$$
$$= \varepsilon \dot{C}_g (T_1 - T_{wsu})$$

where :

$\dot{C}_g = \dot{m}_c\ Cpg$ is the flue gas capacitance flow (W/K),

$\dot{C}_w$ the water capacitance flow

(= $\dot{m}_w C_{pw}$, $\dot{m}_w$ waterflow, C_{pw} water specific heat), T_{ch}, T_{wex}, T_{wsu} are the temperature of respectively the flue gas at the chimney, the exhaust and supply hot water.

ε is the heat exchange efficiency which for a simple counter flow linear model is :

$$\varepsilon = \frac{1 - e^{-Ntu\ (1-\omega)}}{1 - \omega e^{-Ntu\ (1-\omega)}}$$

With :

$N_{tu} = \frac{AU}{\dot{C}_g}$ number of unit transfer,

AU being an equivalent heat transfer parameter (W/K),

$\omega = \frac{\dot{C}_g}{\dot{C}_w} << 1$ is the capacitance flow ratio.

2.3 Heat losses

The heat transfer efficiency has already considered the chimney losses by enthalpy. Thus the remaining losses are only originating from the boiler envelope and the combustion chamber ventilation.

A very accurate estimation is given for a wide range in cycling conditions at Θ_{ON} burner time ON fraction as follows :

$$Q_{losses} = Y_w (T_m - T_i) + \Theta_{ow} DY_w (T_m - T)$$

$$T_m = K_w T_{wex} + (1 - K_w) T_{wsu}$$

where :

K_w is a weighting factor (~ 0.5),

T_m a mean water temperature,

T_i the boiler surrounding temperature,

Θ_{ON} the burner time ON fraction,

Y_w and DY_w are constant heat loss parameters (W/K) Y_w is concerned with the water envelope losses and the combustion chamber ventilation losses in burner OFF,

DY_w qualifies the hot point losses in countinuous operation.

2.4 Dynamic

A rather fair approximation of the dynamic behaviour can be made with a first order model.

A thermal capacitance (J/K) involving the water contents and the structure mass is given by the boiler characteristics. In our simple model principle, this value is attached at some temperature between T_1 and T_{wsu}.

The dynamic heat balance of this model can be written as :

$$\varphi_1 \left(1 - \varphi_1\right) C_1 \frac{d\,T_{c1}}{d\tau} + \varphi_1\, \varepsilon\, \dot{C}_g \left(T_1 - T_{c1}\right) = \left(1 - \varphi_1\right)\, \varepsilon\, \dot{C}_g \left(T_{wsu} - T_{c1}\right)$$

where :
T_{c1} is the equivalent thermal capacitance temperature,
$\varphi_1 \sim 0.1 < 1$ a weighting factor.

In burner OFF operation, the best assumption based on the experimental fit, is $T_1 = T_{wsu}$.

Without entering in too much details, the boiler behaviour in cycling condition can be obtained by a simple linear interpolation on the burner time ON fraction.

In a more detailed model, T_{c1} could characterize very accuratly the hot point losses.[3]

Following this principle, the envelope losses in cycling conditions, has to be written :

$$\dot{Q}_{osses} = \left(Y_w + \Theta_{ON}\, DY_w\right)\left(T_m - T_i\right)$$

where Θ_{ON} is the time ON fraction of burner ON conditions,

3 MODEL PARAMETERS AND STANDARD TESTS

The boiler standard tests are rather simple : in general, one steady state test in continuous operation at standard temperature with the measurement of the temperature, and CO_2 or O_2 in flue gas at the chimney. The fuel and water flows are also measured, the fuel composition is known.

Thus the equivalent specific heat terms defined in 2.1 are known.

The useful heat is measured by an accurate heat balance on the water flow. [5].

For a very accurate fit of the parameters, another test is required in cycling conditions. Very often in the past, this test was performed with a null useful power and was called the environmental losses test.

The formulas expressing the direct relation between the standard test data and the model parameter are given in [3], [4], [5]. The improved formulation will be detailed in a further ASHRAE formulation will be detailed in a further ASHRAE technical paper.

4 MODEL OPERATIONS

As seen before, the boiler can operate in continuous or in cycling conditions

4.1 Continuous operation

Two different continuous mode are to be considered : burner ON mode and burner OFF mode.

In these two modes, the exhaust temperature T_{wex} can be computed in function of the supply temperature T_{wsu}.

Let, in burner ON condition T_H and in burner OFF mode T_L thus $T_H > T_L$.

Due to the aquastat control, the following constraints hold :

$$\text{burner ON mode } T_H \leq T_{aq}$$

$$\text{burner OFF mode } T_L \geq T_{aq} - DT_{aq}$$

where T_{aq} is the aquastat upper setting value and DT_{aq} the aquastat differential.

4.2 Cycling operations

The cycling operation occurs when :

$$T_H > T_{aq}$$

$$\text{and } T_L < T_{aq} - DT_{aq}$$

In these conditions the cycling burner ON ratio Θ can be computed, assuming that :

$$\overline{T}_{wex} = T_{aq} - (1 - \Theta)\, DT_{aq}.$$

$\overline{T}_{wex}$ is the time average of the water exhaust temperature over a cycle.

As shown on Figure 3, the true characteristic

$\overline{T}_{wex} = f\,(T_{aq}, DT_{aq}, \Theta$; boiler dynamic) is very close to this linear approximation. If we consider that the supply water temperature is given, it is simply :

$$\Theta = \frac{T_{aq} - DT_{aq} - T_L}{T_H - DT_{aq} - T_L}$$

4.3 Model operating curves

The main characteristics of the boiler can be summarized by a very simple set of equations.

$$\frac{\dot{Q}_V}{\dot{Q}_b} = \Theta \left[\varepsilon \left(1 - k_b\right) - K_D\right] - K_E$$

With the classical definition of the boiler efficiency η, one can also write :

$$\frac{\dot{Q}_V}{\dot{Q}_b} = \eta \ \Theta$$

$$\frac{\eta}{\eta_{ON}} = \frac{\Theta - \Theta_b}{\Theta\left(1 - \Theta_b\right)} < 1$$

with :

$\eta_{ON} = \varepsilon\,(1 - k_b) - K_D - K_E$ boiler efficiency in continuous operation, burner ON mode

$$\Theta_b = \frac{K_E}{\varepsilon\left(1 - k_b\right) - k_D}$$

Θ_b burner ON time ratio in environmental losses test ($\dot{Q}_u = 0$)

For given values of the water temperatures and all other values, this operating curve is linear as shown on figure 4 with the different previous meaning of the terms. For different conditions a complete set of operative lines can be generated with the same set of parameters, only if two points are given, anywhere on the network but at least one point must be given for $\Theta < 1$, for instance the environmental losses test.

5 CONCLUSIONS

As previously stated [3] [4], this type of model can be improved for condensating boiler and detailed dynamic behaviour analysis.

But, as given in this paper, the model takes into account very slight sensitivities, leading to a very accurate fit.

For a wide range of operations at very different water temperature, for different burner setting, the relative accuracy on the useful power is better than 1% [3] [4]. For very different continuous operations involving different burner setting, the accuracy reaches 0.1% for a classical domestic hot water boiler of about 20KW with the same set of parameters as defined for the proposed model [3] [4]. This model was developed at the CSTB on the previous base [4] [5] for the detailed analyses on an experimental building of Gaz de France Paris [6] [7]. During this experimentation, the measured data and simulation results will be compared for very different boilers operations for individual as well as for collective equipments

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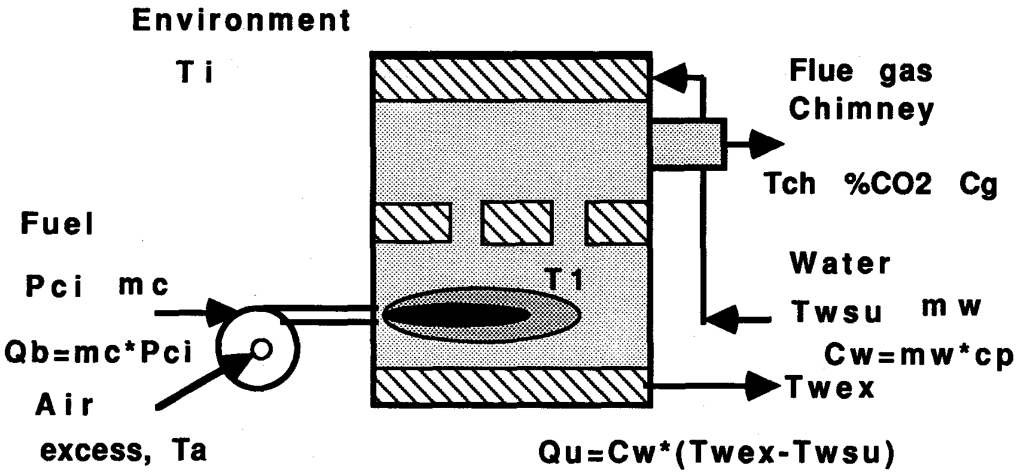

Figure 1. - Boiler schematic diagram.

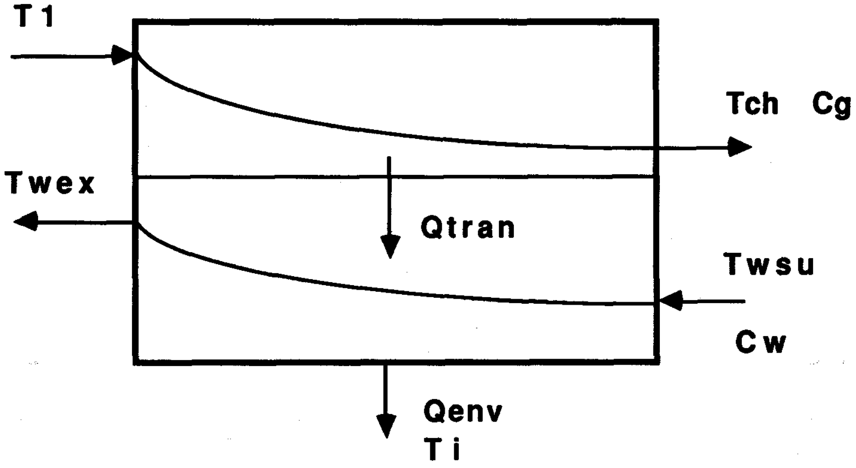

Figure 2. - Scheme of internal transfer.

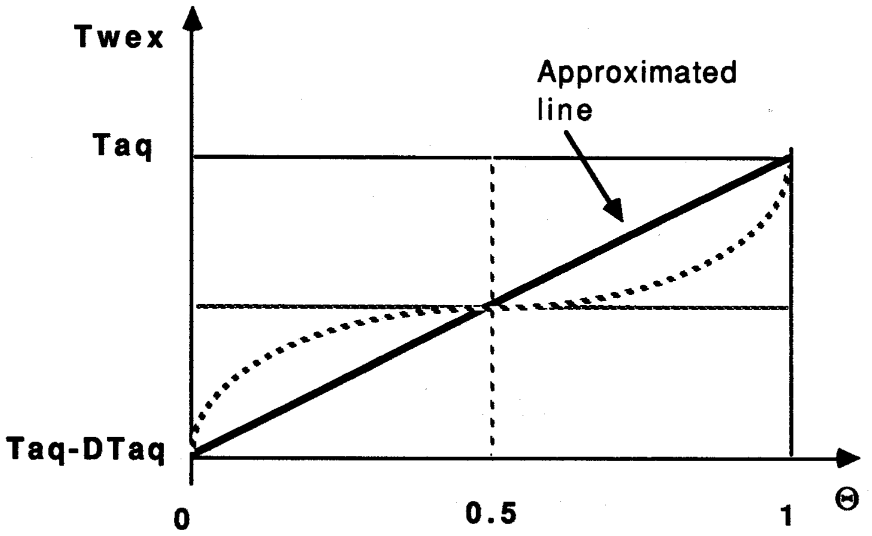

Figure 3. - Approximative aspect of the water exhaust temperature characteristics in cyclic operation.

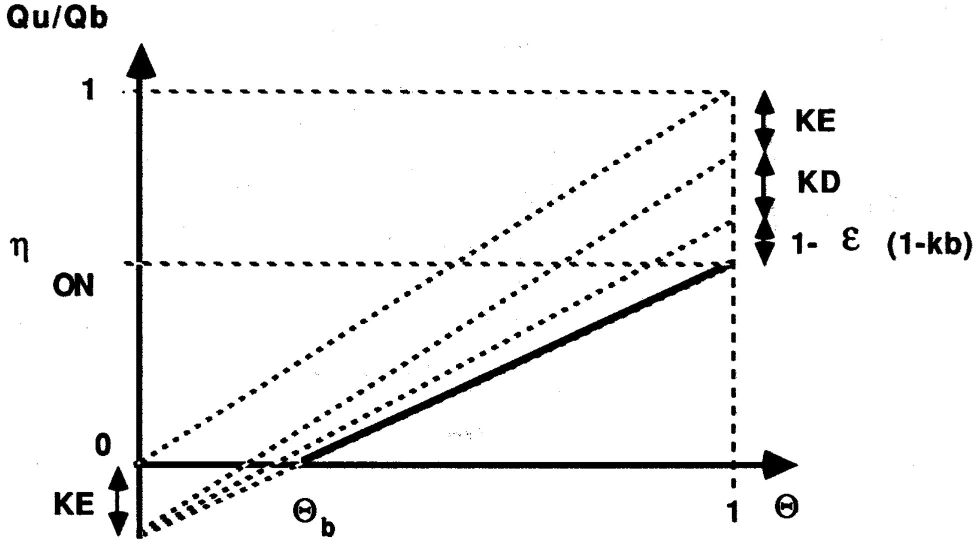

Figure 4. - Model principles : the operative curves for fixed conditions are linear.